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Improving Water Management in Rainfed Agriculture: Issues and Options in Water-Constrained Production Systems

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Executive Summary

Worldwide, more than 80 percent of the cropped area depends on rainfall alone. Rainfed agriculture is practiced in almost all hydroclimatic zones, and can be highly productive. However, in many dry subhumid regions, tropical semiarid and arid regions, as well as in some temperate regions yields tend to be relatively low. With highly variable rainfall, long dry seasons, recurrent droughts and dry spells as well as floods, water tends to be a key constraint for agricultural production systems in these regions. Especially in Sub-Saharan Africa, where 96 percent of the cropland is rainfed, erratic and sparse rainfall often combines with arid conditions, high temperatures, and shallow soils with poor nutrient status to provide extremely uncertain conditions for agriculture. Farmers, and especially the poor, are intrinsically risk-averse, and in these conditions they tend to adopt low-input strategies with limited yield potential even in good rainfall years.

The need to improve water management in water-constrained rainfed areas is often emphasized. In particular by increasing timely water availability and the water uptake of crops, yields can be significantly enhanced and agricultural productivity improved. Research has shown that better water management, coupled with improved soil and crop management, can more than double agricultural productivity in rainfed areas with currently low yields. With climate change and increasing food prices, even more emphasis needs to be placed on addressing water management in rainfed agriculture as a key determinant for agricultural production and productivity. However, governments and donors have tended to pay relatively little attention to this area, and investments remain low. During the last decade, for example, commitments to improving water management in rainfed agriculture in World Bank-supported projects amounted to less than 15 percent of the commitments to the irrigation and drainage subsector.

Improvements in agricultural water management can be categorized into four broad approaches (one physical and three non-physical), with each comprising a variety of measures. The most usual approach comprises soil and water management techniques, including structural measures (such as stone barriers, bunds or terraces) and in-field or agronomic practices (such as mulching, fertilizing, intercropping, crop rotation, agroforestry and reduced tillage). Many of these measures—such as terracing—have been practiced for centuries (and some for millennia); others, designed to serve less settled forms of agriculture, have been demonstrated to be beneficial locally, but few have spread spontaneously in the way that the varieties and practices of the Green Revolution have come to dominate irrigated agriculture through user-demand. Several research centers of the Consultative Group for International Agricultural Research (CGIAR), most importantly the International Centre for Research in the Semi-Arid Tropics (ICRISAT) and the International Centre for Agricultural Research in Dry Areas (ICARDA) as well as other research agencies, have focused for many years on developing ways to improve the productivity of these areas, and have documented a wide array of potential interventions, both indigenous and new.

Other non-physical approaches have also been discussed, and in some cases applied. An innovative approach that could help provide incentives to farmers for adopting soil and water management techniques is payment for environmental services (PES). Some physical interventions can have positive externalities on downstream users. For example, terraces are likely to reduce soil erosion and lead to less sedimentation in downstream reservoirs, and agronomic practices such as mulching do not only lead to better water retention, but also increased carbon stocks in the soil. While most PES schemes are fairly recent, very few exist that pay for changes in agricultural practices in developing countries. To a large extent this is due to administrative complexities, such as the problem of quantifying and monitoring the positive externalities, and high transaction costs.

A third approach is improved risk management, in particular risk-sharing strategies that help farmers cope with climate risks. These include forms of crop insurance that protect farmers from the impacts of poor weather, thus mitigating risk. The majority of these schemes, including both conventional indemnity-based insurance and the more recent index-based products, are targeted more at stabilizing income than inducing higher agricultural productivity. Furthermore, the administrative framework required is substantial: to document what area has been insured for which crop by which farmer; to apply criteria to determine situations where payments are appropriate; and to disburse payments effectively.

The fourth approach is provision of better climatic information. Since the primary problem faced by rainfed farmers is uncertainty regarding water availability, improvements in the prediction of seasonal rainfall, the onset of rains, or specific rainfall events must constitute valuable information. Satellite systems such as the Tropical Rainfall Measurement Mission provide near real-time data on rainfall patterns, but to date there are few documented studies to demonstrate the benefits derived from such systems in less developed areas—either because the evidence is hard to gather and interpret, or because the evidence is absent or not clear.

A review of the four approaches for improving water management in rainfed agriculture shows that while a few examples of successful interventions exist, progress in scaling them up is usually much slower than expected. Various barriers to their wider adoption have been identified. There is also a lack of quantification of their impacts in different settings, and almost no attempts to value them. Rigorous monitoring and evaluation of interventions to assess investment performance *ex post* has generally not been carried out. The use of advanced and well proven watershed-based models appears to offer a basis for estimating the impact of physical and non-physical interventions *ex ante* and hence for designing cost-effective approaches. Yet not many modeling studies have been carried out. This may perhaps reflect the complexity of the water-constrained agricultural production systems, but offers little assurance that enough insights are available to provide a robust framework for planning future interventions.

This is not an encouraging situation. Vast numbers of the world's poorest farmers depend on rainfall to derive a precarious livelihood, increasingly threatened by climate change. The development of non-agricultural employment or the expansion of irrigation services may not be possible, or will at best leave many unaffected, and may not even keep pace with population growth. Doing nothing for the many whose livelihoods will not be insulated from the vagaries of rainfall in the foreseeable future is not an option. Much has been invested in developing techniques and approaches that should significantly improve the potential productivity of rainfed agriculture, but this has not been matched by sufficient attention to improve upscaling.

Of the four approaches, only the first—and possibly the fourth—can be considered a direct “engine” of productivity growth in rainfed agriculture. The other two approaches are supportive indirect approaches, and are likely to only be effective if the “engine” works. It is therefore recommended that coordinated support for physical interventions be provided by national governments, based on recommendations with proven credentials from the international research institutions specializing in these areas, and with the help of donors. This initiative should be at a larger scale—thousands of hectares for ten years, not a few hectares for three or four years. Projected impacts should be significant—such as $100/ha incremental income for $500/ha investment, or similarly clear and well-defined targets.

Monitoring and assessment will be critical, and should not be based on the usual indicators of yield or net return per hectare, or farm income. With rainfall being erratic, it may be problematic to distinguish the pattern of variability in the different years before and after an intervention. The primary indicators of production—transpiration and biomass formation—can be measured by satellite, and compared, year by year, between project and non-project areas. If these indicators demonstrate significant differences, which should in any case be specified in advance by the “design” agency, then we can be confident that the growth engine works, and attention can shift to barriers such as, for example, marketing and seed availability in the local environment. If the engine does not work at scale, then the need for revised priorities for countries, donors and research institutes will be clear.

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Abbreviations and Acronyms

CGIAR	Consultative Group for International Agricultural Research
FAO	Food and Agriculture Organization of the United Nations
GEF	Global Environment Facility
ICARDA	International Center for Agricultural Research in Dry Areas
ICRISAT	International Center for Research in the Semi-Arid Tropics
IEG	World Bank Independent Evaluation Group
IFAD	International Fund for Agricultural Development
IITA	International Institute for Tropical Agriculture
IWMI	International Water Management Institute
PES	Payment for Environmental Services
SIP	Strategic Investment Program for Sustainable Land Management in Sub-Saharan Africa
WOCAT	World Overview of Conservation Approaches and Technologies

1. Introduction

The 2008 World Development Report on "Agriculture for Development" emphasized that in order for agriculture to meet future food demand, productivity improvements need to be achieved in both irrigated and rainfed areas (World Bank, 2007). There are two main reasons for the need to focus not only on irrigated, but on also rainfed production: First, the bulk of the world's agricultural production is rainfed. Of the 1.5 billion hectares of cropland worldwide, 82 percent is rainfed (FAO, 2006). In developing countries, rainfed agriculture accounts for 60 percent of agricultural production (World Bank, 2006). And, second, due to the growing competition for water and high investment costs in irrigation development, the scope for further expansion of irrigated agriculture is limited in many parts of the world (with a few exceptions, such as Sub-Saharan Africa).

Worldwide, rainfed agriculture is practiced in almost all hydroclimatic zones. The need for improving water management is greatest in dry subhumid regions, tropical semiarid and arid regions, but also some temperate regions where yields tend to be relatively low. Due to highly variable rainfall, long dry seasons, recurrent droughts and dry spells as well as floods, water management is often a key determinant for agricultural production and productivity in these regions. Yields can be significantly enhanced by improved water management. The 2008 WDR notes that better water management, coupled with improved soil and crop management can more than double agricultural productivity in rainfed areas with currently low yields. Investments in improved agricultural water management are in many circumstances catalytic—reducing the barriers to adoption of otherwise costly soil and crop management practices by increasing the returns to such investments (World Bank, 2007).

This report, which is based on Economic and Sector Work carried out in the Water Anchor of the World Bank, highlights the importance of improving water management in rainfed agriculture with a focus on those production systems where water is a main constraint.[1] It provides a synthesis of the state-of-the-art thinking and experience, including of the World Bank, with applying the different approaches and measures for improving water management. Considering the various issues that are currently preventing further upscaling of these measures, and better evaluation of the feasibility of applying particular measures or combination of measures, the report proposes options and recommendations for interventions to help overcome these issues. In doing so, the report aims to stimulate discussion and encourage new thinking among World Bank staff and counterparts in client countries who work on enhancing agricultural

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[1] There are also rainfed systems where the main task of water management is to provide for adequate discharge of excess water. They are outside the remit of this report.

productivity and livelihoods in rainfed agriculture through improved water management and related interventions.

The report is organized as follows: Chapter 2 outlines the significance of agricultural production systems where water provided by rainfall is a major constraint to increasing productivity. It also highlights key characteristics of such production systems, and common and often misguided perceptions on the options for overcoming the water constraint. The four main approaches for improving water management are outlined in chapter 3, with more details provided in the four Annexes. Based on a portfolio review of Bank-supported operations between fiscal year 1999 and 2008, the World Bank experience with these approaches is discussed. Chapter 4 reviews the various barriers to the wider adoption of the main approaches, and the key knowledge gaps that further constrain the design of effective interventions. This is followed by chapter 5 which sketches a possible way forward that seeks to overcome some of the constraints experienced in the past.

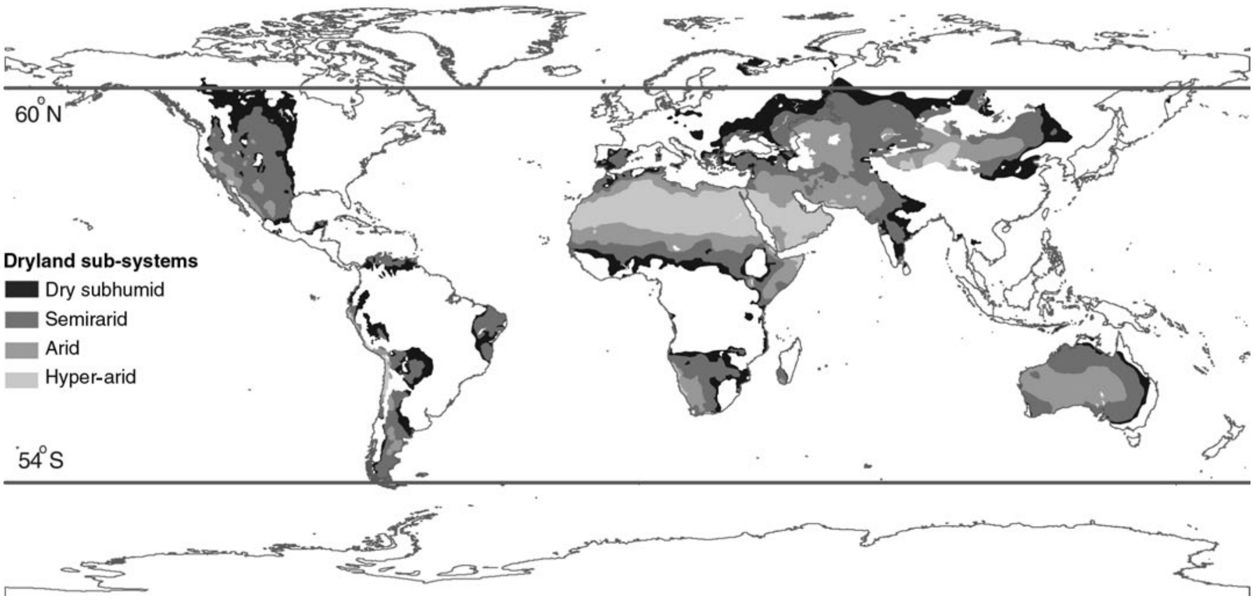
2. Importance of Improving Water Management in Rainfed Agriculture

2.1 Significance of Rainfed Agriculture with Water as a Key Constraint

Worldwide, more than 80 percent of the cropped area depends on rainfall alone. The significance of rainfed agriculture varies regionally. In Latin America around 87% of the cropland is rainfed, in the Middle East and North Africa 67%, in East Asia 65%, and in South Asia 58%. Rainfed agriculture is most prominent in Sub-Saharan Africa where 96% of the cropland is rainfed (FAO, 2002).

Rainfed agriculture is practiced in almost all hydroclimatic zones, and can be highly productive. For example, much of Europe achieves exceptionally high levels of productivity, almost entirely based on rainfall.[2] However, in many dry subhumid regions and tropical semiarid and semiarid regions (as well as in some temperate regions) yields tend to be relatively low. These regions are often referred to as dryland sub-systems. Drylands occur on all continents, and cover about 41 percent of the earth's land surface (Figure 1).

Figure 2.1: Extent of Dryland Sub-Systems



Source: Niemeijer et al., 2005.

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[2] In the United Kingdom, the average yield of wheat is 7 to 8 tons per hectare—amongst the highest in the world—based entirely on rainfall. The country's dominant use of irrigation is on potatoes to ensure that they are uniform in color and suited to supermarket shelves. Yield per hectare is hardly affected by this process, but income per hectare is greatly improved.

Drylands are limited by soil moisture, the result of low rainfall and high evaporation, and show a gradient of decreasing primary productivity, ranging from dry subhumid, semiarid and arid to hyper-arid. Of the total area of drylands, dry subhumid, semiarid, arid and hyper-arid sub-systems cover 21%, 37%, 26% and 16%, respectively. The sub-systems differ in the degree of water limitation they experience. Aridity indices[3] are 0.50-0.65, 0.20-0.50, 0.05-0.20, and <0.05, respectively. About 25% of the world's drylands are croplands, 65% are rangelands, and the remaining 10% other areas (such as inland water systems and urban areas). Croplands and rangelands are often interwoven, supporting mixed, integrated pastoral livelihoods. Due to increasing populations, a transformation from rangelands to croplands is occurring in many areas.

About a third of the world population live in dryland areas, including 43% in dry subhumid, 40% in semiarid, 11% in arid, and 5% in hyper-arid areas. Dryland populations, about 90% of whom live in developing countries, lag on average significantly behind the rest of the world in human well-being and development indicators (Niemeijer et al., 2005).[4]

Current water management challenges in water-constrained rainfed production systems are expected to intensify. Combined with other drivers of change, such as population growth, climate change will increase the need for improving water management in such areas. Climate projections indicate that water resources have the potential to be strongly impacted by climate change. Likely impacts in many areas include changing precipitation patterns, intensity and extremes; reduced snow cover and widespread melting of ice; and changes in soil moisture and runoff. Agricultural productivity in rainfed areas depends critically on the temporal and spatial dynamics of precipitation, which needs to be sufficient to meet evaporative demands and associated soil moisture distribution (IPCC, 2008). Where this is likely not the case, such as in arid and semi-arid regions, rainfed agricultural production is very vulnerable to climate change (World Bank, 2008a).

The recent rise in food prices adds to the urgency of enhancing yields of rainfed crops through better water management. Due to a number of factors, food prices have accelerated sharply in 2008, and are expected to remain high in the medium-term. This rise is already showing severe adverse effects, threatening recent gains in overcoming poverty and malnutrition (World Bank, 2008b). One of the core pillars of an integrated global response to the food crisis in the medium-term is to provide financial and

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[3] Aridity index values lower than 1 indicate an annual moisture deficit. Drylands are defined as having aridity indices below 0.65, implying that mean potential evapotranspiration is at least 1.5 greater than annual mean precipitation.

[4] According to the 2008 World Development Report, one third of the developing world's rural population, or 820 million people, live in less favored rainfed regions, characterized by frequent moisture stress (arid and semi-arid regions) (World Bank, 2007).

technical support for stimulating an agricultural supply response, including for water-related investments (World Bank, 2008c). Accordingly, World Bank's Global Food Prices Response Program created in 2008 seeks, in the medium-term, to facilitate an agricultural supply response and help farmers to better cope with risk.

2.2 Characteristics of Water-Constrained Rainfed Production Systems

In water-constrained rainfed production systems, rainfall (or, more broadly, climate) driven variability leads to low and unstable production and productivity, and is often the dominant source of income and consumption risk for farmers (Dercon, 2002; Zimmermann and Carter, 2003). Climate driven fluctuations in production contribute substantially to the volatility of food prices, particularly where remoteness, the nature of the commodity, transportation infrastructure, stage of market development, or policy, limit integration with global markets. Because market forces tend to move prices in the opposite direction to crop production fluctuations, variability in food crop prices tends to buffer farm incomes, but exacerbates food insecurity for poor consumers.

Several relationships that determine the productive potential of rainfall during the growing season of a crop should be kept in mind when discussing possible interventions for improving water management in rainfed agriculture. Box 2.1 presents terminology. If rainfall is less than crop water requirement, then actual yield will be less than potential yield. Equally important is the distribution of rainfall. If rainfall fulfils 70% of crop water requirements *every day*, then a good yield is possible, but if rainfall is 100% of crop requirements for 70% of the growing season and zero for the rest, the outcome will be quite different. Moreover, the impact of variable rainfall is strongly affected by the nature of the soil and the stage of the growing season. If the soil is capable of storing a large quantity of water in relation to crop demand, then a break in rainfall of a week or more may be tolerable, especially late in the season when the roots are well developed. Conversely, in an arid climate where daily demand is high, crop sensitivity to breaks in the rainfall, especially early in the season, is very high.

An additional complication is that, while biomass varies directly with transpiration (Howell, 1990; Perry et al., 2009), the proportion of grain or fruit in total biomass (the harvest index) is sensitive to when water stress occurs (Fereres and Soriano, 2007). A break in the rainfall at a critical stage in crop development will be far more damaging to eventual yield than a break at another stage.

Box 2.1 Water in Rainfed Agriculture—Some Terminology

Crop transpiration. In order to grow and produce grain, fruit or fibre, crops take water from the soil and transpire it into the atmosphere. As the water vapor passes out through the stomata, carbon dioxide is absorbed and provides the basis for biomass formation. Rates of transpiration and biomass formation are thus directly linked.

Crop water requirement. This is normally defined as the total quantity of water that a crop would transpire if water is freely available and nutrients are adequate. These circumstances lead to maximum yield per hectare; lower yields occur when water and/or nutrients are limited (but also when water supply is excessive).

Evaporation. When the soil of plant foliage is wet, water evaporates directly into the atmosphere without passing through the plant and without contributing to biomass formation. Recognizing that it is often difficult to measure evaporation and transpiration separately, and also that some amount of evaporation is inevitable, it is common to refer to crop 'evapotranspiration'. Conceptually, however, it is important to make the distinction.

Potential evapotranspiration. The potential rate of evapotranspiration is dependent on climate, and is particularly sensitive to temperature, windspeed, and aridity. In very dry, hot climates, potential evapotranspiration may approach 10mm/day. In cooler, more humid areas, the norm is closer to 2mm/day.

Rainfall. The total quantity of rain that falls during the cropping season goes to either of the following:

- (i) soil moisture: some rainfall infiltrates into the soil profile where it remains, available for uptake by the roots of the crop, subject to the depth to which the roots have penetrated the soil;
- (ii) deep percolation: once the soil matrix is full, further infiltration forces water below the root zone, possibly contributing to groundwater recharge; or
- (iii) runoff: if rainfall is at a rate faster than infiltration, it forms surface runoff, possibly contributing to streamflow.

Productivity. This term can be referenced to many variables. Most commonly, yield per hectare is quoted as the primary indicator of productivity—and in the case of purely rainfed agriculture, where production depends on the combination of land and rain falling onto the land, yield per hectare is a key indicator. However, as water is progressively "managed", from mulching to reduce evaporation through to water harvesting and irrigation, the productivity of water defined as yield per amount of evapotranspiration also becomes of interest, both because an increase in total local evapotranspiration may have downstream impacts, and because how the managed water is combined with the (unmanageable) rainfall strongly affects total production.

While all rainfed farmers face a certain risk due to rainfall variability, the risk increases when the amount of rainfall is usually low in relation to crop water requirements; when rainfall occurs erratically and in a few events that contribute largely to runoff; when long gaps between rainfall events are frequent; when soils are not retentive; and when daily crop water requirements are so high that soil moisture storage is rapidly depleted.

Farmers adopt strategies to avoid, mitigate or minimize risk arising from rainfall variability. In a recent study to explore farmers' strategies, maximum potential yields, modeled potential yields for actual rainfall patterns, and actual/observed yields per hectare achieved by farmers growing rainfed wheat in Australia were compared (Passioura, 2006). Results for modelled potential yields showed that farmers could have achieved significantly higher yields than they actually did in most seasons—sometimes close to the maximum potential yield. In fact, observed yields were relatively insensitive to rainfall above a certain level because farmers chose an input strategy (seed type, seeding rate, fertilizer use, etc) that ensured profitability for 'typical' conditions. When rainfall was particularly good, observed yields were marginally better—even though potential yields could have been substantially higher, but production was limited by the chosen level of inputs. This illustrates that farmers in a risky environment tend to balance the possible benefits from adding extra inputs against potential losses if rainfall is poor and input (and other) cost exceed the value of the crop. *Ex post*, once the actual rainfall pattern is known, it is not difficult to determine the optimum farming strategy, but the problem arising for farmers is to make decisions *ex ante*.

3. Interventions for Improving Water Management

3.1 Main Approaches

Efforts to increase yields and enhance productivity in rainfed agriculture often critically depend on improvements in agricultural water management (World Bank, 2007). Such improvements can be categorized into four broad approaches, each comprising a variety of measures: (i) promoting on-farm and communal soil and water management techniques that help increase water availability and crop water uptake; (ii) accounting for positive externalities through payment for environmental services (PES); (iii) improving agricultural risk management so that farmers can better cope with climate risks; and (iv) providing better climatic information to farmers, including on droughts and dry spells, to help them make the necessary anticipatory adjustments. The first approach can be considered to comprise physical interventions, while the other three approaches are non-physical.

In the past, most attention has been paid to the first approach, in particular structural measures among the various water and soil management techniques. More recently, nonstructural measures related to water and soil management, as well as improved risk management and better provision of climatic information, are increasingly being emphasized. Below the four approaches are discussed in more detail.

3.1.1 Promoting Soil and Water Management Techniques

The most common approach to manage water under rainfed conditions are soil and water management techniques. Farmers have adopted many of these techniques, such as terracing, over thousands of years. Different authors have suggested a number of classifications for the different techniques which range from bench terraces through various types of ridging to in-field earthworks and mulching. Generally, the techniques have all been well-documented in terms of design and applicability to various situations—indeed the review of the literature in Annex 1 suggests that much has been written, forgotten, and rewritten over the years.

A useful classification of the soil and water management techniques is to distinguish between structural measures, such as stone barriers, bunds, or terraces; and in-field or agronomic practices, such as mulching, fertilizing, intercropping, crop rotation, agroforestry, and reduced tillage. Depending on the amount of rainfall available, the potential evapotranspiration, and the cropping system, these techniques can achieve one or more of three strategies (Narayana and Babu, 1985, quoted in Hudson, 1987): (i) to provide discharge of excess water; (ii) to retain rainfall *in situ*; and (iii) to harvest rainfall from a wider area. The first strategy, for example, is generally achieved with terraces or bunds with later gradient which allows excess runoff to flow out of a system at speeds that do not permit it to carry significant sediment. The second strategy typically comprises earth or stone structures, or vegetative barriers on the true contour, thus acting as barriers to flow of runoff or sediment. The third strategy is made up of systems that guide runoff from a catchment to be stored in the soil of a cultivated area, or into a pond from which supplementary irrigation is drawn.[5] The focus in the context of this report is on the second and third strategies.

From a watershed perspective, the distinction between water retention and water harvesting may be important. Water harvesting implies that water from a larger area is captured and concentrated on a smaller, cropped area thus increasing the water available per unit of *cropped* land. If the land from which water is harvested does not belong to the farmer, then at some point the issue of water rights will arise, with consequent legal implications[6]. Retaining rainwater *in situ* on the cropped land does not have such implications[7], but given that the farmer's objective is to maximize the runoff of potentially damaging storm water and/or to retain for plant consumption as much as possible of the rest, it is clear that downstream impacts are likely to be negative—excess flows are enhanced, and low flows are reduced by most physical interventions. But there can be many variations. First, farm practices that reduce evaporation are broadly neutral, in that the objective is to “transfer” non-productive evaporation into productive transpiration so that total evapotranspiration remains constant while crop production increases. Second, when natural vegetation is cleared for rainfed farming, the impact is generally decreased evapotranspiration and increased runoff, often with negative erosion and sedimentation impacts. The downstream impacts of *introducing* rainfed agriculture may thus typically be an increase in downstream water quantity and sediment load. The impact of *improving* rainfed farming will typically be the reverse.

The more substantial physical interventions (contour bunding, terracing, small storages) will tend to make more significant impacts on streamflows, but the impacts from scattered interventions are unlikely to be measurable at catchment scale.

Agencies have been working for decades on a national, regional and international basis to increase agricultural productivity in water-short areas, including CGIAR institutions such as the International Center for Research in Semi-Arid Tropics, and the International Centre for Agricultural Research in Dry

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[5] ‘Supplementary irrigation’ describes a system where strategic applications of water are made at key stages in the crop’s growth period.

[6] In Yemen, runoff rights are a recognized legal entitlement, and while another farmer may graze animals on such land, any intervention that disturbs the natural relationship between rainfall and runoff will be challenged.

[7] South Africa's National Water Law is perhaps unique in recognizing “streamflow reduction activities” such as forestry as a consumptive and potentially chargeable use of water.

Areas (ICARDA); the Food and Agriculture Organization of the United Nations (FAO); the network World Overview of Conservation Approaches and Technologies (WOCAT) which has been collecting information for some 15 years; and various other agencies.

However, while the results of this work has been many demonstrations of local success, the overwhelming “message” from the literature over the last 25 years is of failure to achieve widespread, spontaneous adoption of promising techniques on a large scale (see Annex 1, and section 4.1). When farmers are presented with an intervention that makes sense in terms of risks and returns, they will adopt it—as they have adopted myriad water management and other agricultural innovations over the centuries. If farmers do not adopt these techniques, it is urgent to trace the reasons for this and judge critically whether the problem is resolvable at reasonable financial, institutional and social costs. For example, insecurity of land tenure will greatly reduce a farmer's incentive to invest in physical works to improve water availability, and even to adopt agronomic practices (such as mulching or zero tillage) where an element of the benefit is long term improvement in soil structure.

3.1.2 Payment for Environmental Services

An innovative approach that could help improve farmers’ incentive for adopting soil and water management techniques is PES. The concept of PES has been a topic of some interest in recent years. Annex 3 provides a review of the literature on PES in the context of improving water management in rainfed agriculture.

PES related to water management is based on the fact that activities in one part of a watershed may have implications for other parts of the watershed. For example, soil and water management techniques such as terraces are likely to reduce soil erosion and lead to less sedimentation in downstream reservoirs, and/or to change the pattern of runoff. If an upstream farmer’s intervention improves the situation of the downstream user (i.e. if a positive externality is generated), there may be scope to monetize the benefit to the downstream user in the form of a payment to the upstream farmer, potentially to the benefit of both parties as well as to the environment—a win-win-win scenario (World Bank, 2009a.

Some soil and water management techniques also provide other, non-hydrological services. The most pronounced gains are carbon benefits from organic or non-tillage farming. Soils with increased carbon stocks have higher water retention, providing a clear synergy between the two environmental services on hand.

If carbon markets could subsidize the successful adoption of soil and water management techniques, this could potentially lead to both climate benefits and poverty alleviation. Some World Bank pilot projects paying for soil carbon enhancement have been implemented in Kenya, and plans for a larger-scale Agricultural Soil Carbon Investment Facility exist (World Bank, 2009). However, a global mapping exercise by FAO indicates that Africa only provides scattered opportunities; mainly in East Africa (FAO, 2007).

Other potential off-site benefits are unlikely to be large enough to constitute driving forces for PES mobilization in developing countries: increasing organic matter in agricultural soils benefits biodiversity; tourists appreciating traditional rice terraces; wildlife parks and wetlands are all desirable but difficult to evaluate in relation to (often distant) off-site activities that help preserve their valued features.

In sum, the band of positive externalities that could potentially be sold to downstream users appears to be fairly narrow. There are water quality benefits from particular interventions that reduce erosion and sedimentation (most commonly from afforestation measures), which have triggered payments elsewhere in the world, including in some developing countries. Yet very few PES schemes exist in developing countries that pay for changes in agricultural practices.

Most improved land management practices come along with significant carbon benefits, which could be further enhanced, in case they are to be remunerated. Currently, changed land management practices are not eligible under the Clean Development Mechanism, but are being sold in some voluntary carbon markets. Biodiversity and recreational benefits are likely to be minor. As noted in the previous section, carbon-related benefits and water quality improvements may in some cases have to be weighed against diminished water quantity flow downstream.

In terms of practical implementation, quantification and verification of the impacts that would trigger PES pose particular problems in countries where rainfed farming is scattered and sparse, information systems on current land use patterns are poorly developed, and institutions are over-stretched—and as described in the previous section, land tenure may not be clearly enough defined to precisely link areas and interventions to outcomes and hence payments for service. In such conditions, the scope for PES, beyond narrow and clearly definable situations (for example, land use patterns upstream of urban areas that are prone to flood damage) are unlikely to be a major contributing factor to improving the livelihoods of rainfed farmers.

And finally, it is important to be aware of the reaction of farmers to new technologies that allow them to increase their incomes with less negative impacts on the environment. Conservationists sometimes argue that this would create positive spillover effects on the environment: using an intensified cropping technique, farmers would need less land, and thus (for example) slow down or stop the clearing of new lands. The underlying assumption is that farmers would only produce what they need to survive, or at least up to some target-revenue production, and then prioritize leisure. However, when farmers see a profitable opportunity (and face no other constraints), they may allocate more resources to it in order to increase profits, for example, by expanding the intensified production method into new areas, including by chopping down forests. This may in the worst case create more, rather than less environmental pressure, and the assumed agricultural ‘win-win’ options can become victims of their own success. Net impacts depend on many factors, but in most cases of the 25 large-scale interventions for which data are available, technologies for agricultural intensification actually increased deforestation (Angelsen and Kaimowitz, 2001).

3.1.3 Improving Risk Management

In many drylands , erratic and sparse rainfall often combine with arid conditions, high temperatures, and shallow soils with poor nutrient status to provide extremely uncertain conditions for agriculture. In these conditions, a rational response of a risk-neutral farmer would be to limit input levels[8] to an amount that would be appropriate for a ‘typical’ production resulting from an expected ‘typical’ rainfall. From year to year, production will vary; if rainfall is below expectation, production will be lower and the chosen input level will have been excessive. If the rainfall is exactly as expected, the input level will be appropriate and production close to the optimum; and if the rainfall exceeds the expectation, higher levels of input would have led to a higher production.[9]

There are two distinct reasons to consider interventions to limit risk: The first reason is to stabilize income—the farmer pays a premium that guarantees higher income in the poor rainfall year. The second reason, which is of more relevance here, is where it is clear that higher input levels would lead to an increase in the average net value of production (i.e. the extra value of production in good years would more than offset the cost of unproductive, excess input levels in poor years) but the farmer is not prepared to make that investment because his or her utility preference between potential losses and profits leads to a lower level of input use. In this case a scheme to subsidize inputs, or increase the price of produce, so as to align the farmer's preferences with the optimum productivity package, might be considered. While

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[8] Input levels is used here as a generic term to reflect seed selection, planting density, the application of fertilizers and other chemicals, as well as crop husbandry in general.

[9] A more sophisticated discussion of the impacts of the uncertainty associated with climate variability on farmer decisions is in section 2.2 of Annex 4.

the first of these two objectives may be socially desirable, only the second leads directly to production gains[10].

An overview on agricultural risk management with a focus on risk-sharing strategies that help farmers cope with climate risks is provided in Annex 3. It indicates that while the theoretical basis for intervention is strong, the practical examples—especially in developing countries, and particularly in Sub-Saharan Africa—are few. They are dominated by schemes which are designed primarily to achieve income stabilization, with production a secondary objective at best.[11] This includes both conventional insurance (where farmers pay a premium and receive an indemnity after an insured loss occurs—after loss adjustment and correction for deductibles, if any) and the more recent index-based products (where farmers are paid, based on realization of an underlying index relative to a pre-specified threshold, such as average crop yields per unit area) (Barnett et al., 2008).

After assessing these schemes and the data on their impact, it is concluded that the available evidence does not answer questions such as “who benefits from a subsidized insurance scheme?” and “do farmers need government-provided risk protection via insurance?” Additional indicators would clarify these matters, such as the effect that insurance has on farm household income fluctuations. Such ex-post empirical analyses seem, however, not to be available in literature.

In sum, interventions to reduce risk require strong institutional arrangements to avoid inappropriate payments; clearly specified objectives and criteria; and a clear definition of the beneficiary group—farmers benefit directly; their suppliers and the rural community benefit indirectly.

The reported outcome of the various income stabilization schemes is mixed—success, so far in an Indian scheme related to rainfall; limited uptake in Australia; failures in several other countries. More importantly for the purposes here, there are virtually no data on the potential to model and design interventions that will act directly to change farmer incentives and induce higher productivity in rainfed agriculture by influencing how farmers perceive and respond to uncertain rainfall.

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10 It may be argued that income stabilization will also enhance input levels, but the rationale for the intervention is not based on quantitative estimation of the costs and benefits of a change in the level of input use.

[11] This is also indicated in the titles of some of the risk management instruments discussed, including “net income stabilization accounts”, “group risk income protection”, “agricultural income disaster assistance”, “Canadian farm income program”, “Canadian agricultural income stabilization”, “multiple peril crop insurance”, and “group risk plan”.

3.1.4 Providing Better Climate Information

"Climate information" includes information related to a continuum of time scales—such as, what is currently happening; what will happen in the next few days; and what will happen during the season, or over the next decade. Information at these different scales can assist farmers in different climate-sensitive agricultural decisions. To be useful and have value, the climate information must match the time horizon of the particular decision (Table 3.1).

Table 3.1. Climate-Sensitive Agricultural Decisions at a Range of Temporal and Spatial Scales

Farming decision	Frequency (years)
Scheduling of e.g., planting, harvest operations	Intraseasonal (> 0.2)
Tactical crop management (e.g. fertilizer, pesticide use)	Intraseasonal (0.2 – 0.5)
Crop selection (e.g. wheat or chickpeas) or herd management	Seasonal (0.5 – 1.0)
Crop sequence (e.g. long or short fallows) or stocking rates	Interannual (0.5 – 2.0)
Crop rotations (e.g. winter or summer crops)	Annual/bi-annual (1 – 2)
Crop industry (e.g. grain or cotton; native or improved pastures)	Decadal (~ 10)
Agricultural industry (e.g. crops or pastures)	Interdecadal (10 – 20)
Land use (e.g. agriculture or natural systems)	Multidecadal (20 +)
Land use and adaptation of current systems	Climate change

Source: Meinke and Stone, 2005.

The most important decision time scales for rainfed annual crop farmers range from a few days to the following season. While longer time scales (i.e., one to two decades) may influence farm decisions, they are more likely to influence institutional and policy decisions (e.g. plant breeding programs, market development, investment in infrastructure) that influence options and incentives for farmers. Identifying the time horizon of climate-sensitive decisions, and mapping those made annually onto a decision calendar are useful initial steps when identifying climate information needs and opportunities to improve information services.

The potential for value is most obvious for advance information (i.e. forecasts). Historic climate records can have value if they correct biased perceptions of the climatological distribution, for example, where a farming population is new to a region, or where decadal climate variations or climate change have shifted the distribution of climatic conditions. .

To be useful, raw climate information must be translated into impacts and management implications within the system being managed, either through subjective expertise or intuition, or through quantitative methods including statistical and process-oriented models. Value-added climate information that is relevant to rainfed agriculture includes estimates of sowing conditions, crop phenological stage, soil water content, soil temperature, crop water stress, (supplemental) irrigation requirements, and pest and disease risk. More detailed discussions can be found in Annex 4.

Many countries attempt to provide climate information, particularly related to planting dates in monsoon climates and outlooks for seasonal rainfall levels, and these can often be accessed through the World Agro-Meteorological Information Service website. New sources of information are constantly arriving, in particular from remote sensing (satellite) sources. The Tropical Rainfall Measurement Mission provide near real-time information on rainfall patterns for most of the developing world, offering high potential to improve near-term forecasts of rainfall events.[12]

While value of climate information can be theoretically demonstrated, more evidence of development impact for rural climate information services is still needed to mobilize sustained political, financial and institutional support. A weak body of evidence relative to other agriculture-related interventions is due to: (i) the newness of seasonal prediction; (ii) the lag time required to quantify impact particularly in the face of a stochastic driver; (iii) widespread institutional failures that have constrained use beyond pilot projects; (iv) neglect of impact assessment for established agro-meteorological information services and by proponents of seasonal forecasts; and (v) early studies that identified, but didn’t seek to overcome, constraints to using existing operational products. Pilot studies that address known barriers to accessing and using multiple forms of climate information for agricultural management should be oriented toward providing credible, quantitative evidence of their use and value.

3.2 Experience under World Bank-Supported Projects

In order to explore to what extent commitments to agricultural water management have been made in rainfed agriculture, and how the four approaches for improving water management in rainfed agriculture have been considered in World Bank-supported projects, a portfolio review was carried out for projects approved between fiscal year 1999 and 2008. The review was based on an analysis of the Project Appraisal Documents (PADs). It identified 73 projects with relevant text on improving water management in rainfed agriculture in the text. The list of projects is in the Appendix.

The total commitment of the portfolio amounts to \$3.9 billion, of which about 15% (\$613 million) has been allocated to activities related to water management in rainfed agriculture. In about half of the

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[12] See, for example, http://trmm.gsfc.nasa.gov/trmm_rain/Events/thirty_day.html

projects, the share of the commitment dedicated to water management in rainfed agriculture is less than 10%. Compared with the overall commitments for the agricultural sector during the 10-year period, the amount allocated to water management in rainfed agriculture accounts for about 4.5% (while commitments to irrigation and drainage account for a third).

About half of the commitments to water management in rainfed agriculture are focused on the Africa Region, followed by the South Asia and the Middle East and North Africa Regions. Ethiopia and India are the main recipients, followed by Tanzania, Kenya, China, and Yemen.

The projects with activities on water management in rainfed agriculture cover a wide spectrum. Priority issues most often mentioned in the project development objectives are poverty reduction, agricultural development, natural resources management, watershed development, community development, and rural development. Climate change is mentioned once.

Of the four main approaches discussed in section 3.1, the promotion of soil and water management techniques is included in the activities of almost all projects (70 out of 73). A wide variety of techniques is promoted, sometimes without specifying them. For almost half of the projects harvesting water is the main purpose for promoting these techniques, and for 29% retaining water *in situ*. Minimizing soil loss is mentioned in 41% of the projects. No information on the purpose is provided in 30% of the projects.

Accounting for environmental services is recognized as relevant in 62% of the projects. The most frequently cited positive externality is erosion control, followed by increase in groundwater recharge, carbon sequestration, decrease in flood damage, and flow regulation. However, the third approach, PES, is not included in any of the projects.[13] Payment for carbon sequestration has also not yet been included, but benefits of carbon sequestration have been estimated for two projects (in Kenya and Rwanda).

The third approach with measures for improving risk management, in particular climate risk management, is part of three projects: with conventional crop insurance in Kazakhstan, and index-based weather insurance in Ethiopia and Malawi—in the latter case including derivative contracts.

Finally, the fourth approach with better hydroclimatic information provision is incorporated with drought early warning systems and contingency plans in three projects (weather stations and drought studies in Morocco, and improvements in data collection systems in Ethiopia and Kenya); and with early warning systems, including data collection and modeling of climate impacts on agriculture, land cover and floods

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[13] Several forestry-related projects, especially in the Latin America Region, include arrangements for payment for environmental services.

in another three projects (India, Malawi and Mozambique). But no project has focused specifically on providing seasonal forecasts, or making adequate information available to rainfed farmers.

Packages of other agriculture-related interventions are included in almost all projects promoting soil and water conservation techniques (such as better access to markets and information, and seed improvement). The most comprehensive packages tend to be in projects focused on watershed and natural resources management, poverty reduction, and rural development.

4. Issues Related to Improving Water Management

4.1 Removing Barriers to Adoption

A widespread view in much of the literature on rainfed agriculture within water-constrained regions is that there is a large, untapped potential for upgrading systems through improved water management. A review and synthesis of this literature is provided in a chapter of the Comprehensive Assessment of Water Management in Agriculture prepared by the International Water Management Institute (IWMI) (Molden, 2007). It states: "There is generally enough rainfall to double and often even to quadruple yields in rainfed farming systems, even in water-constrained regions. But it is available at the wrong time, causing dry spells, and much of it is lost. Apart from water, upgrading rainfed agriculture requires investments in soil, crop, and farm management. However, to achieve this, rainfall-related risks need to be reduced, which means that investments in water management are the entry point to unlock the potential in rainfed agriculture" (Rockström et al., 2007, p. 316). The main argument for this view is that, especially in large parts of the semiarid and dry subhumid regions, it is not so much the absolute amount of rainfall but rather its distribution within the season and extreme variability that is the key limiting factor to improved yields in rainfed agriculture. This can be overcome with increased attention to managing runoff water, using various water harvesting measures, for supplying supplemental irrigation water to rainfed production targeting the critical stages of crop development.

Water harvesting, supplementary irrigation, and other water, soil and crop management techniques have been used in many countries, including traditional and introduced techniques. Ample evidence exists that these techniques have the potential to significantly boost yields and agricultural productivity (see, for example, Oram and de Haan, 1995; Oweis et al., 1999; and Oweis and Hachum, 2003). Successful dryland area development interventions and water conservation programs are illustrated in Reij and Steeds (2003). De Fraiture (2005) discusses many other techniques, including sloped maize fields in Tanzania, farm ponds in Burkina Faso, *guimelther* in Cameroon, intercropping and silt traps in Ethiopia, small ponds in Burkina Faso, infiltration pits in Zimbabwe, *majaluba* in Tanzania, and traditional techniques in Malawi, Sudan, Syria, and Uganda. IFAD (2007) reports on recent case studies from eastern and southern African countries, and WOCAT (2007) provides in-depth analyses of soil and water conservation techniques practiced worldwide (see also the examples in Annex 1, Part 2.).

At the same time, there is a long-standing concern about farmers' low rate of adoption of many of the techniques and measures (see, for example, IFAD, 1992; WOCAT, 2007). A wide range of barriers preventing wider adoption have been identified and discussed. Critchley in Annex 1 summarizes this literature as follows: "A recurring theme amongst all analysts, is to identify problems associated with a top-down, technocratic, transfer of technology mentality. Amongst the other points highlighted are: an over-emphasis on engineering approaches; failure to train farmers in simple surveying techniques; the use of catchments (watersheds) as the unit of intervention rather than the community; ignoring indigenous knowledge and traditions; and failure to develop partnerships and alliances. Furthermore there is the need to look upon growth in population density as a potential opportunity; the importance of considering livestock while planning improvements in small-scale farming; the danger of becoming obsessed with "quick-fix" technical solutions; an obsession with the benefits of trees (ignoring their potential negative impacts, for example on hydrological regimes and on erosion where undergrowth is suppressed); the misuse of incentives to participating communities, especially the uncritical use of food-for-work, inducing a culture of dependence; and the unrealistic over-funding of small projects which cannot realistically be replicated on a large scale" (p. 23).

The various barriers have also been clustered as follows (Hudson, 1991; GEF, 2007): (i) project design barriers (such unclear objectives and ill-defined, unobtainable targets; rigidity in project design preventing adaptation during implementation; and unrealistically short project duration); (ii) technology barriers (such as the promotion of inappropriate techniques without proof of rapid, significant benefits; lack of local capacity and experience); (iii) economic and financial barriers (such as farmers' lack of access to credit facilities and access to markets; and distortions in the policy environment, such as regard to agricultural prices); and (iv) institutional barriers (such as lack of collaboration between stakeholders; and inappropriate incentive structures, in particular insecure land tenure arrangements).

In order to improve adoption, it is important to identify and analyze the key barriers farmers may be facing, and undertake efforts to address them. Such efforts are now increasingly supported. For example, under the Strategic Investment Program for Sustainable Land Management in Sub-Saharan Africa (SIP), a multi-agency partnership with umbrella financing by GEF, systematic analyses of barriers are carried out in a number of countries to better target soil and water conservation interventions in a comprehensive manner (GEF, 2007).

4.2 Addressing Knowledge Gaps

In addition to these barriers, there are also significant knowledge gaps with regard to the performance of the various approaches and measures. Section 3.1 has already mentioned some of the issues. Overall, there is a surprising lack of hard data on the impacts of the different measures, with the exception of experimental or pilot projects. Beyond a lack of quantification of their impacts in different settings, there have also been almost no attempts to value them. An impact analysis would include an assessment of a particular measure's effect on farm practices, crop yields, agricultural incomes and other factors; while a valuation would comprise an estimation of the respective costs and benefits of a particular measure and help assess its economic viability. Furthermore, the crucial linkages between different approaches and measures have not received much attention. Thus there is currently very limited knowledge on the potential complementarities of adopting a mix of measures simultaneously. For example, on-farm investments in water management techniques may become more attractive and more widespread, if farmers also have access to high-quality climatic forecasts. In addition, very little is known about the actual areal coverage of the different water management measures.

Reasons for these knowledge gaps include deficiencies in monitoring and evaluation, and limited (especially economic) research on water management in rainfed agriculture. While rigorous monitoring and evaluation of interventions could assess investment assessment *ex post*, the use of advanced and well-proven physical watershed-based models combined with economic models could offer the basis for estimating the impact of physical and non-physical interventions *ex ante* and hence for designing cost-effective approaches. A review of the literature carried out in connection with this report has demonstrated that not many modeling studies have been carried out, and none was found that attempted to systematically assess the impact of particular interventions with a focus on changes in yield or other related factors.

The need to improve monitoring and evaluation has been a recurring theme for decades, and continues today (see, for example, de Graaf et al., 2007). In connection with this, the World Bank's Sub-Saharan Africa Water Harvesting Study carried out in the early 1990s, Reij et al. (1988) and Critchley et al. (1992) reported that despite substantial research on specific techniques and impressive yields obtained at research stations, projects did not systematically monitor yield impacts. Water harvesting and other soil and water conservation activities often came to a complete standstill as soon as the projects withdrew, in part because they promoted packages far beyond the means of many dryland farmers. A FAO (1994) study also found that, despite some encouraging results, the majority of projects on water harvesting performed well below expectations.

More recently, Peacock et al. (2007) observed that much of the literature on water management techniques was based on research studies and pilot projects, and few project appraisals and/or rigorous evaluations existed to assess actual investment performance. An exception is a report by IFAD (2007) which studied a wide range of techniques applied in eastern and southern Africa and concluded that, in many cases, water harvesting projects still did not systematically monitor yield impacts and promoted relatively expensive packages that were difficult for many farmers to adopt.[14]

An IEG review of projects supporting water management in rainfed agriculture in Sub-Saharan Africa found that in most interventions, physical targets were achieved or exceeded; but because of very weak monitoring and evaluation, it was difficult to assess what had worked and what had not (IEG, 2007). The review further noted that the literature suggests that small-scale, technically simple water management systems can be effective in rainfed areas. A number of more recent World Bank-supported projects have taken these lessons into account and given more emphasis to innovative monitoring and evaluation as well as impact assessment for addressing the knowledge gaps. An example is provided in Box 4.1.

Box 4.1 Innovative Project Monitoring and Evaluation

The Karnataka Watershed Development Project, implemented from 2001-09 and covering 0.5 million hectares in seven arid rainfed agriculture districts of the Indian state of Karnataka, aimed to improve the productive potential of selected watershed and strengthen community and institutional arrangements for natural resource management. A main component was participatory watershed development and protection which included the promotion of soil and moisture conservation measures such as bunds, recharge pits, the construction of farm ponds, check dams, and ravine reclamation structures; these measures were designed to reduce run-off and soil erosion to enhance agricultural productivity. The monitoring and evaluation system combined the conventional project management information system with modern remote sensing and GIS data analysis, and was carried out in cooperation with an independent and credible partner institution specialized in monitoring and evaluation. This unique set-up for monitoring and evaluation helped to provide a strong tracking and learning mechanism, correcting and realigning the project, and pushing for performance and accountability. Project activities were shown to lead to a rejuvenated of the natural resource base, reduced run-off and erosion and higher groundwater table, changes in cropping patterns, and increased crop yields.

Source: World Bank, 2009.

Other recent studies recommended that a closer and more systematic look should be taken at the problems with adoption and scaling up, and better targeted efforts undertaken to identify and overcome them (IFAD, 2007; Peacock et al., 2007).

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[14] The report noted that researchers did not seem to understand "that the overall objective was to increase farming households' incomes, and that interventions would be judged successful only if they were physically functional for the purpose intended over their expected economic life, and if adopted by poor farmers—which the latter [farmers] were highly unlikely to do at a benefit-cost ratio of less than one" (p. 8).

5. The Way Forward

5.1 Priorities and Recommendations

The review of the main issues related to efforts for improving water management in rainfed agriculture does not reveal an encouraging situation, but yields examples of recent interventions that have been implemented more successfully.

Vast numbers of the world's poorest farmers depend directly on rainfall to derive a precarious livelihood that is increasingly threatened by climate change. The development of non-agricultural employment or the expansion of irrigation services may not be possible or at best leave many unaffected, and may not even keep pace with population growth. The only option to improve their lot is to make agriculture more productive, which predominantly means making better use of the most constraining resource, water. Much is known about the physical interventions to improve the productivity and stability of rainfed; but less is known about why these techniques have not been more widely adopted. New approaches that might strengthen adoption—better information about climate, risk management, payment for environmental services, and *ex ante* and *ex post* impact assessments—remain to a large extent poorly documented beyond the theoretical level, and those examples that exist are often from the developed world. The conclusion, however, can hardly be to abandon this group of farmers to their fate. So the recommendations that come, perhaps paradoxically, out of these studies are[15]:

Proceed more strategically. Despite the serious issues related to improving water management in rainfed agriculture laid out in chapter 4, there surely is a way forward. This analysis has highlighted the lack of performance data, and emphasized the need for more monitoring and evaluation—and research—on impact and spread of the various approaches and measures. But this does not mean that certain measures, particularly some of the soil and water management techniques, have not been implemented successfully and accepted by farmers; and these should not be shelved. The existence of centuries-old traditional water management technologies is *de facto* testimony to the fact that farmers can and will implement systems that they appreciate. There is enough experience of a number of techniques, and the measures that create an enabling environment, to go ahead with a more strategic campaign of promotion (accepting that land users will, and must have, the final say) combined with intensified research and reporting. There is strong, if inadequately documented evidence that, at least in some parts of the dryland sub-systems, rainfed agriculture not only has potential to be improved with better rainwater and fertility management,

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[15] See Annex 1, pp. 25-26.

but also has the potential to reduce rural poverty. It is time to overcome the development stigma that is still attached to small-scale, non-irrigated farming in the drylands.

Promote proven technologies. Some techniques have been demonstrated to function well—in terms of managing water and soil while promoting production—and are acceptable in given situations to certain farmers. Clearly none of these is ubiquitously appropriate: there is no panacea. Some of the techniques lend themselves to hand-based systems, others to mechanized; some depend on a local supply of loose stone; agro-ecological suitability differs; the crops, pastures or trees to be planted will define suitability; the presence or absence of animals within the farming systems has an influence; there may even be no apparent logic why one system is preferred by local farmers to another, or why a technique that appears viable is ignored. The main message is then to promote techniques, or combinations, that have worked in similar conditions, but allow land users the ultimate choice.

Support knowledge management systems. Much knowledge exists locally, nationally, even regionally and globally about rainfed production systems. Knowledge management, from uncovering tacit information to documenting and disseminating it through mechanisms that reach receptive target groups, is of paramount importance. Language barriers—particularly the Francophone/ Anglophone divide in sub-Saharan Africa—must be broken down.

Pay attention to farmers' profits. Farmers will adopt profitable techniques. In-field or agronomic practices make soil and water conservation more "palatable" to land users through their direct connection with improved production; the combination of these with structural measures can increase the returns to investment. Mulching, cover crops, agroforestry and homegarden systems are all production-oriented, but simultaneously "conservation friendly". In these cases, financial models should be brought into play to put numbers onto these benefits and the costs. It is now opportune to apply both hydrological and economic models to improved dryland techniques in developing countries. Even more important is the careful documentation of the actual impact of interventions.

Break out of the conventional three-year project mode and move towards programmatic approaches. Rainfed farming is a "long run average" activity—trading expectations of gain and loss at seasonal and even intra-seasonal levels. Short duration projects cannot adequately demonstrate the feasibility of interventions in this context, and may not be suitable to encourage possible adaptation and upscaling.

Fulfill obligations. Finally—for reasons simultaneously involving poverty and the environment—there is a national and international obligation to invest in rainfed agriculture and associated stewardship of natural resources. The link between climate change and sustainable land management through the huge potential for carbon sequestration in the land, and the enormous amounts of carbon lost through land degradation, should help to focus international attention on what has too often been seen as a local problem. Technology is not the main limiting factor: it is the willingness of governments and development agencies to invest in research and development, alongside concerted implementation efforts over a prolonged period, that is principally lacking.

Outline of an Action Plan. Physical interventions to improve the productivity and stability of rainfed agriculture have been identified, though mostly at pilot scales. The question remains as to whether physical interventions "work" at large scale. If they do not, then there may not be a basic "engine" to power the production growth that is needed, and no amount of "enabling environment" will help. However, if production improvements can be demonstrated at large scale, then governments and donors can focus on removing residual impediments to adoption and invest in the enabling environment within which spontaneous dissemination can be expected. The actors in this process include:

- Governments who should be considering (re)targeting agricultural investment towards rainfed agriculture;
- Technical specialist agencies and networks (such as ICRISAT, ICARDA, FAO, and WOCAT) who should be tasked with designing appropriate and situation-specific physical interventions for rainfed agriculture, for implementation at large scale based on relatively simple criteria (e.g. cost at $500 per hectare maximum; estimated benefit at $100 per hectare minimum; minimum area covered 1000 ha);
- Contractors, where larger physical works are required; farmers who would have to confirm their satisfaction with the works before payments are made by government;
- Donors who fund investments in programmatic approaches, with a far longer time horizon than the conventional three to five year project cycle; a fund should be established to support (i) targeted research and studies, especially on *ex ante* and *ex post* assessment of the linkages between interventions, physical and economic impact, and associated farmer behavior; (ii) interventions meeting specified cost/estimated benefit/scale criteria; and (iii) impact monitoring in the intervention areas over several years in comparison with unimproved areas.
- Monitoring agencies who assess impact independently; since a main objective would be to increase productive evapotranspiration, and the interventions would be at significant scales, there is potential to apply remote sensing for evapotranspiration measurement; but the "design" agencies should also specify simple basic indicators of impact.

Such a program in all probability will neither succeed nor fail, but there surely will be positive components. The experiences gained, provided support is consistent and impacts are monitored over a decade or more, will indicate whether more research is needed on the physical and technical options, or whether technical research is already ahead of the game and more focus should be directed at overcoming adoption constraints.

The actors involved would have to address some critical questions regarding the future of farmers who depend on rainfall. Specifically, for governments, if there is no better alternative for the rainfed farmers concerned, are they prepared to engage with these farmers, and refocus support to a less glamorous (and more institutionally challenging) subsector? For the technical specialist agencies and networks, should they consider the broader applicability of currently proposed “solutions”, and assess their feasibility under varying rainfall and other conditions[16]? For donors, are they willing to support an experimental action plan (albeit based on vast quantities of research data from field experiments and pilots) over a significant period of time, with a consistent underlying criterion for production improvement? If the answers to these questions are positive, then setting an adequate framework for monitoring in this highly variable context is critical. As noted before, many projects and interventions have not generated data from which lessons can be learned—today many of the technologies to monitor and interpret production improvements are available.

5.2 Predicting and Monitoring the Impact of Improved Water Management in Rainfed Agriculture

Rainfed agriculture is inherently risky: the total quantity of rainfall and its distribution over the cropping season determine *potential* productivity, while *actual* productivity further depends on the farmer's behavior (such as aversion to risk) and practices, and additional factors such as pest attacks. Rainfed production in any season is thus the result of a series of uncontrollable and partially controllable factors.

When a measure for improving water management is introduced (such as a new mulching practice, or better weather information), it is expected that, if not for a particular cropping season, then over a number of cropping seasons, the new measure will produce higher average yields. Even this is indeed the case, it may be difficult to measure with traditional indicators such as yield or net return per hectare, or farm income. “Before the project” there may be an oscillating series of yields, and “after the project” the oscillation continues—but is it smaller, or around a higher mean, or less sensitive to dry spells, or more

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[16] In this context, it is relevant to note that the combined budgets of the three CGIAR centers most concerned with rainfed agriculture and Africa (ICRISAT, ICARDA and the International Institute for Tropical Agriculture, IITA) have a combined annual budget of some $120 million.

closely correlated with “good” rainfall years? And if any of these positive effects is observed, how did the rainfall patterns in the two periods compare? Slight variations in the pattern of rainfall can produce significantly different yields, and other factors may further influence production. Even based on these simplistic deliberations, it should come as no surprise that impact monitoring of projects supporting rainfed agriculture have rarely been able to identify clear impacts. However, if a more strategic approach and larger-scale interventions are to be supported, better indicators for predicting and measuring impacts are required. Changes in evapotranspiration, which are closely related to production improvements, are increasingly cheaper and easier to estimate, are a promising indicator in this regard.

This indicator is further suitable for relating not only to on-site, but also to downstream impacts. The primary objective of improving water management in rainfed agriculture is to improve agricultural incomes by increasing production. This implies increased crop transpiration (because crop transpiration is closely related to yield), and a corresponding increase in evapotranspiration—with potential implications for downstream flows and/or groundwater recharge (see Box 2.1). However, different phases with regard to potential off-site impacts are possible. For example, in a first phase, when rainfed agriculture replaces natural vegetation, the impact of this transition on evapotranspiration is likely to be negative, and runoff and/or percolation to aquifers may increase.[17] In a next phase, evaporation may be controlled/minimized through mulching or improved tillage practices. This helps convert non-productive evaporation into productive transpiration.[18] In a basin-wide context, this is a water-neutral process as evapotranspiration remains unchanged. In subsequent phases, when water management in rainfed agriculture is further improved, local evapotranspiration is likely to increase as progress is made in retaining water *in situ* or capturing it for supplementary irrigation from surrounding areas—through to full irrigation.

Table 5.1, derived from a remote sensing analysis of the Inkomati basin in South Africa, illustrates the information needed to predict the likely impact of a proposed intervention. The table shows annual evapotranspiration for a variety of land use classes, the area covered by each land use, and the contribution of each land use class to total evapotranspiration. As might be expected, perennially irrigated crops (orchards, sugar cane) are the land use classes with the highest evapotranspiration—but less obviously, irrigated and non-irrigated areas combined consume *less* water than the natural vegetation

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[17] When forests are cleared for agriculture, an increase in runoff and flooding are commonly reported (usually as negative impact). Natural vegetation adapts to capture rainfall as and when it occurs, and single-season rainfed agriculture may be less effective (even though *crop* transpiration increases).

[18] Rockström et al (2007) argue that in low productivity agriculture (with a production of less than 3 tons per hectare) evaporation is a high proportion of total evapotranspiration, and thus the productivity of water is very low. Techniques that reduce evaporation (such as mulching) and transfer the water thus saved to productive transpiration produce a substantial gain in the overall productivity of evapotranspiration.

in the Kruger National Park with a similar area.[19] The table also indicates that if subsistence rainfed cultivation were improved to increase water consumption by 50% (from 749mm to 1125mm), this would represent an overall increase in consumption at basin level of just over 1%.

Table 5.1 Contributions of Land Use Classes to Total Evapotranspiration in the Inkomati Basin, South Africa

Land Use Class	ET (mm)	Area (ha)	ET (km3)	% Area	% Volume
orchards	1,103	31,492	0.35	1.1	1.7
sugar cane	1,067	62,151	0.66	2.2	3.3
non-pivot irrigated - emerging farmer cash cro	1,029	1,927	0.02	0.1	0.1
non-pivot irrigated - annual cash crops	968	18,453	0.18	0.6	0.9
non-pivot irrigated - grain crops	548	2,555	0.01	0.1	0.1
pivot irrigation - grain crop	344	2,174	0.01	0.1	0.0
pivot irrigation - fallow	339	1,294	0.00	0.0	0.0
Sub-total: Irrigated	*1,029*	*120,046*	*1.23*	*4.2*	*6.2*
plantation eucalyptus	841	100,146	0.84	3.5	4.2
Rainfed cultivation - subsistence	749	62,181	0.47	2.2	2.3
plantation pine	662	230,549	1.53	8.0	7.7
rural scattered	656	21,194	0.14	0.7	0.7
plantation clear felled	582	19,964	0.12	0.7	0.6
plantation wattle	428	1,193	0.01	0.0	0.0
Rainfed cultivation - commercial	345	61,159	0.21	2.1	1.1
Sub-Total: Unirrigated	*666*	*496,386*	*3.31*	*17*	*17*
water	899	10,412	0.09	0.4	0.5
Kruger Park	831	613,884	5.10	21.4	25.6
urban	738	68,486	0.51	2.4	2.5
other	678	3,922	0.03	0.1	0.1
background	621	1,559,150	9.68	54.3	48.5
Sub-Total: *Non-agricultural*	*683*	2,255,854	15.41	79	77
Total		**2,872,286**	**20**	**100**	**100**

Source: LEI and WaterWatch, 2006.

When improved water management in rainfed agriculture leads to an increase in on-site evapotranspiration, downstream impacts should assessed taking into account two perspectives. The hydrological impact will most likely be a reduction in water availability downstream—which may affect abstractions for agricultural and non-agricultural uses, in-stream uses (navigation, fisheries) and environmental uses (such as riparian vegetation, wetlands, and flushing of estuaries). The economic impact should also be considered. As noted before, the first increment of evapotranspiration to rainfed agriculture can be highly productive; with progressively higher increments productivity will revert to the

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[19] Some of the results are no doubt very sensitive to site-specific soil conditions and slopes. For example, rainfed commercial farming in the basin is located in the best areas and consumes as much water as pivot irrigated grain.

average relationship between transpiration and yield—subject to changes in crop husbandry induced by more reliable water availability. An important aspect to assess from a basin-wide perspective is how the higher levels of productivity in rainfed agriculture relate to the decreased levels of downstream water availability.[20] However, as in the example of Table 5.1, the impact of interventions in rainfed agriculture will typically be relatively small because in most basins the rainfed area is small compared to the "natural" area. But downstream impacts should nevertheless be assessed, not least because any successful intervention is likely to spread, with downstream impacts becoming more significant.

The above example focused on predicting the potential impact of water-related interventions in rainfed agriculture; measuring the actual impact, given the high variability of rainfall and other uncertainties of rainfed production, is a separate challenge. However, any water-related intervention in rainfed agriculture would be expected to affect the schedule and intensity of plant activity in ways that distinguish project from non-project areas. Evapotranspiration can be considered as the ultimate indicator of biomass formation which directly relates to increases in yield at farm level. There are also other measures of active plant growth, such as the Normalized Difference Vegetation Index (NDVI). All can readily be derived from satellite data. For monitoring purposes, changes in an indicator such as evapotranspiration in the project area can be compared to surrounding non-project areas. By measuring the indicator simultaneously for project and non-project areas, an estimate of project impact can be derived on a season by season basis, thus avoiding the difficulties of comparing before and after project scenarios.

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[20] Another interesting situation could be where more water would be consumed in rainfed agriculture and, concomitantly less water in irrigated agriculture. In this case, the overall impact on production may be positive or negative, depending on the relative productivity of water in the two sectors.

6. Conclusions

The importance of improving water management in rainfed agriculture, especially in those production systems where water is a main constraint, seems obvious but is related to serious challenges. A wide range of measures is potentially available, and can be categorized into four broad approaches: first, promoting on-farm and communal soil and water management techniques that help increase water availability and crop water uptake; second, accounting for positive externalities through PES; third, improving agricultural risk management so that farmers can better cope with climate risks; and, fourth, providing better climatic information to farmers, including on droughts and dry spells, to help them make the necessary anticipatory adjustments. The first approach can be considered to comprise physical interventions, while the other three approaches are non-physical. Only the first, and possibly the fourth, approach can be considered a direct "engine" of productivity growth in rainfed agriculture. The other two approaches are supportive indirect approaches, and are likely to only be effective if the "engine" works.

It is therefore recommended that a coordinated and programmatic effort between governments and donors as well as technical specialist organizations be undertaken to mainly support physical interventions which should be at a larger scale (thousands of hectares for ten years, not a few hectares for three or four years) and with significant projected impacts (such as $100/ha incremental income for $500/ha investment); and impact monitoring in the intervention areas and in unimproved areas over several years

Monitoring and assessment will be critical, and should not be based simply on the usual indicators of yield or net return per hectare, or farm income. With rainfall being erratic, it may be problematic to distinguish the pattern of variability in the different years before and after an intervention. The primary indicators of production—transpiration and biomass formation—can be measured by satellite, and compared, year by year, between project and non-project areas. If these indicators demonstrate significant differences, which should in any case be specified in advance by the "design" agency, then we can be confident that the growth engine works, and attention can shift to barriers such as, for example, marketing and seed availability in the local environment. If the engine does not work at scale, then the need for revised priorities for countries, donors and research institutes will be clear.

References

Angelsen, A., and D. Kaimowitz (eds.) 2001. *Agricultural Technologies and Tropical Ddeforestation*. Wallingford, UK: CABI Publishing

Barnett, B.J., Barrett, C.B., and J.R. Skees. 2008. “Poverty Traps and Index-based Risk Transfer Products.” *World Development* 36, 10, 1766-85.

Critchley, W., C. Reij, and A. Seznec. 1992. *Water Harvesting for Plant Productions. Volume II: Case Studies and Conclusions for Sub-Saharan Africa*. World Bank Technical Paper No. 157. Washington, DC: World Bank.

Dercon, S., 2002. “Income Risk, Coping Strategies, and Safety Nets.” *The World Bank Research Observer*, 17(2): 141-166.

FAO (Food and Agriculture Organization of the United Nations). 1994. *Water Harvesting for Improved Agricultural Production: Proceedings of the FAO Expert Consultation*. Rome: FAO.

FAO (Food and Agriculture Organization of the United Nations). 2006. "Water for Food, Agriculture and Rural Livelihoods.” Chapter 7 in *Water—A Shared Responsibility. The United Nations World Water Development Report 2*. United Nations Educational, Scientific and Cultural Organization (UNESCO), Paris.

FAO (Food and Agriculture Organization of the United Nations). 2007. *The State of Food and Agriculture. Paying Farmers for Environmental Services*. Report 222. Food and Agricultural Organization of the United Nations: Rome.

Fereres, E., and M.A. Soriano. 2007. “Deficit Irrigation for Reducing Agricultural Water Use.” *Journal of Experimental Botany* 58(2), 147–159.

de Fraiture, C. 2005. *Assessment of Potential Food Supply and Demand Using the Watersim Model*. Report 7 of Component Study for Collaborative Program Investment in Agricultural Water for Poverty Reduction and Economic Growth in Sub-Saharan Africa. Pretoria: International Water Management Institute.

GEF (Global Environment Facility). 2007. Strategic Investment Program for Sustainable Land Management in Sub-Saharan Africa (SIP). Program Brief on a Proposed Grant from the Global Environment Facility Trust Fund.

de Graaf, J., J. Cameron, S. Sombatpanit, C. Pieri, and J. Woodhill. 2007. *Monitoring and Evaluation of Soil Conservation and Watershed Development Projects.* Science Publishers, Enfield.

Howell, T.A. 1990. “Grain Dry Matter Yield Relationships for Winter Wheat and Grain Sorghum—Southern High Plains.” *Agronomy Journal* 82, 914–918.

Hudson, N.W. 1987. *Soil and Water Conservation in Semi-Arid Areas.* Soils Bulletin no 57, Food and Agriculture Organization, Rome.

Hudson, N.W. 1991. *A Study of the Reasons for the Success or Failure of Soil Conservation Projects.* Soils Bulletin No 64, Food and Agriculture Organization, Rome.

IEG (Independent Evaluation Group). 2007. *World Bank Assistance to Agriculture in Sub-Saharan Africa: An IEG Review*. Washington, DC: World Bank.

IFAD (International Fund for Agricultural Development). 1992. *Soil and Water Conservation in Sub-Saharan Africa. Towards Sustainable Production by the Rural Poor*. Report prepared by the Centre for Development Cooperation Services, Vrije Universiteit Amsterdam. International Fund for Agricultural Development, Rome

IFAD (International Fund for Agricultural Development). 2007. *Agricultural Water Development for Poverty Reduction in Eastern and Southern Africa*. Main Report (draft). Rome: IFAD.

IPCC (Intergovernmental Panel on Climate Change). 2008. *Technical Paper on Climate Change and Water*. IPCC-XXVIII/Doc. 13. Geneva: IPCC Secretariat.

LEI and WaterWatch. 2006. *Combining Remote Sensing and Economic Analysis to Assess Water Productivity: A demonstration project in the Inkomati Basin*. Wageningen.

Meinke, H. and R.C. Stone. 2005. "Seasonal and Inter-annual Climate Forecasting: The New Tool for Increased Preparedness to Climate Variability and Change in Agricultural Planning and Operations." *Climatic Change*, 70: 221-253.

Molden, D. 2007. *Water for Food, Water for Life: Comprehensive Assessment of Water Management in Agriculture.* London: Earthscan, and Colombo: International Water Management Institute

Narayana, V.V.D., and R. Babu. 1985). *Soil and Water Conservation in Semi-arid Regions of India.* CSWCRTI, Dehradun, India.

Niemeijer, D. Puigdefabregas, J., White, R., Lal, R., Winslow, M., Ziedler, J., Prince, S., Archer, E. and C. King. 2005. In: *Ecosystems and Human Well-being: Current State and Trends*. Washington D.C.: Island Press, pp. 623-662.

Oram, P.A., and C. de Haan. 1995. *Technologies for Rainfed Agriculture in Mediterranean Climates: A Review of World Bank Experience*. World Bank Technical Paper No. 300. Washington, DC: World Bank.

Oweis, T., A. Hachum, and J. Kijne. 1999. *Water Harvesting and Supplemental Irrigation for Improved Water Use Efficiency in Dry Areas*. System-Wide Initiative on Water Management (SWIM) Paper 7. Colombo: International Water Management Institute.

Oweis, T.Y., and A.Y. Hachum. 2003. "Improving Water Productivity in the Dry Areas of West Asia and North Africa." Chapter 11 in *Water Productivity in Agriculture: Limits and Opportunities for Improvement*, eds. J.W. Kijne, R. Barker, and D. Molden. London: Earthscan, and Colombo: International Water Management Institute.

Passioura, J. 2006. "Increasing Crop Productivity when Water Is Scarce—From Breeding to Field Management." *Agricultural Water Management* 80, 176–196.

Peacock, T., C. Ward, and G. Gambarelli. 2007. *Investment in Agricultural Water for Poverty Reduction and Economic Growth in Sub-Saharan Africa: Synthesis Report* (draft). Collaborative Program of AfDB, FAO, IFAD, IWMI and the World Bank.

Perry, C., P. Steduto, R.G. Allen, and C.M. Burt. 2009. "Increasing Productivity in Irrigated Agriculture: Agronomic Constraints and Hydrological Realities." *Agricultural Water Management* 96 (11): 1517-1524.

Reij, C., P. Mulder, and L. Begemann. 1988. *Water Harvesting for Plant Production*. World Bank Technical Paper No. 91. Washington, DC: World Bank.

Reij, C., and D. Steeds. 2003. *Success Stories in Africa's Drylands: Supporting Advocates and Answering Skeptics.* Paper commissioned by the Global Mechanism of the Convention to Combat Desertification. Amsterdam: Centre for International Cooperation, Vrije Universiteit Amsterdam.

Rockström, J., N. Hatibu, T.Y. Oweis, S. Wani, J. Barron, A. Bruggeman, J. Farahani, L. Karlberg, and Z. Qiang. 2007. "Managing Water in Rainfed Agriculture." Chapter 8 in *Water for Food, Water for Life: Comprehensive Assessment of Water Management in Agriculture*, ed. D. Molden. London: Earthscan, and Colombo: International Water Management Institute, pp. 315-52.

Rockström, J., M. Lannerstad, and M. Falkenmark. 2007. “Assessing the Water Challenge of a New Green Revolution in Developing Countries.” In *Water for Food, Water for Life: Comprehensive Assessment of Water Management in Agriculture*, ed. D. Molden. London: Earthscan, and Colombo: International Water Management Institute.

WOCAT (World Overview of Conservation Approaches and Technologies). 2007. *Where the Land is Greener: Case Studies and Analysis of Soil and Water Conservation Initiatives Worldwide*. Eds. H. Uniger and W. Critchley. CTA, FAO, UNEP, CDE. Bern: WOCAT.

World Bank. 2006. *Reengaging in Agricultural Water Management: Challenges and Opportunities*. Directions in Development. Washington, DC: World Bank.

World Bank. 2007. *World Development Report 2008: Agriculture for Development*. Washington, DC: World Bank.

World Bank. 2008a. *Strategic Framework for the World Bank Group on Development and Climate Change*. Washington, DC: World Bank.

World Bank. 2008b. *Double Jeopardy: Responding to High Food and Fuel Prices*. G8 Hokkaido-Toyako Summit. Washington, DC: World Bank.

World Bank. 2008c. *Rising Food Prices: Policy Options and the World Bank Response*. Policy Note. Washington, DC: World Bank.

World Bank. 2009a. *Harvesting Agricultural Carbon in Sub-Saharan Africa: A Potential Triple-Win*. World Bank Policy Brief (draft). Washington, DC: World Bank.

World Bank. 2009b. *Karnataka Watershed Development Project. Implementation Completion and Results Report* (IDA-35280 TF-26437). South Asia Region. Washington, DC: World Bank.

Zimmerman, F.J., and M.R. Carter. 2003. “Asset Smoothing, Consumption Smoothing and the Reproduction of Inequality under Risk and Subsistence Constraints.” *Journal of Development Economics*, 71: 233-260.

Projects in Portfolio on Agricultural Water Management (AWM) in Rainfed Agriculture (FY99-FY08)

Country	Project Title	Total Project Amount ($m)	Bank Commitment ($m)	Bank Commitment to AWM ($m)*	AWM as % of Bank Commitments	FY Approval	Status as of Sept 09
AFR							
Burkina Faso	Community-based rural development	114.85	66.7	2.81	4%	2001	closed
Burkina Faso	5th Poverty Reduction Support Operation	60	60			2005	closed
Burkina Faso	6th Poverty Reduction Support Credit Project	60	60			2006	closed
Burundi	Agricultural Rehabilitation and Sustainable Land Management Project	40.47	35	2.19	6%	2005	active
Cameroon	CAM: Community Development Program Support Project	82.82	20	2.50	13%	2004	active
Chad	Agricultural Services and Producer Organizations Project	24.62	20	3.93	20%	2003	closed
Chad	Local Development Program Support Project	46	23	0.84	4%	2005	active
Eritrea	Emergency Reconstruction Program Project	16.4	15	1.26	8%	2000	closed
Ethiopia	Food Security Project	110.16	85	43.15	51%	2002	active
Ethiopia	Pastoral Community Development Project	59.96	30	1.17	4%	2003	closed
Ethiopia	Emergency Drought Recovery Project	61.7	60	1.25	2%	2003	closed
Ethiopia	Productive Safety Nets Project 1	70.1	70	15.51	22%	2004	closed
Ethiopia	Productive Safety Nets Project 2	915	175	80.00	46%	2007	closed
Ethiopia	Financial Sector Capacity Building Project	15.91	15	0.98	7%	2006	active
Ethiopia	Tana & Beles Integrated Water Resources Development Project	69.85	45	2.85	6%	2008	active
Ethiopia	Sustainable Land Management Project	37.79	20	11.48	57%	2008	active
Ghana	Community Based Rural Development	69	60	4.38	7%	2004	active
Kenya	Arid Lands Resource Management Project Phase Two	77.9	60	32.11	54%	2003	active
Kenya	Natural Resource Management Project	70	68.5	3.70	5%	2007	active
Madagascar	Irrigation and Watershed Management Project	40	30	0.80	3%	2007	active
Malawi	Irrigation, Rural Livelihoods and Agricultural Development Project	52.5	40	2.34	6%	2006	active
Malawi	Agricultural Development Program Support Project	53.3	32	21.67	68%	2008	active
Mali	Rural Community Development Project	64	60	7.34	12%	2006	active
Mauritania	Community Based Rural Development Project	57.9	45	12.65	28%	2004	active
Mozambique	Market-Led Smallholder Development in the Zambezi Valley Project	26.7	20	2.45	12%	2006	active
Regional	Niger Basin Water Resources Development and Sustainable Ecosystems Management (APL) Project	233.2	186	6.46	3%	2008	active
regional	Senegal River Basin Multi-Purpose Water Resources Development (APL) Project	140.75	110	7.84	7%	2006	active
Regional	Nile transboundary environmental action project	43.6	12.81	3.36	26%	2003	active
Rwanda	First Rural Sector Support Project	55.88	48	4.87	10%	2001	closed
Rwanda	Second Poverty Reduction Support Grant Project	55	55			2006	closed
Rwanda	Second Rural Sector Support Project	38.99	35	3.42	10%	2008	active
Sierra Leone	Bumbuna Hydroelectric Project Support	91	12.5	1.24	10%	2005	active
Tanzania	Social Action Fund Project	71.77	60	7.50	13%	2001	closed
Tanzania	Participatory Agricultural Development and Empowerment Project	69.99	56.58	29.29	52%	2003	active
Uganda	National Agriculture Advisory Services Project	107.92	45	0.78	2%	2001	active
EAP							
China	Western Poverty Reduction Project	311	160	0.50	0.3%	1999	closed
China	Changjiang and Pearl River Watershed Rehabilitation Project	200	100	29.88	30%	2006	active
China	Mainstreaming Climate Change Adaptation in Irrigated Agriculture Project	55.5	20	0.25	1%	2006	active
Indonesia	Initiatives for Local Governance Reform Project	46.3	29.5	3.51	12%	2005	active
Philippines	Laguna de Bay Institutional Strengthening and Community Participation Project	12.45	5	0.41	8%	2004	active
ECA							
Albania	Natural Resources Development Project	19.4	7	0.36	5%	2005	active
Armenia	Natural Resources Management and Poverty Reduction Project	16	8.3	0.24	3%	2002	closed
Kazakhstan	Second Agricultural Post-Privatization Project	96.1	35	0.52	1%	2005	active
Kyrgyz Republic	Agricultural Investments and Services Project	23.4	9	0.14	2%	2008	active
Turkey	Anatolia Watershed Rehabilitation Project	45.11	20	5.34	27%	2004	active

* Estimation of Bank commitment to AWM is based on project component costs presented in the Project Appraisal Documents. When the AWM activity is part of in a list of demand-driven subprojects, the component costs are assumed to be equally allocated between eligible activities.

LAC							
Argentina	Indigenous Community Development LIL	5.88	5	1.67	2%	2001	closed
Brazil	Ceara Integrated Water Resource Management Project (PROGERIRH)	247.2	136	2.75	33%	2000	active
Brazil	Rio Grande do Norte Integrated Water Resources Management Project	59.8	35.9	0.96	3%	2005	active
Ecuador	Poverty Reduction and Local Rural Development (PROLOCAL) Project	41.96	25.2	0.87	3%	2002	closed
Ecuador	Second Indigenous and Afro-Ecuadorian Peoples Development Project	44.97	34	2.61	8%	2004	closed
Guatemala	Western Altiplano Natural Resources Management Project	40.8	32.8	4.82	15%	2003	closed
Mexico	Rural Development in Marginal Area II	73	55	10.35	19%	2000	closed
Panama	Rural productivity project	46.9	39.4	2.22	6%	2007	active
Paraguay	Community Natural Resources Management Project or sustainable agriculture and rural development	46.84	37.5	9.45	25%	2008	active
Peru	Sierra Rural Development Project	34.93	20	4.11	21%	2007	active
Uruguay	Integrated Natural Resources and Biodiversity Management Project	95.85	30	6.29	21%	2005	active
MENA							
Algeria	Second Rural Employment Project	142.89	95	16.42	17%	2003	closed
Egypt	Second Matruh Resource Management Project	45	12.35	0.34	3%	2003	closed
Lebanon	Community Development Project	30	20	0.57	3%	2001	closed
Morocco	Rainfed Agriculture Development Project	40.8	26.8	4.39	16%	2003	active
Tunisia	Northwest Mountainous and Forestry Areas Development Project	44.86	34	9.75	29%	2003	closed
Yemen	Sana'a Basin Water Management Program - Phase 1	30	24	8.16	14%	2003	active
Yemen	Groundwater and Soil Conserveration Project	53.63	40	5.85	34%	2004	active
Yemen	Social Fund for Development III	400	60	7.50	15%	2004	active
Yemen	Rainfed Agriculture and Livestock Project	33.8	20	2.70	13%	2007	active
SAR							
India	Karnataka Watershed Development Project	127.6	100.4	36.60	36%	2001	closed
India	Uttaranchal Decentralized Watershed Development Project	89.35	69.62	22.39	32%	2004	active
India	Hydrology II	135.05	105.51	51.10	48%	2005	active
India	National Agricultural Innovation Project	250	200	14.60	7%	2006	active
India	Himachal Pradesh Mid-Himalayan Watershed Development Project	75	60	13.84	23%	2006	active
Iran	Alborz Integrated Land and Water Management Project	200.3	120	3.45	3%	2005	active
Pakistan	Second Poverty Alleviation Fund Project	368	238	3.40	1%	2004	active
Pakistan	Balochistan Small Scale Irrigation Project	25	25	2.55	10%	2008	active

Soil and Water Management Techniques in Rainfed Agriculture

State of the Art and Prospects for the Future

Background Note

prepared for the World Bank Water Anchor's

Improving Water Management in Rainfed Agriculture

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All photos by the author unless otherwise stated

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ACRONYMS AND ABBREVIATIONS

AfDB = African Development Bank
BPSAAP = Baringo Pilot Semi-Arid Area Project (Kenya)
CA = Conservation Agriculture
FAO = Food and Agriculture Organisation of the United Nations
GEF = Global Environment Facility
GHGs = Greenhouse Gases
ICRAF = World Agroforestry Centre
IFAD = International Fund for Agricultural Development
IPCC = Intergovernmental Panel on Climate Change
ISCO = International Soil Conservation Organisation
IWMI = International Water Management Institute
M&E = Monitoring and Evaluation
NAS = National Academy of Sciences
NEPAD = New Partnership for African Development
NVS = Natural Vegetative Strips
PES = Payment for Environmental (or Ecosystem) Services
RH = Runoff Harvesting
RWH = Rainwater Harvesting
SIP = Strategic Investment Programme (of the GEF)
SLM = Sustainable Land Management
SSA = sub-Saharan Africa
SSWHS = sub-Saharan Water Harvesting Study
SWC = Soil and Water Conservation
SWAT = Soil and Water Assessment Tool
TerrAfrica = Partnership for SLM in sub-Saharan Africa
UNEP = United Nations Environment Programme
USLE = Universal Soil Loss Equation
WCED = World Commission on Environment and Development
WH = Water Harvesting
WOCAT = World Overview of Conservation Approaches and Technologies
WRI = World Resources Institute

PART ONE

Introduction

1. This background note attempts to summarize the current knowledge base on soil and water management techniques in rainfed agriculture. The terms of reference require, in summary, the following:

- (i) systematic review of on-farm and communal soil and water management techniques used worldwide, covering both introduced and traditional technologies – including a classification;
- (ii) description of the different techniques, with their usefulness and shortcomings;
- (iii) compilation of results to qualify and value the various impacts;
- (iv) discussion of examples of techniques that have been successfully applied and an analysis of the underlying factors for their successful adoption;
- (v) analysis of the various barriers to wider adoption; *and*
- (vi) recommendations for the design of future interventions.

2. The task is such that it could constitute a major review in itself, and the product could be a book. However the purpose of this particular assignment is to provide a *background note*, and as such it needs to be reasonably concise and thus inevitably selective. The basis of this note is literature, both recent and from the last three decades - a period that encompasses most of the important writings on the topic. An overall observation is that many of the older reviews are still valid, yet commonly overlooked in the newer literature. Moreover, many of the new are repetitive.

3. Clarification is required from the outset about the strategies used to manage water under rainfed farming conditions. This will be built upon in a subsequent section where a classification of water harvesting[1] – which is a particular focus of this paper – is presented (see paragraph 42). Agreeing with Narayana and Babu (1985: quoted in Hudson, 1987), depending on the amount of rainfall available, the potential evapotranspiration burden and cropping system, farmers under rainfed conditions may choose techniques or systems that *primarily*:

- (i) provide for discharge of excess water;
- (ii) hold rainfall *in situ*; *or*
- (iii) harvest water from a catchment area to supplement rainfall.

These strategies are achieved primarily through the use of:

- (a) support structures (eg barriers of various materials); *combined with*
- (b) in-field/ agronomic practices

4. There is a continuous variation between these systems: there are sometimes no clear cut-off points between them. But the general categories help us distinguish primary strategies in different situations. Where irrigation is applied, systems may depend entirely on irrigated water or on "supplementary irrigation" when strategic applications of water are made at key stages in the crop's growth period. When rainwater harvesting is used to capture water for storage in ponds, then the application of this water is a form of supplementary irrigation, as noted in (iii) above.

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[1] "Water Harvesting" (WH), "Rainwater Harvesting" (RWH) and "Runoff Harvesting" (RH) are terms which are sometimes used interchangeably in the literature. Note that in the classification proposed here and presented in Figure 4, RH is categorised as a subset of RWH which is in turn a subset of WH.

Importance of rainfed agriculture and small-scale farming

5. There has been a recent swing back to acknowledging the need for investment in agriculture as a tool to alleviate poverty and form the basis for economic growth in developing countries (eg DfID, 2005; World Bank, 2008). This is especially emphasized for sub-Saharan Africa where the large majority – around 85% - live in rural areas and are dependent on the land for their livelihoods.

6. Populations on that continent are still growing, and outstripping the modest increases in farm production. To exacerbate the problem, land degradation is not only serious (Bridges et al, 2001), but according to new research, is getting worse (Vlek et al, 2008). Increasing soil nutrient deficiencies are also a problem (see Figure 1), and water management without fertility improvement is not enough. The majority of farm land in sub-Saharan Africa is rainfed: less than 5% is irrigated. Climate change will bring new problems, with drying expected in the Sahel and Southern Africa, and though East Africa may become wetter this is at the expense of more intense and erosive rainfall events.

7. Rockström and colleagues have led the call to recognize – and exploit – the untapped potential of rainfall in sub-Saharan Africa (Rockström, 2000; Rockström and Falkenmark, 2000; Rockström et al, 2003; Rockström et al, 2008). It is accepted wisdom amongst those who have lived, worked and studied in the drylands that a modest amount of extra water at a sensitive time can make a significant difference to a crop. Simultaneously, Rockström (2000) estimates that up to 70-85% of rainfall is "lost" in the sub-Saharan drylands (see Figure 2), and furthermore Rockström and Falkenmark (2000) point to the possibility of "*doubling crop yields with small manipulations*" of rainwater.

8. If rainfall can be translated into "productive green water flow" (water that is transpired productively by plants) rather than lost through runoff, surface evaporation or deep drainage, then especially at low levels of productivity, yields and water use efficiency can be improved dramatically (Falkenmark, 1995; Rockström and Falkenmark, 2000). Molden (2007 p2) in the benchmark report of the Comprehensive Assessment of Water Management in Agriculture states that: *"The greatest potential increases in yield are in rainfed areas where many of the world's poor live and where managing water is the key to such increases".*

9. In 2001, AfDB, FAO, IFAD, IWMI and the World Bank identified the low level of investment in agricultural water in sub-Saharan Africa as a major development issue (Peacock et al, 2007). These agencies came together to develop a collaborative programme, and prepared background studies. In 2002, NEPAD developed the Comprehensive Africa Agricultural Development Programme (CAADP), which gives a central place to the development of agricultural water.

10. The draft synthesis report of the collaborative programme while focusing on irrigation, includes forms of water harvesting in its scope, and notes:

> "Investment in agricultural water can contribute to agricultural growth and reduce poverty directly by: (a) permitting intensification and diversification and hence increased farm outputs and incomes; (b) increasing agricultural wage employment; and (c) reducing food prices and hence improving real net incomes" (Peacock et al, 2007).

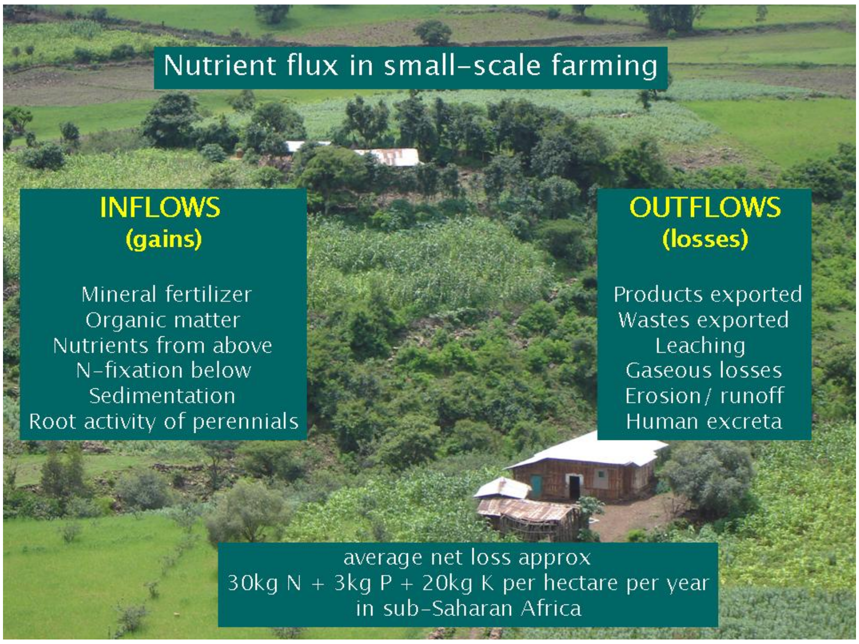

Figure 1: Nutrient fluxes in small-scale farming (Source: based on Hilhorst and Muchena, 2000)

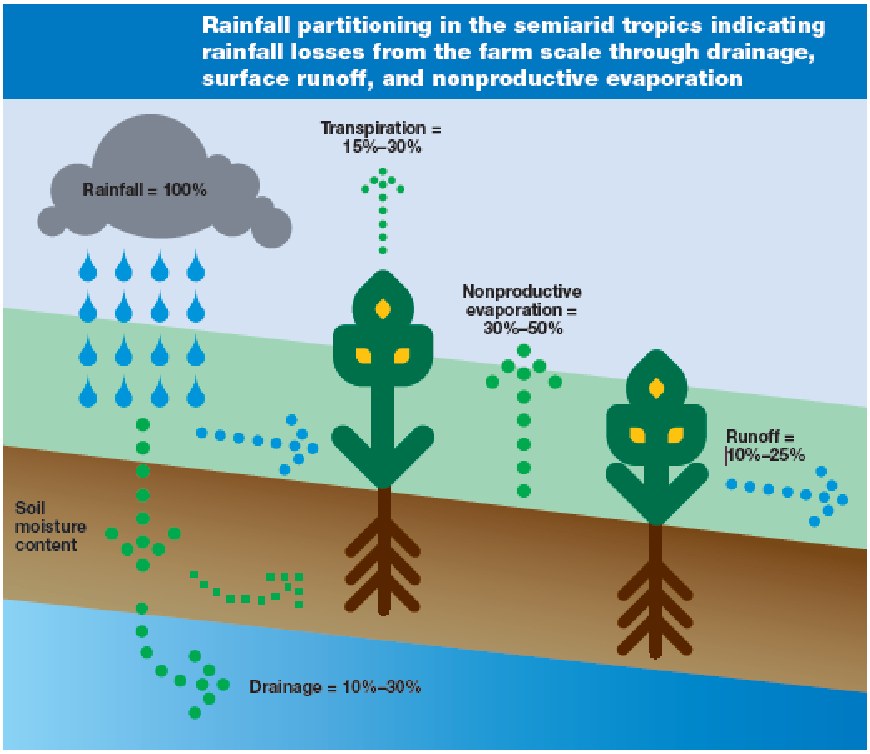

Figure 2: Runoff partitioning in the semi-arid tropics (Source: Molden, 2007)

History, Trends and Milestones

11. Modern international concern with the impact of soil erosion and soil conservation on rainfed farming can be traced back to the 1930s. It was triggered by the “Great Dust Bowl” in the United States of America which put many farmers out of business, and alarmed not just the scientific community but politicians also (Anderson, 1984). Mechanization had opened up vast unprotected tracts of land: combined with drought and wind this caused severe dust storms. Having led to the establishment of the US Soil Conservation Service, it had a strong influence on the policies and practices of colonial agricultural officers, who introduced compulsory terracing schemes. These were often based on channel terraces with waterways: systems suited to the USA but ill-fated in Africa where moisture essential to survival of crops was thereby drained off the land. However, failed conservation schemes have led to reappraisal and significant shifts in conceptual thinking.

12. The evolution of new approaches is traced in Table 1 which looks at trends and milestones. To substantiate the historical timeline, some significant publications are added. Several of these writings (those pertaining to water harvesting in particular) are reviewed in the following section.

13. It will be seen from the timeline that there is a connection between colonial enforcement of soil conservation schemes and the independence of many countries mid-century. A backlash occurred, and such schemes fell out of favor – only to be revived in the wake of the Stockholm conference of 1972. However, this new generation of (largely) donor-driven projects lent heavily on the colonial schemes for their design, and many collapsed. On subsequent analysis it was recognized that top-down, transfer of technology approaches, heavily dependent on structural solutions were inappropriate. Historical (and current) barriers to success, as defined by spontaneous adoption, are analyzed later in this paper (see paragraph 48 onwards and table 5).

14. Two publications demonstrate the emergence of social sciences in the conservation debate. In 1965, Boserup contended that population increase can stimulate intensification and innovation. Then, a year later, Ruthenberg (1966) confounded the critics of land reform in Kenya by demonstrating that small-scale farms could be much more productive than their large-scale neighbors. These analyses were vindicated decades later by Tiffen and colleagues (1994) who documented their research in Machakos, Kenya. They demonstrated that food security *and* the environment had improved despite a five-fold increase in population. In the 1990s this re-emergence of social science was crystallized by Leach and Mearns (1996) who advanced the hypothesis (based on case studies) that land degradation and deforestation were being systematically exaggerated through “development narratives”. The 1990s was also the decade when participation became popularized, and - just as gender issues had been embraced in the 1980s - no project was complete without reference to participatory rural appraisal (PRA) and its related approaches.

15. On the technical front, agroforestry was “named” as a science in 1977 and this gave birth to ICRAF (The World Agroforestry Centre as now known) during the following year. In many ways this illustrated the beginning of the acknowledgement by technocrats that there could be merit in indigenous practices: agroforestry has been practiced since the beginning of agriculture some 10,000 years ago, as crops, livestock and trees co-existed. The 1970s were also the period of severe droughts in the Sahel, and 1977 was furthermore when the term “desertification” came into common use with the Nairobi conference of that year.

16. Indigenous knowledge, ancient traditions and local innovation increasingly received recognition from the 1980s onwards (eg Wilken, 1987; Kerr and Sanghi, 1992; Critchley, et al, 1994; Reij et al, 1996; Critchley 2000). Simultaneously, water harvesting in the drier regions was "rediscovered" in the late 20th century with a number of studies and overviews (eg Reij et al, 1988; Critchley et al, 1992, Agarwal and Narain, 1997 and Oweis, 1999) which reflected, and supported, the growing involvement of projects in this discipline.

17. In the hilly areas, sustaining on-site production was recognized as often being more important, and cost-effective, than focusing on the negative effects of downstream sedimentation and flooding – many of the latter impacts having a geological origin and being impossible to control (Bruijnzeel and Bremmer, 1989; Doolette and Magrath, 1990; WOCAT, 2007). "Conservation agriculture" (with its three principles of minimum tillage, keeping the surface covered and crop rotation) burgeoned from the turn of the century, especially in the Americas.

18. From the 1980s on, it can be said that a new approach emerged. This is broadly characterized (in rhetoric, at least) by participatory, production-oriented, affordable strategies of conservation (WOCAT, 2007). This overall, more "enlightened" attitude is held to be more likely to spread success, particularly amongst resource - poor farmers (Chambers, 1983; Hudson, 1991; IFAD, 1992; Douglas, 1994). Names and terms have moved on also, keeping pace with the new thinking. Thus "soil conservation" progressed first to "soil and water conservation" or "soil and water management". Then "better land husbandry" was popularized (Shaxson et al, 1989) followed by "sustainable land management" which consolidated its position in 1996 at the ISCO conference in Bonn (Hurni et al, 1996), and reflected the new international focus on sustainable development (WCED, 1987). Sustainable land management, with its central notion of combining conservation with production, continues to be the preferred term in the Anglophone world.

19. Recent years have seen the re-emergence of thinking that views agriculture as the "engine of growth" in poor countries. This resonates well with the realization that – in many countries - farming communities are the poorest of the poor, while being simultaneously custodians of the countryside. It has also been acknowledged by the climate change community that poor agricultural practices and land use change are major sources of greenhouse gasses (GHGs). Figure 3 illustrates this in global terms. While most climate change data can be open to question with respect to precision, there is no doubt that very considerable amounts of GHGs (approaching 15%) are derived from agriculture (methane from farm animals and from rice paddies; nitrous oxide from nitrogen fertilizers; carbon dioxide from farm machinery) while around 18% are from forestry/ land use change (carbon dioxide from deforestation, forest degradation - decaying vegetation, as well as from no-longer protected soil). Sustainable land management is thus not simply a local environmental matter: it is central to concerns about poverty and climate change also.

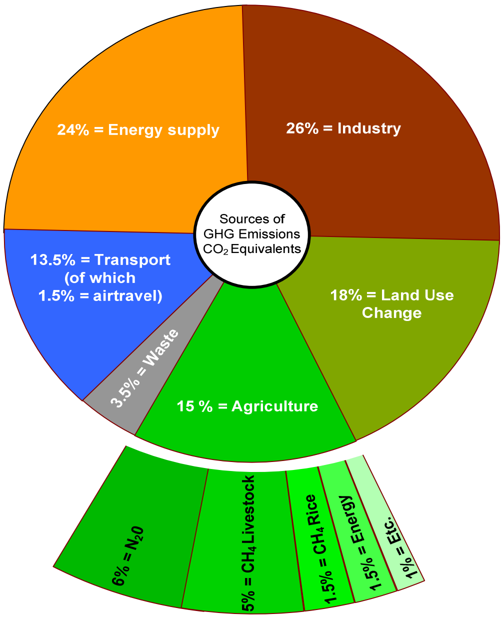

Figure 3: Global Greenhouse Gas Emissions (Source: based on WRI, 2005 and IPCC, 2007)

Table 1: Timeline of Trends and Milestones in Rainfed Agriculture and Rainwater Harvesting

TRENDS		MILESTONES
DUST BOWL is trigger for start of international conservation schemes	1930s	Great Dust Bowl in USA: Soil Conservation Service set up
TERRACING promoted strongly (and coercively) based on USA designs	1940s	Coercive terracing programmes in colonies
	1950s	Promotion of narrow-based channel terraces in Africa
	1960s	Emergence of *fanya juu* terraces in Kenya (local adaptation of narrow-based terraces)
TERRACING rejected as 'colonial'	1960s	Independence of many African countries: soil and water conservation dropped
SOIL CONSERVATION SCHEMES	1965	*Conditions of Agricultural Growth* (Boserup's book on intensification and innovation)
	1966	*African Agricultural Production Development in Kenya* (Ruthenberg highlights productivity of small farms)
RURAL DEVELOPMENT AND SOIL CONSERVATION projects reborn – but many fail	1971	*Soil Conservation* (Hudson's authoritative text book)
	1972	Stockholm conference on the environment (UNEP established)
	1970s	Soil Conservation/ Rural Development projects fail across sub-Saharan Africa and elsewhere
	1974	Kenya's National Soil and Water Conservation Programme set up
AGROFORESTRY "discovered" as a science	1977	Nairobi Conference on Desertification
	1977	"Agroforestry" named as a science (ICRAF – now World Agroforestry Centre - established in 1978)
ANALYTICAL LESSONS drawn from new wave of projects	1981	*Accelerated Development for* sub-Saharan Africa (World Bank's prescription for growth in SSA)
	1982	*Review of Rainwater Harvesting* (Boers & Ben-Asher review water harvesting in Israel, USA etc)
PARTICIPATORY APPROACHES introduced	1983	*Rural Development: Putting the Last First* (Chambers proposes participatory methods)
	1986	*Rainwater Harvesting* (Pacey and Cullis review water harvesting in sub-Saharan Africa)
	1987	*Some Lessons from water harvesting in SSA* (Critchley reports World Bank workshop in Baringo, Kenya)
LAND HUSBANDRY gains favor as new term and approach to conservation	1987	*Our Common Future* (WCED's "Brundtland Report" defines Sustainable Development)
	1989	*La Lutte contre la Desertification* (Rochette's analysis of 21 experiences in the Sahel)
	1989	*Land Husbandry* (Shaxson, Hudson, Sanders, Roose and Moldenhauer propose a new approach)
WATER HARVESTING becomes subject of study and project implementation	1991	*Water Harvesting* (Critchley and Siegert's technical manual for FAO)
	1992	United Nations Conference on Environment and Development produces the "Rio Declaration"
	1992	*Water Harvesting for Plant Production* (Critchley et al 1992- Study Report for World Bank)
INDIGENOUS PRACTICES gain credence	1993	*Water Harvesting for Improved Agricultural Production* (FAO: workshop and book)
	1994	*More People, Less Erosion* (Tiffen et al present evidence of environmental recovery in Machakos, Kenya)
	1994	*Indigenous Soil and Water Conservation: a Review* (Critchley *et al*)
SUSTAINABLE LAND MANAGEMENT accepted as new term for soil conservation	1995	"Blue Water, Green Water" concept first described introduced by Falkenmark (Falkenmark, 1995)
	1996	*Lie of the Land* (Leach and Mearns on exaggeration of land degradation etc)
WH/IK awareness raised in India	1996	International Soil Conservation Organisation (ISCO) Conference Bonn/ *Precious Earth* (Hurni et al)
	1997	*Dying Wisdom* (Agarwal and Narain document traditional water harvesting in India)
CONSERVATION AGRICULTURE takes off in the Americas and elsewhere	2000	Conservation Agriculture (CA) beginning to expand rapidly
	2001	*Response to Land Degradation* (Bridges et al on land degradation worldwide)
GLOBAL ISSUES take centre stage	2001	*Water Harvesting for Upgrading of Rainfed Agriculture* (Falkenmark et al)
	2001	*Making Water Everyone's Business* (Agarwal et al on water harvesting in India)
	2002	Global Environment Facility adds Land Degradation to its portfolio
	2004	*Indigenous Water-Harvesting Systems in West Asia and North Africa* (Oweis et al)
AGRICULTURE (especially small-scale and rainfed) re-emphasized together with a renewed interest in WATER HARVESTING	2007	*where the land is greener: case studies of SWC worldwide* (WOCAT's overview book)
	2006	TerrAfrica established: a partnership for SLM in sub-Saharan Africa
	2007	GEF's Strategic Investment Programme (SIP) for investments under TerrAfrica set up
	2007	*Water for Food, Water for Life* (Molden, ed. compiles the comprehensive assessment of water in agriculture)
	2008	*Water and Cereals in Drylands* (Koohafkan and Stewart look at future needs and potential)
	2008	*Agriculture for Development* (World Bank)
	2009	*Rainwater harvesting: a lifeline for human well-being* (Stockholm Environment Institute for UNEP)

Key Previous Studies and Assessments

20. One of the purposes of this background note is to draw attention to previous studies, reviews and assessments, some of which were carried out 20 or more years ago and are in danger of “disappearing”. This is partially because many have not been digitized (thus web-based searches will overlook them or not provide access to content), partially because there is a tendency for researchers to ignore what has gone before (field research is more appealing than literature reviews) and partially because there is an overwhelming amount of information currently being generated that tends to “bury” the older material. Some newer studies will be highlighted also.

21. *A Review of Rainwater Harvesting – Boers and Ben-Asher, 1982*

After the National Academy of Sciences in the USA drew attention to “runoff agriculture” in their seminal publication “More Water for Arid Lands” (NAS, 1974), this was followed up by a general overview of RWH some years later by Boers and Ben-Asher. The authors note that: “*During the past 25 years water harvesting has been receiving renewed attention. We found roughly 170 articles…which had appeared between 1970 and 1980: about three quarters of them originated from the USA”.* Looking at the reciprocal argument it could be said that around 40 articles from the rest of the world on RWH was rather a pitiful number, and represented relatively *little* “renewed attention”. Their review is very much oriented to technical aspects of RWH experience in the USA and Israel.

22. *Rainwater Harvesting – Pacey and Cullis, 1986*

In African terms this book, which was part review, part handbook/ design manual, was innovative and pivotal. It dealt not just with RWH for crop production (though that was the major emphasis) but also with rooftop harvesting for domestic water supply. The emphasis is on Anglophone East Africa, and one of the authors (Cullis) had hands-on experience with RWH on a project in northern Kenya. Around this time there was an increasing awareness of the need to develop semi-arid areas after a series of droughts in Africa (especially across the Sahel), and a strong movement to acknowledge and appreciate indigenous knowledge was emerging amongst the development community. Unsurprisingly, one of the main conclusions was that: *“Information about existing traditions of runoff farming is inadequate nearly everywhere”.*

23. *Le Sahel en Lutte contre la Desertification: Leçons d’expérience – Rochette, 1989*

During the period of heightened project activity in the 1980s, following on from the severe Sahelian droughts of the 1970s, Rochette travelled extensively around Francophone West Africa, visiting many projects in Burkina Faso, Mali, Mauritania, Niger and Senegal. His book, published in 1989 focused on 21 projects, attempting to give as broad coverage as possible, in terms of countries, agro-ecological zones and technologies. Each “experience” is treated systematically, giving climatic data, an historical context, details of the technical activities (including stone bunds; wind breaks; area closure; sand dune fixation; afforestation etc), and then socio-economic impacts and conclusions. This was a major work, but being produced only in French it had little or no impact on Anglophone Africa. This linguistic divide has hampered (and continues to hamper) exchange of experience.

24. *Water Harvesting – Critchley and Siegert, 1991*

Late in the 1980s, FAO identified the need for a technical handbook and undertook to produce a manual on water harvesting. Subtitled "*A manual for the design and construction of water harvesting schemes for plant production"* its objective was to provide technicians and extension workers with practical guidelines on the implementation of water harvesting schemes. After a categorization of water harvesting systems, water and soil requirements for water harvesting are covered and this is followed by a section on rainfall/ runoff analysis and a design model. The main section of the booklet is then dedicated to technical details of various systems, covering the most common project-based technologies from East and West Africa. These are:

- *Negarim* microcatchments
- Contour bunds for trees
- Semi-circular bunds (*demi-lunes*)
- Contour ridges for crops
- Trapezoidal bunds
- Contour stone bunds
- Permeable rock dams
- Water spreading bunds

Much of the information included in this report was actually derived (with permission) from the World Bank's Sub-Saharan Water Harvesting Study – as described below.

25. *The World Bank's Sub-Saharan Water Harvesting Study, 1987-1992*

This World Bank initiated study marked a renewed interest in water harvesting by the Bank, and was stimulated by positive results from water harvesting under the World Bank's Kenyan Baringo Pilot Semi-Arid Area Project (BPSAAP) and a Sub-Saharan workshop on water harvesting held in Baringo in 1987 which highlighted the amount of activity and interest in the topic (Critchley, 1987). Water harvesting components were characteristic of a number of projects across Africa at the time, and there was a growing realization that indigenous systems were largely unstudied – or even unknown. The initial report of the World Bank's Sub-Saharan Water Harvesting Study (SSWHS) was published in 1988 (Reij et al, 1988). This was a desk-study; a literature review of the state of the art. Over 350 books, articles and reports are listed in the reference/ bibliography.

26. The final report was then published in 1992 (Critchley et al, 1992). Based on field visits and literature review of new materials (both "grey" and published) the report describes details of 13 case studies from seven different countries. All describe different technologies, ranging from stone bunding in West African projects, to contour ridges and semi-circular bunds/ half-moons (*demi-lunes*) in Kenya, to ancient traditions in Somalia and Sudan. The report highlighted the importance of not just technologies/ structures which form the framework for all WH systems, but production aspects (crops, cropping systems and the need for fertility maintenance) also. Under socio-economic and project management aspects, (i) adoption, (ii) costs and benefits, (iii) mechanization, (iv) participation, (v) the use of incentives and (vi) land tenure are all discussed. Within the analytical section there were various recommendations. While not all were original, none of them are outmoded, and many of the same conclusions/ recommendations, especially the more general ones, have been regurgitated regularly over the years. These (abridged, edited and clustered by topic) are as follows:

Table 2: Recommendations from *Water Harvesting for Plant Production* (Critchley et al, 1992)

1.	**POLICY POINTS**
	At the national level water harvesting (WH) should be entrusted to a defined institution for coordination and data storage
	Coordination of WH programmes and incentive systems should be set up at national level to prevent confusing beneficiaries
	To facilitate the transfer of information between projects, clear design data needs to be kept in written form and distributed widely. A manual describing the most common techniques in SSA would be useful
2.	**RESEARCH NEEDS**
	Research on the reasons for adoption or non-adoption of WH techniques is urgently needed
	Attention should always be given by WH projects to the interactions between their activities and land tenure
	Systematic study and analysis of the relationship between microcatchment size and tree performance is required
	More research is required on traditional systems as (a) starting points for projects and (b) to improve them
	A systematic effort is required to identify the necessary conditions for transfer of WH systems across regions
3.	**APPROACH/ PROJECT DESIGN ISSUES**
	Monitoring and evaluation of the socio-economic impact and acceptability should be part of all WH projects
	Incentives and support should be defined with close consultation of local resource users in order to improve chances for post-project expansion of WH activities and proper maintenance of works
	Local resource users should decide how they want to organize themselves for the construction of WH works
	WH is not a free-standing technique but should be treated as part of a village land use management plan
	To increase the benefit women derive from WH, a major effort should be made to provide them with training in techniques, and give them material support, and help them gain access to land
	During design and implementation specific attention should be paid to involvement of poor farmers
	Projects should improve the quality of data collection with regard to costs and benefits
	The most effective spillways in earth-bunded systems drain water around the protected ends of upslope wingwalls. Spillways present an erosion hazard and stone-bunded systems or microcatchment techniques should be preferred wherever possible
	More effort should be made to train farmers for large-scale adoption of WH techniques
	Improved standards of plant (especially crop) husbandry must be introduced at the same time as investments in WH structures
4.	**TECHNICAL ISSUES**
	For WH on individual fields donkey carts, animal plows and other tools should be preferred to the use of heavy machinery
	For small-scale tree planting *negarim* microcatchments are the best option. For larger scale tree planting on even land (especially where machinery is used), contour bunding is preferred
	Where loose stone is available it should normally be preferred to earth for bunding
	Simple surveying instruments such as water levels are adequate for WH; train farmers to use them
	Fertility management is usually the most crucial aspect of crop production where WH is used
	Multiple planting (more than one tree seedling) should be standard practice under WH systems
	Planting grass amongst trees should always be considered to obtain quick benefits
	Under land rehabilitation the incorporation of legumes, trees and live fences can yield longer-lasting benefits

27. *Dying Wisdom: Rise, fall and potential of India's traditional water harvesting systems - Agarwal and Narain, 1997*

While Kerr and Sanghi (1992) had set the ball rolling by writing about traditional systems of soil and water conservation in India, *Dying Wisdom* represented India's recognition of ancient water harvesting systems and their potential for the future. But it was equally a cry for appreciation of indigenous knowledge. The 400 page hardback book is comprehensively researched and very well illustrated. It is not a design manual, but a readable and impressive overview of systems from India's 15 ecological zones. Both irrigation and domestic systems of WH are covered. This milestone book was followed up in 2001 by the more analytical, and geographically broader *Making Water Everybody's Business* (Agarwal et al, 2001).

28. *Water Harvesting for Upgrading of Rainfed Agriculture - Falkenmark et al, 2001*

In this paper, Falkenmark and colleagues continue to write about a favored theme: that of "green water/ blue water" ("green water" includes productive plant transpiration as well as evaporation from the soil surface) and put this in the context of valuable water lost in semi-arid areas. They indicate that (theoretically) a yield upgrade of 1 – 3 tonnes per hectare is possible through water harvesting in these zones. This Stockholm International Water Institute (SIWI) publication goes on to describe water harvesting technologies for sub-Saharan Africa, categorizing them as (a) within-field systems (b) runoff farming (c) floodwater farming (d) storage systems for supplementary irrigation. The publication ends with research gaps, and identifies several. We are told: *"at present very little is known on socio-economic, environmental and hydrological impact of upscaling small-scale water harvesting technologies".*

29. *Indigenous Water Harvesting Systems - Oweis et al, 2004*

ICARDA (The International Centre for Agricultural Research in Dry Areas) launched a regional initiative on "On-farm water husbandry in West Asia and North Africa" in 1996. This book is a compilation of case studies from Egypt, Iraq, Jordan, Libya, Morocco, Pakistan, Syria, Tunisia and Yemen. The editorial chapter stresses the role of indigenous knowledge (and its subset – local innovation) in improving existing systems through blending with western "scientific" knowledge. The history of water harvesting in this zone – the cradle of agriculture – is as old as anywhere in the world. Some of the most ancient systems exist to the present. Nevertheless a range of "new" techniques such as microcatchment systems, including contour ridges and tree *negarims* (as described in Shanan and Tadmor, 1979, and in Critchley and Siegert, 1991) are being introduced and are reported here.

30. *where the land is greener*[2] *– WOCAT, 2007*

The World Overview of Conservation Approaches and Technologies (WOCAT) has been building up a database both of technologies (including soil and water conservation/ sustainable land management/ water harvesting) and the "approaches" that support those technologies for 15 years. *where the land is greener* is WOCAT's first comprehensive written product. What it makes it different from previous publications on the topic is that (i) it is global; (ii) it covers all agro-ecological zones and production systems; (iii) there is a standard (illustrated) format and (iv) there is an analysis with policy points directed at those who make decisions. 42 technologies in total are reported, and 28 cases are matched by associated "approaches" to implementing each technology.

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[2] lower case – as on cover of book

31. Despite the length of time that WOCAT has been operational as a knowledge exchange network, actively seeking out information, the editors note that there is very restricted hard data on impacts of technologies. Thus specific benefits (crop yield increase; soil moisture increase; impact on downstream siltation) could only be rated as little (+), medium (++) or high (+++) by contributors. The following are five (abbreviated) policy points emanating from the analysis of the case studies:

- Monitoring and evaluation in SWC projects/ programmes must be improved;
- Mapping of conservation coverage is essential;
- An urgent area for further investigations and research is quantification and evaluation of the ecological, social and economic impacts of SWC, both on-site and off-site, including the development of methods for the valuation of ecosystems services;
- In dry areas, investments in water harvesting and improved water use efficiency, combined with improved soil fertility management should be emphasized;
- Local innovation and farmer to farmer exchange should be promoted (WOCAT, 2007).

32. *Water for Food, Water for Life - Molden (ed), 2007*

This "comprehensive assessment of water in agriculture" culminated in an exhaustive 640 page report (with a 40 page summary, which was also produced separately) that sets out the prospects for water in agriculture. Not surprisingly there is a note of warning, yet guarded optimism in the key quote: *"Only if we act to improve water use in agriculture will we meet the acute freshwater challenges facing humankind over the coming 50 years".* Of the eight "policy actions" proposed, number 5 is the most relevant to this background note:

> *"Upgrade rainfed systems – a little water can go a long way.* Rainfed agriculture is upgraded by improving soil moisture conservation and, where feasible, providing supplemental irrigation. These techniques hold underexploited potential for quickly lifting the greatest number of people out of poverty and for increasing water productivity, especially in sub-Saharan Africa and parts of Asia". (Molden, 2007).

33. *Water and Cereals in Drylands – Koohafkan and Stewart, 2008*

With years of experience and the institutional knowledge of FAO and West Texas A&M University behind them, the authors present a thoroughly researched, analytical overview of the problems and potentials for increasing cereal production by 50% by the year 2050. The 110 page booklet is of high presentational quality, packed with important statistics and well illustrated with top quality photographs. The chapter on technologies (which comprises about a quarter of the book) includes both *in situ* water conservation and water harvesting. This is not a manual – therefore no design specifications are included – but a range of technologies are described, with a focus on Africa. The following chapter discusses social and economic aspects, and the book ends with a two page concluding section that states boldly "*A considerable body of research knowledge and producer experience exists….therefore the greatest challenge is the implementation and execution of sound management plans".*

34. *Rainwater Harvesting: a Lifeline for Human Well-Being – Stockholm Environment Institute, 2009*

Edited for the Stockholm Environment Institute by Barron, this booklet addresses rainwater harvesting the light of the recent concerns about ecosystem services, human well-being and climate change. There is a powerful plea in the Foreword by the Executive Director of UNEP for more attention to be given to harvesting rainwater. This is a an attractive and informative booklet, with chapters writen by various authors providing worldwide cases, that will undoubtedly serve to further raise the profile of the topic.

State of the Art – and Gaps

35. Classification of Technologies

Technologies to improve rainfed soil and water management can be classified or grouped in various ways, but (referring back to paragraph 3) conceptually the simplest is to consider first different agroclimatic zones under rainfed farming, where farmers' strategies either:

(i) provide for discharge of excess water;
(ii) hold rainfall *in situ*; *or*
(iii) harvest water from a catchment area to supplement rainfall.

These strategies are achieved primarily through the use of:

(a) support structures (the "hardware" of systems); combined with
(b) in-field/ agronomic practices (the "software")

Formerly, support structures – typically stone, earth or vegetative cross-slope barriers, bunds or terraces - were the tools of the soil and water conservation specialists. On the other hand in-field practices – including mulching, fertilizing, intercropping, crop rotation, agroforestry and reduced tillage – constituted the territory of agronomists. However "sustainable land management" now considers the two to be organically inseparable.

36. (a) Support Structures

The first strategy (i) is based generally on terraces or bunds with a lateral gradient which allows excess runoff to flow out of a system at speeds that do not permit it to carry significant sediment. The second strategy (ii) comprises, typically, earth or stone structures, or vegetative barriers (which may allow some gentle drainage) on the true contour, thus acting as barriers to flow of runoff or sediment. The third strategy (iii) is made up of systems that guide runoff from a catchment to be stored in the soil of a cultivated area, or into a pond from which supplementary irrigation is drawn. It is this last strategy – together with *in situ* moisture conservation - that is the main focus of categorization and particular description in this background note.

37. (b) In-Field/ Agronomic Practices

In-field practices have become acknowledged over the last 20 years as especially important - not just because they help protect the soil, and keep it well-structured and thus less erodible – but because they directly impact on farmers' interests. In-field practices help ensure production, and (in Shaxson's evocative phrase from 1988) thereby *"conserve soil by stealth"*. In other words, while the primary purpose may be for improving production, the increased ground cover and improved soil health lead indirectly to better rainfall infiltration and less soil erosion. There is a further dimension to this argument; and that is gender. Whereas support structures tend to be the domain of men, in-field practices in Africa, Asia and Latin America are commonly the primary responsibility of women. This background note will only touch on in-field practices in passing, with some exceptions (mulching; cover crops etc) – and in particular conservation agriculture, a special case which is rapidly spreading and is increasingly appreciated by farmers and conservationists alike for its production and conservation benefits.

38. There are a number of publications that describe, define and analyze support structures – and agronomic measures - in greater or lesser technical detail. Many have been developed on a country specific basis. However the various manuals and handbooks in the Anglophone world at least (eg Singh et al, 1990 for India; Hurni, 1986 for Ethiopia; Thomas, 1997 for Kenya) all owe a debt to the standard texts produced by Norman Hudson and Roy Morgan. Hudson's 1971 *Soil Conservation* was the classic textbook for soil and water engineering students. This was reprinted several times before a new edition followed in 1981. Morgan's 1986 text focused more on erosion – but also describes remedial measures that he classifies into:

(a) agronomic
(b) soil management *and*
(c) mechanical measures.

39. Hudson (1981) gives descriptions and design considerations for a range of techniques, including:

- Stormwater diversion drains
- Channel terraces
- Artificial watercourses
- Bench terraces
- Irrigation terraces
- Orchard terraces
- Contour bunds
- Pasture furrows
- Tied ridges
- Contour cultivation and grass strips
- Ridge and furrow

40. Significantly Hudson followed this standard text some years later with a brave new title: *Land Husbandry* in which he demonstrated his significant move away from pure soil conservation engineering and towards a more holistic approach (first hinted at in Hudson, 1988) bringing in vegetative measures and looking at the production-conservation nexus, including in-field practices (Hudson, 1992). In his introduction he admits that *"the ideas in this book have evolved during years of discussion, correspondence and sometimes argument with many colleagues all over the world".* Nevertheless this book also covers the main support structures, describing the various forms of terracing – their design, construction and applicability. In the Francophone zone of West Africa, it was Eric Roose whose research and texts gained similar authority (see for example, Roose, 1987). Roose edited the *Reseau Erosion* which formed a focal point for exchange of experience and ideas covering not just erosion, but conservation and water harvesting as well (eg Roose, 2000).

41. WOCAT's system of classification is to differentiate between "technologies" and the "approaches" that provide the conditions for technology spread. WOCAT then defines *constituent measures* of "technologies" as (i) agronomic, (ii) vegetative, (iii) structural, and (iv) management. Broadly speaking (i), (ii) and (iv) are equivalent to "in-field practices" and (iii) equivalent to "support structures". WOCAT's "*where the land is greener"* (WOCAT, 2007) sets a benchmark as a different type of technical publication for reasons already given (see para 25). The basis for WOCAT is that there is knowledge, often tacit rather than explicit, that resides in local specialists and farmers themselves. Herein are design criteria for a wide range of technologies derived from the case studies.

42. However for the pragmatic purposes of the book, the WOCAT team decided to cluster technologies (each made up of various constituent measures as above) into groups with recognizable names. These are:

- Conservation agriculture
- Manuring/ composting
- Vegetative strips/ cover
- Agroforestry
- Water harvesting
- Gully rehabilitation
- Terraces
- Grazing land management

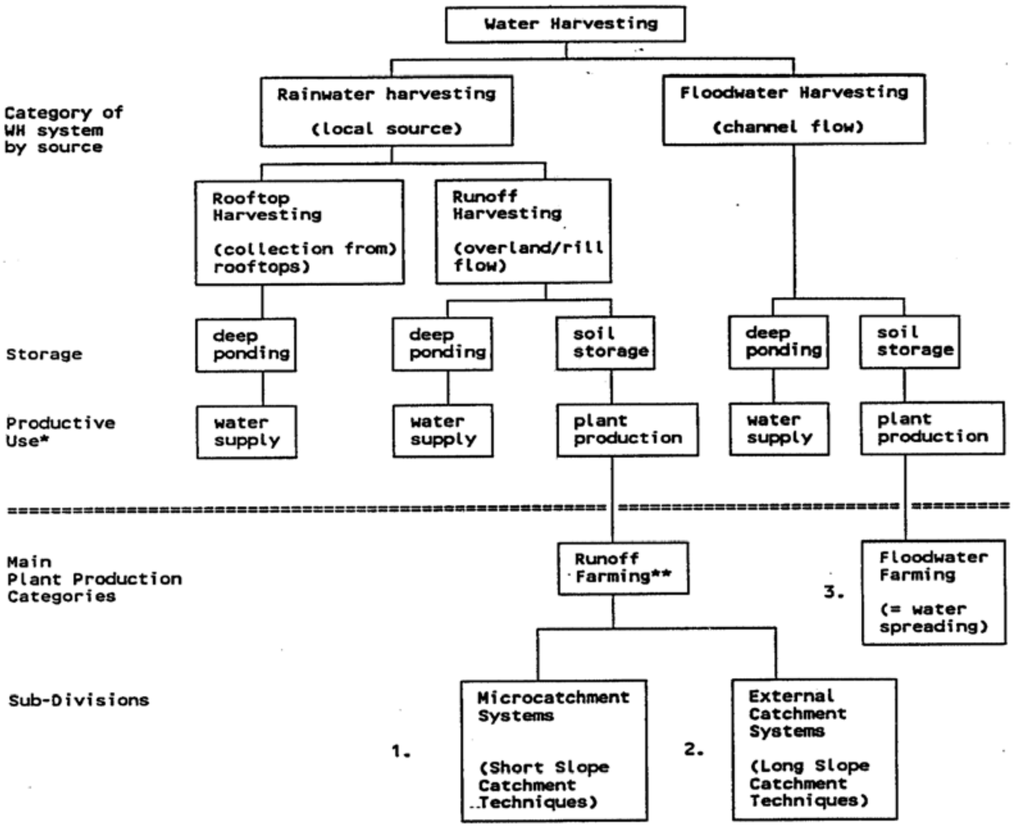
43. Classification of Water Harvesting Systems

While in this section we concentrate on the classification of water harvesting, it must be remembered that rainfed systems of soil and water management techniques can be broadly divided into three strategies (see paragraphs 3 and 34) of which water harvesting is the most applicable where rainfall limits production. Water harvesting can be defined and classified in a number of ways, but most are closely related. For the purposes of simplicity and consistency the original definition and classification proposed by Critchley and Siegert (1991) is used here. Water harvesting is thus: *"The collection of runoff for productive purposes"* and the basic components of a water harvesting system that is dedicated to plant production are (i) a catchment area, (ii) a concentration area and (iii) a cultivated area. When runoff is stored in the soil profile, the concentration area (ii) and the cultivated area (iii) are synonymous. Note that *in situ* moisture conservation systems differ from water harvesting as there is no catchment area: rainwater is held where it falls, rather than being deliberately collected and concentrated.

44. It should be pointed out that "water harvesting" is often understood in some quarters as exclusively meaning "rooftop harvesting for domestic consumption" and there is a plethora of documentation on this topic (eg the 1982 standard text for Africa by Nissen-Petersen). That is not, however, the topic of this paper.

45. Figure 4 presents the classification of water harvesting developed by Critchley and Siegert (1991) and reproduced in FAO (1994). The classifications proposed by Oweis et al (1999), Fox (in Falkenmark et al, 2001) and Oweis et al (2004) differ in details only. It will be seen that this classification (Fig 4) divides water harvesting into "floodwater harvesting" (channel flow) and "rainwater harvesting" (local source/ overland flow), differentiates between ponding and soil storage, and then again between the use of collected water for domestic/ livestock supply and plant production. The final subdivision, where overland flow/runoff is collected and stored in the soil, is into "microcatchment/ within-field systems" and "external catchment systems".

46. This final subdivision is of most concern to those who promote smallholder water harvesting for improved crop production. Storing rainfall runoff in the soil needs only ridges or bunds to retain runoff, and does not need lifting/ pumping equipment that is required in systems where runoff is ponded. However, as with all water harvesting systems, these are vulnerable to drought. Water harvesting only *magnifies* the impact of rainfall. It is self-evident that during periods of drought there is no rainfall to harvest and thus the crop is dependent on the runoff collected and stored previously in the soil. Systems that pond water are less vulnerable: but this comes, literally, at a cost. Table 3 compares and contrasts microcatchment systems with external catchment systems.



Notes:

* Water supply systems (i.e. ponded water) used for a variety of purposes, mainly domestic and stock water but also some supplementary irrigation.

** The term "farming" (as in "Runoff Farming") is used in its broadest sense - to include trees, agroforestry, rangeland rehabilitation, etc.

Figure 4: Classification of water harvesting techniques (Source: Critchley and Siegert, 1991)

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47. Which rainfed soil and water management techniques (water harvesting and other) offer hope for future expansion? Table 4 presents eighteen specific examples that have been demonstrated to be successful. These are grouped under the three strategies, namely (i) provision for discharge of excess water in humid conditions; (ii) holding rainfall *in situ* where rainfall broadly meets crop requirements on average, *or* (iii) harvesting water from a catchment area to supplement rainfall. Note that several of the techniques are appropriate (sometimes with modifications) under more than one strategy. Five of the 18 (namely conservation agriculture, cover crops, homegardens, scattered tree agroforestry and mulching) are in-field practices, and while they may be used alone they are often combined to best effect with the other technologies (which are based on support structures). Part Two of this document then summarises each of these – and gives references that can be followed up for more information.

Table 3: Comparison of Microcatchment and External Catchment Water Harvesting systems

	Microcatchment (eg contour ridges; *negarim*)	**External catchment** (eg road runoff harvesting; large semi-circular bunds)
Location of catchment	Within field	Outside field: hillside/ road etc
Length of catchment	A few meters	Often 50 meters or more
Landscape	Even over whole area	Landscape divided up into catchments and plots
Runoff coefficient	Relatively high	Relatively low: the longer the catchment the lower
Storage of runoff	In strips/ pits etc in soil within-field	In soil over whole of field, or ponded
Spillway	Not required	Needed: to discharge excess runoff
Planting configuration	In strips/ pits etc within-field	Evenly over whole of field
Where suited	Especially where rainfall is reliable	Especially where few runoff events expected

48. However, the knowledge gaps that permeate these various techniques are all too evident. There is a dearth of information on such simple aspects as impact on yields; specific effect on erosion; costs and benefits – as well as actual areal coverage of the technologies. The need to improve monitoring and evaluation has been a recurring theme for decades and continues today (eg de Graaf et al, 2007). The calls have largely gone unheeded. This was particularly evident to those compiling the WOCAT publication "*where the land is greener*". Quantitative information and perceptions abounded, but these were mirrored by a lack of hard data. Nevertheless many measures are *de facto* beneficial and sustainable: their spread amongst farmers and longevity testifies to this. One of the publication's strongest recommendations was to improve M&E, and this was strongly expressed in policy points.

Table 4: Overview of Techniques – and their suitability within different soil and water management strategies

		Discharge excess water (+ minimise soil loss)	Hold water *in situ* (+ soil)	Harvest water (+ soil)
1	Bench terraces	▨	▨	
2	*Fanya juu* terraces	▨	▨	
3	Narrow / broad-based terraces	▨	▨	
4	Vegetative barriers		▨	
5	Tied ridges		▨	
6	Contour ridges			▨
7	*Negarim* microcatchments			▨
8	Stone bunds and *zaï* / *tassa* pits			▨
9	Semi-circular bunds: *demi-lunes*			▨
10	Mechanised *demi-lunes* / *sillons*			▨
11	Farm ponds			▨
12	Sand dams			▨
13	Road runoff harvesting			▨
14	Conservation agriculture		▨	
15	Cover crops	▨	▨	
16	Homegardens	▨	▨	▨
17	Scattered tree agroforestry	▨	▨	▨
18	Mulching	▨	▨	▨

Note:

- 1-13 are based on support structures (see para 35)
- 14-18 are in-field / agronomic techniques (and can be combined in some situations with the support structure-based techniques)
- See Part Two for description of each technique

Barriers to Adoption

49. Various authors over the last 25 years (eg Chambers, 1983; Stocking, 1988; Hudson, 1991; IFAD, 1992; Baum et al, 1993; Lundgren et al, 1993; Douglas, 1994; Pretty and Shah, 1994; Hurni et al, 1996; Hellin, 2006; WOCAT, 2007) have given their analyses of the reasons for success or failure in mainstreaming of soil and water conservation/ sustainable land management programmes – and proposed new ways forward.

50. A recurring theme amongst all analysts, is to identify problems associated with a top-down, technocratic, transfer of technology mentality. Amongst the other points highlighted are: an over-emphasis on engineering approaches; failure to train farmers in simple surveying techniques; the use of catchments (watersheds) as the unit of intervention rather than the community; ignoring indigenous knowledge and traditions; and failure to develop partnerships and alliances. Furthermore there is the need to look upon growth in population density as a potential opportunity; the importance of considering livestock while planning improvements in small-scale farming; the danger of becoming obsessed with "quick-fix" technical solutions; an obsession with the benefits of trees (ignoring their potential negative impacts, for example on hydrological regimes and on erosion where undergrowth is suppressed); the misuse of incentives to participating communities, especially the uncritical use of food-for-work, inducing a culture of dependence; and the unrealistic over-funding of small projects which cannot realistically be replicated on a large scale. Table 5 attempts to capture the essence of the "new" approach and contrasts it with the "old" ways, which often served to act as barriers rather than enabling factors.

Table 5: *Changing emphasis - from* soil conservation *to* sustainable land management

Source: developed from Critchley, 2000

"Soil Conservation"	⇒	**"Sustainable Land Management"**
Concern with soil loss	⇒	Emphasis on moisture and fertility
Conservation of soil as primary objective	⇒	Conservation through production and better land husbandry
Focus on badlands, gullies and off-site impacts	⇒	Focus on-site and on farmers' fields
Watershed as unit of intervention	⇒	Community-based focus
Population growth as a problem	⇒	Human resources as an opportunity
Livestock a problem	⇒	Integration of livestock a key
Structural/ engineering remedies	⇒	Biological answers where possible
On-station research	⇒	Farmer-researchers and on-farm research
Quick technical fixes	⇒	Basket of remedies
Trees seen as a panacea	⇒	Trees recognised to be a "mixed blessing"
Land users ignorant and agents of degradation	⇒	Recognition of indigenous knowledge and farmer innovation
Upland farmers punished for downstream problems	⇒	Upland farmers paid for environmental services (PES)
Soil conservation engineers to plan and implement	⇒	Interdisciplinary teams in partnership with land users
Top-down approach	⇒	Participation at all stages
Legislation and coercion ("*the stick*")	⇒	Extension training and motivation ("*the carrot*")
Projects/ schemes	⇒	Programmes and processes
"Save the soil: cost no object!"	⇒	Most effective use of limited funds
Incentives & rewards necessary	⇒	Voluntary contribution essential
No title to land implies no interest in conservation	⇒	Security of tenure is the crucial issue
Land reform and subdivision leads to land degradation	⇒	Smaller holdings means more incentive to conserve
Monitoring of physical achievements	⇒	Assessing adoption and sustainability
Environmental "doom & gloom" and "marching deserts"	⇒	Debunking myths: reassessment of degradation
Local problem of poverty	⇒	International obligation for livelihoods and the environment

51. Two particular analyses are worth looking at in detail, as they span 15 years and present different but complementary perspectives. Neither, however, deviates far from the prevailing consensus presented in Table 5. Hudson, in 1991, looked back at project-based initiatives in Africa. His mandate was to produce a soils bulletin for FAO which analyzed why some soil conservation projects in Africa had been more successful than others (Hudson, 1991). This was triggered by an FAO study in 1986 entitled "African Agriculture: the next 25 years" (FAO, 1986). Hudson pointed to project design faults that were key to failure, including over-optimism about the impact and adoption of new practices, and over-estimation of the ability of the host country to provide backup facilities (and thus sustainability of the process). The GEF (2007) takes a macro-level, regional perspective which helped formulate design of its Strategic Investment Programme for SLM within sub-Saharan Africa (SIP). In both analyses we see the need to enhance knowledge as well as to learn from experience.

52. The following clusters together the reasons for lack of adoption derived from these two sources:

Project Design Barriers

- unclear objectives and ill-defined, unobtainable targets;
- rigidity in project design preventing growth and adaptation during implementation;
- poorly defined duties and responsibilities of project staff and counterparts (technical assistance);
- an unrealistically short project duration (less than 5 years); and
- inappropriate technologies without proof of rapid, significant benefits and affordable inputs.

Knowledge and Technology Barriers

- inadequate knowledge transfer and management;
- knowledge gaps on specific land degradation and SLM issues;
- compartmentalized approach;
- inadequate monitoring and evaluation of land degradation and its impacts; and
- lack of local level capacities and experience.

Institutional and Policy Barriers

- lack of on-the-ground implementation;
- lack of coordination and collaboration between stakeholders;
- lack of policy harmonization and mainstreaming SLM in expenditure frameworks;
- slow and ineffective decentralization; and
- inappropriate incentive structure; in particular land tenure arrangements.

Economic and Financial Barriers

- inappropriate domestic economic policies including pricing policies;
- trade distortions and barriers;
- poverty and general lack of resources and investment opportunities;
- lack of credit facilities; and
- lack of financial resources at national level.

The Way Forward: Recommendations and Priorities

53. *Proceed with confidence:* Despite the barriers to adoption that have been laid out in this background paper, there surely is a way forward. This analysis has bemoaned the lack of performance data, and has strongly recommended improvements in monitoring and evaluation - and research - into impact and spread of various systems of agricultural water and soil management. But this does not mean that many systems have not been implemented successfully and accepted by farmers. And these should not be shelved. We have now enough experience of technologies, and the approaches that create an enabling environment, to go ahead with a vigorous but strategic campaign of promotion – accepting that land users will, and must have, the final say. There is increased evidence that rainfed agriculture in dry areas not only has considerable potential to be improved with better rainwater and fertility management, but also has the ability to lift the rural poor out of their poverty. It is time to overcome the development stigma that is still attached to small-scale, non-irrigated farming in the drylands.

54. *Promote proven technologies*: Part Two is a summary of 18 technologies that have been demonstrated to function well - in terms of managing water and soil while promoting production – and are acceptable in given situations to certain farmers. Clearly none of these is ubiquitously appropriate: there is no panacea. Some of the technologies lend themselves to hand-based systems, others to mechanized; some depend on a local supply of loose stone; agro-ecological suitability differs; the crops, pastures or trees to be planted will define suitability; the presence or absence of animals within the farming systems has an influence; there may even be no apparent logic why one system is preferred by local farmers to another. So what is the main message regarding technologies? This is: promote techniques, or combinations, that have worked in similar conditions, but allow land users the ultimate choice. This scaling-up must take place not just at horizontal levels – namely spread of technologies amongst farmers, but vertical levels also – namely institutionalization of the processes (FAO, 2007).

55. *Support knowledge management systems*: It is a tenet of WOCAT, and surely self-evident, that much knowledge exists locally, nationally, even regionally and globally about rainfed farming systems, yet the knowledge doesn't reach the places and the people where it can make impact. Knowledge management, from uncovering tacit information to disseminating it through mechanisms that reach receptive target groups is of paramount importance. Language barriers – particularly the Francophone/ Anglophone divide in sub-Saharan Africa – must be broken down. There are many ways of achieving these objectives. It could be support to global information networks (eg WOCAT) that emphasize documention of hitherto hidden "know-how". There again much information is already known and documented: but is hidden in "grey" literature, which is buried ever deeper as students and researchers rely more and more on the internet. And there remains the age-old principle that "travel broadens the mind". Simply moving farmers around and letting them see for themselves is a powerful tool.

56. *Build up our knowledge base*: As highlighted in this background note, there is a dearth of information on impact regarding different systems of soil and water management. It is high time that monitoring and evaluation is improved, and research into specific impact areas initiated. There are questions about on-farm effectiveness and upstream-downstream interactions that need to be addressed. With the development of better modeling – in particular the Soil and Water Assessment Tool (SWAT) (see Arnold et al, 2009 for an up-to-date and comprehensive overview of SWAT and its applications) – and access to better hydroclimatic information, there now exists the possibility of predicting the impact of technologies on yields, as well as hydrology and sediment delivery at the catchment scale.

57. *Don't ignore economic benefits*: Returning to the observation that in-field practices make conservation more "palatable" to land users through their direct connection with improved production, the combination of these with structural support measures can increase the returns to investment. Mulching, cover crops, agroforestry and homegarden systems are all production-oriented, but simultaneously "conservation friendly". One very specific example that is mentioned several times in the descriptions of the techniques (see Part Two), is the integration of fodder grasses, to stabilise structures and simultaneously to provide food for livestock. In these cases, economic models should be brought into play to put numbers onto these benefits and the costs. It is now opportune to apply both hydrological and economic models to improved dryland technologies in developing countries.

58. *Stimulate innovation systems*: There is currently increasing talk of "innovation systems" and stimulating these to work better. An innovation system comprises actors from different constituencies (research, extension, private sector, academia) involved in various activities (research, product development, promotion) that provide new ideas and products. These products may be tangible – new machines, seeds etc – or they may be to do with the "knowledge economy", where better information flow is the factor that limits development and adoption of improved systems. There is, however, another dimension to innovation systems, and that is the stimulation of local adaptation and innovation. If the topic is rainfed agriculture, then farmers have driven the development of such systems for millennia: it is time to recognize this and harness their role in local, adaptive innovation (see Reij and Waters-Bayer, 2001; Critchley and Mutunga, 2002). Ironically climate change may very well be a positive stimulant to local innovation. Nevertheless, researchers need to be brought into the process, to assist farmers to monitor, validate and develop systems.

59. *Encourage the "approaches" that constitute an enabling environment*: An enabling policy framework - with relevant policies and means of implementing them are crucial. WOCAT's analysis (WOCAT, 2007) stresses the need to break out of the conventional three-year project mode and move towards programmatic approaches that involve various partners. Another key is to establish appropriate incentive mechanisms: enough to trigger action/ overcome bottlenecks, but to avoid the dependency syndrome where stimulants become addictive. These incentives may be at micro level, or may pertain to government subsidies. Vitally important (and often overlooked) is security of tenure, without which land users are reluctant to invest in improvements to their productive base. Table 5 has listed other key elements of an "enlightened approach".

60. *Fulfil our obligations:* Finally – for reasons simultaneously involving poverty and the environment - there is a national and international obligation to invest in rainfed agriculture and associated stewardship of natural resources. The link between climate change and sustainable land management through the huge potential for carbon sequestration in the land, and the enormous amounts of carbon lost through land degradation, should help to focus international attention on what has too often been seen as a local problem. Technology is not the main limiting factor: it is the willingness of governments and development agencies to invest in terms of money for research and development, alongside concerted implementation efforts over a prolonged period, that is principally lacking.

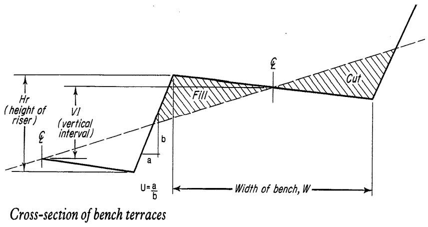
PART TWO

1. Bench terraces

Bench terraces can permit better management of soil and water on cultivated hillsides; they furthermore improve physical access to land, and facilitate farm operations by hand or machine (Bridges et al, 2001). Though often associated with irrigated agriculture, terraces are commonly found under rainfed conditions– and there are many examples of traditional structures dating back thousands of years. The famous Inca terraces of Machu Picchu in Peru are a window on ancient agriculture, and in China there is a history of rainfed terracing in the Yellow River Basin that is 2,000 years old. Terraces are a classic case of a conservation technology evolving independently on different continents. While bench terrace construction was a common feature of conservation programmes last century, with the exception of massive programmes in China (see WOCAT, 2007 for an extraordinary achievement on the Loess plateau), the current emphasis has turned towards low cost contour vegetative barriers.

Level (flat-bed) bench terraces are employed to hold rainfall *in situ*, whereas laterally graded terraces, with a backslope towards the riser, allow for discharge of excess runoff in humid areas. In dry areas, "Zing" or "conservation bench" terraces are an alternative form: in this case flat bench terraces are separated by original-slope catchment areas, which provide runoff for water harvesting (Hudson, 1987). Bench terraces can be constructed by excavation and redistribution of top soil (see diagram below), or (more usually) allowed to develop over time behind bunds through the processes of tillage and water erosion.

rainfed bench terraces in India



back-sloping bench terrace: Hudson, 1981

riser made from limestone in Indonesia

Technical description

Bench terraces can be defined as terraces having a bed (the planting area) with a gradient of 3^0 or less in any direction (otherwise they are better described as "forward-sloping" terraces etc), a bed width of usually 10 metres or less (Critchley et al, 2001). They are generally continuous down a hillside; the top of a given terrace riser elevated slightly above the bottom of the terrace upslope. The terrace "riser", or terrace wall, may be made of stone (almost invariably so, where loose stone is available), or earth. Earth risers are often protected by fodder grass – which can be cut for stall-fed livestock, thus making productive use of a "wasted" belt of land between cropping strips. Unprotected earth risers, being steep and exposed, can constitute a significant source of sediment themselves.

Suitability and limitations to use

Terraces are appropriate on hillsides with deep soils and significant productive potential. However bench terraces are inappropriate for the very steep slopes (often well above legal limits of cultivation) that are being brought into cultivation as populations expand into mountainous areas. Above slopes of $25\text{-}30^0$ construction costs become prohibitive: furthermore risers become higher, terrace beds narrower and the risk of mass wasting – terrace collapse – increases. It is not only the cost of construction that can be a constraint in bench terraces, but the maintenance of terraces (which is extremely important) is time-consuming and expensive also. Globally, there are examples of ancient systems slipping into disrepair, and without investment from outside (see, in this context, the positive initiative from Peru documented in WOCAT, 2007) there is the ironic situation that collapsing conservation structures lead to worse land degradation than comparable untreated slopes.

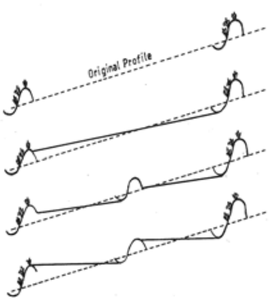
Impacts

Apart from reducing erosion, well-maintained bench terraces allow cultivation by hand, animal draft or machine where the original steep slopes would be difficult or impossible to crop otherwise. Another unique feature of terraces is that they constitute perhaps the best example of truly spectacular and marketable agro-ecotourism (Bridges et al, 2001; WOCAT, 2007). However, bench terraces are not a panacea: for all their merits they are "uncertain steps" on tropical hillsides (Critchley et al, 2001).

2. *Fanya juu* terraces

Fanya juu (“throw the soil upwards” in Kiswahili) terraces are the framework of the successful soil and water conservation campaigns in Eastern and Central Kenya. This is a “hybrid” system, apparently resulting from an introduced technology (channel terraces), modified by farmers. Their usual function is to hold rainfall (thus soil simultaneously) *in situ*, though *fanya juu* terraces may be designed with a lateral gradient in more humid zones where they allow safe discharge of excess rainfall. In drier areas, the trench below the earth bund may also function as an infiltration ditch – to accommodate runoff led into the farm from an adjacent hillside or road. Over time the structures develop into level bench terraces (see diagram) through tillage erosion (the act of ploughing or hand-hoeing which moves soil downslope) and water erosion. *Fanya juu* were the linchpin of the successful National Soil and Water Conservation project in Kenya during the 1970s and 1980s, and these terraces support, literally, rainfed farming over much of Kenya’s smallholder sector. They are currently being introduced into neighboring countries.

fanya juu terraces: Liniger in WOCAT, 2007



evolution into benches: Hudson, 1987

maintenance by women’s group in Kenya

Technical description

Thomas (1997) provides a detailed guide to construction of *fanya juu* (or “converse”) terraces for different slope classes. On, for example, a 15% (8.5 °) slope, the horizontal distance between bunds should be 12 metres, the width of the trench 0.6 metres, and its depth about the same. The upper side of the earth bund needs, in this case, to be around 0.4 metres high. For this particular situation, the labour input required is around 90 person days per hectare. However this requirement increases quickly as the slope rises: thus on a 20% (11°) land gradient 133 person days are needed. *Fanya juu* terraces are most commonly used as *in situ* moisture conservation structures, thus they are normally laid out along the contour without a lateral gradient. If there is an external catchment above the field, then a diversion ditch may have to be constructed to protect the terraces. *Fanya juu* terraces are invariably constructed by hand. A final technical point pertains to the planting of grass on the bund: this is simultaneously to stabilise the structure and to provide fodder for livestock. Much favoured in Eastern Kenya is napier grass (*Pennisetum purpureum*) or the closely related bana grass. In drier areas, the more drought resistant, though less palatable *makarikari* grass (*Panicum coloratum*) is preferred.

Suitability and limitations to use

While difficult to mechanise, *fanya juu* terraces are widely appropriate on a range of soils and slopes, and agroclimatic zones. Thomas and Biamah (1991) give a history and overview of *fanya juu* terracing, showing its widespread applicability. However they caution about the amount of labour incurred in construction on the steepest slopes. Where it is most well known – in Kitui and Machakos Districts of Eastern Kenya - it is often groups that construct and maintain these terraces. A common phenomenon during the peak period of construction, the 1970s and 1980s, was the involvement of women’s *mwethya* (self-help) groups. In this region, *fanya juu* terracing has been instrumental in the area’s environmental recovery (“*More People, Less Erosion”*) documented by Tiffen et al (1994).

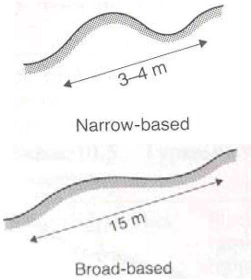
Impacts

WOCAT (2007) describes these terraces, and elaborates on their multiple benefits. These include erosion reduction, crop yield increases (from reduced loss of runoff), fodder production (from grasses planted on the terrace banks) and community institution strengthening (through their association with women’s groups). Holmberg (1985) and Lindgren (1988) reported increases in crop production under *fanya juu* systems, and Kiome and Stocking (1993) found an average increase in maize yields of 21% over standard hand tillage without conservation measures in Eastern Kenya.

3. Narrow/broad-based terraces

Narrow- and broad-based terraces (collectively termed “channel terraces”) have been the support structure of choice for large-scale mechanised farming, especially in the USA, since the early 1900s. These comprise earth bunds made by machine (often a bulldozer or motor-grader) along the contour, with or without a lateral gradient. While mechanised terraces have proved very effective for arable farming in the Americas and elsewhere, their indiscriminate introduction into Africa by colonial soil conservation officers proved short-sighted. Despite performing well in the “White Highlands” of East and Southern Africa, their promotion in the small-scale sector was little short of a disaster. This was because (a) the uneven slopes of small-scale farming sector did not lend themselves to mechanisation, (b) graded terraces and waterways drained valuable moisture from the land, and (c) they were imposed in a coercive way. Showers (2005) describes how a national campaign in Lesotho began in 1935. By 1964, 215,000 hectares had been terraced inappropriately. Terraces were poorly maintained and often led to more erosion than before. In Burkina Faso, a mechanised scheme entitled “GERES” operated in the 1960s. Entire catchments were covered with graded channel terraces that drained precious water from the land: they were abandoned by farmers (IFAD, 1992).

narrow-based system with waterway (left, layout, IFAD, 1992; right in large scale farm)



terrace types: Morgan, 1986

Technical description

Narrow-based terraces are typically 3-4 metres in cross section (including the raised bund and the shallow excavated trench above). These are constructed by sweeping the soil downslope with a plough, motor-grader or bulldozer. Broad-based terraces on the other hand can be up to 15 meters in cross section and these are created by sweeping soil both upslope and downslope (see figure, above right). Broad-based terraces are usually cropped; narrow-based terraces are commonly left to be colonised by grasses which protect the structures – or kept vegetation free to reduce the risk of weed seeds invading the crop. When laid out along the true contour – common in parts of Texas, USA with around 500 mm annual rainfall (B. Harris, *pers com*) - such structures serve to hold rainfall *in situ.* These are sometimes termed “retention terraces”. In more humid areas they are designed with a slight lateral gradient (typically 0.5%) and often called “graded terraces”. In this case they are intended to discharge excess rainfall runoff at a non-erosive velocity (therefore preventing loss of significant amounts of soil), and are drained into watercourses or specially designed grassed waterways. Graded terraces may also need to be protected by a laterally graded diversion ditch at the head of the field (see figure above left) if there is a significant catchment above. The spacing between terrace structures, termed the horizontal interval, is determined by the slope of the land: the steeper the slope, the closer the structures. Design specifications can be found in Hudson, 1981; Unger, 1984; Morgan, 1986; and Thomas, 1997.

Suitability and limitations to use

It is clear from the foregoing that such terraces are only appropriate in situations where (a) there are large-scale farms with erosion problems (b) mechanisation is technically and economically feasible and (c) the correct design is used. Their introduction into Africa in the mid-1900s did as much to deter farmers from conservation as to encourage them.

Impacts

These terraces, invariably combined with contour cultivation, can reduce soil erosion significantly. This is reflected in the “P” (conservation practice) factor within the universal soil loss equation model (USLE, Wischmeier et al, 1958), which is reduced from 1 to values around 0.3. There is an impact on the LS (length/ slope) factor also which further reduces the modeled erosion. Thus soil erosion can be checked (in this example of a graded terrace) by one third or more. Such terraces have a positive effect on crop yields by keeping soil (and fertilizer) in place. Retention terraces have the added benefit of reducing erosion even further, and keeping rainfall *in situ*, within drier zones.

4. Vegetative barriers

Vegetative barriers, and especially those composed of grass, have long been an important form of *in situ* soil and water conservation. Such barriers are generally formed along the contour. They constitute a living barrier and thus can be cheap to establish and maintain. While strips allow some throughflow of excess rainfall runoff, by holding back most sediment levelling of the land occurs between the barriers over time. Pictured (left) is an example from Kenya where a barrier of *Panicum coloratum* has led to a differential in height between terrace beds, of around one metre. Vegetative barriers can also provide secondary benefits of fodder or mulching when vegetation is cut/ pruned. Many species can be used as barriers: contour hedgerows of leguminous trees (eg *Gliricidium sepium*) are used in some locations, while sugar cane is also employed as a dual purpose hedgerow. *Aloe vera* has been used experimentally in South Africa (*pers obs*). It must not be forgotten that dense hedges surrounding fields also act as barriers. An overview of vegetative barriers is given by Barker et al (2004).

Panicum coloratum in semi-arid Kenya

Pennisetum purpureum as fodder

Vetiver zizanioides as a roadside barrier

Technical description

WOCAT (2007) documents and gives specifications for two very different examples. These are (a) “natural vegetative strips” (NVS) from the Philippines – where vegetation is left to grow on an unploughed contour strip, and (b) vetiver grass (*Vetiveria zizanioides*) lines in a sugar cane estate in South Africa. NVS emerged from farmers’ unwillingness to invest much in conservation, and the acceptance by specialists that a “second best” option can be the only way forward. In this case the technicians’ preferred choice was a contour hedgerow barrier of a multipurpose leguminous (nitrogen-fixing) tree. NVS, which are about 0.5 metres in width, are laid out along the contour with the spacing between strips determined on the basis of a vertical interval of 2-4 metres. Vegetation is allowed to grow, naturally as the name suggests, though there is the potential for “enrichment planting” of fruit or fodder species within the strips. Vetiver grass (which for a time was vigorously promoted by the World Bank: see Grimshaw and Helfer, 1995) is an effective barrier against erosion – and the WOCAT case shows where it can be appropriate. However vetiver is poorly accepted by small-scale farmers who prefer vegetation that can be fed to livestock, such as napier grass (*Pennisetum purpureum*; pictured). While Garrity et al (2004), putting forward the case for NVS, note that vetiver “*has very little use as a ruminant fodder*”, Hellin (1999) is more outspoken, terming vetiver “*a classic example of a technology that addresses problems identified by outsiders*”. Pictured is a situation in Uganda where a small-scale farmer *has* established vetiver – but as a dense roadside barrier that keeps soil from leaving his field, while deterring itinerant livestock from entering his farm. The same farmer plants fodder species of grass as barriers within his fields.

Suitability and limitations to use

In terms of applicability, vegetative barriers are widely appropriate in both small-scale and large scale systems. Miriad species can be used, and combinations of plants are also possible. Their suitability increases as conditions become more humid: they are less effective in semi-arid areas with prolonged dry seasons, where it is difficult to establish effective barriers that are dense enough to withstand runoff from early, erosive rainfall.

Impacts

Apart from the indirect benefits of vegetative barriers – including fodder, mulch, fruits and (in some cases) improved biodiversity, the main objective is to control erosion, and maintain most rainfall *in situ.* Critchley et al (2004) reviewed six sets of experimental results from the tropics, worldwide. Two recorded no significant difference between the hedgerow and the control, but the other four demonstrated remarkable effectiveness. Of these four, one was a set of 14 treatments reported by Young (1997) which produced, on average a reduction in erosion from 96 t/ha (control) to 14 t/ha (treatment).

5. Tied ridges

Tied ridges – termed "furrow diking" or "basin listing" in the USA – is the practice of constructing small earth ridges, with furrows between them, and then blocking the furrows with earth "ties". The concept behind the practice is to hold rainfall where it falls: it is thus an *in situ* rainfall conservation system. By capturing rainfall, it simultaneously retains soil in place. The crop is planted on the ridge, keeping it from water logging and ensuring an extra depth of top soil. The system may be constructed through full mechanisation, by an animal drawn ridger (lifted to make the "ties"), or put in place by hand. Making furrows and ridges to hold soil and water has been practiced, in one form or another, for centuries. Jared Eliot, an innovative American farmer, experimented with such systems as long ago as the 18th century (USDA, 1966). However, it was the 1950s before it began to spread in the southern Great Plains. But even then, Unger (1984) tells us, stubble mulch tillage (an early form of conservation agriculture) and terracing were more popular. Hudson (1988) describes how tied ridges have been a system of experiments, in various countries, for many years. Yet their adoption remains localised and relatively limited.

maize under tied ridges in Zimbabwe: Nyagumbo, 2000

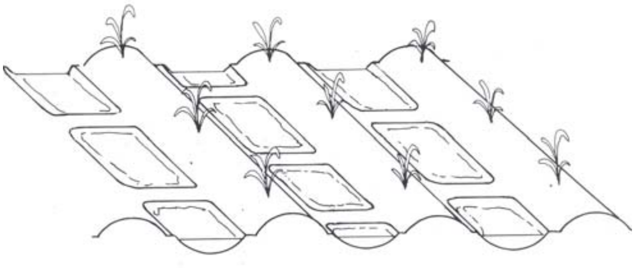


illustration of tied ridges: Hudson, 1987

Technical description

Tied ridges range in dimensions, but a typical height of the ridge as used in Africa is around 20 - 25 cm, the spacing between ridges 0.5 – 1.0 metres (depending on the crop to be grown), and ties spaced at 0.5 – 1.0 metres. In Texas, USA, ridges are lower (7.5 – 12.5 cm) and spacing between is 0.9 – 1.8 metres (B. Harris, *pers com*). Tied ridges are generally "semi-permanent": it is normal practice to renovate ridges each season, until it is necessary to split the ridges and recreate where the furrows were sited previously, in order to exploit the soil fully. This may be after 5-6 seasons according to Nyagumbo (2000) in Zimbabwean conditions. Hudson (1988) recommends safety back-ups in design to reduce the chance of erosion: these comprise (a) aligning the furrows on a gentle grade to assist runoff if the ties fail; (b) making the ties lower than the ridges so that they fail/ overtop before the ridges themselves; (c) backing the system up with conventional graded channel terraces.

Suitability and limitations to use

Tied ridges are appropriate in areas where rainfall needs to be held *in situ*, and where soils drain well (Morgan, 1986). They are also only suitable where there is enough hand labour, or suitable machinery, to construct the system and maintain it over time. For example in Zimbabwe, Hagmann and colleagues (1996) report animal traction requirements, involving various ridging ploughs, as high as 8 to 14 hours per hectare. In subsequent seasons, however, the workload of re-ridging is considerably less – until the ridges need to be split and the furrows recreated. Furthermore tied ridges are not advisable on steep slopes, as the chances of overtopping with rainfall are increased.

Impacts

Comparing tied ridging with control hand tillage in semi-arid Kenya, Kiome and Stocking (1993) found an average increase of 31% in maize yields. Koohafkan and Stewart, 2008, report successful experience from Africa in general, and Kenya and Tanzania in particular. Hudson (1987) goes into considerable detail about the benefits of tied ridging worldwide: "*There is an extensive literature reporting trials of tied ridging….a few of the reports indicate problems and failures but the great majority claim such outstanding success that one…is inclined to wonder why, in the face of so much positive experimental evidence, one does not find the whole of Texas and the whole of Tanzania covered with tied ridging*". But he goes on to point out the potential demerits, including water logging, water table rise, overtopping of ridges (with a consequent domino collapse effect as runoff water cascades downslope). There is also the question of cost. Tied ridging uses considerable hand labour, or if mechanised, more machinery or animal traction hours than simple ploughing.

6. Contour ridges

Contour ridges are a form of microcatchment water harvesting system. They are analogous to *negarim* microcatchments, or *demi-lunes*/ semi-circular bunds but better suited to crop production because of their layout: as each furrow is served by the same area of catchment, the crop is even. These ridges can be made by hand - or by a disc or mouldboard plough. Ridges are constructed on the contour, with the furrow facing upslope. Crops are planted on the side of the ridge. Though the efficiency of the catchment area is high, typical of microcatchments, and yields (of sorghum, for example) can readily be doubled per hectare compared with a control in dry zones, there is a danger of non-acceptance by farmers. To them – as was the case in Baringo, Kenya (MoALD, 1984) - such ridges may appear to imply a visual “loss” of productive area in the field. While this level of benefit may convince researchers, farmers may not use the same evaluation criteria.

contour ridges in Baringo District, Kenya: (left) after construction; (centre) after first rain; (right) the sorghum crop

Technical description

Contour ridges are spaced usually 1.5 to 3 metres apart, and sited on the contour which can be determined simply by a “line level” or a “water-tube level”. The shallow furrow in front of the 20 cm ridge collects and concentrates the runoff generated by the inter-ridge catchment area. The catchment : cultivated area ratio is approximately 2:1. Low “ties” are made every one to two metres to ensure that runoff doesn’t move laterally. Earthworks, for a spacing of 2.0 metres between ridges of 20 cm, on a slope of 0.5% approximate to 360 m^3 per hectare. The crop – sorghum for example because of its drought tolerance and ability to produce a ratoon crop - is then planted on the side of the ridge (Critchley and Siegert, 1991). A field of contour ridges will normally need to be protected from outside runoff by a diversion or infiltration ditch: contour ridges are not designed to cope with runoff from an external catchment. Maintenance is required annually, but this is less than the initial cost of construction. Every few years it is advisable to relocate the ridges so as not to exhaust the soil in the planting zone.

A field trial in Baringo District, Kenya tested the runoff and infiltration from a single rainfall event of 53 mm in a contour ridge system. Previously it had been noted that 50% of showers above 10 mm produced significant runoff. It was found, on this occasion, by examining the wetting front that the average soil water in the “run-on” area (of one metre length) constituted rainfall + 60%, implying an average runoff of 30% in the two metre length runoff catchment. The resultant yield of sorghum for the season (the first and the ratoon crop inclusive) was 890 kg/ha versus 385 kg/ha under the control of deep tillage (MoALD, 1984).

Suitability and limitations to use

Similar to all other simple water harvesting technologies, contour ridges are best suited to low slopes (where the ridge can be low without the danger of overtopping, and thus earthwork requirement relatively little also) and where there is a relatively high runoff coefficient. As noted, this constitutes one of the few systems that can be made equally well by hand, or machine. Their technical suitability is proven; but their acceptability to farmers is another question. This is the main barrier to adoption.

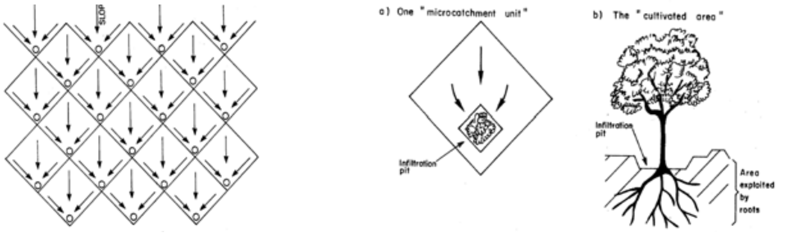
Impacts

Contour ridges perform as well as any microcatchment water harvesting system, with the advantage of producing even crop growth. The very low labour input requirement makes them attractive in areas where hand hoeing is the norm: indeed land preparation input is less than that required for conventional tillage. An added benefit is the possibility of establishing trees within the system. As for the *negarim* microcatchment technique (see no 7), contour ridges can help bring back degraded land in semi-arid areas into production at relatively low cost.

7. *Negarim* microcatchments

Negarim microcatchments originate from the Negev desert in Israel where they are/ have been developed and used for decades for growing trees (Evanari et al, 1971). The term *negarim* is derived from the Hebrew word for runoff: *neger*. These microcatchments work on the principle of creating V-shaped formations through small ridges that direct surface runoff to a pit in the apex. Rainfall that is not enough to sustain trees over the whole area is effectively magnified several times through the collection of runoff and its concentration. This is perhaps the best known and studied form of microcatchment water harvesting, and various traditional and introduced forms can be seen in dry areas throughout the world. Pictured is a prosopis seedling thriving in Turkana District, Kenya: note the runoff in pit (see Barrow, 1983 for a description of practice in northern Kenya).

Prosopis sp in negarim, Kenya



graphics: Critchley and Siegert, 1991 (based on Evanari et al, 1971)

Technical description

Shanon and Tadmor (1979) provide a design manual for *negarim* microcatchments. Based on this, Critchley and Siegert (1991) give specifications for *negarims*, and compare earthwork requirements with alternatives (contour bunds, etc). There must be a balance between the size of catchment and the tree-water requirement at various stages: practically speaking the design must be adequate to establish the tree, but also (especially if fruits are planted) be enough to fulfil its mature requirements. It is important to plant more than a single seedling: just one in the pit may become waterlogged in a wet year; equally a lone seedling on the side of the bund may dry out in a year with low, or erratic, rainfall. With an 8 metre x 8 metre individual microcatchment size on a 2% slope, a ridge height of 25 cm is adequate and total earthworks for a continuous system would represent 310 m^3 per hectare: on a 5% slope this ridge height rises to 35 cm and (because of the greater base width required for the ridge) around twice the amount of soil would need to be moved. Soils must be deep, as this is where storage takes place after initial ponding; however the pit itself must not be too deep to avoid loss of water through drainage: 40 cm maximum is a rule of thumb.

Suitability and limitations to use

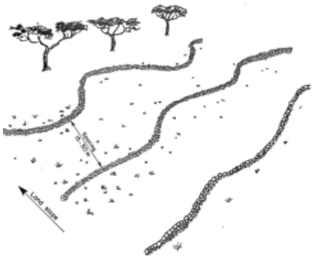
Negarim microcatchments perform best where there is high surface runoff, and low slopes (2% or below). Above this gradient, earthworks increase significantly as noted above and there is a greater danger of overtopping and erosion. It is difficult to mechanise this type of system: though "furrow-enhanced runoff harvesting" is a form of V-shaped microcatchment reported to be working well in Syria for olives (WOCAT, 2007). If machinery is used, it is usually better to construct widely spaced contour ridges with pits adjacent to ties, forming, effectively, similar microcatchments but of a different shape (see technique no 6). Microcatchments need not be built in a continuous block. Indeed on uneven terrain it is impossible to form a regular "fishnet" pattern. One particular, and rather different, use of *negarim* microcatchments is to use them to support the growth of naturally regenerating trees. This has proved very successful in the West Africa Sahel, where some farmers are using this technique to establish *Faidherbia albida* (a renowned agroforestry species) within their fields (C. Reij, *pers com*).

Impacts

The potential benefits of *negarim* microcatchments are considerable. These include not just the establishment and maintenance of trees in areas where they would not normally grow, but the rehabilitation of compacted and "sterile" lands that have become effectively desertified ("desertification" being land degradation in dry areas). Grasses and herbs become established below the trees and if maintained, a productive system can be re-established. Few data are readily available on long term impact, but one example from Rajastan in India serves to indicate the possibilities. *Ziziphus mauritiana* (the "desert date"; or *"pomme du Sahel"* as it is known in West Africa) were planted within 72 m^2 catchments which proved sufficient to obtain excellent fruit yields (Sharma et al, 1986).

8. Stone bunds and *zaï* /*tassa* pits

The combination of stone bunds (or "lines") and *zaï* (as termed in Burkina Faso) or *tassa* (in Niger) planting pits is the biggest success story of water harvesting in West Africa over the last 25 years. Both techniques apparently derive from traditions which have been improved through a process of participatory technology development (PTD). These systems have been extensively studied and written about (see for example Reij, 1991; Anschütz et al, 1998; Hassane et al, 2000; WOCAT, 2007).



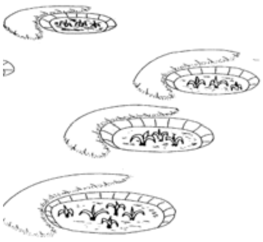


photo: Reij (Niger) *graphics: Critchley & Siegert, 1991(left); Critchley 1991 (right)*

Technical description

These two techniques are often combined by the farmers because stone bunds protect *zaï* pits against damage by external runoff. Stone bunds are semi-permeable structures constructed on the contour, across fields or grazing land, at a spacing of 15-35 metres. Their function is to slow and filter runoff. Bunds are usually 25-30 cm high, and the base width is 35-40 cm. They are set in a shallow trench of 5-10 cm deep, which increases stability. Stone bunds are easy to construct and do not need diversion ditches and spillways. Construction is done according to the "reverse filter" principle - with smaller stones placed upstream of the larger ones (Critchley and Siegert, 1991). They are used on fields already under cultivation but also to expand the cultivated area or rehabilitate highly degraded land, which receive substantial runoff from an external catchment. Planting pits (*zaï)* are dug between the bunds with the objective of concentrating runoff and nutrients. *Zaï* pits are usually 15-20 cm deep, and the diameter is 30 cm. The usual spacing is about 90 cm. During the dry season, farmers place organic material (a mix of manure and grasses) in the *zaï*, which improves the fertility and the structure of the soil; the latter due to increased termite activity. Construction and maintenance of *zaï* pits is relatively easy but labour-intensive. Similarly to the stone bunds, *zaï* are used to rehabilitate barren, crusted soils where spontaneous regeneration of vegetation is not possible any longer. In combination the two techniques work synergistically.

Suitability and limitations to use

The combined use of stone bunds and *zaï* pits permit a versatile crop production system in a wide variety of situations in dry areas. These techniques are easily adopted by resource-poor farmers. However, the construction of stone bunds requires a good supply of locally available loose stone. A perennial grass (*Andropogon gayanus*) is sometimes planted to reinforce/ supplement the stone lines, especially where stone is limiting. *Zaï* pits are suited to low slopes (below 2%), high runoff, and hand labour. The usual crops planted under these systems are sorghum and bulrush (pearl) millet.

Impacts

Stone bunding is particularly attractive to farmers in the Sahel, because on fields already cultivated, it increases the yields directly in the first year by an estimated 40%. Where barren land is rehabilitated, yields of 1,000 kg/ha can be obtained in the first season (Critchley *et al*, 1992). With this technique little land is lost to the structures. Moreover, stone bunds can be constructed in individual plots with little risk of destruction by external runoff from an outside catchment, while the *zaï* act as microcatchments within the field.

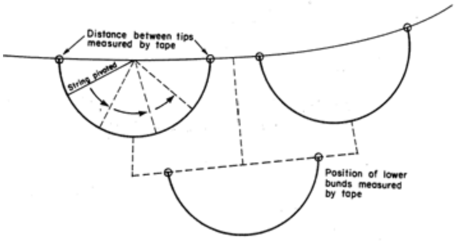
Twomlow et al (in press) describe how planting pits are being introduced with apparent very positive results in Zimbabwe, and similar structures have been recorded as a farmer's personal innovation in Dodoma, Tanzania (Critchley and Mutunga, 2002). Hassane et al (ibid) demonstrate significant millet yield increases in Niger in dry years from such systems: an average of 546 kg/ha over a 5-year period compared with 25 kg/ha from the control plot. Adding fertilizer and manure increased the yields to 757 kg/ha under the treatment.

9. Semi-circular bunds: *demi-lunes* (hand-made)

The principle of the most common design of semi-circular bunds or *demi-lunes* (half-moons) as they are known in French, is to capture water from within the field. They are generally small (radius of 3 - 6 metres) and built in sequence over a whole plot. In this case they function as with in-field, microcatchment system. It can be argued that such small *demi-lunes* are technically less satisfactory for crop production than contour ridges (see technique no 7) because the crop growth is uneven, with the plants in the lower part of the structure receiving a greater depth of water (see centre photo). However there seem to be other non-technical factors that influence their relative popularity. The first is that the construction of these units leaves a visually attractive pattern in the field (see photo, left). The second is also outside the technician's usual terms of reference, and that is "branding": the name "*demi-lunes*" seems to have a particular attraction in West Africa. And the principle is easy to understand. There is a parallel in this respect to the *fanya juu* terrace in East Africa (technique no 2), where the very name itself carries weight, and has a positive association with conservation. A modified, larger design of semi-circular bund, with a diameter of 20 or more metres can act as a single planting plot and accommodate runoff from outside. As such it functions as an external catchment system.

demi-lunes in Niger after construction

demi-lunes in Burkina Faso with millet



graphic: Critchley & Siegert, 1991

Technical description

In the usual design, the radius is a few metres. Layout is staggered: in other words the second line is designed to catch runoff that flows between the structures in the line above; and so on. The precise catchment to cultivated area ratio is determined by the proximity of the *demi-lunes* to each other. Note in the photographs this is very low, possibly less than 1:1. In the design described by Critchley and Siegert (1991), from which the above graphic is derived, the ratio is 1.5:1 (around 70 bunds per hectare, each enclosing just over 55 m^2). The tips of the semi-circular bunds are laid out on the contour, often using a line level (a spirit level on a string suspended between poles). The outline of the structures is drawn in the earth by a peg, at the end of a string which is swung around, having been anchored in the ground at what would be the centre of the full circle (or *pleine lune* = full moon, in French). Only the semi-circle, naturally, is drawn. It may be that learning to lay out the shapes engages farmers' interests and could also add to their popularity. As mentioned, larger designs are suitable for single plot cultivated units accepting runoff from an outside catchment. In this case excess runoff is designed to spill around the wingtips, sited on the contour and fortified with stone. While other shapes of plot may be used for external catchment systems (field configuration can dictate this) the semi-circular design is the most efficient in terms of the length/ volume of bund to enclosed area relationship.

Suitability and limitations to use

Semi-circular bunds need low slopes. Otherwise, in common with most water harvesting systems, earthwork volumes rise considerably. Another constraint is that they are most readily and efficiently made by hand. They are difficult to mechanise, and though the technique described in no 10 (mechanised *demi-lunes*) seems to refute this, the mechanised version produces structures that point in opposite directions and are inherently less efficient.

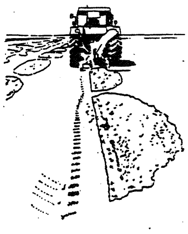
Impacts

In the same trial described under the previous technique (no 8: stone bunds and *zaï/tassa*), Hassane et al (2000), demonstrated the potential for improvement in millet (*Pennisetum typhoides*) yields in Niger under *demi-lunes.* Yields were raised from 27 kg/ha in a control plot with standard hand cultivation to 285 kg/ha under *demi-lunes*. Adding manure and fertilizer increased the yields to 566 kg/ha. However, benefits of *demi-lunes/* semi-circular bunds are not limited to crop production: these structures may be used for planting grass to rehabilitate degraded lands – and in this case uneven vegetative growth is not such a problem as it is for crops. And, furthermore, a pit may be excavated in the lowest point of the structure to plant trees, and establish an agroforestry system. In this case the semi-circular bund become analogous to the *negarim* microcatchments described in technique no 7.

10. Mechanised *demi-lunes/ sillons*

This is a relatively new technology which, since its development in 1988, has been tested in numerous countries (Burkina Faso, Chad, China, Egypt, Jordan, Kenya, Morocco, Niger, Senegal, Sudan, Syria and Tunisia) where nearly 100,000 ha have been treated in total (Malagnoux, 2008). According to Antinori, 1994, there are two types of modified tractor ploughs: the "train" and the "dolphin". Their function is to open up small continuous furrows (*sillon*) or mini semi-circular hoops (*demi-lunes*) respectively. The great advantage of these machines is that they are flexible, can be adapted to different soil types and are able to reclaim large areas of degraded land in a short time. They can potentially cover up to 1,000-1,500 ha of denuded land per season, and bring these back into productivity (Doumbia and Reij, 2007). In the areas where they are best utilised, there is a high runoff coefficient despite the low slopes, and runoff harvesting here is very effective.

demi-lunes after construction and after planting with grass in Burkina Faso



graphic: Critchley et al, 1992

Technical description

These tractor-pulled ploughs are designed to construct water harvesting catchments along contour lines previously laid out. The "train" creates an angled furrow about 50 cm deep and piles up the excavated fertile topsoil only on the lower (downhill) side. This soil forms a ridge that stops or slows down runoff water which infiltrates into the furrow (ICARDA, 2006). The "train" plough is particularly suitable for plains. It is used for development/ improvement of agro-sylvo-pastoral productive systems, afforestation and creation of windbreaks. Its purchase cost is approximately € 50,000 (see www.vallerani.com).

The "dolphin" digs crescent-formed microcatchment basins at a rate of up to 5,000 - 7,000 per day. These micro-basins are connected to each other by the tracks left by a ripper working at a depth of 70 cm. Rain and runoff water, fine fertile topsoil and organic matter are harvested and concentrated in the micro-basins. Note that the *demi-lunes* on alternative rows face upslope and downslope respectively. Thus they can only *both* collect runoff where the slope is negligible (c.1% maximum). This plough is suitable in varied types of terrain (rugged lands, stony and compacted soils) with a slope compatible with the utilization of a tractor. It is used for production of trees and shrubs, improvement of pastureland and crop production. Its current cost is approximately € 30,000 (see www.vallerani.com). Direct sowing is an additional measure to this system. It is carried out with a "sowing tube" on the sides and base of the *demi-lunes* and on the sides, base and divisions of the furrows, thus allowing germination and establishment under different rainfall conditions.

Suitability and limitations to use

This is a flexible, multi-purpose technology that can be easily adjusted to various natural conditions. The outstanding question about such systems is post-implementation maintenance of the land and the machinery – rather than the efficacy of the technology. Limiting factors can be the need for external technical knowledge, unavailability of equipment within reach and at an affordable price, credit required to purchase or rent the equipment, acceptance and participation of local communities. The latter can be addressed through exchange visits and training at demonstration sites.

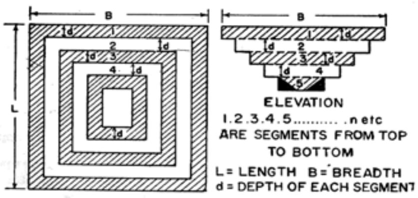
Impacts

The system generates multiple benefits: no negative environmental impacts (only 10-20% of the land is ploughed), reduced soil erosion, increased yields, enhanced waterholding capacity of soil, regeneration of vegetation cover, rehabilitation and increased value of previously abandoned land. The benefits of this mechanised system for rangeland rehabilitation can be optimised if indigenous species and seeds with good germination ability are used and young plants are protected from grazing in the first few years.

11. Farm ponds

Harvesting water to collect in ponds is an ancient system in many parts of the world (Kerr and Pangare, 2001). The principle behind this approach is to concentrate water spatially and temporally in order to reduce farmers' dependency on highly seasonal and erratic rainfall patterns. In the last few decades, farm ponds have been promoted by several national and regional programmes, with the objective of increasing food security and reducing poverty on a massive scale. Unfortunately, most of these programmes seemed to have been influenced more by a political rather than a rural development agenda. With respect to smallholders, globally, this top-down approach resulted in too many ponds being dug, many of which were poorly sited and constructed, with insufficient technical support and lack of farmers' participation (Miller, 2009).

farm ponds in India



graphic: Singh et al, 1990

Technical description

Farm ponds are excavated structures in which harvested water is stored for supplementary irrigation (Singh et al, 1990; Rämi, 2003). Such ponds are situated immediately below the area to be irrigated, and rely on a catchment above the cultivated area. Ponds can be of various designs and materials. Commonly, they are aproximately 20 x 20 m or 30 x 30 m at the surface with sloping sidewalls (normally I:I or gentler) and 2.5 – 3.0 metres deep. Thus capacity is often around 200 cubic metres. The catchment area supplying the pond needs to be at least 2 hectares (theoretically 10 mm average runoff would fill the pond : but allowance needs to be made for losses). Pond systems generally have an inlet with a silt trap, and a spillway or overflow for excess water. They can be lined either with clay, cement, plastic or geo-textiles. Plastic lined ponds generally hold more water and for a longer period, and are less susceptible to construction failures. However, they are comparatively more expensive than those constructed using locally available materials (eg clay). Geo-textile lined ponds perform better but are more expensive, more difficult to maintain and cannot be repaired *in situ*. The initial labour requirement to build a pond may be high, but a well-built pond will have a longer lifespan. Regular maintenance is necessary in order to keep the pond functional, while fencing of the pond and conservation treatment of the catchment prevents contamination.

Suitability and limitations to use

Ponds are justified only under certain environmental conditions and, therefore represent a niche technology that may be suitable in specific areas or situations. Due to their limited capacity ponds are economically viable only if no other water source is available (Segers et al, 2008). In general, household-based ponds have proven to be a better option than ponds for collective use due to ownership and maintenance problems. There are several drawbacks associated with this technology: (1) ponds consume space; (2) they require a catchment area close to the farm; (3) their cost is high if all the storage is achieved through excavation on flat surfaces; (4) siltation is a problem, (therefore the requirement for a silt trap and polythene lining) as is seepage and evaporation; (5) withdrawal of water and application by hand is laborious; (6) ponds provide a suitable breading ground for mosquitoes, which in turns may increase the incidence of malaria (raising fish in the ponds helps control water-borne diseases as they prey on mosquito larvae).

Impacts

Farm ponds can potentially provide a number of benefits: water for domestic and livestock consumption, acquaculture, irrigation for high-value crops. Ponds can provide crop-saving supplementary irrigation in times of drought to around a quarter of a hectare – or could irrigate a small vegetable plot fully (± 200 m^2). Miller (2009) states these benefits can lead to a reduction of risk (through diversification / integration of farm activities), improved nutrition for farm families, contribution to income and employment. However, a study conducted by the Poverty Reduction and Environmental Management Programme showed that in Tigray region, Ethiopia, ponds have had (so far) little impact on household poverty alleviation (IVM, 2007).

12. Sand dams

Sand dams are constructed across ephemeral rivers to harvest water and store it in sand behind barriers. This technology is not new: it has been used in India for centuries. However, in the last decades, it has been promoted for its potential to increase water availability for rural communities. While they function well, they are very site-specific in applicability due mainly to the requisite geological characteristics of the construction site, runoff patterns of the catchment and the sediment transport regime of the seasonal river. Sand dams are particularly common in parts of eastern Kenya. Variations of this technology have been introduced in other countries with similar dry environments, including Burkina Faso, Ethiopia, Namibia, Thailand and the USA .

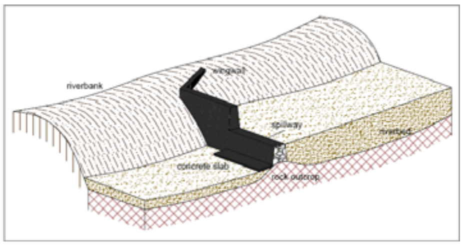


photo (Kenya) and graphic: Borst and de Haas, 2006

Technical description

A sand dam collects water (rainwater, stream and surface runoff) in dry, sandy river beds and stores it within the sand which accumulates behind the impermeable barrier of 2-5 metres in height. The barrier is usually built of concrete on an impermeable foundation of bedrock or clay. The structure's lifespan varies from 30 to 80 years or more. The location is a river valley with gradient between 1% and 2% where coarse sand, not fine sediment, accumulates. Where possible, sand dams are built in a sequence, or "cascade" along a river bed. During the wet season, runoff water infiltrates these permeable deposits and the bordering riverbanks, creating artificial aquifers. When the aquifers are fully recharged, usually after one or two significant rainfall events, the river starts to flow as it did previously, in the absence of the dam. However, groundwater flow is obstructed and additional groundwater storage is created as a result. During the dry season, water levels will drop due to minor evaporation, possibly leakages through the dam or the bedrock and the abstraction of water through scoop holes, hand-dug wells or tube wells. Detailed design specifications are given in Nissen-Petersen and Lee (1990), and Nissen-Petersen (2006). There is also a practical guide to sand dam implementation by the Rainwater Harvesting Implementation Network (RHIN, 2008). Sand dam construction is labour intensive and requires the involvement of the local communiy to reduce the construction costs and ensure sustainability. According to Di Prima (2007) who reviewed experience with sand dams in Kitui District, Kenya, while up to 18% of the population has benefited from these dams, their construction cost is relatively high: currently around US$ 10,000 for each dam to provide an average of 5-8,000 cubic metres of water each season for (potentially) 50 years or more.

Suitability and limitations to use

Sand dams are highly site-demanding in suitability as has been noted in the foregoing (rock outcrops for firm foundations; sites with high riverbanks and lower slopes; sandy riverbeds, seasonally dry, etc). The technology is labour and capital intensive, hence impoverished rural communities cannot implement them without external aid. The required technical skills and availability of stone for construction *in situ* can be additional limiting factors for spread.

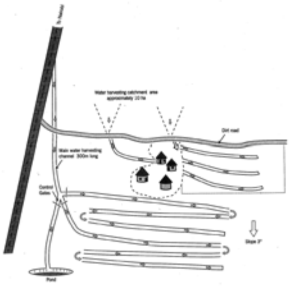
Impacts

This particular type of water harvesting has proven to be an attractive decentralised water source in specific areas (see www.rainfoundation.org). Compared to some other water harvesting techniques, sand dams are particularly environmentally friendly as they control erosion, manage silt deposition within river basins (through associated watershed management programmes) and can contribute to groundwater recharge. Furthermore, the water collected is of good quality due to the filtering effect of the sand and reduced contamination by livestock. Benefits include closer access to water, an increase in domestic water use of about 50%, and associated health improvements: furthermore modest amounts of withdrawals (up to 440 litres/ family/day) can also assist in riverbank vegetable production (Lasage et al, 2007). Time saved on fetching water can be reallocated to more productive farming and off-farm activities.

13. Road runoff harvesting

Road runoff harvesting is practiced in many parts of the world – wherever there is a combination of dry conditions and farmland alongside a road. The advantages are obvious: roads provide a hard surface with a high runoff coefficient (whether tarmac or "dirt"), and drainage is integral to road design: runoff is *de facto* available. Thus landusers can "tap into" this supply of free water. This is a specific form of an external catchment system. Despite its ubiquitousness, it rarely features in water harvesting manuals, and it is certainly underestimated in extent and contribution to small-scale farming in dry areas. There are exceptions: Ngigi (2003; quoting Ministry of Agriculture, 2001) estimates that some 4,000 hectares of land within one dry district in Kenya (Kitui District) benefit from this additional supply of water. Furthermore, Qiang and Yuanhong (2003) describe how road runoff is a vital source of water for filling tanks to irrigate crops and trees in Gansu Province, China.

runoff harvested from road (Uganda)



innovator's system (Mutunga & Critchley, 2001)

citrus watered by road runoff (Kenya)

Technical description

There are two basic sources of road runoff. The first is drainage purely from the proximal (near) side of the road surface itself – in other words the width of the catchment comprises half of the road (assuming a camber on the road from its mid-point ridge to either edge) and the length is defined by the distance to the crest. The catchment area is thus easy to compute: half the road's width times the length of the slope to the watershed. The second form of road runoff is water that drains under the road from the far side through a culvert. This water originates from a combination of the land on the other side of the road, as well as the road itself. In this situation the catchment area is less simple to calculate, and the flow often less easy to predict or manage. Runoff may be used to flood a field, and in this case constitutes a common form of external catchment arrangement. Alternatively, runoff may be led into the farm and reticulated around the planted area: the diagram above demonstrates an example of this from Mwingi District, Kenya, where a farmer innovator, Musyoka Muindu, has ingeniously designed a system that supplies water to around five hectares of arable land from a catchment of approximately twice that size (Mutunga and Critchley, 2001). The runoff – originating from a culvert - is led around the field in a channel that moistens the adjacent land as it flows. Alternatively (or simultaneously) runoff may be ponded, and then either allowed to seep into the ground, irrigating fruit trees planted alongside the pond, or water may be extracted for irrigation by hand or pump.

Suitability and limitations to use

As in all external catchment situations, the availability of a suitable catchment – in this case a road – determines whether such a system is feasible or not. There are situations also, where the flow of water from the road (especially when this is delivered through a culvert) can be erosive, and the flow too high to control and use. There may also be competition for the resource, with land users higher up the road diverting water onto their land. Where runoff is derived from busy, tarmac surfaced roads, there may be some oil pollution. While this description has focussed on roads, similar systems are also common from footpaths. A close "relative" is harvesting from roofs and house compounds (see also technique no 16). In these cases, manure from stallfed livestock is sometimes added to the channels by innovative farmers to "fertigate" fruit trees in fields below in what can be termed "water-borne manuring systems" (Mutunga and Critchley, 2001).

Impacts

Little quantified information is available about the - self-evidently - important benefits of road runoff systems. This is an area in urgent need of investigation and analysis. Apart from production benefits to farmers, there is also the positive downstream impact of reducing otherwise erosive drainage water.

14. Conservation agriculture

The emergence of "conservation agriculture" (CA) has been one of the most notable success stories in rainfed agriculture of modern times (see Goddard et al, 2007). Though no-till farming was introduced tentatively during the 1970s on large scale farms in Europe, the USA and elsewhere, it was only with the emergence of new less-toxic non-selective herbicides and specialised machinery (seed drills and straw-chopping combine harvesters, etc) that CA took off in the late 1980s. Based on the three principles of (i) no- (or minimal) tillage, (ii) maintaining a surface cover, and (iii) crop rotation, CA reduces the energy (and carbon emissions) involved in, and costs associated with, preparing land. It also maintains good soil structure and underground biodiversity; reduces surface erosion, and increases soil moisture in dry zones. FAO has recently established a "Community of Practice" and a "Framework for Action" which emerged from a landmark conference in 2008 (see www.fao.org/ag/ca). Conservation agriculture has grown by three times over the last decade, to occupy currently 100 million ha (2% of the world's cropped land). The largest areas under CA are in the USA, Brazil, Argentina, Canada and Australia. The exponential uptake amongst relatively small-scale farmers in South America, especially Brazil, is a significant development in world farming.

drilling into stubble
(UK: Liniger in WOCAT, 2007)

measuring runoff and sediment loss (UK)

modified ox-drawn implement
(Kenya: Liniger in WOCAT, 2007)

Technical description

The transition to conservation agriculture means investment in new, no-till specific machinery. The plough is dispensed with. After harvest, the soil may be loosened and straw incorporated, and then spraying with a non-selective herbicide kills the weeds and volunteer plants that emerge. In UK a cultivator-drill follows: the surface soil is lightly disturbed (though not inverted) and seed drilled into this seedbed. The seedbed may then be consolidated with a roller. At maturity, combine harvesting takes place with simultaneous chopping of straw (WOCAT, 2007). Naturally CA systems vary from country to country, and depend on the size of farm, the degree of mechanisation, the production system and the affluence of the farmer.

Suitability and limitations to use

While conservation agriculture has been particularly successful in the medium/ large scale sector in the Americas, Australia and Europe, it can also be applied to smallholder farming in the developing tropics (see WOCAT, 2007). Mazvimavi and Twomlow (in press) describe how "conservation agriculture" for small-scale farmers in Zimbabwe is based on a broad interpretation of the principles, and includes planting pits (see technique no 8). However CA's usual reliance on herbicides means a weed-removal problem for low income farmers. Furthermore, in dry areas availabiity of mulch is a constraint: crop stover for example has high alternative value as livestock feed. Thus CA's wider applicabiity in Africa is questionable (see Giller et al, in press).

Impacts

Ploughing – the standard land preparation treatment worldwide for millennia – is detrimental to the soil, because of the disturbance it causes to micro-organisms, organic matter and soil structure. The development of relatively safe herbicides and specialised machinery renders ploughing unnecessary. Soil health improves under CA, and waterbodies are less polluted with agrochemicals because of reduced runoff and erosion. Furthermore greenhouse gas emissions are lessened by maintaining the organic carbon stock in the soil and economising on fossil fuel consumption in farm operations. While crops yields are not necessarily increased, the costs of production are reduced, and in the case of large scale arable enterprises, the speed with which land can be planted within a limited "window" of time is extremely important: for example the planting of winter wheat in UK during the autumn. In Texas, USA, under conditions where annual rainfall of 500 mm limits production of cotton and wheat, conservation agriculture can save 25 – 75 mm of water each year (B. Harris, *pers com*).

15. Cover crops

Cover crops – sometimes called “green manures” or “live mulch” - are a common and well known component of small-scale farming in the more humid tropics. This is an agronomic technique that helps keep rainfall *in situ*. While there has been a flurry of attention on cover crops in recent years (eg Anderson et al 2001; Hellin, 2006), this is a technique that has been known and promoted for decades. In the classic textbook “A Handbook of Tropical Agriculture”, Masefield (1949) explains that cover crops “*are planted either under perennial crops or in temporarily unused land to prevent erosion, suppress weeds and improve the condition of the soil*”. A century earlier than that, Edmund Ruffin was trying out leguminous cover crops in the southern states of the USA (USDA, 1966).

Centrosema sp planted under rubber in Indonesia

Mucuna sp planted between pineapples in Uganda

Technical description

There are multiple types of cover crops but, increasingly, legumes are preferred and promoted for their nitrogen-fixing capability: these include *Mucuna pruriens* (“Velvet bean”: an annual, useful for fodder and mulch and promising in Africa), *Canavalia ensiformis* (a versatile easily-managed cover crop much favoured in Latin America)*, Crotalaria juncea* (“Sun Hemp”: from India and used to reclaim *Imperata cylindrical* infested grassland in Indonesia)*, Centrosema pubescens* (from tropical South America – it covers the ground quickly and can be used as a fodder or ploughed in as a green manure)*, Pueraria phaseoloides* (“Kudzu”: suitable at high altitude) *and Dolichos lablab* (“Lablab bean”: drought resistant and produces a grain that is eaten in parts of Africa); see Anderson *et al* (2001) for more detail. Sown – as Masefield (1949) points out – below another crop or as a fallow crop, cover crops provide multipurpose benefits to the soil. They are generally used in two ways: either the stover or seed is made direct use of, for food or animal fodder, or the stover is cut for mulch or ploughed into the ground (hence “green manure”). However low-growing legumes are not the only type of cover crops: in the broadest sense, shrubby plants such as *Cajanus cajan* (pigeon pea), and *Tephrosia candida* can also be considered cover crops, as can many “multi-purpose” leguminous tree species that are lopped for mulch (eg *Leucaena sp, Gliricidium sp, Sesbania sp and Calliandra sp*). In Switzerland, “green cover” under grape vines is simply natural vegetation: it is encouraged for biodiversity puposes. Cover crops are described here independently from more holistic systems under which they are a component: thus conservation agriculture – as practiced in humid areas under smallholder conditions – considers cover crops to be an option within that overall system.

Suitability and limitations to use

There are cover crops for most situations, covering a wide range of agro-ecological zones, and a broad scope of farming systems. However there are barriers to their suitability. Most notably, cover crops being a *living mulch*, use water – and thus in areas where rainfall is limiting they deplete soil moisture and crops can suffer as a result. In these regions, unless cover crops are grown primarily for food, they are not recommended. Another limitation sometimes cited is the cost of seed for small-scale farmers.

Impacts

Little hard data exists to quantify the overall benefits of cover crops. Nevertheless their rapid expansion (for example of *Mucuna pruriens* in Central America) pays testimony to the fact that many farmers appreciate them and benefit. These benefits include soil improvement, reduced erosion, weed suppression, material for fodder, edible seeds, material available to be cut for mulch, and in specific cases (eg the Swiss example quoted above), biodiversity.

16. Homegardens

Homegardens are a form of agroforestry: multi-strata, multi-species highly intensive mixtures around the homestead. While the most diverse and productive forms are found in the humid tropics, homegardens of one type or another are characteristic of perhaps the majority of rural households worldwide. A homegarden is simply defined by Hoogerbrugge and Fresco (1993) as "*a small-scale, supplementary food production system by and for the household members that mimics the natural, multi-layered ecosystem*". Homegardens are visually striking. In 1901, Gelpke (translated from the original Dutch) wrote: "*He who enters a mixed garden with a botanical eye, sees before him a diversity of plants of which the uninitiated can form no idea….that wealth of vegetation is all the more striking when the observer regards it from an economic point of view. He sees palms, bamboos, bananas….all seemingly much alike with various winding plants clinging to them*". Homegardens generally represent the most biodiverse location within a farm, and the most intensively cultivated. Animals form an integral part also. There is a concentration of water (runoff from roofs and compound; wastewater); organic matter (from animals and crop processing) thus fertility; and both human activity and ingenuity (Critchley et al, 2008). Homegardens are excellent examples of "micro-environments unobserved" (Chambers, 1990). In 1986, Fernandes and Nair lamented the fact that, because of their complexity, these important systems had hitherto been ignored by the scientific and development community and deserved more serious attention. In the last two decades the development community have certainly focussed more on homegardens – especially on vegetable production and zero-grazed livestock – but research remains weak, particularly in the drier, rainfed zones.

a highly diversified homegarden in Java, Indonesia

trees and crops concentrated around a homestead in Ethiopia

Technical description

There are multiple types of homegardens: they are very complex systems with a very sophisticated structure and a large number of components, and each farm unit is "*a specialised entity in itself*" (Fernandes and Nair, 1986). Thus it is practically impossible to define a "typical" homegarden. The same authors, however, state that homegardens are "*characterised by a high species diversity and usually 3-4 vertical canopy strata*" (ibid). In Tanzania, for example, tall trees such as *Cordia africana* and *Olea welwischii* form the top strata, while shorter trees such as *Tectona grandis* and*Trema guineensis* – and currently the popular *Grevillea robusta* - characterise the second. Shrubs/ bushes, including coffee are found in the third strata, while the lowest comprises root crops, taro or "cocoyams" (*Colocasia antiquorum*) for example, and vegetables. In drier regions, while there may not be the same well defined vertical strata, species diversity and the presence of trees is still characteristic.

Suitability and limitations to use

Homegardens in their various forms are suitable worldwide – though naturally their composition, species diversity and size depend closely on the particular situation. Their importance in terms of food production is often underestimated: In Sri Lanka, almost half of the agricultural land is under these systems, while in Java, Indonesia, the proportion of homegardens to farmland generally is in the region of 20 – 50%. It has even been argued that urban agriculture "*is basically the homegarden migrating from its rural origins together with the people that used to tend it there*" (Critchley et al, 2008).

Impacts

Hoogerbrugge and Fresco (1993) point out that production data are "*rarely reported*" and anyway "*difficult to compare*". They quote figures of up to 1.5 kg of fresh produce per day from plots of 18m^2 in a Thai homegarden, and state that plantain production may be five times as high as the same crop in a plantation. The same authors quote Ensing et al (1985) as having calculated that 80% of staples, 80% of fruit and 60% of leaf vegetables come from homegardens. As well as their productivity, Young (1997) notes their effectiveness in controlling erosion – in an area, around the house, where considerable runoff is generated, and if not harnessed for production, can lead to gullying and sheet wash in surrounding fields.

17. Scattered tree agroforestry

Agroforestry – according to Young (1989) - "*is a collective name for land-use systems in which woody perennials (trees, shrubs etc) are grown in association with herbaceous plants (crops, pastures) or livestock, in a spatial arrangement, a rotation, or both; there are usually both ecological and economic interactions between the trees and other components of the system*". Scattered tree agroforestry is the most widespread form of the practice. Under this system, dispersed indigenous trees are mixed in fields with, usually, annual crops. These local tree species are consciously and deliberately nurtured by the farmers due to their specific (eg fruit) or multiple (soil amelioration; timber; fodder etc) benefits.

Faidherbia albida with millet in Burkina Faso

Acacia abyssinica and wheat in Kenya

mixed-species agroforestry in Ethiopia

protected natural regeneration in Ethiopia

Technical description

There are no precise technical specifications for scattered tree agroforestry. The very wide range of local traditions defies such description. There may be as few as one to two large specimens per hectare, or as many as 100 trees on the same size plot. Typically, there is one dominant type of tree found in the system: these include, for example: *Faidherbia albida* in parts of West and Southern African; *Croton macrostachys* or *Cordia africana* in parts of Ethiopia; *Acacia tortilis* in semi-arid Kenya; *Sclerocarya birrea* (marula) in South Africa; *Prosopis cineraria* in Gujarat, India. In some areas, most notably the West Africa Sahel, there is a characteristic "parkland" mixture of varying proportions of *Faidherbia albida, Vitellaria paradoxa* (shea nut), *Parkia biglobosa,* and *Adansonia digitata* (baobab). The trees grown in scattered agroforestry systems are generally derived from one of two sources: either they are retained remnants from original forest or savannah woodland that has been cleared for farming, or they have naturally regenerated and have been protected and nurtured (see pictured example above, from Ethiopia, of *Acacia seyal*). Rarely, under traditional systems, are trees planted.

Suitability and limitations to use

Various forms of scattered tree agroforestry are widely appropriate. There are trees that can be grown in all areas where cropping is possible, however arid, at whatever altitude. There are two main reasons however why trees may be disliked within a system. The first is competition. Almost all trees compete with crops for light, water and nutrients, so benefits must outweigh disadvantages. The other limitation is machinery: randomly scattered trees make mechanisation of farming difficult.

Impacts

As for most traditional systems of agroforestry (or other forms of indigenous soil and water management techniques in rainfed agriculture) there exists very little data on benefits and impacts. Nevertheless, the fact that trees are maintained in cropping (and grassland) production systems by farmers indicates that they perceive real benefits. Many of the trees are legumes (*Acacia* spp; *Prosopis* spp etc), thus soil improving, while others are useful for timber and other products. *Faidherbia albida* is a special case in that, as Young (1997) notes "*it is the species beneath whose canopy increases in crop yields are most widely and consistently observed*". This results from partial shade, nitrogen fixation, droppings of animals feeding on pods, and leaf litter. It is heralded for its contribution to the current cycle of regreening in the Sahel, though it is limited to zones with a water table.

18. Mulching

Mulching is an in-field/ agronomic practice that comprises keeping the soil covered with organic matter (or sometimes plastics, or micro-fibre). It is a traditional practice in small-scale subsistence farming within the tropics, and equally has a place in large-scale mechanised commercial agriculture elsewhere. Its multiple benefits have been known for a long time. Writing in 1949, Stallings summarises the advantages of mulching for farmers in the USA: "*The use of crop residue as a means of reducing runoff and soil loss by erosion is growing in importance. Recent experiments point to several definite conclusions such as increasing the organic content in the soil, improving the aggregate structure and maintaining a high infiltration rate*". Coincidentally, the same year, writing about Masefield (1949) states that: "*Mulching the ground between the plants with cut grass is very beneficial to reduce erosion and maintain fertility*…".

The most common materials used are plant stover/ wastes (pictured left is trash from harvested sugar cane under a ratoon crop in Australia) and grasses/ weeds (middle picture shows grass between vegetables in the South Pacific). However various other materials are used. The photo on the right illustrates the use of volcanic *tephra* on Lanzarote in the Canary Islands – which not only protects the soil but is hygroscopic, absorbing moisture from the atmosphere.

mulch under sugar cane, Australia

mulched vegetables, Solomon Islands

volcanic tephra as mulch, Lanzarote

Technical description

There are so many types of mulching materials and so many variations of their application that there cannot be a generic "technical description". The principle though is simple: cover the soil surface with materials – organic where possible – to protect the soil. This is effectively "imitation of forest floor conditions". In undisturbed forest, decaying organic matter covers the ground and contributes significantly to forest function. Application of mulch may be by hand, for example in vegetable gardening. Or it may be mechanised, as is the case with the "green cane trash blanket" in Australia, and with forms of conservation agriculture where straw is chopped during combine harvesting of cereals and left to lie on the land (WOCAT, 2007). Mulching may be used on its own as an in-field/ agronomic conservation technique, or be part of an overall system of production as it is with conservation agriculture (see technique no 14). Mulching may also be combined with support structures: an example of this is where coffee is grown on steep hillsides in Kenya, and mini-bench terraces are employed to facilitate cultivation and protect the slopes from erosion.

Suitability and limitations to use

While widely applicable, in both small-scale and large-scale production systems, the main drawbacks to mulching are limited availability of organic materials, competition for their use as fodder, especially in drier areas and the related costs involved - especially under hand-based cultivation systems. Briggs and Twomlow (2002) examined organic matter flows in South West Uganda, where trash and weeds from annual crops grown on the hillsides are used to mulch bananas in the valleys below. They found that there was a net loss of organic materials from the annual crops of 36.5 t/ha/yr and a net gain of 21 t/ha/yr in the bananas. Here, there is a problem of sustainability as fertility steadily migrates from the hillsides to the valley below.

Impacts

Mulch has multiple benefits: it protects the soil from rainfall splash, increases infiltration, inhibits runoff, reduces evaporation from the soil surface, suppresses weeds, moderates soil temperature, builds up organic carbon stocks, adds nutrients to the soil, improves biodiversity, and protects the soil from compaction. Improved yields under mulches are reported from such widely different systems as annual crops in Nigeria (Lal, 1975), hand-cultivated banana plantations in Uganda (eg Briggs and Twomlow, 2002), and mechanised sorghum production in the USA (eg Koohafkan and Stewart, 2008).

References

Agarwal A. and Narain, S. (eds) (1997) *Dying Wisdom: rise, fall and potential of India's traditional water harvesting systems* Centre for Science and Environment, New Delhi, India, 404 pages

Agarwal A., Narain, S. and Khurana I. (eds) (2001) Making Water Everybody's Business: practice and policy of water harvesting Centre for Science and Environment, New Delhi, India, 456 pages

Ali, A., Oweis, T., Abdul Aal, A., Mudabbar, M., Zubaidi, K. and Bruggeman, A. (2006) The Vallerani Water Harvesting System. International Center for Agricultural Research in the Dry Areas (ICARDA), Caravan issue no. 3

Anderson, D. (1984) Depression, dust bowl, demography, and drought: the colonial state and soil conservation in East Africa during the 1930s. *Africa Affairs* 83, 321-343

Anderson, S., Gundel, S. and Pound, B. (2001) *Cover Crops in Smallholder Agriculture: Lessons from Latin America.* ITDG Publishing, London

Anschütz, J., Kome, A., Nederlof,M. de Neef, R and van de Ven, T. (1998) *La Collecte de L'Eau et la Retention de L'Humidité du Sol.* Série-Agrodok, CTA, Wageningen

Antinori. P. (1994) Experiments with water harvesting technology with new special ploughs. In: FAO, (1994) *Water Harvesting for Improved Agricultural Production.* Proceedings of the FAO Expert Consultation, Cairo, Egypt, November 1993, pp 113-132

Arnold, J., Srinivasan, R., Neitsch, S., George, C., Abbaspour, K., Gassman, P., Hua Hao, F., van Griensven, A., Gosain, A., Debels, P. Won Kim, N., Somaru, H., Ella, V., Leon, L., Jintrawet, A., Reyes, M. and Sombatpanit, S. (2009) *Soil and Water Assessment Tool (SWAT): Global Applications.* WASWC, Bangkok

Barker, D., Watson, A., Sombatpanit, S., Northcutt, B. and Maglinao, A. (2004) *Ground and water bioengineering for erosion control and slope stabilisation.* Science Publishers, Enfield, New Hampshire

Barrow, E.G.C. (1983) Use of micro-catchments for tree planting in soil conservation for semi-arid areas. In: Thomas, D.B. and Senga, W.M. (eds) *Soil and Water Conservation in Kenya*. Proc. of the second National Workshop, Nairobi, March 10-13, 1982:324-331

Baum, E., Wolff, P. and Zöbisch, M.A. (eds) (1993) *Acceptance of Soil and Water Conservation Strategies and Technologies.* Topics in Applied Resource Management in the Tropics. DITSL, Witzenhausen

Baumert, K.A., Herzog, T. and Pershing, J. (2005) *Navigating the Numbers- Greenhouse Gas Data and International Climate Policy*. World Resources Institute

Biamah, E.K., Rockstrom, J. and Okwach, G. (2000) *Conservation tillage for dryland farming: technical options and experiences in East and Southern Africa.* RELMA, Nairobi

Boers, T.M. and Ben-Asher, J. (1982) Review of rainwater harvesting. Agricultural Water Management 5: 145-158.

Borst, L. and de Haas, S. (2006) Hydrology of sand storage dams: A case study in the Kiindu catchment, Kitui District, Kenya. Mimeo, VU University Amsterdam

Boserup, E. (1965) *The Conditions of Agricultural Growth. The Economics of Agrarian Change under Population Pressure.* Allen and Unwin, London (republished, 1993: Earthscan Publications, London)

Bridges, M. E., Hannan, I.D., Oldeman, L.R., Penning de Vries, F.W.T., Scherr, S.J. and Sombatpanit, S. (2001) (eds) *Response to Land Degradation.* Oxford and IBH, New Delhi

Briggs, S.R., Critchley, W.R.S., Ellis-Jones, J., Miiro, D.H., Tumuhairwe, J. and Twomlow, S. (1998) *A Final Technical Report from Environment Research Project No R4913, "Conserve water to Save Soil and the Environment"* 1995-1998. DfID/ Silsoe Research Institute

Briggs, L. and Twomlow, S. (2002) Organic material flows within a smallholder highland farming system of South West Uganda. *Agriculture, Ecosystems & Environment, Volume 89, Number 3, p. 191-212*

Bruijnzeel, L.A. and Bremmer, C.N. (1989) Highland-Lowland Interactions in the Ganges Brahmaputra River basin: A review of Published Literature. ICIMOD Occasional Paper No 11, Kathmandu

Chambers, R. (1983) *Rural Development: putting the poor first*. London: Longman

Chambers, R. (1990) *Microenvironments unobserved*. Gatekeepers Series no22, International Institute for Environment and Development, London

Critchley, W.R.S. (1987) *Some Lessons from Water Harvesting in* Sub-Saharan Africa. Report from a workshop held in Baringo, Kenya, 13-17 October 1986. World Bank, Eastern and Southern Africa Projects Dept., Washington D.C.

Critchley, W.R.S. (1991) *Looking After Our* Land – Soil and Water Conservation in Dryland Africa. Oxfam Publications, UK

Critchley, W.R.S. (2000) *Groundtruthing. New Perspectives on Soil Erosion and Conservation in the Tropics.* PhD Thesis, Vrije Universiteit, Amsterdam

Critchley, W.R.S. and Siegert, K. (1991) *Water Harvesting: A Manual for the Design and Construction of Water Harvesting Schemes for Plant Production*. FAO, Rome

Critchley W.R.S. and Mutunga K. (2002) Local innovation in a global context: documenting farmer initiatives in land husbandry through WOCAT. *Land Degradation and Development*, vol 14, pp 143-162

Critchley, W.R.S., Reij, C. and Seznec, A. (1992) Water Harvesting for Plant Production, Volume II: Case Studies and Conclusions for Sub-Saharan Africa. World Bank Technical Paper Number 157, Africa Technical Department Series, Washington D.C.

Critchley, W.R.S., Reij, C, and Willcocks, T.J. (1994) Indigenous Soil and Water Conservation: A Review of the State of Knowledge and Prospects for Building on Traditions. *Land Degradation and Rehabilitation*, 5: 293-314

Critchley, W., S. Sombatpanit, S. and Medina, S. (2001) Uncertain steps? : Terraces in the tropics. *In:* Bridges, M. E., Hannan, I.D., Oldeman, L.R., Penning de Vries, F.W.T., Scherr, S.J. and Sombatpanit, S. (eds) *Response to Land Degradation.* pp 325 – 338. Oxford and IBH, New Delhi

Critchley, W., Sombatpanit, S. and Schwilch, G. (2004) Vegetative Barriers: Green belts or a waste of space? *In*: Barker, D., Watson, A., Sombatpanit, S., Northcutt, B. and Maglinao, A. *Ground and water bioengineering for erosion control and slope stabilisation* pp. 355-364. Science Publishers, Enfield, New Hampshire

Critchley, W. and Negi, G. and Brommer, M. (2008) Local Innovation in Green Water Management*.* In : Bossio D. and Geheb K., *Conserving Land, Protecting Water*. pp107-119

Department for International Development (DfID) (2005) *Growth and Poverty Reduction: The Role of Agriculture*. DfID, London

Di Prima, S. (2007) Sand dams in Kitui district, Kenya. Internal Working Document. VU-CIS Amsterdam,15 pp.

Doolette, J.B. and Magrath, W.B. (eds.) (1990) *Watershed Development in Asia. Strategies and Technologies.* Technical Paper 127. The World Bank, Washington, D.C.

Douglas, M. (1994) *Sustainable Use of Agricultural Soils. A Review of the Prerequisites for Success or Failure*. Switzerland: Group for Development and Environment, University of Berne

Doumbia, M. and Reij, C. (2007) La Collecte des Eaux de Ruissellement au Mali: bilan et perspectives. Rapport préliminaire

Ensing, B., Freeks, G. and Sangers, S. (1985) Homegardens and homegardeningin the Matara district: the present situation and future prospects. MSc thesis, Social Science and Economics Dept, University of Leiden, Netherlands

Evanari, M., Shanan, L. and Tadmor, N. (1971) *The Negev: The Challenge of a Desert.* Harvard University Press, Cambridge, Massachusetts

Falkenmark, M. (1995) Land-water linkages: a synopsis. In: Land and water integration and river basin management. FAO Land and Water Bulleting. No 1, pp 15-17. FAO, Rome

Falkenmark, M., Fox, P., Persson, G. and Rockström, J. (2001) Water Harvesting for Upgrading of Rainfed Agriculture: Problem Analysis and Research Needs. SIWI Report 11, Stockholm

Falkenmark, M. and Lannerstad, M. (2004) Consumptive water use to feed humanity – curing a blind spot. *Hydrology and Earth System Sciences Discussions* 1: 7-40

FAO (1986) *African agriculture: the next 25 years.* Rome

FAO (1994) *Water Harvesting for Improved Agricultural Production.* Proceedings of the FAO Expert Consultation, Cairo, Egypt, November 1993

FAO (2007) *SARD and scaling-up of good practices.* Sustainable Agriculture and Rural Development (SARD) Policy Brief 21. Food and Agriculture Organisation, Rome

FAO (2008) Investing in Sustainable Agriculture Intensification. The Role of Conservation Agriculture: A Framework for Action, FAO, Rome

Fernandes, E.C.M. and Nair, P.K.R. (1986) *An evaluation of the Structure and Function of Tropical Homegardens*. ICRAF working paper no 38

Garrity, D., Stark, M. and Mercado, A. (2004) Natural vegetative strips: a bioengineering innovation to help transform tropical smallholder conservation. *In*: Barker, D., Watson, A., Sombatpanit, S., Northcutt, B. and Maglinao, A. *Ground and water bioengineering for erosion control and slope stabilisation* pp. 263-270. Science Publishers, Enfield, New Hampshire

GEF, (2007) Strategic Investment Program for Sustainable Land Management in Sub-Saharan Africa (SIP). Program Brief on a Proposed Grant from the Global Environment Facility Trust Fund

Gelpke, S. J. H. (1901) *Naar aanleiding van Staatsblad 1876*, no110. Batavia

Giller, K.E., Witter, E., Corbeels, M. and Tittonell, P. (in press) Conservation agriculture and smallholder farming in Africa: The heretic's view. *Field crops research.*

Goddard, T., Zoebisch, M., Gan, Y., Ellis, W., Watson, A. and Sombatpanit, S. (eds) (2007) *No-Till Farming Systems.* WASWC Special Publication no. 3, Bangkok

de Graaf, J., Cameron, J., Sombatpanit, S., Pieri, C. and Woodhill, J. (2007) *Monitoring and Evaluation of Soil Conservation and Watershed Development Projects.* Science Publishers, Enfield

Grimshaw, R.G., and Helfer, L. (eds) (1995) *Vetiver grass for Soil and Water Conservation, Land Rehabilitation, and Embankment Stabilization.* World Bank Technical paper no 273

Hagmann, J., Murwira K. and Chuma, E. (1996) Learning together: Development an extension of soil and water conservation in Zimbabwe. *Quarterly Journal of International Agriculture* 35, pp 142-162

Hassane, A., Martin, P. and Reij, C. (2000) *Water Harvesting, Land Rehabilitation and Household Food Security in Niger: IFAD's Soil and Water Conservation Project in Illéla District.* IFAD, Rome

Hellin, J. (2006) *Better Land Husbandry: from soil conservation to holistic land management.* Science Publishers, Enfield

Hilhorst, T. and Muchena F. (2000) *Nutrients on the Move: Soil Fertility Dynamics in African Farming Systems.* International Institute for Environment and Development, London

Holmberg, G. (1985) *An Economic Evaluation of Soil Conservation in Kalia Sub-location, Kitui District, Kenya*. Ministry of Agriculture, Kenya

Hoogerbrugge, I. D. and Fresco, L. O. (1993) *Homegarden Systems: Agricultural Characteristics and Challenges*. Gatekeeper series no 39, International Institute for Environment and Development, London

Hudson, N.W. (1971; 1981 second edition) *Soil Conservation.* Batsford, London

Hudson, N.W. (1987) *Soil and Water Conservation in Semi-Arid Areas.* Soils Bulletin no 57, Food and Agriculture Organisation, Rome

Hudson, N.W. (1988) Tilting at windmills or fighting real battles? In: Moldenhauer, W. C. and Hudson, N.W. (eds.) *Conservation Farming on Steep Lands.* World Association of Soil and Water Conservation, Ankeny, Iowa, pp 3-8

Hudson, N.W. (1991) *A Study of the Reasons for the Success or Failure of Soil Conservation Projects.* Soils Bulletin no 64, Food and Agriculture Organisation, Rome

Hudson, N.W. (1992) *Land Husbandry.* Batsford, London

Hurni, H. (1986) *Guidelines for Development Agents on Soil Conservation in Ethiopia.* Community Forests and Soil Conservation Development Department, Ministry of Agriculture, Ethioipia

Hurni, H. (‘*with the assistance of an international group of contributors*’) (1996) *Precious Earth. From Soil and Water Conservation to Sustainable Land Management*. International Soil Conservation Organisation and Centre for Development and Environment, University of Berne

Institute for Environmental Studies, VU University Amsterdam (IVM) (2007) Poverty Reduction and Environmental Management Programme (PREM) *Small-Scale Water Harvesting in Northern Ethiopia: Can it alleviate household poverty?* - Policy brief No.15

International Fund for Agricultural Development (IFAD), (1992) *Soil and Water Conservation in* Sub-Saharan Africa*. Towards Sustainable Production by the Rural Poor*. Report prepared by the Centre for Development Cooperation Services, Vrije Universiteit Amsterdam. International Fund for Agricultural Development, Rome

Intergovernmental Panel on Climate Change (IPCC), (2007) Fourth Assessment Report. IPCC, Geneva, Switzerland

Kerr, J. and Sanghi, N.K. (1992) *Indigenous Soil and Water Conservation in India’s Semi-Arid Tropics.* Gatekeeper Series no 34, International Institute for Environment and Development, London

Kerr, J. and Pangare G. (2001) Water Harvesting and Watershed Management. In: Ruth, S., Meinzen, D. and Rosegrant, M.W. *Overcoming Water Scarcity and Quality Constraints*. International Food Policy Research Institute, Washington DC, USA

Kiome, R.M. and Stocking, M.A. (1993) *Soil and Water Conservation in Semi-Arid Kenya*. Bulletin 61, Natural Resources Institute, Kent, UK

Koohafkhan, P. and Stewart, B.A. (2008) *Water and Cereals in Drylands.* Earthscan, London

Lal, R. (1975) *The role of mulching techniques in tropical soil amd water conservation.* I.I.T.A. Technical Bulletin No 1. Nigeria

Lasage, R., Aerts, J., Mutiso, G-C. M. and Vries, A., de (2007) Potential for community based adaption to droughts: Sand dams in Kitui, Kenya. Physics and Chemistry of the Earth 33: 67-73.

Leach, M. and Mearns, R. (eds) (1996) *The Lie of the Land. Challenging Received Wisdom on the African Environment*. International African Institute, Heinemann/ James Curry, Oxford

Lee, M. and Visscher, J. (1992) *Water Harvesting: A Guide for Planners and Project Managers*. Technical Paper Series no 30, IRC International Water and Sanitation Centre, The Hague, The Netherlands

Lindgren, B. M. (1988) Machakos Report 1988: An Economic Evaluation of the Soil and Water Conservation Project in Machackos District, Kenya. Ministry of Agriculture, Kenya

Lundgren, L. and Taylor, G. (1993) *From Soil Conservation to Land Husbandry: guidelines based on SIDA’s experience.* SIDA, Stockholm

Malagnoux, M. (2008) Degraded Arid Land Restoration for Afforestation and Agro-Silvo-Pastoral Production through New Water Harvesting Mechanized Technology. In: Lee, C. and Schaaf, T. The future of Drylands. Springer, Netherlands

Masefield, G. (1949) *A Handbook of Tropical Agriculture*. Oxford University Press

Mazvimavi, K. and Twomlow, S. (in press) Socioeconomic and institutional factors influencing adoption of conservation farming by vulnerable households. Zimbabwe *Zimbabwe Agricultural Systems*

McDonald, A. (1941) *Early American Soil Conservationists*. U.S. Dept. of Agriculture

Miller, J. (2009) *Farm ponds for water, fish and livelihoods*. FAO, Diversification booklet, no 13

Ministry of Agriculture and Livestock Development, Government of Kenya (MoALD) (1984). Baringo Pilot Semi-Arid Area Project. Interim Report

Ministry of Agriculture, Government of Kenya (MoA) (2001) Soil and Water Conservation Report, Kitui District

Molden, D. (ed) (2007) Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture. London: Earthscan, and Colombo: International Water Management Institute

Morgan, R.P.C. (1986, 1995 2nd edition.). *Soil Erosion and Conservation.* Longman, Harlow

Mutunga K. and Critchley, W. (2001) *Farmers' Initiatives in Land Husbandry: promising technologies for the drier areas of East Africa.* UNDP and RELMA, Nairobi

Narayana, V. V. D and Babu, R. (1985) *Soil and Water conservation in semi-arid regions of India.* CSWCRTI, Dehradun, India

National Academy of Sciences (1974) *More Water for Arid Lands: Promising Technologies and Research Opportunities.* NAS, Washington, DC

Ngigi, S.N. (2003) *Rainwater Harvesting for Improved Food Security: promising technologies in the Greater Horn of Africa.* Kenya Rainwater Association for the Greater Horn of Africa Rainwater Partnership.

Nissen-Petersen, E. (1982) *Rain Catchment and Water Supply in Rural Africa: A Manual.* Hodder and Stoughton, London

Nissen-Petersen E. and Lee, M. (1990) *Sub-surface and sand-storaqe dams*. DANIDA, Kenya

Nissen-Petersen E. (2006) *Water from Dry Riverbeds*. ASAL Consultants Ltd., Kenya

Nyagumbo, I. (2000) *Conservation technologies for smallholder farms in Zimbabwe.* FAO. *In:* Biamah, E.K., Rockstrom, J. and Okwach, G. (2000) *Conservation tillage for dryland farming: technical options and experiences in East and Southern Africa.* pp 70-86 RELMA, Nairobi

Oweis, T., Hachum, A. and Kijne, J. (1999) Water Harvesting and Supplementary Irrigation for Improved water Use Efficiency in Dry Areas. SWIM Paper No 7. ICARDA/ IWMI

Oweis, T., Hachum, A. and Bruggeman, A. (eds) (2004) *Indigenous Water Harvesting Systems in West Asia and North Africa.* ICARDA, Aleppo

Pacey, A. and Cullis, A. (1986) *Rainwater Harvesting: the Collection of Rainfall and Runoff in Rural Areas*. IT Publications, London, UK

Peacock, T., Ward, C. and Gambarelli, G. (2007) Investing in Agricultural Water for Poverty Reduction and Economic Growth in Sub-Saharan Africa. Synthesis report for ADB, FAO, IFAD, IWMI and the World Bank (draft, February 21st 2007)

Pretty, J.N. and Shah, P. (1994) Soil and Water Conservation in the 20th Century: A History of Coercion and Control. Rural History Centre Research Series No 1. University of Reading, Reading

Qiang, Z. and Yuanhong, L. (2003) *Drought-Proofing villages in Gansu Province*. LEISA magazine , Volume 19 no2, ILEIA, The Netherlands

Rämi, H. (2003) Ponds filled with challenge*.* Water harvesting – experiences in Amhara and Tigray. Report for UN-OCHA, Ethiopia

Reij, C. (1991) *Indigenous Soil and Water Conservation in Africa*. Gatekeeper Series no 27, International Institute for Environment and Development, London

Reij, C., Mulder, P. and Begemann, L. (1988) Water harvesting for plant production. World Bank Technical Paper No.91, Washington, D.C.

Reij, C., Scoones, I. and Toulmin, C. (eds) (1996) *Sustaining the Soil.* Earthscan Publications, International Institute for Environment and Development, London

Reij, C. and Waters-Bayer, A. (eds) (2001) *Farmer Innovation in Africa.* Earthscan

Rochette, R. M. (1989) *Le Sahel en Lutte Contre la Desertification: Leçons d' éxperiences.* GTZ, Eschborn

Rockström, J. (2000) Water Resources Management in Smallholder Farms in Eastern and Southern Africa: An Overview. *Physics and Chemistry of the Earth*, 25(3): 275-283

Rockström, J. and Falkenmark, M. (2000) Semiarid Crop Production from Hydrological Perspective: Gap between Potential and Actual Yields. *Critical Reviews in Plant Sciences*, 19 (4): 319-346

Rockström, J, Barron, J. and Fox, P. (2003) Water Productivity in Rain-fed Agriculture: Challenges and Opportunities for Smallholder Farmers in Drought-prone Tropical Agroecosystems. In: Kijne, J.W., Barker, R. and Molden, D., *Water Productivity in Agriculture: Limits and Opportunities for Improvement,* CAB International

Rockström, J., Kaumbutho, P., Mwalley, J., Nzabi, A.W., Temesgen, M., Mawenya, L., Barron, J., Mutua, J. and Damsgaard-Larssen, S. (2008) Conservation farming strategies in East and Southern Africa: Yields and rain water productivity from on-farm action research. *Soil & Tillage Research* 103: 23-32

Roose, E. (1987) Gestion conservatoires des eaux et de la fertilité des sols dans les paysages Soudano-Sahelien D'Afrique Occidentale: Strategies anciennes et nouvelles. Communication au Séminaire "Gestion des eaux, des sols et des plantes" Niamey, 11-16 January 1987

Roose, E. (1988) Soil and water conservation lessons from steep-slope farming in French-speaking countries of Africa. In: Moldenhauer, W.C. and Hudson, N.W. (eds.) *Conservation Farming on Steep Lands.* Soil and Water Conservation Society of America, Ankeny, pp 129-139

Roose, E. (ed) (2000) *Bulletin du Reseau Erosion 20.* IRD/ GTZ, Montpellier

Ruthenberg, H. (1966) African Agricultural Production Development in Kenya 1952-1965. IFO-Institut für Wirtschatfsforschung. Munich

Segers K., Dessein, J., Nyssen, J., Haile, M. and Deckers, J. (2008) Wanted by the State: farmers making headway – a case study in Tigray, Northern Ethiopia. *International Journal of Agricultural Sustainability* 6 (2008), pp 173-182

Shanan, L. and Tadmor, N.H. (1979) *Micro-catchment Systems for Arid Zone Development; a Handbook for Design and Construction.* Hebrew University, Jerusalem

Sharma, K. D., Pareek, O.P. and Singh, H.P. (1986) Microcatchment water harvesting for raising Jujube orchards in an arid climate. *Transactions of the ASEA* 29 (1), 112-118

Shaxson, T.F. (1988) Conserving soil by stealth. In: Moldenhauer, W. C. and Hudson, N.W. (eds.) *Conservation Farming on Steep Lands.* World Association of Soil and Water Conservation, Ankeny, Iowa, pp 9-17

Shaxson, T.F., Hudson, N.W., Sanders, D.W., Roose, E. and Moldenhauer, W. C. (1989) *Land Husbandry. A Framework for Soil and Water Conservation*. Soil and Water Conservation Society, Ankeny, Iowa

Showers, K. (2005) *Imperial Gullies: Soil erosion and conservation in Lesotho*. Ohio University Press, Athens, Ohio

Singh, G., Satry, G.V. and Joshi, B.P. (1990) *Manual of Soil and Water Conservation Practices.* Oxford and IBH, New Delhi

Stallings, J. H. (1949) Crop residues conserve soil and water. *Journal of Soil and Water Conservation, pp 103 - 127*

Stockholm Environment Institute, (Barron, J. ed) (2009) *Rainwater Harvesting: a Lifeline for Human Well-Being.* United Nations Environment Programme

Stocking, M.A. (1988) Socioeconomics of soil conservation in developing countries. *Journal of Soil and Water Conservation* 43 (5), 381-385

Thomas, D.B., (ed.) (1997) *Soil and Water Conservation Manual for Kenya.* Soil and Water Conservation Branch. Ministry of Agriculture, Livestock Development and Marketing, Republic of Kenya

Thomas, D.B. and Biamah, E.K. (1991) Origin, application and design of the *fanya juu* terrace. In: Moldenhauer, W.C., Hudson, N.W., Sheng, T.C. and San-Wei Lee (eds.) *Development of Conservation Farming on Hillslopes*, Soil and Water Conservation Society, Ankeny, Iowa, pp 185-194

Tiffen, M., Mortimore, M. and Gichuki, F. (1994) *More People, Less Erosion. Environmental Recovery in Kenya*. Wiley, Chichester

Unger P.W. (1984) *Tillage systems for soil and water conservation.* FAO Soils Bulletin, Number 54. Rome

Vlek, P.L.G., Bao Le, Q. and Tamene, L. (2008) Land Decline in Land-Rich Africa: A Creeping Disaster in the Making. Consultative Group on International Agricultural Research. Centre for Development Research (ZEF), University of Bonn, Germany

World Commission on Environment and Development (WCED) (1987) *Our Common Future'.* Oxford University Press, Oxford

Wilken, G.C. (1987) *Good Farmers.* University of California Press, Berkeley, California, USA

Wischmeier, W.H. , Smith, D.D. and Uhland R.E. (1958) Evaluation of factors in the Soil-Loss Equation. *Agricultural Engineering, 39, 8, 458 – 462, 474.*

WOCAT (Liniger H. and Critchley, W. eds) (2007) *where the land is greener: case studies and analysis of soil and water conservation initiatives worldwide.* CTA, FAO, UNEP, CDE, Bern

World Bank (1981) *Accelerated Development for* Sub-Saharan Africa*: An Agenda for Action.* The World Bank, Washington, DC

World Bank (2008) *Agriculture for Development.* World Development Report. The World Bank, Washington, DC

Young, A. (1989) *Agroforestry for Soil Conservation.* CAB International, Wallingford, UK

Young, A. (1997) *Agroforestry for Soil Management.* CAB International, Wallingford, UK.

Annex 2

Payment for Environmental Services

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Contents

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1. Introduction

Many of the developing world's farmers, especially the poorest ones, continue to depend on rainfed agriculture. In spite of the development of improved production technologies that rationalize resource management, the degree of on-the-ground adoption of those has so far been disappointing. At the same time, payments for environmental services (PES) have recently been pointed to as a promising strategy for providing economic incentives in environmental management, including in watershed management (e.g. Asquith & Wunder 2008). Hence, it is tempting to reflect upon the possibilities for applying the innovative PES tool to the old adoption problem of improved water management in agricultue: to what extent could the two be joined in a happy marriage, i.e. providing a wider field of application for PES, and a more efficient water use in agriculture?

It is this overriding question that forms the basis for this background paper. The text is structured as follows. Chapter 2 starts out with a brief introduction to watershed management approaches and their consequences for rainfed agriculture, including the main environmental externalities. Chapter 3 then introduces the PES concept, its basic mechanism, and what constraints it has met so far – and could possibly meet in its application to the problems of rainfed agriculture. Chapter 4 reviews global PES experiences, with special emphasis on developing countries and on PES with agricultural service providers. Chapter 5 turns to a more quantitative (incl. modeling) approach, and discusses for an applied case how biophysics and economics could be integrated to value benefits and costs. Finally, Chapter 6 discusses how and how much PES schemes can go to scale, and what trade-offs are likely involved. Chapter 7 closes with a synthesis of the main arguments.

2. Watershed Management Approaches and Rainfed Agriculture

2.1. The rationale for watershed management

Ranging from micro watersheds to river basins, watersheds provide fundamental units of biophysical and human interaction (Darghouth et al. 2008). This concerns the hydrological services that result from the interdependence between upstream and downstream users (Asquith & Wunder 2008). But other watershed-specific services relate to carbon, biodiversity, and landscape beauty, given that the watershed also for these non-hydrological services in many cases provides a natural boundary of interactions (Aylward 2007). Finally, humans in a watershed also tend to depend on each other, and the institutions and relations developing around shared natural resources usually also have important implications for human welfare (Kerr 2002).

Seen in a recent historical perspective, watershed management approaches in the 1970/80s were mostly characterized by engineering solutions; the interests and livelihoods of upstream watershed inhabitants were often ignored. This led to a high rate of failure in watershed projects. In the 1990s, the popularity of a 'farmers first' ideology led to more emphasis on farming systems, including more demand-driven and decentralized approaches. While these approaches and projects were more successful in engaging upstream dwellers, they often were not able to document any likely provision of downstream benefits in a satisfactory way. In addition, they often ran into trade-offs between human welfare (upstream) and the environment (downstream) that they were not able to resolve well (Darghouth et al. 2008).

Both approaches thus had some success, but also registered partial shortcomings. The payments for environmental services approach is a relevant answer to consider in both respects. PES are particularly adequate to address hard trade-offs in natural resource management, using compensation payments to turn losers into winners (Wunder 2007; Chapter 3 of this report). Also, their inherent feature of conditionality implies an imperative to measure and/ or model land use proxies and direct service outcomes (Chapter 5). In the following, we will briefly describe the water quantity, quality, and other service provision goals of watershed management in rainfed agriculture and dryland farming.

2.2. The importance of rainfed agriculture

Cereals continue to be the most important source of foodstuff, providing more than half of global calories consumed, with a particular importance in developing countries. In the recent past, production of cereals clearly outperformed population growth: according to FAO data, between 1961 and 2005 the former grew 2.6 times; the latter only 2.1 times (Koohafkan & Stewart 2008: 1). However, continued growth is necessary for supply to keep up with higher demand from continuing population growth, and competing demand for non-human intake, such as animal feed (growing with societal wealth) and biofuels. On the supply side, climate change will make production more challenging, especially in the tropics and sub-tropics, and particularly in drylands.

Rainfed agriculture, i.e. cropping without the use of irrigation, today still accounts for the majority of the world’s agricultural production. In drylands, rainfed agriculture has the highest potential for improving productivity through improved water management and conservation farming (World Bank 2009). Drylands are by FAO defined as having between 1-179 annual days of growth, and subdivide into arid, semi-arid, dry and sub-humid zones (Koohafkan & Stewart 2008: 5). In Sub-Saharan Africa, two thirds of land areas are deserts or drylands, and 98% of agriculture is rainfed (World Bank 2009). Thus, in our below review of global PES schemes, we will also pay particular attention to “drylands” and to “Sub-Saharan Africa”.

Norman Borlaug estimated in the mid-1990s that technical improvements in overall crop management could increase yields by 100-200% in most of Sub-Saharan Africa compared to 50-100% in other developing/emerging countries, and almost nothing in Europe, North America and China, where agricultural systems already have been optimized (Borlaug 1996). Much of this huge African potential lies in dryland rainfed farming, where crop growth is effectively constrained at least part of the year by the lack of water. Soil, water, and nutrient management thus need to be integrated so as to reach successful outcomes. Conversely, inappropriate techniques can lead to land degradation and desertification, a risk that will be accentuated by climate change. Soil salinization is another common risk (Koohafkan & Stewart 2008: ch.1).

2.3. Improving the management of water quantities

Given these opportunities and risks, what methods of improved agriculture can achieve a more efficient use of water quantities? Water is a key and growingly constraining bottleneck; roughly 86% of soils in Sub-Saharan Africa are moisture-stressed (World Bank 2009: 5). Hence, improved on-farm water management has often a high potential for raising on-farm productivity.

Box 1, firstly, briefly outlines a number of interventions designed to improve *in situ* water conservation, often combined with reduced erosion and soil fertility conservation (terracing, contour techniques, land leveling, etc.). The methods vary in costs and management efforts, and thus their applicability is scenario-dependent. An overall concern is mainly to within the water cycle increase the ‘green water’ share (referring to the water uptake and evapotranspiration by crops), at the expense of ‘blue water’ (surface runoff, aquifer recharge and soil evaporation).

[Box 1 here]

Secondly, some improved farming techniques are primarily directed at other farming objectives, for instance, limiting soil-fertility loss or increasing organic matter. These can be methods such as no- or low-tillage farming, mulching, or the recycling of crop residues. For instance, no-tillage farming aims at growing crops from year to year without disturbing the soil structure. No-tillage decreases erosion, and increases the amount and variety of life in and on the soil. However, these techniques will usually also increase the water balance available for plant evapotranspiration. This may also affect the water quantity and quality received by downstream users – the latter ‘externality issues’ to be addressed in greater detail below.

Finally, innovative water harvesting techniques can increase the supply of water available in each upstream farm. This includes the construction of reservoirs, cisterns, rooftop and floodwater harvesting, etc. While these innovations can bring large benefits to both upstream farmers, and possibly to some downstream users (who may e.g. benefit from a larger runoff of ‘saved’ water in the driest season), they fall outside of our scope of work: it is not an “environmental service”, but an “engineering solution” that is being provided -- based on the construction of small-scale water infrastructure, combined with a local water governance/ management regime. In a sense, we are talking here about one of the alternatives or supplements to the reliance on environmental services. In the following, we will thus not consider water harvesting measures in a PES context.

2.4. Improving water quality

Upstream dryland farmers’ main water interests will be to make the most efficient use of the water resource on-farm in quantitative terms. Downstream water users, however, may be interested in a whole range of subservices related to both water quantity (total and dry-season flow, stormflow protection) and quality (minimizing sediments, organic matter, nitrates, agrotoxical residues, etc.). Several of the on-farm quantity management measures described above have positive side-effects on water quality downstream. For instance, mulching or contour farming will likely reduce erosion, and may thus also cut water turbidity and sedimentation experienced by downstream users. However, in some cases no-tillage farming goes along with the increased use of herbicides, which might negatively impact water quality downstream. A positive synergy between improved water management upstream and water quality improvements downstream thus has to be confirmed on a case-by-case- basis. Especially when downstream areas hold high population densities, the concern (and willingness to pay) for good water quality may outstrip water quantity concerns, including because of powerful health implications. Table 1 shows the main pollution categories from agriculture, with physical, organic and toxic pollutant types, and their respective origin.

[Table 1 here]

Among pollution effects from agricultural landscapes, we are in particular interested in non-point sources, since environmental service payments are best suited to deal with these. Yet, a PES scheme may occasionally also include regulation of point source pollution, such as prohibiting the use of a certain agro-toxic input so as to maintain drinking water quality (Aylward 2007). Table 2 links different agricultural activities to possible downstream impacts. For instance, land clearing for upstream expansion of agriculture into marginal production areas can lead to serious negative externalities for downstream users.

[Table 2 here]

2.5. Identifying stakeholders and externalities

The importance of externalities

While many of the above mentioned techniques, especially those affecting water quantities, have the potential of increasing on-farm productivity and incomes, sometimes significantly so, we are in this paper mainly interested in the subset of those that also generate positive environmental externalities. In other words, we are looking for any upstream adopted change that triggers off-farm net benefits to downstream water users and other off-farm population, vis-à-vis a predefined 'business-as-usual' scenario. This is because, as we will see in the next chapter, the PES tool crucially depends on the presence of positive externalities: if nobody looks to receiving a significant net downstream benefit, then also nobody would voluntarily be willing to pay, and there is no meaning in looking at the PES option.[1]

Note that runoff water quality improvement (or, respectively, avoiding water quality deterioration) typically has a cost for the upstream farmer acting as service provider – unless these improvements come bundled with water-quantity measures that pay for themselves through on-farm productivity increases, such as from terracing or mulching. They may thus require PES compensations in order to be adopted.

Figure 1 can serve us as a conceptual guideline not only in this chapter, but throughout this background paper. Starting upstream (top of page), the owners or users of farm-, range- and forestlands are our potential service providers, although we should not forget that the intervention of other upstream actors (road builders, miners, etc.) in some cases can have larger impacts than those under landowners' control: badly built roads, for instance, are often disproportionately high sources of soil erosion (Aylward 2007). Note that not necessarily all service providers (or providers of disservice-avoided) are also service sellers: many may provide services without receiving payments.

[Figure 1 here]

The service provided can come from interventions that in sectoral terms originate either in forestry (afforestation, reforestation, forest conservation), from the introduction of trees into agriculture (agroforestry, silvopasture), or from our particular interest case of changes in

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[1] One could also imagine that either government or a donor is making payments to upstream farmers in order to reward the adoption of improved techniques. The 'externality' targeted would, for instance, be an increase in national crop supply and enhanced national food security. However, this is not a PES, since there are no environmental externalities involved. Such an intervention could make perfectly sense, but should be viewed as a production subsidy.

cropping practices (e.g. in-situ water conservation and ecological farming techniques – as explained above). As a result, within the watershed, both water quality and quantity services may be provided, as explained above. As mentioned, not all watershed services are hydrological. Interventions may also affect carbon balances, biodiversity, and landscape beauty. To the extent that these services are positive, some stakeholders (local, national, global) may in the best case also be willing to pay for them. The potential buyers of hydrological services are discussed in the following. Note that, analogous to the provider side, some service users are buyers, while others are free-riders: they receive a service, but do not pay for its provision.

Downstream water users and hydrologic service demand
What users are typically interested in what type of upstream service, or in many cases, "avoidance of disservice"? Box 2 summarizes what the main water quality and quantity concerns for the five typical water user types that worldwide have made payments into PES schemes. Hydroelectric power plants, for instance, are in addition to water quantities (total annual flows) typically interested in erosion reductions, which prolong the reservoir lifetime and reduces turbine damages. The same is true for irrigators, who in quantity terms often also have strong interests in maintaining dry-season flows. The water-quality concerns of drinking-water users are due to human health aspects farther ranging. For industrial water users, the requirements depend on final use of the water. All of these users may also have an interest in mitigating stormflow events. Finally, government can in some cases become the direct water-service buyer (see Chapter 3), and will then typically try to weigh different stakeholders' interests within a larger vector of PES objectives (e.g. in the United States Conservation Reserve Program – Claassen et al. 2008).

[Box 2 here]

Hydrological externalities from rainfed agriculture
A special interest of this paper is in *in-situ* water conservation techniques that help increasing the on-farm productivity in upstream dryland agriculture. From the above, what can we say about the likely externalities being created by the adoption of these techniques in upper watersheds?

First, in water quantity terms, one can say that downstream effects depend on the net impact on the water cycle and the partitioning of rainfall. Figure 2 provides the typical quantitative ranges for semi-arid regions. Boosting 'green water' for plant transpiration has to come at the expense of the different 'blue water' components, i.e. soil evaporation and interception, surface runoff, and drainage/ aquifer recharge. How these balances are altered will determine the net effect on downstream flows. To the extent that drainage and surface runoff are the main 'losing' channels, this could potentially *reduce* water availability downstream – in which case downstream users may object to the changes, rather than wanting to pay for them. However, one could also imagine positive downstream quantity effects, i.e. due to increased soil capacity to hold onto humidity and stabilize seasonal runoff. Various internally contrarian effects may be at play. These would need to be measured or modeled, in order to safely determine the net impact on various sub-services (Chapter 6).

As a second category, many of the aforementioned improved agricultural practices reduce erosion, thus providing an unambiguous benefit of improved water quality, which we could see from Box 2 that most downstream water users will appreciate. Erosion control has probably been the main hydrological benefit so far being paid for in existing PES schemes worldwide, so this constitutes a promising potential. Since in many upstream watersheds with a rugged topography and variable soil conditions, erosion tends to occur in a spatially highly heterogeneous way, modeling can again be a highly recommendable tool to predict with spatial specificity the likely externalities from the envisaged changes. To the extent that other on-farm production processes are being altered, water quality impacts may also be affected. For instance, if more chemical inputs such as herbicides are needed in the adopted agricultural techniques (e.g. in no-tillage farming), this may harm potentially downstream drinking water consumers or industrial water users.

Carbon externalities from rainfed agriculture

Some of the improved agricultural practices also provide other, non-hydrological services. The most pronounced gains here are carbon benefits, related e.g. to organic or non-tillage farming, and other of the above described methods. Soils with increased carbon stocks have a better retention of water, providing a clear synergy between the two environmental services at hand. It is assumed that under favorable conditions around annually 3 tCO2e/ha, or little less than one ton of carbon per hectare,[2] could be sequestrated in agricultural soils, making this a considerable potential option for climate change mitigation. However, the effect of modified cropping systems varies dramatically by practice and location. Experiments led by FAO on plots in India and Nigeria indicate projections of up to a maximum of 40 t/ha over a fifty-year time horizon, assuming retention of crop residues and substantial addition of farmyard manure – but some techniques would only reach half that potential (FAO 2007: 18-19).

How large is the scope for realizing this synergy? Agriculture’s annual global greenhouse gas mitigation potential has been estimated to be up to 5500-6000 MtCO2 equivalents by year 2030 (of which 900 MtCO2e in Africa), depending on carbon prices and allowed crediting options. 90% of this potential relates to soil carbon storage. Agricultural land management is not currently eligible under the Clean Development Mechanism, which only credits for biogas, improved livestock feeding and manure storage practices. Nevertheless, 60-70% of the US voluntary market transactions on the Chicago Climate Exchange have apparently been related to improved agricultural practices, especially no-tillage farming.

African agriculture accounts for 13% of global agricultural greenhouse gas emissions, and the continent’s share has been rising. If carbon markets could subsidize the successful adoption of improved agricultural practices, this could potentially lead to both climate benefits and poverty alleviation. Some World Bank pilot projects of paying for soil carbon enhancement have been implemented in Kenya, and plans for a larger-scale Agricultural Soil Carbon Investment Facility exist (World Bank 2009). However, according to one global mapping exercise by FAO, the clearly largest soil carbon gaps on croplands are in China, with Africa only providing more scattered opportunities, especially in East Africa (FAO 2007:18).

Other non-hydrological externalities from rainfed agriculture

Other off-site benefits from improved agriculture could accrue to service users, but are unlikely to be large enough for constituting driving forces for PES mobilization in developing countries. By increasing organic matters in agricultural soils, biodiversity in and on these soils is also enhanced. While this is an undeniable conservation benefit, it is unclear whether the positive externalities in question would be significant enough to mobilize e.g. private biodiversity funds – in the face of large alternative threats against natural habitats (forests,

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[2] 1 tC = 3.67 tCO2e

bushlands, coral reefs, etc.), and opportunities to counteract those. The experiences so far seem to suggest otherwise.

This consideration applies even more to landscape aesthetic benefits. While tourists do appreciate certain improved/ elaborate agricultural landscapes for their beauty – e.g. traditional rice terraces being contemplated in Bali – it is probably too small and uncertain an externality to justify payments that could help financing the establishment of such systems.

In sum, the band of positive externalities that could potentially be sold to downstream users thus *ex ante* seems to be fairly narrow, but not insignificant. First, there are water quality benefits from in particular reduced erosion and sedimentation, which have certainly triggered many payments elsewhere in the world, including in many developing countries – although not in Africa (see Chapter 4). Second, most improved agricultural practices come along with significant carbon benefits, which could be further enhanced, in case they are to be remunerated. Currently, changed land management practices are not eligible under the Clean Development Mechanism, but are being sold in some voluntary carbon markets. Biodiversity and recreational benefits are likely minor. The two major benefits of carbon sequestration/ avoided emission and water quality improvements may in some cases have to be weighed against a diminished water quantity flow downstream. It is highly recommendable to quantify the (likely) service flow from changed agricultural practices in a more formal way, e.g. through *ex ante* modeling combined with *ex post* monitoring of service outcomes.

3. Payments for Environmental Services and Rainfed Agriculture

Having dealt with the nature of environmental services and externalities created by improved dryland agricultural practices, we will in this section turn to the incentive side of things: What preconditions would need to be in place for mobilizing a willingness to pay among service beneficiaries, and for potential service providers to be willing to accept these payments as an effective incentive to adopt changes practices? We will start out be looking at the general characteristics of PES, and then turn to a discussion of the specific preconditions.

3.1. The concept of PES

Among donors and environmental practitioners, PES is increasingly seen as an innovative way to bridge hard conservation trade-offs through negotiated solutions, and to cost-effectively achieve conservation outcomes even under adverse circumstances (Ferraro & Kiss 2002). A widely accepted PES definition is (Wunder 2007):

(1) a voluntary transaction where
(2) a well-defined environmental service (or a land use likely to secure its provision)
(3) is being bought by at least one buyer
(4) from at least one provider effectively controlling service provision
(5) if and only if the service provider secures service provision (conditionality).

The notion of conditionality is the most innovative feature, making PES the flagship of a new conservation paradigm focused on ‘contractual conservation’ where economic incentives and *quid pro quo* are in focus. PES can be used for preserving, restoring and creating new environmental services. In terms of farmers’ land-use choices, there are three ways they could provide environmental services: change towards environmentally more benign agricultural practices, refrain from converting natural areas to farmland, and retiring environmentally sensitive areas (FAO 2007). The present report focuses primarily on the first of these three options.

PES systems could be envisaged for many externalities, but are currently being implemented worldwide for four stated service types: carbon, watersheds, biodiversity, and landscape beauty (Landell-Mills & Porras 2002, and Chapter 4). While the first is a universal service, the latter three are typically highly specific in place: it is particular parts of the landscape that provide the (highest) environmental service.

The five PES principles above hold for several real-world schemes, but the number of existing ‘PES-like’ schemes – satisfying most but not all criteria – is much larger. As a notable distinction, two prototypes exist (Engel et al. 2008; Wunder et al. 2008). The first is ‘user-financed’ PES schemes, normally initiated at the initiative of service buyers or intermediaries like non-governmental organizations. Typically, these are small-to medium-scale in size, tend to be focused on a single service, often use differentiated payments and are often highly targeted in the landscape to high-service and/or low-cost provision areas. Since both buyers and sellers per definition engage voluntarily, these schemes are what economists call “Coasian bargains”, i.e. users pay a tax that in a market-like transaction matches a conditional subsidy given to providers. They manifest PES in their purest form, closely in line with the five criteria above. In particular, many small-scale watershed and carbon projects fit this description, and have in developing countries been widely implemented in Latin America (Southgate and Wunder 2009; Kosoy et al. 2006), somewhat less so in Asia (Huang et al. 2009), and only exceptionally in Africa (Ferraro 2009) (see Chapter 4).

The second prototype of PES schemes is financed by government, acting as a buyer on behalf of service end-users – who thus cannot voluntarily choose whether to pay or not. In economic theory terms, these schemes resemble ordinary subsidies, i.e. without a corresponding tax on service users. They can be conceptualized as subsidies contingent upon service delivery, i.e. with strong conditionality (Engel et al. 2008). Government PES schemes are typically much larger in size, tend to combine several services, but also feature various side objectives (poverty alleviation, regional and sectoral development, electoral concerns, etc.). These multi-faceted objectives bolster political support for action at a large scale, but may endanger PES effectiveness in reaching specific environmental goals. Examples include the national PES schemes in Costa Rica (Pagiola 2008), the national hydrological services payment scheme in Mexico (Muñoz-Piña et al. 2008), the Sloping Land Conversion Program in China (Bennett 2008), and the large range of public agri-environmental schemes in OECD countries designed to counteract the negative impacts of agricultural intensification or, sometimes, extensification (Baylis et al. 2008; Claassen et al. 2008; Dobbs & Pretty 2008; FAO 2007).

What conditions need to be in place for PES to work and, conversely, what obstacles will impede or weaken the case for PES? Drawing on the classification in Wunder (2008a), we distinguish in the following between four different preconditions: economic, cultural, informational, and institutional. For each of these, we will briefly discuss the agricultural case, drawing *inter alia* on the insights from last chapter.

3.2. Economic preconditions

The key economic rationale for PES is that an “externality” exists, i.e. compensating a service benefit that the landowner provides to off-farm beneficiaries. But the value of the service(s) at hand -- determining the service user's willingness to pay -- must exceed the service provider's provision (incl. opportunity and transaction) costs, i.e. the profit foregone from abandoning the first-best land-use plan (see also Chapter 5). The latter will determine service providers' willingness to accept PES to make the required changes. In some situations, profits from currently favored land uses may be too high for conservation to compete, or transaction costs are prohibitive for PES.

Our assessment above showed that upstream adoption of improved water management and farming techniques would trigger positive water quality and carbon externalities for off-farm users. However, the situation differs from the classical PES scenario in that most of these improved techniques probably were already profitable in their own right, even without PES: opportunity costs were negative, the *de facto* adopted land-use plan does not provide first-best returns, and expected profitability alone cannot explain the lack of more widespread adoption among farmers of the improved techniques. Adoption obstacles, in turn, rather seem to include factors such as risk, lacking know-how and management capacity, credit and labor constraints, as well as insecure property rights (FAO 2007; Koohafkan & Stewart 2008).

Does it help to 'throw (PES) money' at farmers under such circumstances, in order to incentivize adoption? In some cases, this can probably make sense. FAO's report on environmental technology options for giving PES to farmers (FAO 2007: 52-3) distinguishes between various incentive scenarios:

1) permanent decreases in farm incomes (due to some combination of yield decline and increased management costs) – thus triggering positive opportunity costs
2) immediate net benefits to farmers (labeled "information barriers") and
3) net benefits after upfront investments (labeled "investment barriers").

In the first case, payment in perpetuity for the compensation of opportunity costs would be needed to remove the obstacle. In the latter two cases, the main barriers are not recurrent payments, but information and credit. Yet, a recurrent PES subsidy could still tip the balance for the farmer in order to adopt the practice, e.g. in getting a commercial loan to make the initial investments, especially perhaps in the third scenario where the investment costs could be co-financed.

In order to address scenario 3), in some cases the PES payments could be mostly frontloaded, so as to match high initial adoption costs; this is common in re- and afforestation PES (e.g. Wunder & Albán 2008). The danger of too much frontloading is that the service buyer loses all leverage over the provider's compliance, since the threat of payment discontinuation disappears. This is an inherent tradeoff that needs to be evaluated on a case-by-case basis.

It is also important to remember that adoption constraints and risk aversion can vary much across individual farmers. Thus, a flexible menu of environmentally benign land-use options to adopt can also do a lot to overcome adoption constraints. This was also one of the lessons in a World Bank-sponsored PES project in Colombia, Costa Rica and Nicaragua, where Global Environment Facility funds were used to make temporary payments (2-4 years) to cattle ranchers for introducing a suite of silvopastural practices, the majority of which should have been profitable *per se* to most farmers (Pagiola et al. 2007). The adoption bonus did make a difference to farmers, and consequently adoption was widespread.[3]

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[3] It is still too early to judge about permanence, i.e. to what extent farmers actually maintained these practices after the project, and with that the PES payments, were terminated. See also the Colombian Fúquene case (Chapter 4) for a similar experience with transitory adoption premiums.

In a similar follow-up project, and based on the previous field experiences, a revised classification of three profitability scenarios is being used (Figure 3[4]). All scenarios require initial investment costs, thus triggering negative incremental farm incomes (Y axis). Over time (X axis), Scenario A delivers lastingly very high economic returns, implying that PES payments should in principle not be necessary for adoption. Scenario B yields returns that only marginally exceed current practices, and there is a tradeoff vis-à-vis the initial investment cost. In this situation, a temporary adoption premium, designed as a service-delivery dependent (and thus contingent) PES payment, might help persuading farmers to adopt the practice. In Scenario C, the environmentally desirable option provides long-term returns that fall short of the current practice. Here, only the provision of long-term, continuous PES payments can make this option attractive for farmers to adopt. The design of the incentive necessary for adoption is thus closely linked to the diagnosis of the dynamic profitability ranges of different practices.

[Figure 3 here]

We thus now have a perspective for what is needed for farmers to respond positively to an economic adoption incentive. But what about the service user's economic incentive to provide a payment in the first place? Are the services provided by improved dryland agriculture sufficiently attractive for prospective service buyers to pay?

For carbon services, payments should come from the global society, e.g. voluntary or future compliance markets for greenhouse gas mitigation. The mitigation potential seems attractive to buyers, but agriculture has at least two drawbacks (shared with forestry) to overcome. First, carbon sequestration is non-permanent, because any change in practice is reversible over time. Although different solutions can be imagined, it seems most likely that agriculture's credits should be regarded as transitory, and will thus carry a market-determined discount that may come to be around 40% (Dutschke and Schlamadinger 2003). Second, agriculture's mitigation record can also be highly fluctuating from year to year, because it depends on external natural factors such as drought, rainfall, and wildfires[5] (IFAP 2009). A response to this in forestry has been to 'bank' a certain share of carbon credits as an insurance against unexpected losses.

For water quality benefits, and even more so for any prospective water quantity gains relying on contrary gross effects, quantifying the amount of services is usually a necessary first step before these services can actually be sold (see 3.5. below on informational preconditions). Modeling the biophysical service linkages is the best option in practical terms, and can be linked to the calculation of incentives (Chapter 5). Once the biophysical linkage and service provision have been quantified, or at least been verified within a reliable range, the next question is how valuable it is to water users in economic terms. If the agricultural area in question is close to multiple users, e.g. with a sizeable urban area downstream, the likelihood to sell services to many water users is much higher than if most of the watershed's population is concentrated in the upper catchment and the number of downstream users is low. Similarly, if there is a single powerful buyer that values the service highly, e.g. an industrial water user or a hydroelectric plant, this obviously raises the economic feasibility of PES. In the case of government PES, consideration will depend on the government's revenue base, and its willingness to spend it in marginal production areas.

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[4] With thanks to Stefano Pagiola, World Bank.

[5] In fact, fire can in causal term be of mixed origin, i.e. result from an interplay of human action (e.g. badly controlled agricultural burning) and natural conditions (e.g. a prolonged drought).

3.3. Cultural preconditions

Economic incentives constitute the core of PES. If service providers thus lack a willingness to accept payments, feel little motivated by them, or consider them socially inappropriate, then PES will not work. When non-economic value systems, e.g. based on “social markets” (collective systems of norms based on reciprocity) are well-functioning, there may be strong resistance to the introduction of PES. Nowhere is this as apparent as with water access, often being considered a human right that is threatened by PES monetization. The so-called “Andean Water Vision”, built on indigenous systems of upstream-downstream reciprocity, has in particular proved to be at odds with watershed PES, and is locally considered a neoliberal Trojan Horse. According to psychological experiments, introducing (small) monetary payments on top of (strong) preexisting intrinsic values (e.g. paying people to protect their own sacred forest) could at worst undermine rather than strengthen conservation outcomes.

It seems, however, that in most cultural contexts, PES are currently being accepted as positive incentives. Where traditional systems become dysfunctional (e.g. due to increased resource pressures), PES can gain acceptability. Using non-monetary PES payments can in some cultural circumstances be preferable (Asquith et al. 2008). The provision of (a certain share of) collective payments, whenever the sense of community decision making is strong, as for instance in some African contexts, may be relevant (Frost & Bond 2008).The PES mechanism may thus be designed adaptively, to be complementary to preexisting human values, and be customized to variable decision-making levels and natural resource management systems.

The other side of the coin is to what extent buyers have developed a culture of willingness to pay for services rendered. In developing countries where a sense of abundance of natural service remains, it may sometimes be hard to develop a *de facto* willingness to pay – different from the one stated hypothetically in contingent valuation exercises… This is especially so for hydrological services. In addition, the sense of ‘payment culture’ varies typically with the type of water users. Single large users such as hydroelectric or industrial plants are often more willing and able to pay, and can even see side benefits of neighborhood perceptions of its good corporate behavior. Club good users (e.g. municipal water users) are intermediate. At the other extreme, agricultural water users (e.g. irrigators) worldwide exhibit the clearly lowest willingness to pay for hydrologic services. As agriculture is socially seen as satisfying basic human needs (unlike industrial or electric users), its free-rider privileges are often deeply rooted in society, in spite of the disproportionate amounts of water it uses.

For the application of improved watershed management in dryland agriculture, we have no reason to believe that the cultural preconditions should be either better or worse than in other settings. People are just as likely to react positively to economic incentives as in any other setting. Farmers live from selling products to the market, and are thus sufficiently familiar with monetary incentives. Community-based payments may be relevant, but the follow-up question is to what extent the community in question is able to internally enforce the rules required for service provision. This is most of all an institutional question, to be dealt with now. On the buyer side, Africa has basically no ‘payment culture’ for PES, but this is to be discussed further in Chapter 4.

3.4. Institutional preconditions

Although natural-resource externalities are widespread globally, in few places have PES been developed completely autochtonously by local-level actors alone: external agents such as donors or NGOs have often been catalytic in setting up PES. Schemes require trust between service users and providers – expecting mutual contract compliance, and excluding frequently suspected impious motives (e.g. users grabbing providers' lands by cheating them into contracts). Since users and providers often have inherently conflictive interests, trust seldom develops naturally between them; an intermediate honest broker may be required. Hence, in situation of high conflict, negotiating a PES deal may be challenging. These government constraints, especially in remote agricultural frontier areas, may affect dryland agricultural zones as much as any other area in developing countries.

A *sine qua non* for PES relates to land tenure conditions. When rights to the land providing the service are not (and cannot be rendered) exclusive, PES cannot be applied: the landowner will then not be able to control land uses and secure service provision. Compared to forest areas, croplands typically exhibit a higher degree of land tenure security, which is an advantage for agricultural PES deals. However, if tenure is collective, or is not perceived as entirely secure, this may jeopardize the adoption of improved agricultural practices: only if land tenure is fully secure and attributable will the farmer be able to safely reap the yields from the upfront investments that are typically required in the adoption of improved techniques. For instance, it will not be rational for me as a farmer to build a terrace if an immigrant newcomer could possibly occupy that piece of land, if the village chief could allocate it to another community member or to himself, if I am renting the land from the owner, or if I had to share the incremental production benefits equally across the entire village, including with people who did not participate in the investment. This is a precondition which, for instance, in many African contexts can constitute a real bottleneck for PES. Upstream farmers may also need a certain level of coordination to simultaneously provide a service, the preconditions of which may or may not be granted.

On the other hand, PES is frequently also an apt response to some institutional shortcomings, in particular vis-à-vis the difficulties to apply command-and-control policies in developing countries. In developed countries, e.g. much watershed protection has occurred through effective legal land protection, sometimes coupled with compensations. In developing countries, this has been restricted by poor governance and the moral imperative not to hurt poor farmers, traditionally occupying productively marginal yet environmentally fragile lands. Land is often historically considered abundant, and its occupation and transformation is commonly accepted as a livelihood strategy for the poor. PES can thus also be an effective and more equitable conservation response to those institutional limitations.

What institutional preconditions are required on the service user side? A frequent misunderstanding is that PES necessarily require "markets" to function. While some carbon markets have developed, the other three remunerated services (watersheds, biodiversity, and landscape beauty) are usually too spatially specific to allow for true competition: the users have to work with the providers happening to occupy the land that provides "their" targeted service. Most existing self-organized PES are thus monopsonies (transactions with one single buyer, e.g. the State or a single company) or oligopsonies (few buyers). Under genuine market preconditions with atomistic supply and demand conditions, most PES schemes would in fact never happen, because the transaction costs of negotiating PES deals would be too high. Thus, PES design needs to draw much more on contract theory than on the marketing literature. For our specific case of agricultural improvements, carbon markets may play a role in mobilizing funding, while hydrologic services will typically be monopsonic/ bilaterally negotiated deals.

In Latin America, hydroelectric plants, municipal water utilities, and industrial users have led a boom in watershed PES (Southgate & Wunder 2009). In Asia, these conditions have existed in a minor scale (Huang et al. 2009). In Africa, in turn, the situation is severely constrained both by greater poverty (limiting industrial users payments), a topographically more limited hydroelectric potential and, perhaps most importantly, the fact that water utilities are often ill-functioning, and thus are unable to provide a vehicle for user payments. African user-financed watershed schemes have thus basically been non-existent (Ferraro 2009, and Chapter 4). If service users do not have a strong coordination agency, or a strong intermediary taking the initiative, PES usually will not happen. This is also bound to be a major binding constraint for water user-financed agricultural PES development, particularly in dryland Africa.

Government could obviously invest resources instead, as certainly has happened in the South African Working for Water program (Turpie et al. 2008). But this requires a state with both sufficient resources to spend, with the necessary foresight to self-invest in natural resource management of upper watersheds, and that is seen as trustworthy by farmers – probably also a combination of conditions that will be exceptional to find in Sub-Saharan Africa. The only hope would seem to be a major financial injection from carbon markets, supplemented possibly by donor-leveraged climate-change adaptation funds, which would absolve domestic service users from payment.

3.5. Informational preconditions

Watershed services are information-wise the most demanding environmental service: it is less apparent than for e.g. biodiversity and carbon services what exact land uses where in the landscape provide the targeted service. The continuous controversy to what extent tree presence in the landscape is ‘good’ for various watershed services is one illustrative example (Bruijnzeel 2004; Calder 1999). Hydrological services ultimately depend on site-specific factors such as soils, topography, precipitation, land cover, and temperature. For carbon, above-ground carbon can be approximated relatively easily, but soil carbon seems to be more fluctuating, and more complicated to monitor.

In both these service cases that dominate the dryland agriculture story, land-use proxies must be used to pay farmers for their efforts, rather than holding them directly responsible for service delivery: in shaping the latter, Mother Nature is ill-behaved, and farmers are unlikely to carry these risks. But setting the right proxies and spatial priorities requires knowledge that can *ex ante* best be generated through biophysical modeling (Chapter 5). The measurement of services within a watershed, and in ‘control watersheds’ nearby can certainly be a useful supplement, but will not be a substitute since long-term data are needed to control for confounding effects. Measuring hydrological linkages to scientific standards may come at costs grossly exceeding the required payments proper, which in most cases of smaller-sized PES schemes will constitute a deal breaker. An exception is where service values are very high, as in the case of French Vittel water bottlers, where both extensive measurements and modeling were used prior to devising action (Perrot-Maître 2006).

On the other extreme, in many cases watershed PES schemes have been initiated without any prior measurement or modeling efforts. The municipal watershed PES scheme in Pimampiro (Ecuador), for instance, protected upstream forests entirely based on the municipality's perception of the precautionary principle: keeping the standing but threatened forest undisturbed was a risk-averse strategy, since the forest actually had delivered the desired services so far (Wunder & Albán 2008). This is a quite common situation for forest conservation PES worldwide (Porras et al. 2008). However, the situation differs substantially from the improved agriculture case, where a service is not passively preserved but actively created or restored, with upfront investment costs at stake. Transaction costs related to hydrological research can potentially be sizeable; hence for smaller-sized PES proposals, rapid hydrologic assessment tools need to be applied (Asquith & Wunder 2008).

In general, PES are a relatively information-intensive tool. This triggers transactions costs, related e.g. to participant search, baseline setting, deal negotiation, compliance monitoring, and sanctioning. In upper watersheds with croplands that are densely populated with smallholders, transaction costs may become excessive, unless multiple smallholders can be bundled into larger collective groups. Especially PES start-up costs tend to be high, whereas costs are more competitive in the operational phase (monitoring, enforcement/ sanctioning, administration) (Wunder et al. 2008). Donors have in various cases subsidized these upfront costs to make PES development feasible.

To the extent that agricultural PES has to deal with multiple tiny producers in large upper watershed areas, the coordination among these farmers could in the worst case render PES cost-inefficient. Also, monitoring of agricultural PES compliance cannot, as for forestry, be done almost exclusively by remote sensing: while some approximations are possible, the adoption of different techniques will normally have to measured through detailed ground truthing, which may be much more expensive if multiple atomistic farmers need to be held to their PES agreements. For instance, the direct farm-level monitoring of non-point source pollution (e.g. nutrient concentration targets) in a water-quality PES has proved to be prohibitively expensive (Ribaudo 2001). Land-use proxies, bundled group contracts, and community self-monitoring coupled with expert verification can be some of the practical measures helping to keep down PES transaction costs.

4. Experiences with Payments for Environmental Services

The previous chapter has shown that PES is a 'smart' environmental management tool designed to bridge hard conservation tradeoffs, but it is also 'demanding' in terms of some basic preconditions that need to be met or adjusted – of which the rainfed agricultural improvement PES would need to perhaps pay particular attention to institutional and informational factors. Turning now to an empirical PES overview, we will in the first section look at the results from a series of global or regional PES reviews (focusing on watershed PES), and then in the second look into case studies of agricultural PES applications. This stocktaking will show us that agriculture only in exceptional cases has been PES targeted, lagging much behind e.g. forestry. In the third section, we will thus discuss some hypotheses of why this is the case. This review of empirical factors with a theoretical underpinning should thus also help us understand better the factors determining the feasibility of PES for improvements in rainfed agriculture.

4.1. Global and regional PES reviews

Global

Most PES schemes are very recent, and especially in the last decade PES implementation has been mushrooming. Most comparative reviews are thus also very recent. One slightly earlier desk-study review of PES schemes received much attention (Landell-Mills and Porras 2002). It reviewed 287 PES experiences, based on all four commercialized services (water, carbon, biodiversity, and landscape beauty), in both developed and developed countries, but with a much broader definition of PES than used in this report.[6] One of the authors recently led a follow-up review of specifically watershed PES worldwide, using a more stringent PES definition (Porras et al. 2008). The authors here found 50 ongoing watershed schemes and 45 proposals (more than in 2002), but also found that many of the proposals and pilots portrayed in the 2002 report had since been discontinued. This illustrates on the one hand a rising interest in PES over time, but also a high failure rate in this experimental stage of application.

The global overview by Porras et al. (2008) allows for some further insights into the nature of existing watershed PES scheme. Water quality and quantity concerns are as motives more or less equally represented, and often overlapping in the same schemes, but service provision prospects are often based exclusively on local beliefs about land use – service linkages, rather than measurements or modeling. Monitoring of hydrological service delivery is often weak or absent. Provider compliance is thus measured in terms of land-use proxies, which include reforestation, restoration, and conservation objectives. Only in exceptional cases were the payments made for changes in cropping practices (see below).

A special issue of *Ecological Economics,* published in April 2008, made a comparative analysis of 12 PES and 2 PES-like schemes in both developed and developing countries, the results of which are summarized in Wunder et al (2008). Unlike the sample by Porras et al. (2008), these include also examples of agri-environmental schemes, some of which pay for changes in agricultural practices,[7] but all are in OECD countries (US, EU, England, Germany, and Australia). A key conclusion from the comparative analysis relates to the fundamental design and impact differences between user- and government-financed PES schemes (see Chapter 3). Government-financed schemes face more problems of lack of spatial targeting to high-value and low-cost provision areas, their predominant use of fixed payment rates per land unit greatly reduces cost efficiency, and the problems of low conditionality and additionality are thus higher for those type of schemes. Their advantage over user-financed schemes is in their larger size and administrative cost efficiency; user financed-schemes tend to have high start-up costs that can often only be sustained by external donors.

Africa

A recent special issue of the *Journal of Sustainable Forestry* (Yale University) features three regional reviews of watershed PES schemes in Africa, Asia, and Latin America, respectively. The African review by Ferraro (2009) has particular interest for our purpose. Defining PES similar to our paper, Ferraro concludes that "one could reasonably argue that there are **no** PWS [payments for watershed services] currently operating in Africa" (ibid: 526, my addition). There are two large public work programs in South Africa with an environmental

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[6] The authors included several broader economic incentives and interventions, e.g. land purchases and user-financed integrated conservation and development projects. In addition, several PES proposals were included that subsequently never took off the ground.

[7] A classical and large-sized example is the US EQIP program, paying for changed agricultural practices, including for watershed benefits (Claassen et al. 2008).

focus, the Working for Water (Turpie et al. 2008) and the Working for Wetlands programs. Labor is being contracted here to undertake clearing of exotics and regeneration of wetlands functions, but there have so far not been agreements with landowners to continuously look after the provision of watershed services over time -- e.g. by preventively anticipating the spread of exotics, or *ex post* impeding their return to an already cleared area, although this may now be changing.[8] So far, this is an environmental public works program, not a PES. In addition, the Working for Water program has also recently linked up with WWF's Water Neutrality program, and managed to get corporate co-funding for exotics clearing from companies offsetting their water footprint to receive certification (Nel et al. 2009).

Ferraro further reports eight watershed PES initiatives under preparation in Africa. These include the large-scale Maloti-Drakensberg project in South Africa (aiming at improved water supply for the Johannesburg area), WWF/Care/IIED's Uluguru Mountain watershed project in Tanzania (targeting water supply for Dar es Salaam, the coast, and the Morogoro region), and ICRAF's Sasuma Water Treatment project in Kenya, hoping to economize on water treatment costs for Nairobi through upstream erosion reductions.

Ferraro goes on to analyze why PES development in Africa has remained so incipient to date, especially compared to Latin America (ibid: 535-46). He believes that commonly cited obstacles such as lacking technical and market information, inadequate legal frameworks, or absent business models are not the key factors to blame. Instead, he cites various of the structural obstacles also mentioned in Chapter 3 of this report. Regarding potential water buyers, there is a lack of institutions with a willingness to pay for water itself (let alone for services for its improved provision), rudimentary organization of urban water consumption that favors free-riding, lower baseline and less development of the continent's hydrological potential than in Latin America, a lower tax base limiting the ability to organize public PES programs, and 86% of water resources being withdrawn by irrigators that across the board do to pay (ibid: 538). Hence, there is typically no user payment vehicle in Africa.

On the service provider side, a number of factors may drive up PES transaction costs, and restrict PES development: a much higher rural population density than in Latin America, more transboundary watersheds (60 in total), and general difficulties in enforcing contracts (incl. higher corruption indices). Finally, there is more land tenure insecurity than in Latin America, and more customary collective tenure systems with overlapping usufruct rights, which often makes it more difficult to hold individuals accountable for PES contract compliance. Ferraro also believes that the prime preoccupation with poverty alleviation over environmental goals in Africa's few PES attempts (e.g. the South African public-works programs being politically driven by employment creation for poor people) have eventually backfired in terms of impeding these programs from achieving their targeted environmental results. These factors together may thus help us to explain why PES, like a number of other more complex business arrangement types, have not at all 'taken off' in Africa.

Asia

The corresponding review article on Asian watershed PES finds 15 initiatives in action, although most in their early stages, and some of them not yet having reached a payment stage (Huang et al. 2009). The scheme size ranges from a fifty-hectare plot protection in Cidanau

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[8] Following a mission to South Africa in June 2008 that included the undersigned, the Working for Water program was given the recommendation to integrate landowners more into the program's incentive structure, which would move into a proper PES direction. The program is actually experimenting with such interventions currently (C.Marais, pers.comm., February 2009).

watershed (Indonesia) to 26.7 million hectare enrolled in the Chinese Forest Ecological Service Compensation Fund and 7.2 million hectare in China's Sloping Land Conversion Program for retiring and reforesting marginal farmlands. The programs cover activities in China, India, Indonesia, Nepal, Philippines, and Vietnam.

Asian watershed PES schemes suffer from some of the same drawbacks as the African initiatives, while other preconditions are clearly different. There is also a high rural population density, driving up the transaction costs of dealing with multiple small suppliers. However, lands are often state-owned, sometimes with recognized customary rights, and overlapping tenure rights are less frequent than in Africa. There is also a much better payment culture, ability, and institutional organization on the service user side. Conditionality is often weakly enforced, raising question about environmental efficiency. While large government-run schemes exist in centralist China and Vietnam, smaller user-financed initiatives are dominant in the other countries. Participation in the former state-run schemes is not always voluntary, as stipulated in our PES definition.

Latin America

Although the area contracted under PES or PES-like programs is clearly largest in Asia (because of the two huge Chinese programs), the number and diversity of experiences is clearly highest in Latin America: in the early IIED study, 24% of all PES initiatives were Latin America (Asia 10%; Africa 7%) (Landell-Mills and Porras 2002: 4).

The review of Latin American watershed PES schemes by Southgate & Wunder (2009) thus does not describe all the existing schemes, but looks closer into a number of selected cases in Ecuador and Mexico. It does, however, outline some general trends. Like in Asia, conditionality is sometimes weakly enforced. Land tenure is relatively well-defined, with private tenure being more common than in the two other continents. This fits with the observation by Porras et al (2008: 38) that more than three fourths of running watershed PES schemes worldwide are contracted with private landowners. However, there are also some striking differences within Latin America. In the Amazon region where rainfall and rivers are plentiful, basically no watershed PES schemes exist (PES schemes there are more focused on preserving carbon-rich forests). The rapid development of PES schemes has advanced mostly in Central America and in the Andes region, where growing urban population densities have gone hand in hand with increased colonization pressures in the mountainous uplands where water sources originate. The increased scarcity resulting from higher demand and less stable supplies have thus created a rapidly increasing interest for watershed PES, focused on both water quantity and quality concerns.

Another review looks specifically into 14 watershed schemes with innovative financing mechanisms in the Andean region (Garzón 2009). While most are PES schemes by our definition, the sample also includes some trust funds financed by water users and donors that do not conditionally pay landowners for service provision, but rather use funding to buy environmentally sensitive lands (e.g. Loja, Ecuador) or carry out more traditional integrated water management projects (e.g. FONAG-Quito, Ecuador). Most of these schemes are small in size of contracted area, from 14 ha (Mayrana, Bolivia) to 2,774 ha (Los Negros, Bolivia) – defined by the size of the watershed in question, or of particular critical areas within that watershed. Some programs are much larger, such as the reforestation program Procuenca (Chinchiná) in Colombia (12,500 ha), or FONAG. Payments are made both for the protection of natural areas (natural forests and *páramo* alpine grasslands), natural regeneration of degraded lands, the introduction of agroforestry practices, and -- in one single case -- changed agricultural practices (Fúquene, Colombia). Obviously, the latter is of particular interest to us, and we will return to it in the following section.

4.2. Review of agricultural PES

Very few real-existing PES schemes in developing countries pay for changes in agricultural practices, as would be the introduction of improved technologies into dryland agriculture. In the tropics-wide sample of Porras et al. (2008), 3 out of 50 ongoing reported ongoing schemes include some payment for agricultural change; in the Asian review by Huang et al. (2009), the ratio is 2 to out of 15, there are zero hits in Ferraro's African review (Ferraro 2009), and for the Andean assessment it is 1 out of 14 cases.[9]

Forestry, including natural forest conservation, forest regeneration, reforestation, and at the borderline agroforestry are the clearly dominating practices being paid for in land-use based PES schemes in non-OECD countries. It is telling that when FAO dedicated its authoritative State of Food and Agriculture report to the theme "Paying Farmers for Environmental Services" (FAO 2007), the report was overwhelmingly about the vast potential for using this tool for agriculture in the future, with very few practical examples from already ongoing initiatives. We will later in this chapter discuss why this might possibly be the case. However, in this section the focus will be on 'hunting down' and describing the few agricultural PES schemes that exist in developing countries. At the end of the section, we will also look at some developed country examples, to enrich the otherwise quite limited sample.

Perhaps the best example of an existing PES scheme following the sought-after concept in this report is Fúquene Lake in Colombia (Box 3). Organic farming was introduced in the uplands to reduce lake eutrophication and sedimentation. At the farm level, the improved techniques could reduce the negative environmental externality by some 70%, and at the same time in a 'win-win' increase farm profitability moderately vis-à-vis the baseline, at the cost of an initial investment of about US$250 per hectare. The scheme thus perfectly fits the scenario named "Alternative B" in Figure 3 above, and the incentive that was (successfully) introduced also fits the recommendations in Chapter 3: a subsidized credit to ease adoption even in the face of liquidity constraints. From a PES definitional point of view, the scheme has a clearly defined service (1), there is at least one provider (3), it is voluntary (4) and highly conditional (5) – but there is no payment from water users proper (2); instead, external benevolent donors (Ford Foundation and German GTZ) paid for setting up a revolving fund, and for running costs. The scheme thus has some resemblance with a government –financed PES: the service users are not paying directly. Finally, one should note some of the obstacles regarding scaling-up of the project experience from its current 178 hectares to a larger part of the watershed. On the one hand, scale restrictions are binding when the water users do not pay: if they were paying, perhaps subsidized credits could also be provided to the less poor producers, to persuade them to convert practices. On the other hand, tenure arrangements with land leases can put a hold on the adoption of techniques that otherwise would seem to be profitable for producers. This underscores one of the main institutional points raised in Chapter 3.

[Box 3 here]

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[9] As previously mentioned, we exclude here from the review borderline cases such as agroforestry (including silvopasture) adoption and agricultural set-asides, since we particularly are interested in those PES that promote changed cropping practices.

A number of other PES programs support changed agricultural practices in non-OECD countries, but none fitting in focus as nicely as Fúquene. In Sumberjaya (Indonesia), a long-standing ICRAF (World Agroforestry Center) site, and part of the South/Southeast Asian RUPES program ("rewarding the upland poor for environmental services"), agroforestry options are being promoted to reduce upstream erosion. However, ICRAF with partners also arranged for a procurement auction to find the lowest-cost providers of terracing works in the watershed. Procurement auctions, in this case a so-called uniform price auction, are among the best practices for achieving cost efficiency in conservation design (Ferraro 2008). In this case, the auction was a success, a number of contracts were awarded, and valuable revealed-preference information about the conservation supply curve was extracted (Jack et al. 2009). However, the situation differs fundamentally from Fúquene, in the sense that farmers' opportunity costs of adopting the change is assumed to positive – i.e. it is a 'win-lose' case being bridged by compensation payments. Another interesting aspect in Sumberjaya is that ICRAF attempts to reward agroforestry adoption with the provision of secure land tenure (settlers are long-term present on state-owned lands), conditional upon their continuous adherence to environmentally friendly land uses. While the initiative is certainly interesting, the question from a PES perspective is to what extent conditional land tenure could really be reversed in the case of non-compliance: the political costs of implementing such a reversal, for ICRAF or others, may be excessive – in which case one may wonder about how incentive-compatible the arrangement is in practice.

The PASOLAC program, supported by the Swiss Development Cooperation, is involved in 10 watershed PES experiences in Nicaragua, El Salvador and Honduras, some of which have already been making payments for several years.[10] While the Swiss finance the transaction costs of setting up the scheme, the relatively modest recurrent payments are being financed by the respective municipalities through water-user fees. While PASOLAC in many cases finances forest conservation, at the San Pedro del Norte site (Nicaragua), payments are made to rehabilitate degraded agricultural lands, by building natural dikes, living fences, and some rehabilitation of degraded forests. These measures are designed to reduce erosion and increase dry-season flows. The project reports some positive hydrological results (e.g. Porras et al. 2008: 96/7) that, however, due to the short duration of the project, can hardly be attributable to the PES intervention – at least not for the reported seasonal water flow improvements, which are only likely to be observed as more long-term processes.

In Sukhomajri village (Northern India), livestock grazing by some community members in the upper watershed caused heavy erosion that threatened to silt an irrigation pond for the common use of the village. The ingenuous PES-like solution was to privatize benefits from the pond, dividing water rights into household shares, and to use some of the proceeds to compensate upstream herders to change grazing practices and reduce erosion. The scheme was a big success, and apparently some similar small-scale, self-help schemes exist in other parts of India. Note, however, that due to the intra-village character of the scheme, upstream herders were both 'service providers' and 'users' at the same time. Also, changed herding practices apparently did not require an investment in changed practices, but required more of a recurrent cost subsidy, e.g. for not grazing on highly steeped slopes.[11]

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[10] For more information on PASOLAC, see http://www.pasolac.org.ni/paginas/documentos/PASOLAC-Payment%20for%20Environmental%20Services%20-%202005.pdf and http://www.watershedmarkets.org/documents/PASOLAC_CR_N_C.pdf .

[11] For more information on this case, see http://www.ifad.org/rural/rpr2008/chapter2/2.pdf, pp.91-96, Kerr (2002), and Huang et al. (2009: 16-17).

Government-financed PES programs have not played an important role in promoting targeted change in cropping practices in developing countries. Brazil's Proambiente program, for instance, was designed to promote sustainable agriculture in the Amazon region. The focus here has mostly been on 'no burning' agriculture, including stopping deforestation – i.e. not primarily water management – and not in drylands. The program has had weak conditionality, definition of services, and financing basis, so that its future is uncertain. The Mexican PROCAMPO program was designed as a cash transfer program, providing a transition for Mexican farmers in the wake of the NAFTA free trade agreement and its detrimental impacts on Mexican crop prices, allowing them to invest in new production or value-added options. One of the program's funding windows was allegedly designed to promote sustainable agriculture, but apparently it was not used a lot by Mexican farmers, so no results exist.[12]

Lacking further clear-cut developing country examples, we may also want to look at some cases from developed countries. Box 4 describes some examples with a specific agricultural focus. Two of these (Northeim and Wimmera) are recent pilot schemes, carried out with the perspective to later upscale them as government-run schemes in Australia and in the EU (see below). The third one (Vittel) is a classical user-financed scheme in the PES literature; it is characterized by very high transaction costs and compensation amounts, but also by a very high service value, providing the necessary support for its extravagant cost structure.

[Box 4 here]

4.3. Why are there so few agricultural PES?

If the purpose is to see PES as a widespread co-financing option for upgrading rainfed agriculture, then the results from the review in this chapter may be somewhat worrisome: only in highly exceptional cases do such PES schemes pre-exist. In understanding if this is merely a question of lacking inertia, or has more structural roots, this final section will offer some food for thought regarding possible causal explanations. Basically, we discuss a number of hypotheses for why agriculture/ cropping practices have not achieved a higher priority in the service supply side of PES schemes so far.[13]

Hypothesis 1: 'The agricultural sector has so far done too little to position itself as a potential environmental service-providing sector.'

The first potential explanation is thus focused on "strategizing", and stands in stark contrast to the forestry sector. The argument is that forestry PES projects are much more advanced because the forestry research and policy community has provided information and lobbying that was necessary for a policy push. Only recently is agriculture thus appearing seriously on the scene vis-à-vis Kyoto mitigation options (e.g. IFAP 2009). In many countries, the forestry sector has been able to frequently side strategically with environmental interests, whereas there is a direct conflict with agriculture – including because agricultural land demand is the key single cause of deforestation tropics-wide (e.g. Chomitz 2006). Brazil is one country where a long-standing trench warfare between 'ruralists' and 'environmentalists' exists. In Costa Rica, the national PSA program was born directly out of a transformed forest-sector subsidy program, and environmental services are thus in Costa Rica – in PSA administrative

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[12] L.Lipper, pers.comm., May 2009. On Proambiente, see e.g. Hall (2008).

[13] In shaping these hypotheses, I am grateful to those who have responded my e-mail on this central question, and commented on earlier versions of this paper (see Acknowledgments).

terms – provided exclusively by forests (Pagiola 2008). This is not an uncommon attitude in tropical conservation.

Hypothesis 2: *'Changing agricultural practices produces typically less environmental services than securing the presence of trees and forests'*

Where hypothesis 1 is about 'packaging', this one is about 'content': if, hypothetically speaking, agriculture really had few environmental services to offer, then "the Emperor has no clothes", and promotional efforts would probably soon be doomed. Personally, I would buy into that hypothesis for certain services and places, for others not. For biodiversity conservation, as well as the less prominent recreational services, the presence of trees and natural habitat makes a vital difference for service outcomes. For carbon, Chapter 2 showed that the soil carbon accumulation at up to one tC/ha/yr could be significant. Yet, if we compare it to the stakes of avoided tropical deforestation, with carbon stock values conservatively estimated at 100 tC per hectare, then this puts the incremental agricultural sequestration potential into a certain perspective.[14] Since those two services are usually global in scope, and thus also of prime donor interests -- and many PES schemes in developing countries are being heavily pushed by donors, this hypothesis could have some explanatory power. For watershed services (annual/ seasonal flow, quality), however, changed agricultural practices and soil management can make a lot of difference, and are probably currently under-estimated in general, whereas correspondingly the hydrological benefits of trees may be overestimated in popular perceptions (Bruijnzeel 2004).

Hypothesis 3: *'Transaction costs in agricultural PES are higher than in forestry'*

As shown in Chapter 3, high transaction costs can be a killer assumption for PES. In prime agricultural areas, population density is typically higher, so agricultural PES implementers may have to deal with many more smallholders than in marginal, scarcely populated, forested areas. For watershed services in particular, in most cases the actions of these multiple service providers needs to be coordinated, too. This is probably a challenge in many agricultural landscapes. Secondly, monitoring PES compliance can be easier in forested landscapes (e.g. using remote sensing for a gross overview) than if one has to monitor active land management, i.e. make sure a farmer is continuously using no-tillage farming, terracing, mulching – and calculating how much carbon or hydrological benefits this will likely provide. Some methods do exist, but low-cost service monitoring methods are currently still lacking (World Bank 2009). On the other hand, land tenure in forested areas on average tends to be less secure in developing countries, and exclusion rights tend to be less articulate than in croplands. This clearly draws somewhat into the opposite direction, favoring agricultural lands over forestlands, be it because these transaction costs are lower, or simply as a *sine qua non* precondition for embarking at all on the PES pathway.

Hypothesis 4: *'Opportunity costs in agricultural PES are higher than in forestry PES, and their technological complexity is higher'*

This supply-side argument would state that the basic farm economics are going against agricultural PES, because farmers' service provisioning costs are excessive, and because farmers are too risk-averse to adopt complex technologies that reduce their flexibility. The

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[14] This simple comparison obviously ignores all other arguments regarding comparative additionality, leakage, and permanence in the two sectors, which this would not be the place to discuss.

discussion in Section 3.2 seems to widely contradict the first part of the hypothesis: it seems that, following initial adoption costs, various improved cropping techniques can pay for themselves in terms of yield increases and higher on-farm economic returns. This means that a subsidized credit or a frontloaded payment may be the most appropriate incentive, though some later payments may still be needed to leverage adequate maintenance. This is *per se* a privileged situation, compared to at least the conservation of natural forests, where economic returns typically are uncompetitive, so that a permanent subsidy – a 'PES forever' scenario – is necessary (Scenario C in Figure 3). Paying for a short adoption period, and then resolve the problem once and for all, is also for the service buyer a much preferred option to payments *ad infinitum*– that is, if the initial 'win-win' diagnosis was actually correct.

For the second part of the hypothesis, higher complexity seems to be more of a real issue, where uncertainties can relate to capital, labor, and know-how constraints, lacking supply for new required inputs or markets for new outputs, etc. It is thus definitely much simpler and universally applicable to delimit a forest area as a 'no-go zone', or revert a marginal production area to natural regeneration – in both cases leaving the option value to revert that decision later on a no-regret basis – than to get farmers to go out of their usual ways and continuously apply innovative production technologies.

Hypothesis 5: *'If improved agriculture is very attractive to farmers, it will tend to create negative spillover effects on the environment'*

Let us for the sake of the argument assume momentarily that hypothesis 4 can be solidly rejected: opportunity costs are negative and the technological package is not overly complex, so the only thing farmers need is a transitory investment subsidy to help them co-finance adoption. Conservationists used to argue that this would create positive spillover effects on the environment: using an intensified cropping technique, farmers would need less land, and thus slow down or stop the clearing of new lands. The underlying Chayanovian assumption is that farmers would only produce what they need to survive, or at least up to some target-revenue production, and then prioritize leisure. In reality, however, most farmers are more like the rest of us: when they see a good opportunity, they jump at it and allocate more labor and land to it in order to maximize profits. In other words, more often than not they actively *expand* this new wonderful intensified production method into new production areas, including by chopping down forests. This may in the worst case create more, rather than less environmental pressure, e.g. the carbon sequestrated in soils (or the avoided erosion on existing fields) may fall short of the incremental carbon emitted from forest burning (the incremental erosion on new, more steeply sloped fields). In other words, under some circumstances, the assumed agricultural 'win-win' options can become victims of their own success. The empirical evidence on how about two dozens of major agricultural technology improvements tropics-wide have affected deforestation is summarized in Angelsen & Kaimowitz (2001). The net impacts depend on many context factors, such as labor supply, output price elasticities, and forest stock size, but in most cases analyzed, technologies for agricultural intensification actually *increased* deforestation.

In sum, the public relations explanation (hypothesis 1) of agriculture's severely lagging performance in the PES market certainly contains some truth, but there are also more structural reasons to it. On the demand side, (non-tree) agriculture's potential to provide biodiversity and carbon services probably lags behind those of forestry, though it may still outperform some mitigation options in other sectors, whereas agriculture's hydrological service potential may currently often be under-valued (hypothesis 2). Likewise, high transaction costs from monitoring the active land management of multiple smallholders can turn off potential service buyers (hypothesis 3). On the farmer side, low or negative opportunity costs certainly seem attractive, while the complexity of changes may constitute a more binding constraint for service providers *in spe* (hypothesis 4). Environmental service buyers may rightly be worried that 'win-win' agriculture sometimes may be so successful that negative spillover effects come to dominate over the original environmental targets (hypothesis 5).

5. Valuing the cost and benefits of payments for environmental services

This chapter joins considerations from chapters 2 (externalities) and 3 (basic economics of PES) to discuss how to quantify the costs and benefits in PES schemes, starting with a conceptual introduction (Section 1). On the biophysical service production-side, the chapter makes the case for modeling in particular hydrological and carbon benefits, but we do not here go into the technical details of environmental service models (Section 2). This has to be coupled with socioeconomic quantification about how much it costs the farmer to provide the service. A practical example shows how the biophysical and socioeconomic components might be integrated (Section 3).

5.1. Conceptualizing costs and benefits

Figure 4 shows how, in principle, the costs and benefits under a PES scheme are distributed. Q1 denotes the private benefit for the farmer in producing under a 'business as usual' scenario, e.g. deforesting for agricultural expansion. However, on the negative side, this creates an environmental externality Q2, e.g. for downstream water users suffering from increased sedimentation, which they have to compensate for by incremental water treatment costs. The farmer also has an environmentally friendly land-use alternative available, which provides him or her with a private return Q3 that is somewhat lower than Q1, but which does not cause a negative externality for the downstream user.

[Figure 4 here]

If the service user can somehow compensate the farmer for this private income shortfall by paying Q3 in PES, then both the farmer and the service user can be made better off than under 'business as usual'. But how large exactly should the PES payment Q3 be? In this bilateral case, this is basically a question of negotiation between the two parties. The compensation has to be minimum Q3=Q1-Q4 – otherwise the service-providing farmer will be made worse off, by not being fully compensated for the opportunity cost. On the other hand, it can maximum become Q3=Q2 – otherwise the service user will pay more than the externality suffered originally, and thus become worse off. Hence, we have $Q4-Q1 \leq Q3 \leq Q2$ as a possible range for the size of PES. The service provider's net gain over and above his or her opportunity cost, Q3+Q4-Q1 (which also determines the minimum 'willingness to accept')[15] is sometimes referred to as the landowner's "information rent": as long as the user

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[15] In a more complex world, the willingness to accept can differ from the opportunity costs in various ways. First, there will also be transaction costs on behalf of the service provider, and possibly other provision costs – e.g. increased monitoring efforts to make sure that third parties do not deforest the plot illegally. Second, on the relative benefit side, the farmer will beyond of profits also consider other decision parameters such as risks, food security implications, etc.

does not know the provider's opportunity cost, the provider may successfully inflate those, and charge a higher PES compensation. Obviously, the same applies in the reverse: as long as the farmer does not know the value of the marginal externality, i.e. the service value (Q2) (that also equals the service buyer's maximum 'willingness to pay'), the latter can try to downplay the gain in order to keep payments as close as possible to the minimum willingness to accept, and get a service-user rent. Information about service values and about opportunity costs is thus not only important for the farmer and the service user's own respective decisions; knowledge about the counterpart's decision parameters can be used strategically in PES negotiations. The PES rate Q3 is typically negotiable in user-financed PES schemes, while it is administratively set at either uniform or differentiated rates in government-financed PES schemes.

5.2. Biophysical dimensions of service value

It would seem self-evident that the service user prior to entering a PES scheme should calculate the value of the service at hand, so that an upper limit for bargaining was *ex ante* established. If so, the first step would be to have a clear idea about how much services will actually be delivered, given a certain biophysical linkage between the land-use proxies proposed (e.g. 'deforestation avoided'). Watershed protection services in particular are where 'informational constraints' (Section 3.6) are clearly most binding, since many of the biophysical linkages are extremely scenario-dependent.

However, as we saw in Chapter 4, the reality in existing PES schemes is quite different. While in carbon schemes, the amount of carbon saved or sequestered will usually be quantified and closely monitored, for watershed services very little measurement or quantitative approximation is done prior to entering a PES deal, and the *ex post* service monitoring is usually also weak. There can be rational or irrational reasons for that. A rational situation would be, for instance, when the proposed PES scheme is:

- restricted to a micro watershed (e.g. in the 50-1500 ha range – see Chapter 4);
- when the proposed land use is already known to provide a good service, and
- requires no major upfront investments (e.g. conserving pre-existing natural forests or grasslands more effectively);
- when researching service quantities would be prohibitively expensive – e.g. research costs exceeding some relatively modest compensation payments;
- when the service is destined for a limited set of users who are happy to pay without quantitative proof for service delivery being provided;
- when it is a priori clear that probably no cost-efficient alternative to the production of the environmental service exists.

In this case, applying the precautionary principle can make perfect sense, as a basis for promoting a certain conservative land use through PES, even though the size of the service benefits delivered are actually not known. Conversely, an irrational situation would be to ignore service quantification when in fact:

- the area of intervention and number of providers and beneficiaries is large;
- the area in question is spatially heterogeneous, so that the question where to intervene in the landscape gains significant importance;
- significant investments are needed, e.g. to restore an environmental service by rehabilitating degraded lands;
- the reversibility of these investments would not be straightforward;

- when reasonable doubts can be raised about the direction or effectiveness of measuring service delivery indirectly through proposed land-use changes/ proxies;
- when cost-efficient methods exist to appraise with a reasonable likelihood the service delivery implications from a proposed set of interventions;
- when services are being formally counted in service-crediting frameworks, or service users demand some quantitative proof of delivery;
- there seem to be cost-wise viable alternatives to the environmental service route for eliminating the externality problem – e.g. through engineering solutions.

It would seem that the PES interventions proposed for improvements in rainfed agriculture would more often than not fall into the second category, where some however rudimentary service quantification is indeed recommendable. One reason is that significant investments often have to be made to establish the new cropping systems. A second refers to the type of service: if the prospective focus is on soil carbon storage and water-quality improvements (see Chapter 2), then both of these services tend to occur in a heterogeneous manner in the landscape, where it becomes vital to determine spatial priorities within the landscape. Furthermore, carbon buyers will usually want to know how much carbon actually has been gained by the actions they have (co-)financed. For water quality issues, it also not always obvious that the environmental services from improved agriculture or from forest conservation are the optimal solution. Aylward (2007) concludes from case studies (mostly in developed countries) that the cost-efficeincy of ecosystem approaches vs. environmental engineering solutions is dominated by threshold effects: which method is best performing depends on the target level of environmental services provided.

A strong recommendation from this report is thus, given the type of externalities at hand, to pre-assess different options and biophysical outcomes through modeling tools, so as to clarify the direction and size of the hydrological and carbon benefits at hand. Table 3 provides an overview of some of the modeling tools that are currently available.

[Table 3 here]

5.3. Integrating biophysics and socioeconomics – a case example

In the following, two small-scale municipal case studies will be resumed to illustrate how the Soil & Water Assessment Tool (SWAT), combined with an economic optimization model, could spatially predict effects on dry season flows, sediment yields, and socioeconomic impacts from different land-use alternatives. This approach may serve as a relatively low-cost predictive tool for the spatial allocation of PES interventions.

In the Andes, demand for water is growing and upland land-use changes are increasing. Water quality, quantity and seasonal flow have thus also become environmental services with a potential monetary value. Yet, currently the region's pioneer PES schemes are not paying for measured environmental services, but for proxy land uses thought to provide the(se) service(s). Hydrological modeling makes explicit the tacit causal relationships and tests underlying assumptions. Ideally, when combined with an economic analysis of land-use alternatives, this could inform decision makers on how much to pay for different interventions in different spatial locations.

In recent work led by the International Center for Tropical Agriculture (CIAT), we tested some of these linkages for two Andean watersheds: Moyobamba (Peru) and Pimampiro

(Ecuador). In the first case, a municipal water company is preparing a payment for environmental services (PES) scheme to reduce upstream sediment loads. In the second, a forest conservation municipal PES scheme has operated since 2000, but the underlying hydrological linkages have never been tested. Applying SWAT, we identified in both watersheds biophysically critical areas for service delivery, and compare services for current land uses with change scenarios: deforestation, reforestation, live barriers, and agroforestry.

For the simulation, the watersheds were delineated using a digital elevation model. Sub-watersheds and hydrological response units with unique soil and land use characteristics were defined. For each, SWAT calculated the soil loss through water erosion and the water yield, thus featuring the two main hydrological services of our interest. The water balance for each unit was calculated taking into account three storage volumes: soil profile, shallow and deep aquifer. The soil profile was subdivided into multiple layers, according to the number of horizons identified in soil-profile descriptions. The soil-water processes modeled with SWAT included infiltration, evaporation, plant uptake, lateral flow and percolation to lower layers. Thus, we calculated water yields (total amount of water leaving the spatial unit and entering the main channel) and sediment yields (amount of sediment contributed by each unit to the stream), and routed them through drainage to the watershed outlet. The model was calibrated to reduce parameter uncertainty and increase robustness of the results, i.e. some parameters were marginally adjusted until the best possible correspondence between observed and simulated streamflow at the basin outlet was obtained.

We then used the ECOSAUT optimization model, developed by CIAT, to predict net economic benefits for service providers. The model uses linear programming to optimize net farm income from different land-use systems, taking into account social, economic, and environmental criteria. It was employed to evaluate the socioeconomic impacts of PES-promoted land use systems.

In Pimampiro, for our baseline we assumed a hypothetical linear projection of pre-PES deforestation and farmland extensification rates of 0.5 ha year^{-1} per farm (Wunder and Albán 2008). The net present values of the baseline were compared with those of the current PES scenario with forest conservation. We found that farmers were actually accepting payments that are slightly less than their ECOSAUT estimated opportunity costs.

For Moyobamba, we collected secondary data for those land areas and production systems that currently produce the highest sediments (local slash-and-burn cropping cycles). We used this system as our baseline scenario, assuming it will continue to expand if farmers do not receive incentives to change to more benign land uses. In addition, we simulated the erosion control and livelihood impacts of the three alternative land-use scenarios: (1) shade-grown coffee, (2) reforestation, and (3) live barriers.

As for service-delivery results, in Moyobamba switching to shade-grown coffee would halve sediment yields, and also increase significantly farmers' economic benefits. Coffee systems require high up-front investment, but the willingness to pay of water users in Moyobamba town may suffice to cover the upfront costs. In Pimampiro, resumed deforestation would hypothetically increase sediments by >50% and reduce dry-season flow by 0.5%, thus reinforcing the rationale of the existing PES scheme, focused on conserving native forests and grasslands. Six critical land units, making up only 8.65% of the watershed's land area, contributed two thirds of projected sediments. Correspondingly, enrolling another 115 ha of critical areas under PES would cut current sedimentation loads by two thirds.

Conversely, abandoning the Pimampiro PES scheme and allowing for incremental reconversion to agriculture would cause a tripling of current erosion over 25 years, while increasing it by 53% over the eight-year lifetime of the PES scheme. Over the same period, the PES scheme cost US$77,800 -- US$37,500 startup costs plus US$5037.50 average annual running costs over 8 years (Wunder and Albán 2008:689). Thus, the implicit price of PES-avoided sedimentation has been US$3.1/ton of sediment. The Municipality received the start-up costs from a donor, so it only paid US$40,300, i.e. US$1.6/ton, which given various side benefits might be considered a worthwhile investment.

Our two examples here differ from the case of change in cropping practices: one PES scheme is used for natural forest and grassland conservation, the other proposed one focuses on agroforestry. However, the first one lets us analyze *ex post* what the likely costs and benefits to farmers and service users have been over the last decade, compared to a baseline based on the previous deforestation trend. The second looked *ex ante* at productive options to combine with a PES system, and found that agroforestry may provide the best win-win outcome, if adoption barriers can be overcome with a transitory PES payment serving as conditional adoption subsidy, similar to what might be relevant in the improved cropping case.

6. Scaling Up the Use of Payments for Environmental Services

6.1. Dimensions of scale[16]

Implementers of watershed PES programs may be faced with considerations of how to choose between different scales of operation, including temptations to upscale a successful pilot scheme. A particular PWS scheme may function better at one scale than another, in terms of cost-efficiency, sustainability, equity, or other output performance indicators. For user-financed PES schemes, experience suggests that the scale of organization should probably fit closely to the scale of the principal biophysical service that users are demanding – e.g. the appropriate order of catchment corresponding to the range within which a certain service is being provided and used (Asquith & Wunder 2008).

Hence, the micro watershed is by default also the most logical spatial unit to plan in from the start (Darghouth et al. 2008). The biophysical aspects of the service within the watershed thus fundamentally also set the stage for PWS scale choices. Nevertheless, decisions are ultimately equally influenced by the economic, social, and political-administrative management contexts, especially as we move to government-financed schemes with significant political dimensions. Box 4 provides a small checklist of factors to consider regarding scaling decisions, e.g. the units utilized, financing sources, the (sub-)services provided and their respective users, the biophysical and administrative contexts, the possible two-way direction of scaling, and temporal scale dimensions.

[Box 4 here]

For instance, a PWS scheme could prove too small in scale if it does not integrate sufficient service providers, so that non-paid upstream actors could ultimately jeopardize service provision. Conversely, it can be too extensive if the catchment is so large that links between

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[16] This chapter draws significantly on Asquith & Wunder (2008).

upstream land-use practices and downstream water yield and quality become overwhelmingly obscured by intermediate processes or ‘background noise’, e.g. variations in rainfall across sub-watersheds cancelling out peak flows in larger basins.

Imagine a watershed PES scheme for reduced sedimentation that was piloted successfully in a single village. A first consideration can thus be whether to scale up an intervention within a certain watershed, e.g. to make the scheme encompass the entire watershed that makes up the potential area of influence for the targeted sedimentation outcome. This can make sense if there is enough willingness to pay on behalf of the water users to extend the payments, if the pressures and environmentally critical areas are fairly distributed within the entire watershed, and if service delivery thus could be significantly enhanced by extending intra-watershed coverage. For instance, this was the case in the Fúquene Lake example from Colombia, as described in Chapter 5. Conversely, if environmental threats are concentrated in ‘hotspots’ that are already covered by then program, and if resources from user payments are likely to remain limited, such an intra-watershed upscaling process may not be desirable. For example, the latter was the case in the aforementioned Pimampiro case in Ecuador.

A second question is if a PES schemes should be extended beyond a single watershed. There can sometimes be biophysical arguments in favour. Under certain environmental conditions, functions such as aquifer recharge may depend on processes functioning in neighbouring watersheds—an argument for larger PES size. Another point in case is if several services from the same watershed are sold simultaneously. If a PES scheme aimed at establishing improved dryland cropping systems provides not only hydrological but also carbon services – and pretends to equally sell the latter—then an extension beyond a single watershed can be meaningful, since carbon services are not bounded by the watershed. If the scheme is to produce more integrated ecological effects, a larger size can also be positive (e.g. for creating biodiversity corridors).

Larger PES scale can generally make good economic and administrative sense, because transaction costs of both starting and running a PES scheme tend to be relatively lower at larger scales. If the state is generally recognized as a good custodian of resources, a national-level initiative may secure legitimacy for PES more quickly than for an NGO or user-led initiative. Marketing of PES systems to investors may also be easier at larger scales. Donors financing the start-up costs of PES schemes often like the prospects of larger-scale impacts that benefit more people and provide more powerful examples in their own advocacy work.

Sub-national government –financed PWS schemes can also make sense, in cases where decentralization has made regional government the most powerful actor in service-buyer coordination. In Colombia, for instance, current efforts to create a nationwide PWS system may have the best chances of success at the level of the *corporaciones autónomas* – regional environmental agencies collecting legally mandated payments from both hydroelectric power producers and industrial water consumers.

6.2. When does it make sense to scale up?

The previous section makes the argument that scale needs to be customized to the specific objectives of a watershed PES scheme. This also means that “upscaling” should not be any blueprint strategy for any thinkable PES program. Indeed, for some of the large-scale government PES schemes, one may argue that the operational scale is excessive to target stakeholders’ real needs, and there are inherent dangers of sidelining the original environmental goals for politically convenient side-objectives. The Mexican national watershed scheme, for instance, had initially been well targeted towards areas that were highly threatened by deforestation. Over the years, this focus was partially lost, as targeting shifted much more towards the poorest providers – but in part at the expense of compromising the environmental additionality of the scheme (Muñoz-Piña et al. 2008).

In large-sized PES schemes, it generally tends to become harder to target high-value, high-threat zones, and to differentiate payment rates in space – which is certainly one of the pathways to make PES schemes more efficient (Wünscher et al. 2008). This is a handicap in terms of achieving additionality and economic efficiency for national-level PES schemes, such as in China, Costa Rica, or Mexico. When payment rates are fixed, and thus fail to reflect variations in quality or amount of the service provided, key economic signals between buyers and sellers are lost, making resource allocation less efficient. In particular, there is a high risk to pay for actions that would have happened anyhow (zero additionality).

In pilot phases, it may be particularly unfortunate to start operating exclusively at the large scale. Because uncertainty and the risks of making mistakes are higher initially, starting out on a small-scale trial basis may allow more effective adaptive management. For evaluations of "what works, what doesn't?" limiting experiences to single-design, large-scale schemes from the outset would preclude important learning-by-doing experimentation. In some cases, large-scale government PES schemes might also preferably be scaled down, or at least broken up, in order to provide a better fit and higher transparency in the interaction between service providers and users. In a way, it is by the same overall reasoning that current policies of decentralization and devolution are being justified in many developing countries. In other cases, such as the 'avoided deforestation' schemes for climate change mitigation that are currently being developed, maintaining the national scale is clearly preferable, since national carbon accounting frameworks can limit any project-induced displacement of environmental threats in space ('leakage'). PES scale decisions should thus perhaps be taken in accordance with the subsidiarity principle. In other words, PES ought to be organized at the least centralized competent authority level, given the nature of the environmental problem the program is trying to solve. Table 4 summarizes some main arguments for and against scaled-up PES schemes.

[Table 4 here]

In general, one can say that the charms of maintaining PES at low scales are in the likely greater flexibility, targeting, and effectiveness. Upscaling may at best achieve administrative economies of scale, and higher impacts in terms of area size and of links to policies. Finally, non-excludable services that invite user's free-riding, e.g. for biodiversity conservation, are often better addressed in large-scale schemes that are not financed by voluntary user payments.

6.3. How to scale up PES?

There is a comprehensive literature on upscaling issues, both in natural resource management (e.g. Gibson et al. 2000; Tomich et al. 2004) and in other sectors such as health and education (e.g. summarized in Pereira 2008). Figure 5 summarizes some main features. In a stylized upscaling process, a good idea develops in a suitable context for innovation, and is being piloted. In case it is decided that the pilot deserves to be scaled up (see Section 6.2), this can happen vertically, i.e. it is taken up to a higher level of decision making. For instance, a pilot

PES scheme in Los Negros (Bolivia) (Asquith et al. 2008) was recently the direct inspiration for the Department of Sta. Cruz to start developing a larger-scale PES scheme for flood protection in the Rio Grande basin. Similarly, the Ecuadorian government developed recently a national forest conservation PES (*Sociobosque*) that was clearly inspired by NGO's pilot field projects. In both cases, some of the same NGO actors also lobbied for the legal steps required to upscale vertically, and provided technical assistance in the process.

[Figure 5 here]

Not in all cases, however, is vertical upscaling a spontaneous bottom-up process. The seven-million hectare Chinese Sloping Land Conversion Program, the British Environmentally Sensitive Area program, or even the same Sociobosque commissioned pilot phases to try out program tools in different circumstances, with the *ex ante* stated aim to later scale these experiences up. Unlike in spontaneous upscaling, one can here control for certain factors of variation in the choice of pilot samples.

The second pathway for upscaling is horizontal,[17] and does not involve taking the initiative up to a higher political-administrative level. It can on the one hand refer to the gradual inclusion of additional participants with a predefined zone, e.g. extending coverage of a PES scheme within a watershed, as discussed above. The same Los Negros scheme can again serve as an example, since it started off with only a few households under contract in 2004, but then through word of mouth and gradual trust building, coverage was gradually increased to 2774 hectares. The other horizontal upscaling sub-option is replication. The Los Negros scheme has by the implementing NGO Fundación Natura Bolivia been replicated since 2007 in two neighbouring watersheds (Comarapa and Mairana). With 14 and 300 hectares contracted, these schemes are at this stage still much smaller (Garzón 2009: 11). The Ecuadorian NGO Cederena piloted the Pimampiro watershed PES in 1999, and has since replicated similar schemes in two other sites (El Chaco and Celica). As mentioned above, the Pasolac program is involved in the execution and development of ten different watershed PES schemes in Central America. This illustrates that, while each of the areas contracted are often quite small, a repeated replication of these small schemes can arguably yield a significant cumulative impact. Moreover, replicating the same type of scheme under different circumstances certainly helps us to collective learn more about PES modalities.

Among PES experiences so far, neither much up- nor downscaling has occurred: big schemes tend to remain big and small schemes tend to remain small – although, as mentioned, the latter may be *replicated* at similar scales elsewhere. Exceptions apart, the transaction-cost and political economy obstacles to moving across scales may simply be prohibitive: renegotiating incentives and redesigning contracts is cumbersome, ongoing payments are often expected to continue, etc. This reinforces the need to select the appropriate scale from the outset, before the initiative becomes locked into certain modalities.

Note, also, that multiple PES scales can co-exist and supplement each other. Both in Mexico and Costa Rica, there are plans to supplement the national schemes with additional smaller-scale, spatially more focused government schemes. In Costa Rica, FONAFIFO functions already to some extent as an umbrella under which local water consumers (e.g. a brewery or a water-utility company) can earmark payments for recipients in their particular target watershed. What makes multi-scaling interesting is that one can aim for the best of both

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[17] Some also refer to this type of processes as "scaling out".

worlds: get the legitimacy and managerial economies of the national-scale PES; while retaining the flexibility and focus of small-scale schemes. In some contexts, parallel implementation of national and small-scale schemes could provide for complementary cross-fertilization of knowledge.

What upscaling processes and obstacles could one possibly imagine for PES programs focused on dryland agriculture? This is si somewhat speculative, since such PES schemes barely exist so far. The Fúquene case from Colombia (Box 3 above) is the only example that can possibly give us some remote clues (Quintero & Otero 2006). Targeted poor farmers receiving subsidized credits willingly adopted the organic farming package, but upscaling within the watershed remained limited. One core reason was that “service users do not pay” – had more funding from service buyers been available beyond donor resources to also pay the better-off farmers, adoption rates might have been higher. In spite of being a ‘win-win’ intervention, and the revolving fund being a good idea, it has so far not been possible to sell the organic farming concept to commercial banks, in order to make use of their credit channels. Technical assistance proved to be scarce and costly, due to low levels of producer organization that in part could have auto-disseminated the concept. In similar settings, the lack of markets for new seeds and other inputs can also constitute bottlenecks for scaling up these new cropping packages, in spite of their superior economic returns. These bottlenecks will have to be analyzed on a case by case basis.

7. Conclusions and perspectives

Improving water management in rainfed agriculture is being seen as a ‘win-win-win’ proposal: it can help farmers produce more by managing on-farm resources better, it could help downstream farmers receive hydrological benefits, and it could also produce carbon sequestration for global beneficiaries vis-à-vis the Kyoto mitigation goals (World Bank 2009). The question in this report was thus if two of those alleged winners (carbon and off-farm water users) could be made to co-finance the party by paying for the environmental services they receive, and thus invest in their further expansion.

A ‘win-win-win’ sounds like an almost irresistible proposition, especially to a donor: who would not want to simultaneously do good in the world on three different fronts that are all much worthy of support (poverty, water, climate change)? Nevertheless, double- and triple-win proposals have been around in the conservation debate for some time, and probably more often than not, they have not quite worked out as planned. What seemed a ‘win’ from a technocratic point of view and from a laboratory analysis did not materialize in practice, because some details or stakeholders were missing, and hence it could not be successfully applied on a broader scale under the tricky socio-cultural constraints of developing-world marginality. Even an optimistically inclined reader should thus first ask him- or herself two questions. First, have all the important stakeholders and costs likely been taken into account? And, second, are there any hidden obstacles to adoption?

Starting with the first question of costs and benefit, this desk study confirmed that farmers in a variety of contexts can be made better off from adopting organic farming and improved water management techniques, once they have covered the upfront investment costs. Hence, the private benefits seem well-confirmed. The downstream hydrological benefits come in the form of water-quality improvements, while the direction of downstream water-quantity changes could seem to go either way. The carbon benefits from improved cropping techniques also seemed to lie beyond any doubt, but the size of those benefits seems difficult to measure. In both cases, some modeling of the biophysical linkages can thus be an appropriate answer. This will help potential service buyers to understand whether the changes are worth paying for – and the sellers will know better how much they can charge for services rendered.

The second question concerns adoption. The type of problem to solve, i.e. to make a farmer adopt a technology that is in his own best interest (in addition to that of the rest of the world), is atypical for PES. Existing PES schemes usually make recurrent payments to bridge ‘win-lose’, not to convince people about entering into ‘win-win’. The typical economist question is thus: “If it’s profitable, why do those guys not do it already?” One answer can be that they are credit-constrained, in which case a (subsidized) credit such as in the Colombian Fúquene case can be the answer. If they are also information-constrained, technical assistance perhaps needs to be part of the adoption package. If they are lacking providers of seeds or required new machinery, then that may prove to become an obstacle at least in the upscaling stages. If they are labor-constrained and highly risk-averse, then maybe a PES adoption premium will also not help?

However, on the bright side, the GEF silvopastural project in Colombia, Nicaragua and Costa Rica showed that PES subsidies can be attractive ‘helpers’ for adoption: if there is an incentive to gain, then maybe it can tip the balance, and farmers will actively eliminate some of these constraints on their own? This is not a question that can be answered generally from a desk; it has to be tried out in the particular scenario. Note, however, that the predominance of insecure land tenure, overlapping customary claims, land rental and sharecropping, or other types of complex tenure and access regimes can certainly kill off not only the PES option, but also any strategy to invest in land intensification or improvement: if the landowner risks to be (partially) separated from the returns of the investment, it is unlikely be a worthwhile project to undertake.

Before starting a PES scheme for promoting improved agriculture, a number of practical questions should be addressed (see Box 6). Regarding the first question of incremental costs and how to set specific PES rates, procurement auctions are one particular mechanism that can help soliciting farmers' revealed willingness to accept. They can be designed on a small scale, so as to extract basic economic information – arguably in a more objective way than the traditional opportunity cost studies – that is, if the local ideological context allows for auctions to be used.

[Box 6 here]

What can be said firmly is that if the new technology is clearly more profitable, then a (subsidized) credit PES-type of tool is preferable. If it is only marginally more profitable, then a non-reimbursable adoption premium might be adequate. If there is a lasting income shortfall, then continuous payments a la traditional PES need to be provided, linked somehow to payment vehicles from the carbon markets and from water users.

Looking at the world of PES today, agriculture is completely marginalized, both on the service buyer and provider side – at least in non-OECD countries. There are several supplementary explanations for that. Agriculture has so far not positioned itself a lot as a 'green' sector. On the demand side, (non-tree) agriculture's potential to provide biodiversity and carbon services probably lags behind those of forestry, whereas agriculture's hydrological service potential is often under-valued. Likewise, high transaction costs from monitoring the active land management of multiple smallholders can turn off potential service buyers. This can be a real bottleneck for in some agricultural landscapes. On the farmer side, low or negative opportunity costs certainly seem attractive, but complex changes may constitute a more binding constraint for service providers; a menu of adoption options can often help. Finally, environmental service buyers may rightly be worried that 'win-win' agriculture sometimes may be so successful that negative spillover effects come to dominate over the original environmental targets.

One focus of this report is on the options of establishing agricultural PES in Sub-Saharan Africa. If it is worrying that agricultural PES are the exception to the rule in the tropics, then it must be at least as worrying that watershed PES basically does not exist in Africa. A couple of PES-like initiatives exist in frontrunner country South Africa; about a dozen of advanced proposals exist there and in East Africa. Most African governments lack the fiscal revenues, the environmental consciousness, and sometimes the national cohesion to start off government-financed PES schemes. For user-financed schemes, the great problem on the user side is the generally lacking payment vehicle, including culture of e.g. water users to pay. There seems more hope for carbon payments in Africa. On the provider side, however, land tenure has to be clear, and transactions costs musts be kept reasonable. This is not to discourage any particular PES implementers in Africa, but while PES is a 'smart' tool for environmental sustainability, it is also a somewhat 'demanding' one, including some upfront investments and some preconditions of basic institutions and clarity in rules, which in the majority of African contexts may not yet be present.

References

Angelsen, A. and D. Kaimowitz eds. 2001. *Agricultural technologies and tropical deforestation*. Wallingford (UK): CABI Publishing

Asquith, N. and S. Wunder eds. 2008. *Payments for watershed services: the Bellagio conversations*. Santa Cruz de la Sierra: Fundación Natura Bolivia.

Asquith, N.M., Vargas, M.T., and Wunder, S., 2008. Selling two environmental services: In-kind payments for bird habitat and watershed protection in Los Negros, Bolivia. Ecological Economics.

Aylward, B. 2007. "Agricultural landscapes and domestic water supply: the scope for payments for watershed services with special reference to sub-Saharan Africa. Report to the Food and Agriculture Organization." FAO & Ecosystem Economics LLC: Rome.

Baylis, K., Peplow, S., Rausser, G., and Simon, L., 2008. Agri-environmental policies in the EU and United States: A comparison. Ecological Economics.

Bennett, M. T., 2008. China's sloping land conversion program: Institutional innovation or business as usual? Ecological Economics.

Bertke, E., and Marggraf, R., 2005. An incentive based tool for ecologically and economically efficient provision of agrobiodiversity. CIFOR, Bogor,

Borlaug, N. 1996. "Feeding the world: the challenges ahead," in *Norman Borlaug on world hunger*. A. Dil ed. San Diego: Bookservice International, pp. 485-89.

Bruijnzeel, L.A., 2004. Hydrological functions of moist tropical forests: not seeing the soil for the trees? Agriculture, Ecosystems and Environments, 104:185-228.

Cacho, O., Marshall, G. R., and Milne, M., 2005. Transaction and abatement costs of carbon-sink projects in developing countries. Environment and Development Economics, 10:597-614.

Calder, I., 1999. The Blue Revolution: Land Use and Integrated Water Resource Management. Earthscan, London.

Chomitz, K.M., 2006. At Loggerheads? Agricultural Expansion, Poverty Reduction, and Environment in the Tropical Forests. World Bank, Washington.

Claassen, R., Cattaneo, R., and Johansson, R., 2008. Cost-effective design of agri-environmental payment programs: U.S. experience in theory and practice. Ecological Economics.

Darghouth, S. , C. Ward, G. Gambarelli, E. Styger, and J. Roux. 2008. "Watershed management approaches, policies, and operations: lessons for scaling up." *Water Sector Board Discussion Paper Series No. 11 May*: 137. World Bank: Washington DC.

Dobbs, T. L., and Pretty, J., 2008. Case study of agri-environmental payments: The United Kingdom. Ecological Economics.

Dutschke, M. and B. Schlamadinger. 2003. "Practical issues concerning temporary credits in the CDM." *HWWA Diskussionspapier Nr. 227.*

Echavarría, M., 2002. Financing watershed conservation: The FONAG water fund in Quito, Ecuador. In S. Pagiola, J. Bishop, and N. Landell-Mills (Editors), Selling Forest Environmental Services: Market-based Mechanisms for Conservation and Development. Earthscan, London.

Engel, S., S. Pagiola, and S. Wunder. 2008. "Designing payments for environmental services in theory and practice: an overview of the issues." *Ecological Economics*, 65:4, pp. 663-75.

FAO. 2007. "The state of food and agriculture. Paying farmers for environmental services." 222. Food and Agricultural Organization of the United Nations: Rome.

Ferraro, P. J., 2008. Asymmetric information and contract design for payments for environmental services. Ecological Economics.

Ferraro, P. 2009. "Regional review of payments for watershed services: Sub-Saharan Africa." *Jounal of Sustainable Forestry*, 3-4:28, pp. 525-50.

Ferraro, P. J., and Kiss, A., 2002. Direct payments to conserve biodiversity. Science, 298:1718-1719.

Ferraro, P. J., and Simpson, R. D., 2002. The cost-effectiveness of conservation payments. Land Economics, 78(3):339–353.

Frost, P. G. H., and Bond, I., 2008. The CAMPFIRE programme in Zimbabwe: Payments for wildlife services. Ecological Economics.

Garzón, A. 2009. "Estado de la acción sobre los mecanismos de financiamento de la protección o recuperación de servicios ambientales hidrológicos generados en los Andes." 66. Ecodesión: Quito.

Gibson, C.C., E. Ostrom, and T.K. Ahn. 2000. "The concept of scale and the human dimensions of global change: a survey." *Ecological Economics*, 32, pp. 217-39.

Grieg-Gran, M., Porras, I., and Wunder, S., 2005. How can market mechanisms for forest environmental services help the poor? Preliminary lessons from Latin America. World Development, 33: 1511-1527.

Hall, A. 2008. "Better RED than dead: paying the people for environmental services in Amazonia." *Philosophical Transactions of the Royal Society B*, 363:1498, pp. 1925-32.

Huang, M., S.K. Upadhyaya, R. Jindal, and J. Kerr. 2009. "Payments for watershed services in Asia: a review of current initiatives." *Jounal of Sustainable Forestry*, 28:3-4, pp. 1-25.

Jack, K. , B. Leimona, and P.J. Ferraro. 2009. "A revealed preference approach to estimating supply curves for ecosystem services: use of auctions to set payments for soil erosion control in Indonesia." *Conservation Biology*, 23:2, pp. 359-67.

Kerr, J., 2002. Watershed development, environmental services, and poverty alleviation in India. World Development, 30(8):1387-1400.

Koohafkan, P. and B.A. Stewart. 2008. *Water and cereals in drylands*. London & Sterling (VA): Earthscan, pp.110.

Kosoy, N., Martinez-Tuna, M., Muradian, R., and Martinez-Alier, J., 2006. Payments for environmental services in watersheds: Insights from a comparative study of three cases in Central America. Ecological Economics, 61(2-3):446-455.

Landell-Mills, N., and Porras, I., 2002. Silver Bullet or Fool's Gold? A Global Review of Markets for Forest Environmental Services and their Impact on the Poor. IIED, London.

Muñoz-Piña, C., Guevara, A., Torres, J.M., and Braña, J., 2008. Paying for the hydrological services of Mexico's forests: Analysis, negotiations and results. Ecological Economics.

Nel, D.C., C. Marais, and J.N. Blignaut. 2009. "Water neutrality: a first quantitative framework for investing in water in South Africa." *Conservation Letters*, 2, pp. 11-18.

Pagiola, S., 2008. Payments for environmental services in Costa Rica. Ecological Economics.

Pagiola, S. and G. Platais. 2007. "Payments for environmental services: from theory to practice." World Bank: Washington DC.

Pagiola, S., and Ríos, A. R., 2008. The impact of payments for environmental services on land use change in Quindío, Colombia. World Bank, Washington.

Pagiola, S., Arcenas, A., and Platais, G., 2005. Can payments for environmental services help reduce poverty? An exploration of the issues and the evidence to date from Latin America. World Development, 33:237-253.

Pagiola, S., Ramírez, E., Gobbi, J., de Haan, C., Ibrahim, M., Murgueitio, E., and Ruíz, J. P., 2007. Paying for the environmental services of silvopastoral practices in Nicaragua. Special Issue on Ecosystem Services and Agriculture, Ecological Economics, 64(2):374-385.

Pearce, D. W., and Warford, J. W., 1993. World Without End: Economics, Environment, and Sustainable Development. Oxford University Press, Oxford.

Pereira, L. 2008. "Scaling up payments for watershed services: patterns and lessons from other sectors” (unpublished project paper). 35. CIFOR: Belem.

Perrot-Maître, D., 2006. The Vittel payments for ecosystem services: a ‘perfect’ PES case? Project Paper No.3. IIED, London.

Quintero, M. and W. Otero. 2006. "Mecanismo de financiación para promover agricultura de conservación con pequeños productores de la cuenca de la laguna de Fúquene. Su diseño, aplicación y beneficios." 32. CONDESAN & CIP: Lima.

Rojas, M., and Aylward, B., 2003. The Case of La Esperanza: A small, private, hydropower producer and a conservation NGO in Costa Rica. Land-Water Linkages in Rural Watersheds Case Study Series. FAO, Rome.

Ribaudo, M.O., R. Heimlich, R. Claassen, and M. Peters. 2001. "Least-cost management of nonpoint source." *Ecological Economics*, 37:2, pp. 183-97.

Ross, M., Depro, B., and Pattanayak, S., 2006. Assessing the economy-wide effects of the PSA Program. Paper presented at the Workshop on Costa Rica’s Experience with Payments for Environmental Services, San José, 25-26 September.

Salzman, J. 2005. "Creating markets for ecosystem services: notes from the field." *New York University Law Review*, 80:June.

Sánchez-Azofeifa, G. A., Pfaff, A., Robalino, J. A., and Boomhower, J., 2007. Costa Rica's Payment for Environmental Services Program: Intention, implementation, and impact. Conservation Biology, 21(5):1165-1173.

Shelton, D., and Whitten, S., 2005. Markets for ecosystem services in Australia: Practical design and case studies. CIFOR, Bogor.

Southgate, D. and S. Wunder. 2009. "Paying for watershed services in Latin America: A review of current initiatives." *Journal of Sustainable Forestry*, 28, pp. 497-524.

Tomich, T., K. Chomitz, H. Francisco, A.-M.N. Izac, D. Murdiyarso, B.D. Ratner, D.E. Thomas, and M. van Noordwijk. 2004. "Policy analysis and environmental problems at different scales: asking the right questions." *Agriculture, Ecosystems and Environment*, 104, pp. 5-18.

Turpie, J.K., Marais, C., and Blignaut, J.N., 2008. The Working for Water programme: Evolution of a payments for ecosystem services mechanism that addresses both poverty and ecosystem service delivery in South Africa. Ecological Economics.

Wünscher, T., Engel, S., and Wunder, S., 2008. Spatial targeting of payments for environmental services: A tool for boosting conservation benefits. Ecological Economics.

Wunder, S. 2007. The efficiency of payments for environmental services in tropical conservation. *Conservation Biology* 21 (1):48-58.

Wunder, S., 2008. Payments for environmental services and poor: concepts and preliminary evidence. Environment and Development Economics, 13(3): 279-97.

Wunder, S., 2008a. Under what conditions will payments for environmental services emerge and function? Paper presented at the Workshop on Economics and Conservation in the Tropics: a Strategy Dialogue, San Francisco, 31 January – 1 February.

Wunder, S., and Albán, M., 2008. Decentralized payments for environmental services: The cases of Pimampiro and PROFAFOR in Ecuador. Ecological Economics.

Box 1: Examples of in-situ water conservation methods in rainfed agriculture

Terracing
Terracing is used to control runoff and erosion, thus avoiding the excessive loss of water and soil fertility. It is usually very labor-intensive, and employed only under high population density that dramatically increase food demand and lowers the cost of labor.

Conservation bench terraces and contour furrows
These practice use surface manipulation to collect runoff from the catchment to improve soil moisture on cropped areas. The latter requires less oil movements than the former, and is thus more easily adapted by smaller farmer.

Contour bunds
This method is equally used to reduce water runoff and soil fertility loss, using earth and stone materials. Examples of use include Kenya and Ethiopia.

Land leveling
Land leveling is done with laser, to impede soil erosion and runoff. It is a very efficient, but also very expensive method, which is only used under extreme land scarcity.

Tied ridges
This method uses furrow dykes to retain precipitation on the soil surface until it can infiltrate. It can be combined with low-tillage practices, and can be used in both mechanized and labour-intensive systems.

Source: Koohafkan & Stewart (2008), and others.

Box 2: Main water quality and quantity demands from downstream user and buyers

1. Hydroelectric power plants

- Low erosion, to limit turbine damages and reduced dam lifetime from sedimentation
- Total annual flow amount, to generate electricity

2. Water utility companies/ drinking water consumers

- Low erosion, to limit water turbidity (or save on water cleaning costs) and risks of damages to water-intake facilities
- Low content of organic matter, toxics, nitrite, etc., to limit health hazards.
- Maintain dry-season flows, to avoid seasonal shortages, and avoided flooding

3. Large-scale industrial users

- Low erosion to limit damage to infrastructure
- If for drinking water (e.g. water bottlers, breweries), then same concern as water consumers (2.)
- Maintain dry-season flows, to avoid seasonal shortages, and avoided flooding

4. Irrigation agriculture

- Reduced erosion to limit sedimentation of reservoirs and irrigation channels
- Maintain dry-season flows, to avoid seasonal shortages, and avoided flooding

5. Government

- Multiple water quality and quantity goals, often including biodiversity, recreational uses, and carbon.

Source: Own compilation

Box 3: Paying for improved agricultural practices: the case of Fúquene (Colombia)

Lake Fúquene is located in the department of Boyacá, N of Bogotá, and an important water source for that region. It has been threatened by a rapidly progressing process of eutrophication, due to high concentrations of nitrogen and phosphates in the water, coupled with high sedimentation rates. The main pathway for change was to persuade upland farmers to use fewer fertilizers; they specialize in potatoes, cereals, peas, maize, and dairy farming.

Since 2004, the Consortium for the Sustainable Development of the Andean Ecoregion (CONDESAN) and CIAT (International Center for Tropical Agriculture), supported by German GTZ's Andean Watershed project, engaged in actions designed to improve the lake's situation. Hydrological modeling was carried out through SWAT (Soil and Water Assessment Tool), and a 'business as usual' baseline of continued deterioration was constructed. Calculations about the farm-level opportunity costs of improved alternatives were made. It was found that a switch to organic farming, with reduced tillage, green manure, permanent vegetation cover, and less fertilizer use would provide an environmental service to the lake's water users by reducing sediments by around 70%, These changes would also be more profitable to farmers, following an initial investment necessary to switch to new practices (about US$250/hectare). Yields for potatoes would rise by about 20% and peas by 30%, and even after the incremental recurrent costs, production would be 18-25% more profitable, and soil fertility would be conserved on-farm.

In negotiation with farmers, the preferred solution was thus to provide cheap credits (0.9% interest rate) to 39 of the smallest and poorest farmers (>2ha). to undertake the switch in practices to conservation farming. A revolving fund was created for that purpose, using funding from GTZ and Ford Foundation. The revolving fund was locally administered. This credit subsidy was conditional upon the farmer presenting an approved land-use plan, accompanied later by technical follow-up assistance from a GTZ technician.

Compliance with the land-use plan was around 97%, and over time the scheme doubled its initial cultivation area to 178 hectares. In this sense, the project clearly was a success; the mechanism worked as planned, and seems to be sustainable. The project was so far less successful in scaling up the initiative within the entire watershed, which is sized 99,137 ha, 55,662 ha of which are under cultivation. Transferring the idea to the commercial banking sector was so far not successful. Some producers remain skeptical about changing cropping practices with a century-long history. Some particularly larger landowners are leasing out their lands to commercial producers of in particular potatoes. When the functions of landowner and farmer are divorced, the latter has little incentive to preserve soil fertility for the future, or to make investments in the land that give returns beyond the short-run lease period. The tenure arrangements are thus one significant obstacle for upscaling.

Sources: Quintero & Otero (2006); Garzón (2009), http://www.condesan.org/cuencasandinas/

Box 4: Examples of developed-country PES cases with an agricultural focus

The Vittel (Nestlé Waters) watershed protection program in Eastern France
Since 1993, mineral water bottler Vittel has conducted a PES program in its 5,100 ha catchment at the foot of the Vosges Mountains, in order to maintain aquifer water quality to its highest standard. The program pays all 27 farmers in the watershed of the "Grande Source" to adopt best practices in dairy farming. The program is implemented through Agrivair, a buyer-created agricultural extension agency, which has a solid local base and is trusted by farmers. It has persuaded farmers to reconvert to extensive low-impact dairy farming, including abandoning agrochemicals, composting animal waste, and reducing animal stocks. The program is fairly complex in design, combining conditional cash payments with technical assistance, reimbursement of incremental agricultural labor costs, and even arrangements to take over lands and provide usufruct rights of the farmland to the farmers. Contracts are long-term (18-30 years), payments are differentiated according to opportunity costs on a farm-by-farm basis, and both land use and water quality are closely monitored over time. Total costs (excluding the intermediary's transaction costs) have been almost US$25 million over 1993-2000. Through carefully researched baselines, an improvement of the service vis-à-vis the declining ES baseline is well documented, and the high service value clearly makes the investments profitable.

The Wimmera Catchment pilot program for salinity control in Victoria, Australia
This program, initiated in 2005, aims to reduce recharge to saline aquifers. It focuses on land uses in the steep, hilly part of the watershed – a 28,000 ha area within the Upper Wimmera Catchment. The beneficiaries are various downstream water users. The Catchment Management Authority is using taxpayer money to organize inverse auctions to obtain the most desired land-use changes from upstream landowners at the lowest possible cost. Landholders submit voluntary offers to provide the targeted services, and the authorities rank these offers according to cost per unit of expected salt reduction. Then it approves applications for cash payments up to a budget limit or a preset reserve price. The program is designed as conditional, but this is de facto reduced by high upfront payments and low sanction risks. Nevertheless, compliance is still expected to be high, due to local mechanisms of social control. Start-up transaction costs have been relatively high, but this is seen by the authorities as an investment for future upscaling of the program.

The Northeim Model Project for agrobiodiversity in Lower Saxony, Germany
Like Wimmera, the Northeim project is a pilot program using tendering procedures to determine payments to farmers for changed land uses, with a view to a later upscaling of the experience by incorporating it into the European Union's Common Agricultural Policy. A private foundation pays farmers to reduce agricultural intensification and to adopt practices that favor species richness, boosting both biodiversity (regionally endangered plant species) and recreational benefits from landscape beauty (enjoyed by visitors). Payments were carried out since 2004 to 28 farmers (out of 159 bids) on 288 ha. The University of Göttingen assists in this trial to scientifically document the outcomes.

Sources: Wunder et al. (2008); Perrot-Maître (2006), Whitten and Shelton (2005), Bertke and Marggraf (2005).

Box 5: Variables measuring and influencing PWS scales

1. **Units**: # of persons, hectares, m^3 of water, $ of payments
2. **Financing**: User vs. government-financed schemes
3. **Services:** Sub-services (e.g. sedimentation, dry-season flow, flood control) with their respective spatial range of supply and demand
4. **End users** (e.g. hydroelectric power plants vs. drinking water); layered services (e.g. hydrological + carbon services)
5. **Watershed dimensions**: Micro watershed (e.g. drinking water quality) vs. higher- order catchments (e.g. flood risks in greater river basin) vs cross-watershed functions (e.g. aquifer recharge)
6. **Administrative units**: Municipal, departmental, national scales, transboundary water courses
7. **Scaling direction**: Is both “scaling up” and “scaling down” potentially relevant?
8. **Temporal aspects**: Choice of contract length; identifying long-term payment vehicles

Source: Asquith & Wunder (2008)

Box 6: Practical questions before starting a watershed PES

- *Cost.* What is the incremental cost (upfront, running, net present value) to farmers to switch to the desired practices?
- *Relevance.* What is the existing level of investment in water treatment infrastructure, as an alternative to ecosystem service investments?
- *Willingness to pay.* Is there evidence that downstream utilities, water boards or other users are willing and able to pay for hydrological services?
- *Other service users.* Are users of non-hydrological services likely to financially contribute to a layered service program?
- *Complexity users.* Is the number of buyers small enough or are they socially cohesive enough to eliminate free-riding behavior?
- *Complexity buyers.* Is the number of farmers small enough, or does enough social capital exist to suggest a widespread adoption and good coordination of a payment system for improved cropping systems?
- *Capacity and intermediaries*. Is there the human resource and organizational capacity to develop a payment scheme? Does a likely intermediary already exist or will it need to be created?

Source: Adapted from Aylward (2007)

Table 1. Water pollutant types

Type of pollutants	Pollutants	Origins
Physical	Sediment, Temperature, Turbidity	land surface erosion litter and mismanaged solid waste organic matter runoff from buildings or construction sites diversion of flow from rivers storage of water behind dams
Organic	Nitrogen, Phosphorus, Microbes, Bacteria	organic matter fertilizers sewer overflow detergents animal and human wastes
Toxic	Chlorinated compounds Solvents, Acids, Alkalis, Heavy Metal, Pesticides and Oil	Pesticides herbicides runoff from buildings and roads (oil) detergents

Fulton, cited in Aylward (2007: 5)

Table 2. Agricultural activities and their likely hydrological impacts

Agricultural activities	Surface water impacts	Groundwater impacts
Land clearing	Erosion causing turbidity in rivers, siltation of bottom habitat, etc. Disruption of hydrologic regime, groundwater recharge and transpiration effects typically increase annual surface runoff. Effects on dry-season flows depend on balance between ET and infiltration, if lowered then concentrate nutrients and contaminants in surface water. Erosion and flow changes can affect public health due to loss of potable water.	Decreased groundwater recharge. Typically less transpiration of soil moisture.
Tillage/ploughing	Sediment/turbidity: sediments carry phosphorus and pesticides adsorbed to sediment particles; siltation of river beds and loss of habitat, spawning, etc.	
Fertilizing	Runoff of nutrients, especially phosphorus, leading to eutrophication, causing taste and odor in public water supply, excess algae growth leading to deoxygenating of water and fish kills.	Leaching of nitrate to groundwater: excessive levels are threat to public health.
Weed and pest control	Runoff of pesticides leads to contamination of surface water and biota; dysfunction of ecological system en surface waters by loss of top predators due to growth inhibition and reproductive failure; public health impacts from eating contaminated fish. Pesticides are carried as dust by wind over very long distances and contaminate aquatic systems 1000s of miles away (e.g. tropical/ subtropical pesticides found in Arctic mammals.	Some pesticides may leach into groundwater causing human health problems from contaminated wells.
Livestock feed and disease control	Spillage or excretion of animal feed or activity; undigested veterinary medicines may runoff contributing to eutrophication and or toxicity of surface water.	Nutrients and medicines may leach through to groundwater
Manure spreading	Carried out naturally or as a fertilizer activity; spreading on frozen ground results in high levels of contamination of receiving water by pathogens, metals, phosphorus and nitrogen leading to eutrophication and potential contamination.	Contamination of ground-water, especially by nitrogen
Feedlots/animals corrals	Contamination of surface water with many pathogens (bacteria, viruses, etc.) leading to chronic public health problems. Also contamination by metals contaminated in urine and faeces.	Potential leaching of nitrogen, metals, etc. to groundwater.
Irrigation	Runoff of salts leading to salinization of surface waters; runoff of fertilizers and pesticides to surface waters with ecological damage, bioaccumulation in edible fish species, etc. Trace elements such as selenium can cause serious ecological damage and human health impacts.	Enrichment of groundwater with salts, nutrients. Prevention of seepage trough piping/lining of canals can reduce community access to clean water.
Aquaculture	Release of pesticides and high levels of nutrients to surface water and groundwater through feed and surfaces, leading to serious eutrophication.	

Source: Aylward (2007)

Table 3: Models for environmental service outcomes at the watershed scale

NAME	APPLICATION	TIME SCALE	SPATIAL SCALE
HPSF (Hydrologic Simulation Program-Fontran)	Hydrology, water quality for conventional and toxic organic pollutants	Event, daily, continuous	Watershed
SHE (Système Hydrologique Européen)	Hydrology, with water quality modules	Event, daily, continuous	Watershed
SWAM (Small Watershed Model)	Hydrologic processes, sediment, nutrients and pesticides	Daily, continuous	Watershed
SWAT (Soil and Water Assessment Tool)	Hydrologic processes, sediment, nutrients and pesticides	Event, daily, continuous	Simultaneous simulation for hundreds of sub-basins
SWRRB (Simulator for Water Resources in Rural Basins)	Water balance and hydrologic processes and sedimentation	Event, daily, continuous	Watershed

Source: Aylward (2007:45)

Table 4: Pros and cons of scaling up PES experiences

Low scale (typically, user-financed PES schemes)	**High scale** (typically, government-financed PES schemes)
Participatory processes & negotiated solutions	Higher degree of top-down decision making
Locally customized, flexible solutions	Some standardization and fixation of interventions necessary
Service providers and users interact directly through 'simulated markets' or bilateral contracts	Buffering role of the state limits direct signals between users and providers, potentially fostering inefficiencies
Typically high transaction costs per 'benefit unit', especially with respect to start-up investments	Typically enjoying economies of scale in administration and management
Innovations remain confined in space in their effect	'Good ideas' are replicated quickly in space for higher impact
Policy framework is given	Policies can be fine-tuned according to interventions and lessons learnt
Focus on solving specific problem facilitates targeted design	Political processes tend to overload goals with side-objectives (social, electoral, etc.)
Ill-suited to deal with phenomena related to non-excludable, large-scale societal benefits (free riding, leakage)	Can through aggregation potentially charge wannabe free-riders, control for leakage, and bundle/ layer multiple benefits to multiple beneficiaries

Note: Assumed pro-upscaling arguments stated in blue, and counterarguments in red
Source: Own elaboration

Figure 1: A watershed PES typology

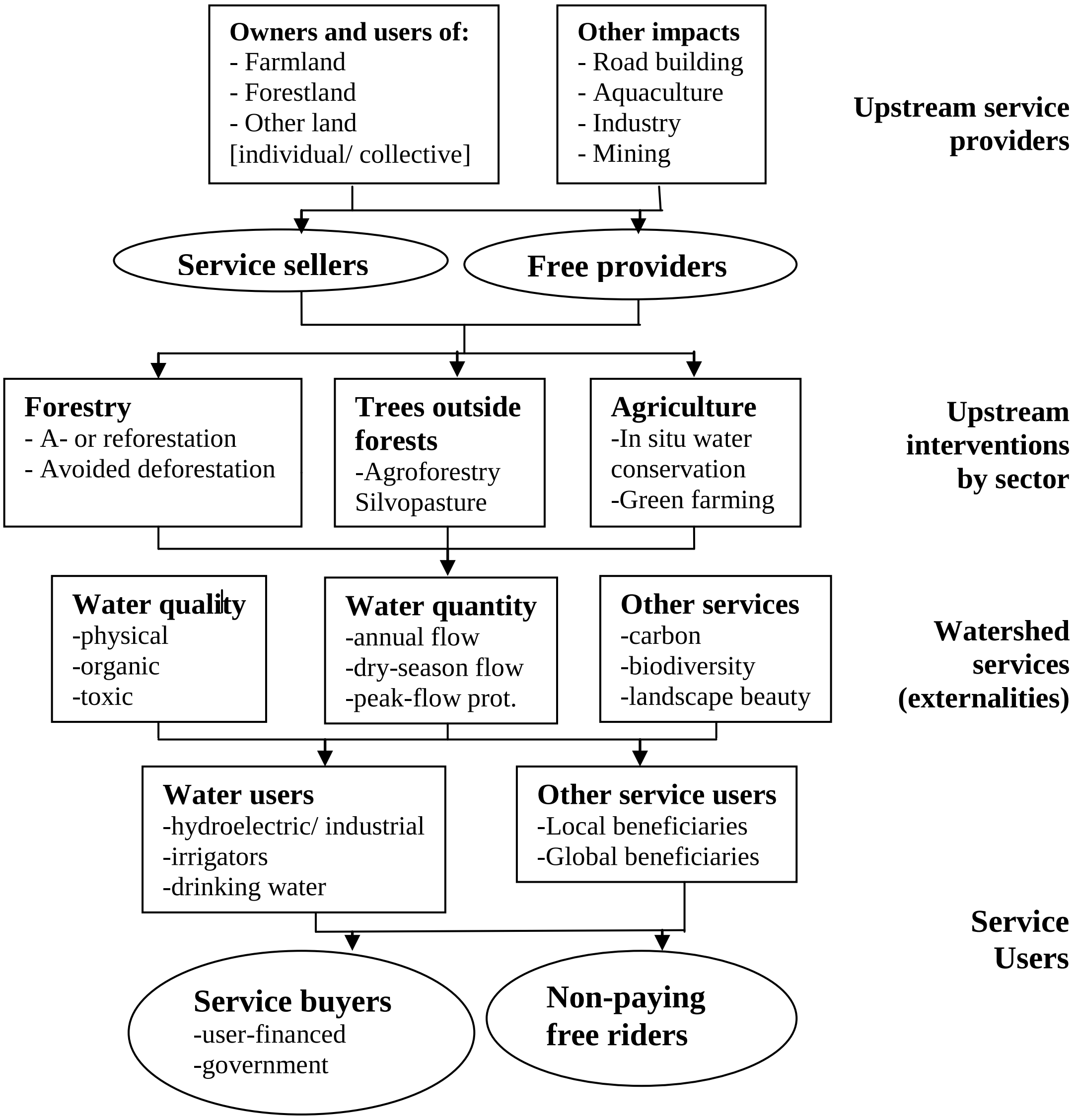
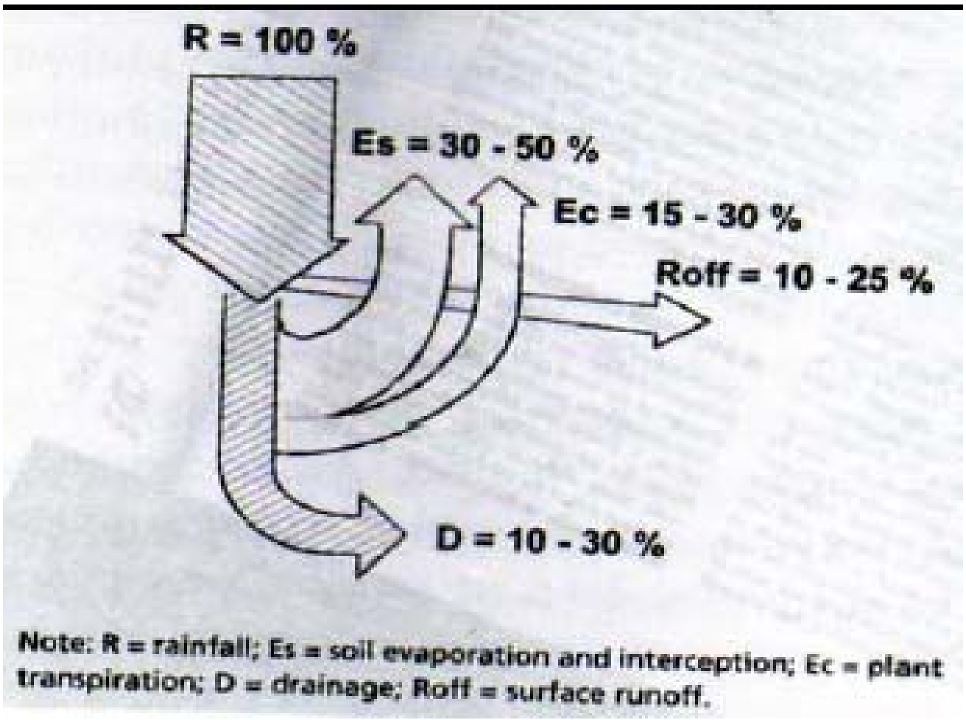


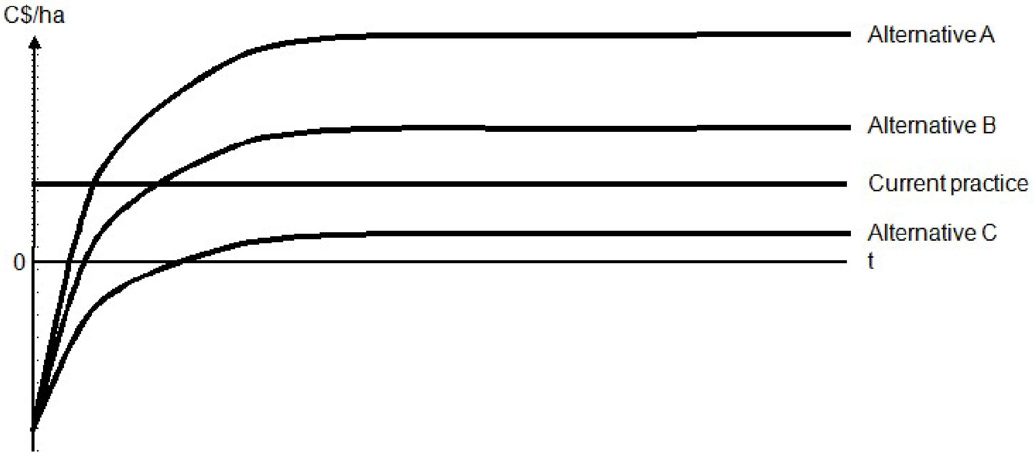
Figure 2: Rainfall partitioning in semi-arid regions



Note: R = rainfall; Es = soil evaporation and interception; Ec = plant transpiration; D = drainage; Roff = surface runoff.

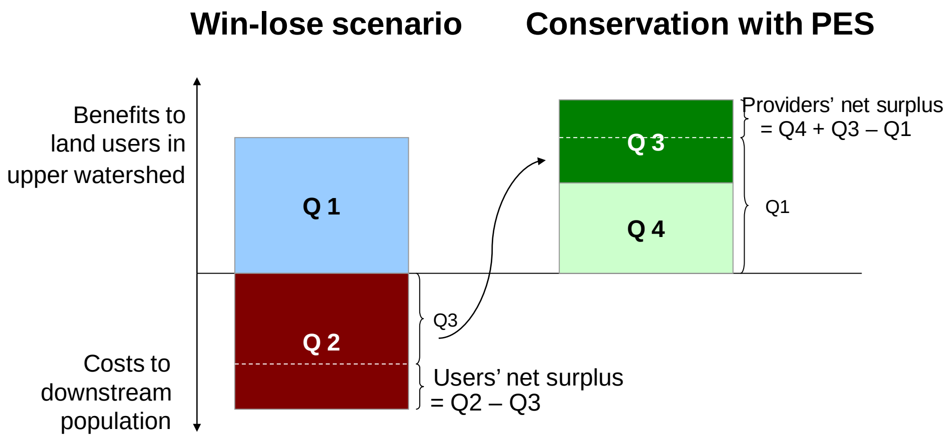
Source: Koohafkan & Stewart (2008: 28)

Figure 3: Adoption costs, returns, and economic rationales for PES



Source: Stefano Pagiola, pers.comm., June 2009.

Figure 4: Conceptualizing PES costs and benefits



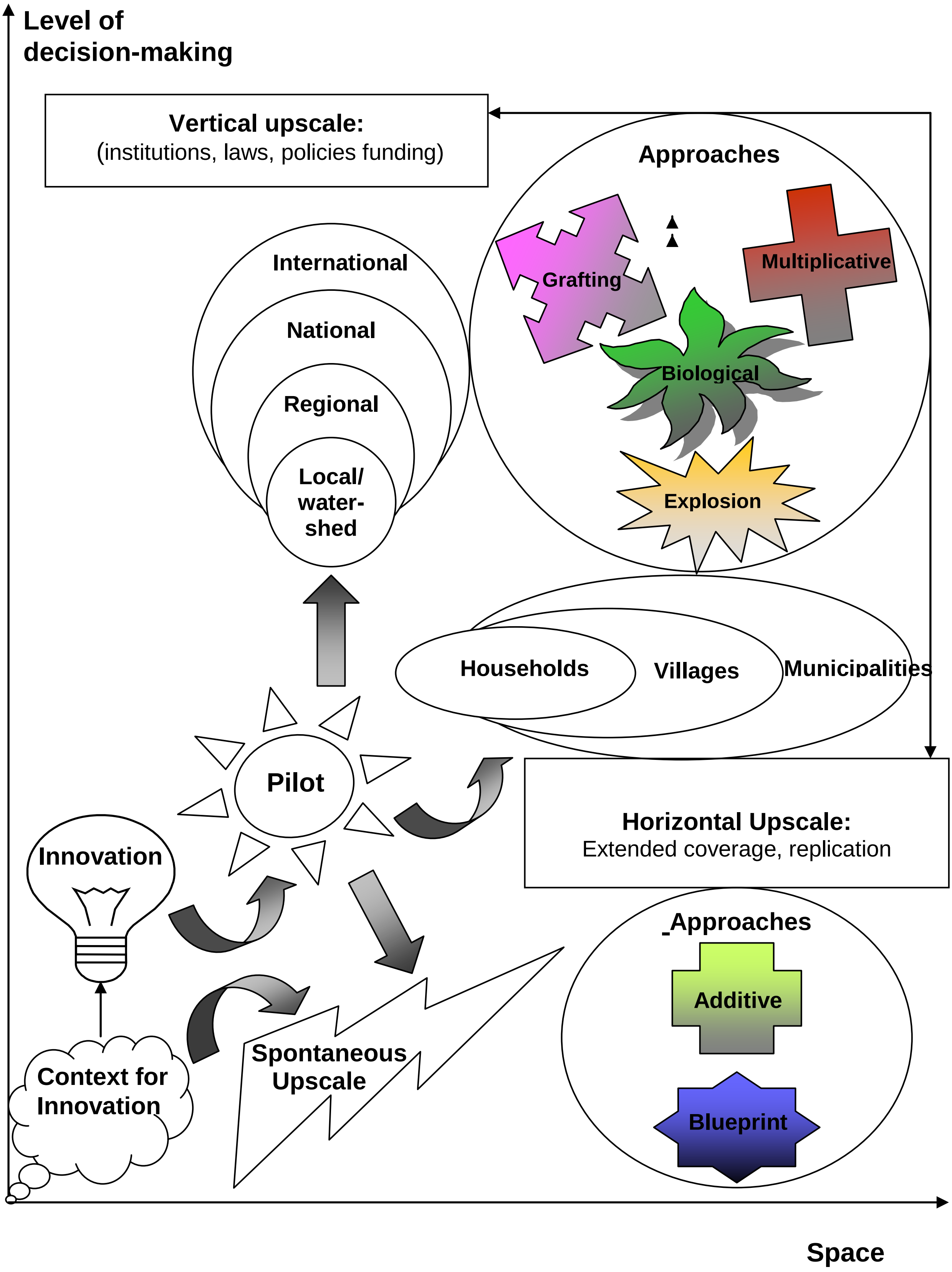
Win-lose scenario

Conservation with PES

Q 1 : Most profitable land use (e.g. deforestation for farming)
Q 2 : External effects from Q1 (e.g. decline in water quality)
Q 3 : PES paid by downstream users; conditions: Q3 < Q2 and Q3+Q4 > Q1
Q 4 : Service-friendly land use (e.g. agro-forestry, pure protection)

Source: Pagiola and Platais (2007)

Figure 5: Modalities of upscaling



Source: Modified from Pereira (2008)

Annex 3

Risk Management

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Contents

1. Introduction

Dryland agriculture

Drylands cover about 41% of Earth's land surface and are inhabited by more than 2 billion people (about one third of world population). Drylands are limited by soil moisture, the result of low rainfall and high evaporation, and show a gradient of increasing primary productivity, ranging from hyper-arid, arid, and semiarid to dry subhumid areas. They occur on all continents (Figure 1.1), but are certainly not uniform. They differ in the degree of water limitation they experience and various ecosystems exist per subtype. From the total area of drylands, hyper-arid, arid, semiarid and dry subhumid areas cover 16%, 26%, 37% and 21% respectively. Aridity indices[1] for these areas are <0.05, 0.05-0.20, 0.20-0.50 and 0.50-0.65 respectively Niemeijer et al. (2005).

Dryland agriculture covers a wide range of commodities, i.e. not only arable crops but also horticultural crops, wood production, aquaculture and livestock. In general, most of the world's dryland area is divided by land cover and land use between rangelands (65%) and croplands (25%)[2], although some of these are actually interwoven rangeland and croplands, supporting a mixed, integrated agropastoral livelihood. Niemeijer et al. (2005) indicate that due to increasing human populations a transformation from rangelands to croplands is occurring.

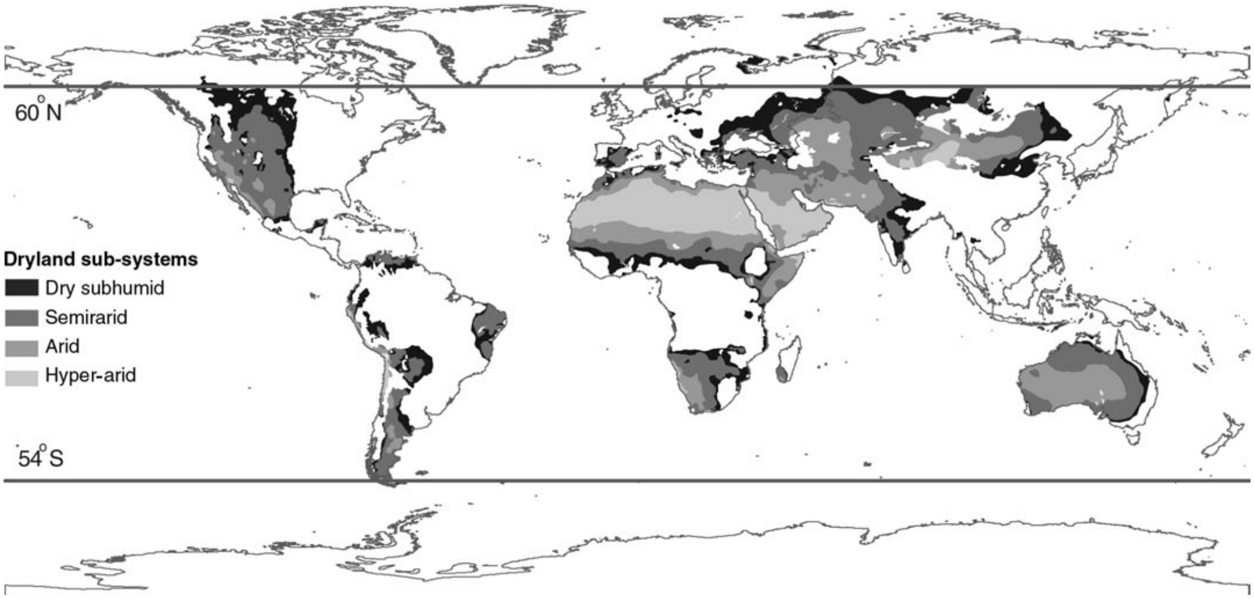

Figure 1.1: Dryland systems and subtypes (Niemeijer et al., 2005).

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[1] Aridity index (AI) values lower than 1 indicate an annual moisture deficit. Drylands are defined as having AIs below 0.65 implying areas in which mean potential evapotranspiration is at least 1.5 greater than annual mean precipitation.

[2] Other areas include urban areas (2%), inland water systems (3%) and "other" (5%).

Socioeconomic environment

From the total population in dryland areas 5% lives in hyper-arid areas, 11% in arid areas, 40% in semiarid areas and 43% in hyper-aridf areas. Dryland populations on average lag far behind the rest of the world on human well-being and development indicators. The current socioeconomic condition of dryland peoples, about 90% of whom are in developing countries, lags significantly behind that of people in other areas (Niemeijer et al., 2005).

Climate change will intensify agricultural water challenges

Brown and Hansen (2008) state that anticipated climate change combined with other drivers of change is expected to intensify current agricultural water management challenges in Africa and India. More generally Niemeijer et al. (2005) state that dryland-specific and comprehensive information and predictions for dryland systems are not readily available, but that it can be inferred that global warming has driven climate changes that have also affected many drylands. These may include the more frequent, persistent, and intense warm episodes of the El Nino-Southern Oscillation phenomenon since the mid-1970s and the increased frequency and intensity of droughts in parts of Asia and Africa in recent decades. These trends are expected to continue, whereas precipitation will either decrease or increase in different regions. Impacts are expected to be different for different dryland subtypes but, overall, climate change is expected to exacerbate desertification. Moreover, existing water shortages in drylands are projected to increase over time due to population increase and land cover change.

Ways out

Besides negative developments in the area of water risk, a number of authors also describe “ways out” by among others small-scale irrigation plans of high-value crops and improved soil, water and range technologies to reduce soil erosion (Brown and Hansen, 2008). Due to such techniques there is increasing evidence that negative feedback loops need not to occur. Rather, dryland populations, building on long-term experience with their dynamic environments as well as active innovation, are believed to be able to stay ahead of degradation by intensifying their agricultural practices and enhancing pastoral mobility in a sustainable way. In line with this, Mirza (2003) states that lending agencies and donors need to reform their investment policies in developing countries to focus more on capacity building instead of just investing in recovery operations and infrastructure development.

The role of risk management

Dercon (2000) states that [..] households in risky environments have developed sophisticated (ex-ante) risk management and (ex-post) risk coping strategies, including self-insurance via savings and informal insurance mechanisms to do so while formal credit and insurance markets appear to contribute only little to reducing income risk and its consequences. Informal credit and insurance, however incomplete, helps to cope with risky incomes. Despite these strategies, vulnerability remains high, and is reflected in fluctuations in consumption. Brown and Hansen (2008) add to this and state that many of the coping responses that vulnerable households employ ex-post to survive an uninsured climate shock can have adverse, long-term livelihood consequences. They argue that—in addition to investment in agricultural water management technologies—breeding for drought stress and diversification strategies can reduce dryland populations’ vulnerability. Additionally, they see an important role for innovations such as the use of climate forecasts and monitoring, and the ability to manage risks financially through risk sharing at the microscale and macroscale.

Focus and outline of paper

This paper focuses on the opportunities of risk management in dryland agriculture. More specifically, the objectives of this paper are (1) to provide insight into the impact of risk on dryland agriculture; (2) toidentify potential risk management strategies and actions currently undertaken; (3) to list possible ways of estimating the value of risk management strategies; and (4) to suggest necessary (policy) frameworks for scaling up the provision and use of risk management strategies.

As "risk" and "risk management" are quit broad concepts, we narrowed down the scope of the paper. Although other sources of risk are sometimes even more important in dryland agriculture (as will be discussed briefly in Chapter 2), we mostly focus on *water risk* as the current paper is part of the Water Anchor Project of the World Bank[3]. Furthermore, risk management instruments are generally subdivided into on-farm strategies, such as diversification and the gathering of information, and risk-sharing instruments, such as finance and insurance. Both categories of risk management instruments are important and have different considerations of efficiency and institutions needed. We focus on *risk-sharing instruments* as these may provide more formal ways of dealing with (farm-level) crisis risk. Such instruments generally face difficulties if structural trends, such as desertification, declining water table depths and declining water quality, are included. They work better for risky events that strongly deviate from the trend, such as extreme abundance or shortage of rainfall. Therefore, we will focus on *risk*, not structural trends.

Chapter 2 discusses water risks in a dryland perspective and introduces some classifications of agricultural risk management strategies. Chapter 3 builds on actual experiences with risk management strategies, mostly focusing on insurance. A number of case studies are presented as well. Chapter 4 identifies costs and benefits of risk management strategies and discusses ways of incorporating agricultural risk management in the watershed modeling exercise. Chapter 5 concludes with items to be addressed for scaling up the use of agricultural risk management measures including policy implications and ways to go forward in the field of modeling exercises.

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[3] Throughout the paper the terms "water risk" and "weather risk" have the same meaning, i.e. extreme abundance or shortage of rainfall.

2. Agricultural risk management and dryland agriculture

2.1 Impact of water risk on agriculture

Role of major agricultural risks

Although water risk is often reported to be the causing factor of major shocks (e.g. Dercon, 2000), it is not the only source of risk farmers need to cope with. Water risk is a so-called non-market related risk. Other risks in this category are for instance logistical and infrastructural risks and management and operational risks (Table 2.1). Market-related risks on the other hand refer to risks such as changes in supply and demand with regard to timing, quality and food safety attributes (Jaffee et al., 2008). Also, the availability of inputs and markets for farm outputs in itself is a market-related risk (Roberts, 2007).

Table 2.1: Categories of major risks in agricultural supply chains (Roberts, 2007; Jaffee et al., 2008).

Type of risk	Examples
Market related risks	Changes in supply and/or demand that impact domestic and/or international prices of inputs and/or outputs, changes in market demands for quantity and/or quality attributes, changes in food safety requirements, changes in market demands for timing of product delivery, changes in enterprise/supply chain reputation and dependability
Non-market related risks	
Weather related risks	Periodic deficit and/or excess rainfall or temperature, hail storms, strong winds
Natural disasters (including extreme weather events)	Major floods and droughts, hurricanes, cyclones, typhoons, earthquakes, volcanic Activity
Biology and environmental risks	Crop and livestock pests and diseases, contamination related to poor sanitation, human contamination and illnesses, contamination affecting food safety, contamination and degradation of natural resources and environment, contamination and degradation of production and processing processes
Logistical and infrastructural risks	Changes in transport, communication, energy costs, degraded and/or undependable transport, communication, energy infrastructure, physical destruction, conflicts, labor disputes affecting transport, communications, energy infrastructure and services
Management and operational risks	Poor management decisions in asset allocation and livelihood/enterprise selection, poor decision making in use of inputs, poor quality control, forecast and planning errors, breakdowns in farm or firm equipment, use of outdated seeds, not prepared to change product, process, markets, inability to adapt to changes in cash and labor flows, etc.
Policy and institutional risks	Changing and/or uncertain monetary, fiscal and tax policies, changing and/or uncertain financial (credit, savings, insurance) policies, changing and/or uncertain regulatory and legal policies, and enforcement, changing and/or uncertain trade and market policies, changing and/or uncertain land policies and tenure system, governance related uncertainty (e.g., corruption), weak institutional capacity to implement regulatory mandates
Political risks	Security-related risks and uncertainty (e.g. threats to property and/or life) associated with politico-social instability within a country or in neighboring countries. Interruption of trade due to disputes with other countries. Nationalization/confiscation of assets, especially for foreign investors.

Role of climate risks in dryland agriculture

The magnitude of risk generally varies considerably among different countries and among distinct locales within those countries—given underlying climatic conditions, geography/topography, demographics, and agrarian and industry structures. The relative importance of different types of risks also varies among supply chains for different commodities, resulting from specific "technical" properties (i.e. their perishability/storability), prominent features of their markets, and trends in regulatory developments and consumer preferences (Jaffee et al., 2008). These authors classified the relative importance of 5 types of risk, i.e. (i) price volatility of commodity, (ii) loss of product (quality) due to logistical breakdown, (iii) constrained market access due to sanitary and phytosanitary concerns, (iv) disruption of production due to adverse weather, and (v) market concerns with environmental or social dimensions of production. Classification (high, medium, low) was done for 16 commodities from export-oriented developing countries whose primary market orientation is higher income industrialized countries. Among the commodities considered, weather risk was most often classified as medium risky[4]. From the various sources of risk, price volatility scored most frequently in the high-risk category.

The relevance of other sources of risk is also mentioned by Rashid and Assefa (2007), who state that in Ethiopia there is [..] continued high variability in prices—but that price risk mitigation has lost its importance in the country's policy agenda. For Malawi, Syroka (2009) states that one of the reasons for discontinuing a rather successful weather insurance scheme is [..] a nascent agricultural supply chain with many problems greater than weather. In a study on the Ethiopian supply chain of potato seeds, Tufa et al. (2009) found that for the majority of chains main improvement issues relate to production and storage methods, seed quality, and seed availability and distribution.

Impact of climate risks in dryland agriculture

Various authors, among others Brown and Hansen (2008), argue that farmers face considerable *ex-ante opportunity costs* due to weather uncertainty. These are due to among others inefficiencies, selection of less risky (and less profitable) crops, and avoidance of investments in production assets, fertilizers and improved technologies. A number of authors also argue that there are high *ex-post costs* of climate fluctuations as coping responses employed by vulnerable households can have adverse, long-term livelihood consequences. Examples can be found in liquidating productive assets, defaulting on loans, withdrawing children from school and over-exploiting natural resources.

2.2 A review of agricultural risk management

Review of agricultural risk management strategies

Many strategies exist and they are classified in various ways. Hardaker et al. (2004) classify risk management strategies in on-farm strategies and risk-sharing strategies. On-farm strategies include among others the gathering of information. For example, asking for the weather forecast, analyzing feed or soil samples and consulting experts. Also particular risks can possibly be avoided or prevented. It is known that certain activities carry more risks than other. Another good strategy to minimize risks is not to put all one's money on a single farm activity. By selecting a mixture of activities, risks can be considerably

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[4] Low (3x): cotton, sugar, fish; low-medium (2x): spices, cut flowers; medium (7x): coffee, cocoa, oil palm, rice, tobacco, ground nuts, beef; medium-high (2x): fruit, vegetables; high (2x):

reduced. The same holds for having various suppliers and buyers. Flexibility can be mentioned as a last measure at farm level. Flexibility refers to how well a farm can anticipate on changing conditions. For example, by investing in multi-purpose assets. The second set of measures refers to sharing risks with others (Huirne et al., 1997). One possibility here is buying insurance. Several types of insurance are available, with which, by payment of a premium, risks can be reduced or even eliminated. The farmer may also be able to conclude contracts for example with suppliers and buyers in which price agreements are laid down. Agreements can be made on the duty to deliver and to buy as well as on the quality of the products or raw materials. Lastly, by using the futures market, price risks can largely be eliminated. The futures market is not yet very well known in many countries, but in the US it is popular for a number of agricultural products.

Angelucci (2008) classifies risk management strategies in a risk retention layer (ex-ante self-insurance and ex-post behaviors) and a market insurance layer. Table 2.1 relates this categorization to the instruments mentioned in the previous paragraph. Insurance, contract marketing and trading in commodity derivatives is regarded as a combination of ex-ante and ex-post risk management.

Meuwissen et al. (2008a) distinguish between risk management solutions addressing entrepreneurial (normal business) risks versus crisis risk (idiosyncratic risk causing crises for single farms or systemic risk causing crises for multiple farms). The on-farm strategies dealing with crisis risk are however generally not perceived to be sustainable (Brown and Hansen, 2008). Also, the degree to which finance and insurance organizations can deal with crisis risk depends on their scale, e.g. small-scale mutuals have difficulties in coping with large-scale (systemic) events (Meuwissen et al., 2003).

The distinction between private and public risk management instruments links the instruments to policy involvement. Although governments are indirectly involved in many of the instruments, i.e. in their role as facilitator for instance for collecting information, facilitating asset markets or providing the legal infrastructure for contracts, their role is often most directly visible in farm financing and insurance. This can be among others through providing some form of “lender of last resort”, by making insurance schemes compulsory, or by providing some form of subsidy. For instance, MIA (micro Insurance Agency Holdings) works in partnership with among others rural banks and humanitarian organizations.

Varangis et al. (2002) distinguish between formal and informal risk management markets in which debt and savings, price-pooling, forward contracting and hedging on a futures market belong to the first and self-insurance and income-and-responsibility sharing belong to the latter.

Table 2.2: Classification of risk management strategies[1].

	Ex-ante/ Ex-post	**Entrepreneurial/ Crisis risk**	**Private/ Public**	**Formal/ Informal[2]**
On-farm				
Avoiding or reducing exposure to risk	Ex-ante	Entrepreneurial	Private	Informal
Collecting information	Ex-ante	Entrepreneurial	Private	(In)formal
Selecting less risky technologies	Ex-ante	Entrepreneurial	Private	Informal
Diversification	Ex-ante	Entrepreneurial	Private	Informal
Flexibility	Ex-post	Entrepreneurial	Private	Informal
Self-insurance and savings	Combi	Combi	Private	Informal
Sales of assets[a]	Ex-post	Crisis	Private	Informal
Replace in-farm by off-farm labor[a]	Ex-post	Crisis	Private	Informal
Withdrawing children from school[b]	Ex-post	Crisis	Private	Informal
Reducing consumption[b]	Ex-post	Crisis	Private	Informal
Migration to urban centers[b]	Ex-post	Crisis	Private	Informal
Food aid[c]	Ex-post	Crisis	Public	Formal
Risk-sharing				
Farm financing	Ex-post	Crisis	Public-private	Formal
Insurance (indemnity-based, index)	Combi	Crisis	Public-private	Formal
Contracts (production, marketing)	Combi	Entrepreneurial	Private	(In)formal
Trading in commodity derivatives	Combi	Entrepreneurial	Private	Formal

[1] Classification and examples are from Hardaker et al. (2004). Strategies marked with (a), (b) and (c) are from Angelucci (2008), Brown and Hansen (2008) and Dercon (2000) respectively.

[2] Formal is defined as arrangements in which other institutions are involved. With informal strategies no other institutions are involved.

Agricultural risk management strategies important for climate risks

Reviewing the long list of potential risk management strategies shown in Table 2.2, one wonders about relevant strategies for coping with climate risks. On-farm strategies are generally perceived to be costly. Also, the capacity for self-insurance is limited. Therefore, policy makers and development-minded institutions increasingly explore ways in which the reach of markets for risk management instruments can be extended for the benefit of households and businesses in developing countries (Varangis et al., 2002). In this framework new capital market instruments have been introduced (Freeman et al., 2003), such as weather derivatives (index insurance). Also other products (not in Table 2.2) have been introduced, such as catastrophe bonds, contingent surplus notes, exchange traded catastrophe options, catastrophe equity puts, catastrophe swaps and Although it is likely that farmers generally access such innovative instruments indirectly, i.e. through local banks or cooperatives using them, they likely enhance farmers' risk management opportunities because of enlarged capital availability.

In line with Varangis et al. (2002) and Brown and Hansen (2008) we see largest opportunities for the group of risk-sharing instruments, although experience is very diverse (next chapter). Major tools are explained below—following the order of Table 2.2 and leaving out trading in commodity derivatives as this tool seems quit unlikely for most dryland areas around the world.

Farm financing (commercial and micro-finance)

Finance works most basically through individuals and business organizations depositing money in a bank. The bank then lends the money out to other individuals or corporations for consumption or investment, and charges interest on the loans. Microfinance beholds the same principles but specifically refers to the provision of financial services to low-income clients, including consumers and the self-employed, who traditionally lack access to banking and related services. More broadly, it aims at "a world in which as many poor and near-poor households as possible have permanent access to an appropriate range of high quality financial services, including not just credit but also savings and insurance. […] those who promote microfinance generally believe that such access will help poor people out of poverty (Wikipedia).

Harwood et al. (1999) state that farmers' reliance on accessing credit reserves to obtain liquidity during times of adversity, introduces risk in terms of lenders' responses. Lenders' decisions regarding the availability of credit are directly affected by a farm's capital structure, conditions in the agricultural sector and financial market conditions.

Indemnity-based insurance (commercial and micro-insurance)

The key principles of conventional, i.e. indemnity-based, insurance are that as a farmer you pay a premium and you receive an indemnity after an insured loss occurs (after loss adjustment and correction for deductibles, if any). If provided, conventional insurance seems to be a relatively popular risk management instrument (compare e.g. section 3.1 for industrialized countries). It however also faces several difficulties, among others due to market failure:

- If a pool consists of large numbers of independent risks, the party who pools the risk may be able to estimate average losses and so the amount of money (e.g. an insurance premium) needed for dealing with these losses. *Asymmetric information* between the risk-sharing parties (such as between insurer and insured), however, can lead to established premiums being insufficient to cover the losses (Harrington and Niehaus, 1999). Asymmetric information includes moral hazard and adverse selection. In insurance, adverse selection means that exposure units most at risk buy more insurance than others but the extent to which this happens is not known a priori to the insurer. With moral hazard, insured entities change their behavior after having bought insurance in a manner not predicted by the insurer (e.g. by becoming more careless) (Arrow, 1996).

- Pooling independent risks reduces the variance of losses. But if *systemic* (i.e. positively correlated) risks are pooled, the variance of losses decreases less. In pooling completely systemic risks, variance does not decrease at all (Harrington and Niehaus, 1999). Risks that are completely systemic, such as prices and interest rates, generally cannot be commercially insured but can be efficiently dealt with on exchange markets, e.g. by use of futures. Risks that are not completely independent nor completely systemic, the so-called 'in-between risks', (Skees and Barnett, 1999) are more problematical. Examples include droughts affecting crop yields over a substantial area and widespread epidemics of livestock diseases. Organizations that pool such risks face higher costs of pooling because of the need to hold substantial reserves in case systemic events occur (Doherty, 1997).

Micro-insurance has the same principles as outlined above, but this term is used to refer to insurance characterized by low premium and low caps or low coverage limits, sold as part of atypical risk-pooling and marketing arrangements, and designed to service low-income people and businesses not served by typical social or commercial insurance schemes.

Index insurance[5]

In contrast to indemnity-based insurance, index-based products are financial instruments that make payments based on realizations of an underlying index relative to a pre-specified threshold[6]. The underlying index is a transparent and objectively measured random variable. Examples include area average crop yields, area average crop revenues, cumulative rainfall, cumulative temperature, flood levels, sustained wind speeds, and Richter-scale measures. Some highly standardized index-based products are actively traded in secondary markets. However they are mostly customized to fit the specific risk management needs of the purchaser.

If an index-based product is to be effective, the underlying index must meet several conditions. It must be highly correlated with the loss being insured against over a relatively large geographic area. Sufficient historical data must exist from which to estimate the probability distribution of the index. The index must be measured and reported in a timely manner by an objective third party. It must be observable, transparent, secure, and independently verifiable (Hazell and Skees, 2006).

Index-insurance schemes have a number of advantages relative to traditional farm-level yield or revenue insurance. Since realizations of the index are exogenous to policy-holders, index insurance is not subject to the asymmetric information problems that plague traditional insurance products. Transaction costs are much lower since the insurer does not have to verify farm-level expected yields or conduct farm-level loss assessment. This is particularly important in low-income countries where farmers often do not have records of historical yields. Index insurances also have one significant limitation relative to traditional insurance—it is possible for a household to experience a loss and yet not receive a payment from. It is also possible that the household will not experience a loss and yet receive a payment. This ‘‘basis risk’’ occurs because the index is not perfectly correlated with farm-level losses. Of course, basis risk exists with many risk-management instruments (e.g., hedging using futures or options contracts). If the basis risk is relatively small, the instrument can still be a highly effective risk management tool. If the basis risk is quite large, the instrument will likely not be very effective.

Index-based products may be targeted to micro/household, meso, or macro level users. The target market has important implications for the choice of the underlying index. In choosing an appropriate target market and associated index, tradeoffs generally exist between transaction costs and basis risk. For example, separate rainfall Index-based products could be offered based on each of several local weather stations. Alternatively, a single rainfall index-based products could be offered where the index is a weighted average over all of the individual weather stations. If separate Index-based products are offered for each weather station, transaction costs will be high but basis risk may be low relative to the single weighted average index. The single weighted average index will have lower transaction costs but may subject micro-level users to high basis risk, especially if rainfall events tend to be highly localized.

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[5] This section is based on Barnett et al. (2008). For the many references used in their text we refer to their paper.

[6] Index-based products can take on any number of forms including insurance policies, option contracts, catastrophic bonds, or derivatives.

In many cases, households are not the appropriate target for Index-based products. The transaction costs of servicing many small, household-level insurance policies are quite high. Further, at the household level, idiosyncratic risk may be a major component of overall risk exposure. Meso-level commercial enterprises, such as agricultural input suppliers, microfinance institutions, marketing cooperatives, transportation providers, agricultural commodity processors, and retail insurance suppliers, may be better targets for Index-based products. These institutions can, at least to some degree, pool their exposure to household-level idiosyncratic risks but often remain heavily exposed to covariate risks. In addition, decision-makers within meso-level commercial enterprises are more likely to have some prior familiarity with contingent claims instruments than are household decision-makers. Local governments could use Index-based products to transfer some of their exposure to covariate risks. Alternatively, national governments or donor agencies could purchase Index-based products on behalf of local governments.

Both indemnity-based and index insurance have pros and cons

Table 2.3 summarizes the general pros and cons of the two types of insurance.

Table 2.3: Pros and cons of indemnity-based versus index insurance[1].

	Indemnity-based insurance	**Index insurance**
Pros	- Applicable to a wider range of situations than index insurance, as it can cover all risks where losses are involved. - Actuarial procedures for indemnity-based schemes are well established and thus schemes should be easy to run. - As claims are paid by assessing losses directly, there is no issue of basis risk.	- No problem of moral hazard as the behavior of the client does not influence the pay-out. - No problem of adverse selection as pay-out is independent of losses. - No need to assess claims so lower transaction/overhead costs. - Pay-outs can be rapid because claims are verified easily through the index rather than assessment of losses. - Policies can be sold as standard packages.
Cons	- Moral hazard is an issue unless there are deductions built into the premium for risk reduction. - Adverse selection can occur with voluntary schemes, in particular if there is asymmetric information and the client knows more about their risk than the insurer. - Transaction costs and overheads are high because of the need to assess losses. - The loss assessment process can be time-consuming, leading to slower pay-out of indemnities. - Difficulties to deal with covariate risks	- Basis risk, where correlation between payouts and losses breaks down and payment occurs without losses, or *vice versa*. - Historical data needed to create the index, but this may not be an accurate predictor of future conditions. - Needs a relatively homogenous area to ensure that losses correlate to the index.

[1] Derived from among others Skees et al., 1999; Miranda and Vedenov, 2001; Skees et al., 2006; and Agelucci, 2008.

Contracts

Production contracts typically give the contractor considerable control over the production process. Contractors enter production contracts to ensure timeliness and quality of commodity deliveries. For farmers, a guaranteed market access, ensured access to capital and lower variability of incomes are important reasons to enter such contracts. Production contracts are widely used in the broiler industry, and are becoming increasingly important in egg and hog industries (Harwood et al., 1999).

Marketing contracts are agreements between a buyer and a producer that set a price and/or outlet for a commodity before harvest or before the commodity is ready to be marketed. The producer usually remains fully responsible for the management decisions during the production process. The most commonly used marketing contract is the fixed forward price contract. With this type of contract farmers can completely eliminate the price risk. Other forms of marketing contracts do share the price risk between the buyer and seller of the contract (Harwood et al., 1999). (Hedging on futures markets is rather similar to a fixed forward price contract, except for i) futures contracts are standardized contracts that are widely traded (i.e. prices are more competitively determined), and ii) under a futures contract, delivery of the commodity normally does not take place (Hardaker et al., 2004).)

3. Experience with risk management instruments

3.1 A global quick scan

Industrialized countries

A number of authors investigated farmers' perception and use of risk management strategies. For instance, Palinkas and Székely (2008) show significant differences among crop and livestock farmers in selected EU-member states (Table 3.1). For instance, crop insurance is more frequently used in Germany and Spain when compared to Hungary and Poland. In the latter countries, holding financial reserves is perceived as relatively more important. Marketing and production contracts are the least important in Spain. Hedging on futures markets is among the least used strategies in all countries investigated.

Table 3.1: Current use of risk management instruments by crop and livestock farmers in selected EU member states. Numbers are % of respondents using the instrument (Palinkas and Székely, 2008).

	Germany (n=201)	**Hungary (n=195)**	**Netherlands (n=226)**	**Poland (n=206)**	**Spain (n=191)**
On-farm					
Diversification	28.4	23.1	11.5	33.5	18.8
Off-farm investment	49.8	4.1	6.2	1.9	5.8
Off-farm employment	36.8	19.0	17.7	20.4	4.7
Risk-sharing					
Holding financial reserves	61.2	40.5	22.6	51.5	22.5
Avoiding credit	31.3	37.9	38.1	40.3	36.6
Crop insurance	68.7	21.5	30.5	14.1	59.2
Livestock insurance	42.8	4.1	37.2	6.8	36.6
Property insurance	75.1	41.5	66.8	67.5	29.8
Marketing contracts	49.3	38.5	18.6	35.4	12.6
Production contracts	16.4	15.9	20.8	16.0	5.8
Vertical integration[1]	7.0	3.6	4.4	5.8	12.6
Use of futures markets	5.0	1.5	1.3	2.9	1.0

[1] Combination of production and marketing contracts.

Harwood et al. (1999) reported that in the US, operators in the largest gross income category (> $250,000 annually) are most likely to use hedging, forward contracting, and virtually all other risk management strategies. In contrast, operators with less than $50,000 in sales were less likely to use forward contracting or hedging, and significantly less farmers were found to use diversification as a method for reducing risk. Keeping cash on hand for emergencies and good buys was the number one strategy for every size of farm, for every commodity specialty, and in every region.

In New Zealand, a survey among sheep and beef farmers (Martin and McLeay, 1998) revealed 5 categories of farmers, i.e. income spreaders (scoring high on diversification and information gathering), capital managers (scoring high on keeping debt low and having insurance), part-timers, risk managers (scoring high on debt and feed management) and production managers. The latter score relatively high on feed management including maintaining feed reserves and not producing to full capacity.

In a Norwegian study of risk management of cash crop farmers, Koesling et al. (2004) concluded that good liquidity was the top rated strategy. The next most highly ranked strategy was to prevent and reduce crop diseases and pets, followed by buying farm business insurance, and producing at lowest possible costs.

In Australia, the risk management market is dominated by private industry (not much public involvement) and the weather risk market is relatively underdeveloped. A few years ago the state government of Western Australia created a task force to investigate alternatives to multi-peril crop insurance. This task force investigated the possibility of using weather derivatives but expressed concerns that transaction costs would put such schemes out of reach of the average farmer. In 2007, a water stress insurance was launched (as part of a wheat insurance policy covering both field perils and water stress). The water stress coverage uses a crop simulation model to trigger payments. Simulated yield values must show a reduction in simulated yield from the forecast value produced at the start of the season to the value produced at the end of the season. Actual indemnities to the farmer depend on (i) evidence of actual loss of yield on property insured, confirmed by an agronomist; and (ii) the residual value of the crop after correcting for the insured field perils. Up till now the uptake is relatively low. Research is underway to investigate why this is so.

In general, for industrialized countries, it can be concluded that there is a myriad of risk management instruments. Usage varies among countries due to such factors as government subsidies (compare subsidized crop insurance in Spain versus non-subsidized insurance markets in Australia) and acquaintance with markets (compare degree of hedging on futures market in US versus Europe and elsewhere). It also becomes clear that, among others due to climate change, even highly developed countries such as Australia are searching and trying out new risk management strategies to support their farmers.

Developing countries

On the exact usage of risk management instruments in developing countries not much information exists. Statements found in literature, by country or type of instrument:

- *Insurance*. For micro-insurance, Roth et al. (2007) state that in Africa only 4% of lives is covered with micro-insurance. More generally, insurance coverage in developing countries is stated to be low as only 3% of losses caused by disasters is covered by insurance. Table 3.2 indicates commodities insured in low-income countries. Literature does not describe whether they are commercial schemes or micro-insurance schemes. None of them refers to African countries. Typical problems reported for indemnity-based and index insurance schemes in low-income countries are listed in Table 3.3. Problems relate both to the availability and uptake of the insurance schemes. To “combine the best of both products”, several authors, among others Skees et al. (2006) suggest to develop “*blended products*” in which (i) the covariate risk is covered by index-products deployed by governments, reinsurers or banks; and (ii) the idiosyncratic part of risk is covered by conventional insurance products sold by local companies. Additional possibilities are to design “*bundled products*” in which insurance is linked with e.g. loans and the possibility to buy improved seed (as was the case in Malawi, see next section).

- *Micro-finance*. It is estimated that about two-third of the world's population has no access to financial institutions. However, current interest of commercial companies in investing in micro-finance projects is believed to reduce this share drastically in the following decades (Trouw, July 18, 2009). With regard to the experience of micro-finance projects there are numerous studies that demonstrate the tremendous successes of micro-finance programs throughout much of the underdeveloped world. However, the universal effectiveness of microfinance institutions in alleviating poverty is still in question, and not free from debate. Much of the evidence cited for the successes of microfinance and microcredit are merely anecdotal or involve in-depth case-study approaches, which provide vivid examples and rich details of the impact and effectiveness of specific programs in specific locations at a specific time, but generally fail to achieve a more rigorous standard that would allow for research findings to be widely generalized. Some more rigorous studies have been conducted and more are surely to follow, but in the meantime, NGO leaders and government policy makers must exercise caution and restraint in applying the microfinance approach universally as a means of alleviating poverty (Westover, 2008).

- *Contracts*. Contract farming in developing countries has experienced a mixed fortune, yielding some successes and many failures (Kirsten and Sartorius, 2002). Literature criticizes contract farming as an institution leading to an increase in the marginalisation of farmers and communities that do not participate in contacting. In this respect, it is argued that technological advances are passed on to the minority, resulting in uneven benefits that do not necessarily suit the needs of the developing country concerned. Furthermore, there is evidence of an increase in landlessness as a result of contract farming expanding land requirements. In the African context, contract farming has been observed to disrupt power relations with farm households; to exploit an unequal power relationship with growers; and to lead to growers becoming overly dependent on their contracts. Kirsten and Sartorius (2002) argue that possibilities for a more viable contract farming approach in developing countries exists, but only if put in the right context of contract enforcement mechanisms, principle-agent problems and governance structures.

- *Reduced consumption*. The poorest households are typically least insured against shocks. It has been reported that for the poorest in the world, 40 percent of an income shock is being passed onto current consumption (Dercon, 2000). (By contrast, consumption by the richest third of households is protected from almost 90 percent of an income shock.) This seems to be in line with findings for Ethiopia (also from Dercon, 2000), that between 52% and 100% of surveyed households (n=520) cut back on food during crises in the 1980s.

Table 3.2: Ongoing indemnity-based insurance schemes for selected groups of commodities and countries

	Related countries
Arable crops	Greece, Argentina, Brazil, Cyprus, Malaysia, Phillippines
Horticulture	Cyprus, Brazil, India, Malaysia
Livestock	Brazil, Ecuador, Mexico, Panama
Woodland	Malaysia
Aquaculture	Bangladesh (pilot), Brazil (pilot), Chile

[1] Derived from Roberts, 2005; Roberts, 2007; Angelucci, 2008; and Garrido and Bielza, 2008.

Table 3.3: Reported difficulties of indemnity-based and index insurance for agriculture in low-income countries[1]

Indemnity-based insurance	Index insurance
- High loss ratios	- Limited data availability
- Limited availability	- Frauding with data
- Hesitations to include droughts	- Basis risk
- Lack of knowledge	- Difficult to understand, therefore low uptake[2]
- Lack of insurance expertise	- Difficulty of ex-ante paying of premium rates
- Lack of historical farm data	
- Relatively high administrative costs	
- Difficulty of ex-ante paying of premium rates	

[1] Derived from among others Dercon, 2004; Bryla and Syroka, 2007; MicroInsurance Agency, 2007; Skees et al., 2008; and Cummins and Mahul, 2009.

[2] "How could the participation by neighbors ever overcome the problems of covariate risk so often faced under mutual insurance arrangements".

The impact of subsidies

If governments subsidies part of the insurance costs (premium, administrative costs, reinsurance), insurance becomes more affordable and provision and uptake will likely be higher. An example can be found in the US. Here, in contrast to many countries in the world, a myriad of agricultural insurance products has emerged including enhancements on traditional crop insurance and revenue insurance. In the USA, private companies deliver and service crop and revenue insurance schemes. Subsidies are provided for the farmer-paid premiums, for delivery and administration, and for the private sector reinsurance. Farmers in the USA pay about 25 per cent of the total cost of risk management programs (Meuwissen et al., 2003).

Also in Spain, a very extensive—and heavily subsidized—insurance program exists. The scheme covers all types of crop production, beef, sheep and goat production, and specific forms of fish farming. Risks covered include: (a) for crops, the main natural risks (hail, frost, flood, drought, wind, fire etc.); (b) for livestock, mortality or culling, whether accidental or due to specific diseases; and (c) for aquaculture, accidental damage and losses due to contamination or specific diseases. The insurance program is subsidized by the Ministry of Agriculture and (to a small extent) by regional governments. Costs are subsidized up to 45 per cent, depending on the type of commodity and the terms of the contract. Table 3.1 showed a relatively high uptake of crop insurance in Spain compared to non-subsidized countries such as the Netherlands and countries in which insurance is not well developed yet (Hungary and Poland).

Possible distortions occurring from subsidies

Although seemingly interesting, subsidies have often been argued to bring distortions to the system through resource misallocation, rent seeking, capitalization, moral hazard and crowding out:

- In economics, rent seeking occurs when an individual, organization or firm seeks to make money by manipulating the economic and/or legal environment rather than by trade and production of wealth. Typical examples include a farm lobby that seeks an insurance subsidy, tariff protection or income support. Other examples would be farmers manipulating yields or choice of crop to grow to maximize receipts from subsidized yield insurance, or commercial insurers off-loading their worst risk to a government reinsurer.

- One fundamental point meriting consideration is the effect of capitalization (Browne et al., 1992). Almost all farm subsidies thus also premium subsidies, tend to get capitalized into asset values (mainly manifesting itself by increased land prices or increased costs to require production rights).
- Another point is the impact that moral hazard has on the alteration of the production plan in order to maximize the subsidy at the expense of the overall welfare (i.e., excessive risk exposure). Governmental support to farmers may create these perverse incentives. Literature suggests that subsidized crop insurance encourages production in marginal, high-risk, areas (Wu, 1999). If this is true subsidies cause losses to become self-perpetuating and society's scarce resources to be misallocated (Barnett, 1999).
- Governmental support crowds out demand for private sector risk management tools (Skees and Barnett, 1999) and/or inhibits the development of innovative new risk management tools by commercial insurers. The extent depends both on the level of subsidy provided as well as on how it is directed. Cummins and Mahul (2009) suggest least distorting ways for government involvement in catastrophe risk financing (section 3.4).

3.2 Case studies on insurance in dryland agriculture

Index products in many countries in designing or pilot phase

While index-based programs are either in place or under development in several middle or low-income countries, there is not yet sufficient experience to draw definitive conclusions about the long-run sustainability of these programs. Except for India (see below), existing index-based programs are in pilot stages so the volume of sales has been limited (Barnett et al., 2008). Some ongoing and discontinued case studies are elaborated on below[7].

Rainfall index insurance in India (ongoing)

In India, ICICI Lombard General Insurance Company has sold Index insurance to farmers since 2003. ICICI Lombard partners with local financial institutions to market the policies to farmers. The Index insurance were first offered in the state of Andra Pradesh and marketed through the microfinance institution BASIX (Hess, 2003). In Andra Pradesh, the Index insurance schemes currently protect against insufficient rainfall during the sowing and crop growth phases of the Kharif (monsoon season) and against excessive rainfall during the harvest phase. ICICI Lombard's rainfall-based index-insurance offerings have continued to expand such that in 2005, more than 7,600 policies were sold across six Indian states. In 2004, the Indian parastatal insurance company AICI also began selling weather-based Index insurance to farmers. In 2005–06, AICI sold index-based policies to more than 125,000 farmers, however most of the policies were sold in only one state Maharashtra. Syroka (2009) summarizes the product's success due to

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[7] Largely based on Skees et al. (2007), Barnet et al. (2008), Skees and Collier (2008) and Skees et al. (2008). For further readings and references we refer to their work.

the following critical factors: collaboration, piloting product concepts, channeling customer feedback into product design, continuous improvements in each product cycle, emphasis on product communication to customers who are illiterate, and efficient policy distribution and claim servicing.

Index-based livestock insurance in Mongolia (ongoing) – example of "blended product"

Livestock herding plays a very important role in Mongolia, contributing to 87% of agricultural GDP, and the importance of herding to the livelihoods of rural people has increased since the decline of collectivized agriculture (the number of herding families doubled from 1990-1997). Livestock herders are vulnerable to large losses due to drought or dzuds (very severe winters/springs), and traditional coping strategies or government aid are often not enough to mitigate the problems that these severe events cause. For example during the dzuds of 2000-2002 it is estimated that 11 million animals died. In addition, government or donor aid provides very little incentive to herders to reduce the risk to their herds. Improved pastoral risk management is an integral part of Mongolia's Poverty Reduction Strategy. Conventional insurance for livestock has not worked in the Mongolian context due to problems of moral hazard (if losses are replaced there is no incentive to reduce risk) and difficulties in verifying claims in the wide expanses of Mongolia. The World Bank has been working with the government of Mongolia to develop an index-based scheme as an alternative to support pastoral risk management.

Based on historic data about livestock losses, an index (based on area livestock mortality rate) has been developed where payouts to herders occurs when livestock losses at the regional scale exceed a trigger point (7%), and become larger the greater the livestock losses are, until an "exhaustion point" (25% or 30%). A government run "disaster response product" begins to pay out if losses exceed the exhaustion point. Herders take out premiums based on the value of their animals and the number that they want to insure, and then if regional losses exceed the trigger point there is a sliding scale of increasing payment until the exhaustion point. The premium buys the herders the Basic insurance product, which covers them for regional losses up to 25-30%, and automatically registers them for the government run "disaster response product" which begins to pay out if regional losses are above this, so in effect provides a safety net. Being based on regional losses, the scheme avoids the problem of moral hazard, as a herder who protects his animals better than his neighbor will still receive the same pay-out, but will benefit by having more animals survive.

So the insurance scheme actually operates in three tiers; small losses are absorbed by the herders themselves through traditional measures, large events cause the private sector to pay-out to herders, and catastrophic events where losses larger than the exhaustion point of the scheme occur, cause the government scheme to provide additional payouts. This limits the losses to the commercial insurers, encouraging them to be involved in the scheme: (i) up to 7% regional losses: no payout, herders must absorb the losses; (ii) 7-25 or 30% regional losses: basic insurance product (run by commercial companies) pays out; and (iii) above 30% regional losses: disaster response product (run by government) begins pay-outs.

Skees et al. (2008) state that plans are also underway to link the base insurance product (first tier) to rural lending to improve herders' access to credit and to remove some of the banks' risk of lending to herders who may lack traditional sources of collateral. Also, there is continued research to reduce basis risk by incorporating other indexes, for example, the Normalized Difference Vegetation Index.

Some discontinued index programs

- *Ethiopia*: Index-linked crop insurance. A small pilot weather insurance program was launched for maize farmers in Alaba, a region of Southern Ethiopia. The insurance protected farmers against rainfall shortages during the maize growing season. Only 30 policies were sold during 2006. The program was closed after the pilot. Key reasons for failure: (i) Insufficient quantity and quality of weather data. The weather observing network and available weather data in Ethiopia was insufficient. The spatial distribution of the 500 weather stations and rain gauges were inadequate. Basis risk remained at unacceptable levels. Only farmers living near good weather stations were in a position to benefit from the insurance product. (ii) Lack of pre-existing rural network. The pilot failed to identify any organizations that could be used to reach clients effectively and provide capacity building and product education to farmer clients. Commonly, banks act as a distribution agent, but in this case no banks were willing to get involved since their fertilizer loans (to farmers) were already guaranteed by the government. As the insurance company had no existing goodwill in the region, it was unable to inspire trust among skeptical farmers. (iii) Inability to secure reinsurance. The Ethiopian Insurance Corporation was unable to secure international reinsurance. This is likely due in part to the small values for this risk transfer and may be remedied by increased client uptake of the product.

- *Morocco*: Rainfall index insurance. In 1995 the Moroccan government introduced the program, “Secheresse” (Drought Program), a state sponsored yield insurance scheme. The program was very popular (in 2002 subscriptions reached 80 percent of the 300,000 authorized hectares), but was affected by high costs associated with fraud, monitoring for moral hazard and adverse selection, and loss adjustment. In 2001 the Moroccan Government agreed to a World Bank project to evaluate the possibility of introducing weather index insurance. The product, based on a rainfall index, was more sophisticated than many index products including multiple triggers in an attempt to reduce basis risks. The product weighted the different plant growing phases and introduced a rainfall “cap” that accounted for the occurrence of rainfall in excess of the soil storage capacity resulting in a close correlation coefficient with cereal production. Though the complicated structure reduced basis risk, farmer test groups did not seem to be impressed with these changes and may have had more difficulty in estimating the value of the product. The rainfall index insurance was to be sold through branches of the agricultural mutual insurance company, MAMDA, as it had a significant presence in rural areas and already managed the state sponsored Drought Plan. Implementation never took place. The rainfall precipitation data in the selected implementation areas showed a downward trend. Based on this information the reinsurance company that was prepared to accept the risk proposed a high premium that could not be passed on to policyholders.

- *Malawi*: index-linked crop insurance (“bundled product”). Malawi yield data are limited and may be unreliable, and thus, alternative methods for structuring the rainfall insurance payout were pursued after the first year of the pilot (2005). The Malawi product used the FAO Water Requirement Satisfaction Index (WRSI) to establish the contract structure for drought insurance for groundnut. The WRSI is the ratio of water availability for a crop to water requirements for a crop during a season. The WRSI is weighted based on water needs during critical stages of development. The index insurance program was bundled with a loan and a specific input package that had improved seed. Without the associated drought index insurance, farmers would not be offered credit to purchase the improved seed varieties. Farmers who purchased the index insurance agreed to sell their yields to NASFAM (National Smallholder Farmers Association). NASFAM acted as a delivery channel for the loan and insurance payouts and deducted the price of the loan from its payments to farmers for their yields. Insurance policies only covered the cost of seed for which farmers borrow from the bank, paying premiums at 6–7 percent of loan values. In the event of a payout, NASFAM deducted the amount from the farmer's loan and passed the payout on to the bank. NASFAM deducted the leftover loan liability from farmers' yield proceeds. In the event of a total payout, indemnities equaled the value of the loan, and NASFAM did not deduct any amount from yield proceeds for loan payments. The program discontinued in 2007 (Syroka, 2009), among others because (i) groundnuts markets being prone to side-selling, leading to non-weather related defaults; (ii) a nascent agricultural supply chain with many problems other than weather; and (iii) banks stopped lending to groundnuts in 2007, so "no need for insurance".

4. Estimating the value of risk management instruments

4.1 Benefits of risk-sharing instruments

For the farmer

In general, it is assumed that farmers are risk averse, i.e. they are willing to pay a premium to reduce exposure to risk. If farmers can trade away part of the risks on their farm at an acceptable cost, the expected utility of the farmer will increase (Arrow, 1996; Harrington and Niehaus, 1999).

Although sharing risks can increase a farmer's utility, (s)he is not likely to share all risks. It is (largely) up to each individual farmer to decide which risks—and which part of them—to share. Factors that may influence this decision include a farmer's degree of risk aversion, the costs involved in risk sharing, the relative size of a risk, the correlation of the risk with other risks, other sources of indemnity, a farmer's perception of the nature of risk, and a farmer's income and wealth (Harrington and Niehaus, 1999; Hardaker et al., 2004).

Also important for the farmer's decision about which risks to share and which to bear is that this decision is part of the overall risk management problem facing of the farmer of selecting a risk-efficient portfolio of on-farm and off-farm risky instruments. Thus, for example, a decision about whether to insure against a particular risk, and if so to what extent, cannot properly be made without reference to other risky choices. In general, it will be impossible to say whether the net effect of the introduction of a new risk management instrument will increase or reduce either the mean or the variance of net returns. It depends on how the interactions with other risks on the farm and with other risk management instruments work out.

This was also illustrated by Meuwissen et al. (2008b) who indicate that the effect of more direct payments in EU agriculture not necessarily implies less volatility. Increased stability of part of the income (from subsidies in the EU example) is likely to induce farmers to take more risk in the other part of the business. Although the size of this effect is not clear, it likely reinforces the volatility of markets and prices.

The above statements imply that there are no universal rules about which risks to share and which not. Only in a few cases is it not completely up to the farmer what risks are managed and by what type of strategies. For example, lenders may require that farmers use one or more risk management strategies, such as crop insurance and forward contracting, when a loan is contracted (Harwood et al., 1999).

For society

If farmers are able to share (part of) their risk, society may be better off, as discussed by Arrow (1992), Rejda (1998) and Hardaker et al. (2004), among others:

- If two individuals freely enter a contract, then both of them must be better off (i.e. there must be an increase in utility for both). The sum of many such contracts makes society better off (unless other individuals are injured in some way).

- The possibility of sharing risk permits individuals to engage in risky activities which they would not otherwise undertake. That way, the expected return to society is increased over what would prevail if individual agents were constrained to accept only those risks they could afford to bear themselves. If farmers can trade away part of their risks, so that they can move closer, not fully because there are costs involved, to the point of expected profit maximization, the result is a more socially desirable allocation of resources.

- Trading away risks is likely to result in more stable farmers' incomes. More stable incomes are likely to lead to more stable expenditures on farm inputs and family consumption, thereby implying more stability for rural businesses with possible flow-on benefits for the society as a whole, for example via more rural employment. Moreover, it seems likely that more stable farm incomes may contribute to the viability of rural towns since there appears to be a degree of irreversibility in the provision of retail and service activities in such communities. A downturn in farm incomes and hence in spending by farm families leads to the closure of some local businesses and to the withdrawal of government and commercially-provided services, yet these lost facilities are seldom fully replaced when farmers incomes recover later.

- More stable rural incomes for farmers (and other rural businesses) mean more reliable repayment of loans. That should be reflected in improved access to credit and/or lower borrowing costs, implying increased productive investment in the rural sector.

- If farmers are able to trade away (part of) the disastrous risks they face, the resilience (or sustainability) of farms increases, which may mean less human, animal and environmental distress after the occurrence of disasters such as severe floods or droughts. This, however, is only true if moral hazard is dealt with properly. Otherwise, farmers may, for example, pay less attention to the prevention of disease outbreaks, leading to an increase in the number of disasters occurring. Or, farmers may pay less attention to their stock during droughts, leading to more—instead of less—animal distress.

4.2 Estimating the value of risk-sharing instruments

During the last decades several authors have been investigating the value of risk-sharing instruments, mainly insurance schemes. "Value parameters" range from empirical loss ratios to normative shortfall risks. Table 4.1 summarizes methods, risk-sharing instruments investigated and parameters under consideration from various sources. Hazell (1992) and Cummins and Mahul (2009) refer (among others) to developing countries.

From the right-hand column of Table 4.1 it can be seen that various "value parameters" are reported in literature. But when can case studies said to be effective? Although effectiveness is more easy to measure than efficiency, there obviously can be no single criterion that captures the complete information about the achieved effect. (Note that, contrary to efficiency, the focus of effectiveness is the achievement of defined objectives of stakeholders, not the resources spent in achieving the desired effects.) Based on criteria of effectiveness, quantitative indicators can be derived to evaluate an insurance strategy. Commonly, the proportion of insured production (i.e. penetration), premium subsidies (e.g., measured as a percentage over total premium), and loss ratios (i.e. ratio of losses to earned premiums) are reported to compare and evaluate insurance schemes. It should be noted however that these criteria still provide only a partial analysis since they do not answer questions such as “who benefits from a subsidized insurance scheme?” and “do farmers need government-provided risk protection via insurance?” Additional indicators would clarify these matters, such as the effect that insurance has on farm household income fluctuations. Such ex-post empirical analyses are however not available in literature.

Table 4.1: Methods and parameters for estimating the value of risk-sharing instruments

	Method	Schemes considered[1]	Countries	Parameters
Hazell (1992)	Empirical	Agricultural insurance (public and private)	Brazil, Costa Rica, India, Japan, Mexico, Philippines, USA	Loss ratio
Meuwissen et al. (1999)	Partial analysis (normative)	Yield insurance, revenue insurance	9 regions in EU	Mean, CV, shortfall risk
Baltussen et al. (2008)	Expert elicitation	NISA, GRIP, crop insurance, subsidized loans, AIDA and CFIP, CAIS, ad-hoc government support, CAP direct payments, animal disease funds, business interruption insurance, rainfall mutual, disaster loans, revenue insurance, MPCI, GRP	Canada, USA, Estonia, Netherlands, Germany, Spain, Poland	Basic performance, efficacy, distortions[2]
Van Asseldonk et al. (2008)	Whole farm optimization (normative)	Yield, revenue and index insurance	Spain, Poland, Germany, Netherlands, Hungary	Mean, CV[3]
Cummins and Mahul (2009)	Empirical	Property catastrophe insurance for homeowners, agricultural insurance, sovereign catastrophe risk insurance	Turkey, Romania, China, Mongolia, India, Malawi, Central America, Thailand, Ethiopia, Senegal, Kenya, Nepal, Bangladesh, Vietnam, Indonesia, Mexico, Colombia, South Pacific Islands	Status, volume, donor role
OECD (2009)	Empirical	Ex-ante and ex-post strategies[4]	OECD and emerging economies (Brazil, Chile, China, Russia, South Africa, Ukraine, Argentina, Israel	Availability of schemes

[1] NISA = net income stabilization accounts, GRIP = group risk income protection, AIDA = agricultural income disaster assistance, CFIP = Canadian farm income program, CAIS = Canadian agricultural income stabilization, CAP = common agricultural policy, MPCI = multiple peril crop insurance, GRP = group risk plan.

[2] Basic performance = loss ratio and loss adjustment costs; efficacy = efficacy from farmers' and government perspective, deductible, differentiation and participation; distortions = degree of adverse selection, moral hazard, incentives for misreporting, incentives for excessive risk exposure, crowding out privately offered instruments.

[3] CV=coefficient of variation.

[4] Ex-ante = subsidies to risk management tools, income tax smoothing, income diversification support, farm relief service; ex-post = disaster relief, ad-hoc assistance, social assistance, debt rescheduling.

4.3 Incorporating agricultural risk management in watershed modeling exercise

Although assessing the value of risk-sharing strategies is not straightforward (see sections 4.1 and 4.2) the most commonly used ex-ante method to gain insight into the value of a risk-sharing tool is by means of (i) simulation to generate (future) data; (ii) whole-farm optimization to analyze the impact on mean and variance of farm income; and (iii) aggregate level simulation to gain insight into risks and financial consequences of e.g. (governmental) reinsurers. In order to do so we propose various steps, as outlined below. They largely converge with those identified by Cummins and Mahul (2009) who state that a catastrophe risk model should consist of various modules, i.e. a stochastic module, a hazard and vulnerability nodule and a financial module, in order to come up with aggregate loss functions.

Selection and design of risk management instruments

- For savings and finance: interest rates and payback periods.
- For indemnity-based insurance: level of deductible (e.g. strike level at 80% of the mean which implies a deductible of 20%), risk premium (expected claim costs)[8] and loadings.
- For index-products: level of basis risk (e.g. chance of payments is 75% if actual losses occur), risk premium and loadings.
- For contracts: thresholds for quantity and price, and level of penalty if quantities are not met.

Choice and design of (a mix of) strategies depends on the particular circumstances under investigation. Although insurance schemes often seem most straightforward other tools may be relevant as well.

Measuring the risk

Depending on the tool(s) selected, data need to be gathered on e.g. weather, correlation with price, and correlations among commodities. Such data can then be described in various ways:

- "Let the data speak", i.e. derive cumulative probability distributions (Hardaker et al., 2004).
- By estimating its mean and variance, i.e. by assuming a normal distribution. Although yield distributions are typically negatively skewed, the normal distribution is computationally convenient. In addition, yield deviations from normality may not be great (Harwood et al., 1999).
- By estimating the probability of outcomes below some critical level (shortfall), e.g. of yields falling below 70 percent of its expectation.

Yield (and weather) data typically also need to be corrected for trend. For instance, for index insurance Barnett et al. (2008) state that [..] the process that generates random realizations of the index must be either inherently stationary and homoskedastic (as is true for some climatic variables) or else one must be able to manipulate the historical data using statistical trend adjustment and heteroskedasticity correction procedures to generate an accurate probability distribution of the index (as is often done with area yield indices).

Modeling effectiveness from a farmer's perspective

Given the information from the previous two steps, we can then derive farm income distributions for various scenarios varying in (the portfolio of) risk management strategies applied. Several methods are available to assess the effectiveness of the strategies:

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[8] Result from combining risk data and strike levels.

- The “safety-first” approach. An example of this method involves choosing the set of activities with the smallest probability of yielding an expect return below a specified disaster level. This method is particularly applicable where survival of a farm is the paramount concern. However, in most business risk management situations, the use of safety-first methods is somewhat arbitrary because no single goal is clearly dominant (Harwood et al., 1999).

- The expected value-variance approach and quadratic programming. In this approach the optimal combination of activities for the farmer occurs at the point that provides the preferred combination of expected return and variance of return. It is assumed that the farmer always prefers more (rather than less) of the variable in question (such as income), and is assumed not to be risk preferring with respect to that variable (Hardaker et al., 2004). Other optimization methods have been used for optimizing farm portfolios as well, such as Utility-efficient programming (Van Asseldonk et al., 2008) and shortfall models (Berg and Starp, 2006).

- Stochastic Dominance Approach. Unlike the E-V analysis, which is based on the mean and variance of a distribution, stochastic dominance involves comparing points on two or more entire distributions (Hardaker et al., 2004). Various rules of dominance can be applied.

- Expect utility approach. If a decision maker’s risk preference can be described mathematically and the probability distributions associated with each risky alternative are known, his or her choice among the alternatives can be optimized directly. Although this method enables to rank all alternatives, its major drawback is that utility functions are difficult to estimate (Harwood et al., 1999).

All of the proposed analyses allow to consider the whole portfolio of activities on a farm, i.e. they are not partial analyses.

Modeling aggregate loss distributions, e.g. to model financial impacts for governments

For financial institutions and governments it is mostly the aggregate picture that is relevant. For instance, if reinsurers or governments provide stop loss coverage, figures such as annual probability of payment and extent of payment are useful for calculating reinsurance premiums and budgetary consequences respectively, see e.g. Meuwissen et al. (2003) and Meuwissen et al. (2006). To move from the risk data as described above to data for modeling the aggregate loss distribution, insight is needed into the correlation of losses among farmers (idiosyncratic or systemic).

5. Scaling up the use of agricultural risk management measures

5.1 Multiple items on the agenda

Mind the whole package

From previous chapters it can be concluded that, among others due to changing climate, there is increasing need for dryland populations to manage risks financially through risk sharing at the microscale and macroscale (Brown and Hansen, 2008). It can also be learned that in the field of risk-sharing instruments to cope with water risk, some successes can be listed (e.g. index-insurance in India) but that at the same time many difficulties exist (e.g. Malawi index insurance, low uptake of water stress insurance in Australia, relatively limited availability of micro-finance, and skepticism on the viability of contract farming). Successes and failures at the same seem very case specific. A general conclusion from reviewing the literature on risk management in dryland agriculture is that “things never come alone”; it is always a package of measures that is needed to develop viable strategies. We therefore go through a number of layers of “the package” that are deemed necessary.

Getting the basics right

Hazell et al. (2007) bring forward three central elements on the agenda of smallholder development for growth and equity:

(1) *Stability and transparency*. This step includes ensuring that the macro-economy is stable and that public goods, such as rural roads, rural education and health case, and agricultural research and extension, are funded by the state. This also includes good governance for agricultural and rural development, ensuring the rule of law, providing opportunities for resolving disputes, and making any public interventions in food and credit markets as transparent and predictable as possible.

(2) *Enhance markets*. This involves encouraging farmers to follow demand and to improve marketing systems. Improving marketing systems so that farmers receive a greater share of market prices may involve upgrading transport infrastructure and systems, providing credit to traders and processors, and forming farmer associations for bulk marketing.

(3) *Institutional innovation in the provision of inputs and services*. Experience has shown that liberalized markets often do not work well in rural areas. Institutional innovations are required to overcome coordination problems in the provision of inputs, finance, and technical and output marketing services.

Multiple layers of risk management

Dick (2009) argues that adequate agricultural risk management models consist of four central elements: (i) *institutional capacity building*, among others with respect to data management, information and education, program administration, and technical expertise; (ii) *agribusiness segmentation*, i.e. to distinguish between social versus commercial insurance, and traditional, emerging and commercial farming sectors; (iii) *agricultural risk assessment*, consisting of risk identification, risk quantification and a probabilistic agricultural risk model; (and iv) *agricultural risk financing*, in which risks are layered (retention, insurance, commercial reinsurance, catastrophe government reinsurance) and consequently most viable options are investigated (index, pooling, rural finance).

This model comes close to the statement of Varangis et al. (2000) who state that [..] today, an adequate risk management framework must involve multiple strategies (prevention, mitigation, coping, management) and arrangements (informal, market-based, public) for dealing with risk, and instruments that take account of the sources and characteristics of rural risk.

In case of an index-based product: also multiple aspects to consider

From previous chapters, it becomes clear that index-products are piloted in a number of countries, stand-alone, or in blended or bundled strategies. In any case, for index-products to work effectively a number of conditions needs to be fulfilled. Skees et al. (2007) summarize them as follows:

(1) *Forecasting weather events*. Farm households often have means of forecasting the weather based on observation and experience. Sales closing dates must be set far enough in advance that the clients cannot rely on these forecasting means to determine the likelihood of an insurance payout.

(2) *Contract structure*. Careful consideration should be given to how the insurance contract is structured. In fact, failure to understand the structure of the insurance contract is one of the key reasons farmers cite for choosing not to purchase insurance. Some products have complex structures that reduce basis risk by using a combination of indexes to determine losses. However farmers' concerns regarding basis risk does not seem to be significantly reduced by these more complex contracts. It is unclear if these increases in basis risk outweigh the sacrifices to transparency and flexibility of simpler contracts.

(3) *Meteorological infrastructure, data availability and data quality*. Appropriate meteorological data remains vital to the success of index insurance products. Adequate data must exist to assess and price the risk. Quality real-time data and sufficient density of data stations is also needed to estimate losses and minimize basis risk.

(4) *Delivery channel*. The transaction costs of insurance must be reduced to facilitate the development of financial markets in rural areas of developing countries. Paying agents to sell insurance and deliver payments in remote areas can be expensive. These costs increase the price of insurance. For the poor to afford insurance products, low-cost delivery mechanisms are needed, such as through governments or other networks with pre-existing connections to rural households.

(5) *Marketing and education*. Major marketing and education are needed to ensure the success of index insurance products. Effective marketing in lower income countries increases the familiarity of target clients with the index insurance product. Households in some countries report having had negative experiences using insurance products in the past so differentiating index insurance from past insurance schemes may be an important goal for marketing initiatives.

(6) *Client uptake*. Client uptake is clearly affected by marketing and education implementation; however, other factors of product design affect the uptake and long-term viability of index insurance products.

  - Products must be affordable to clients. Index insurance has quickly gained popularity because its structure yields lower administrative costs over traditional agricultural insurance; however, given constraints such as delivery costs, marketing and education needs, catastrophic weather financing, index insurance may still be unattractive to insurance markets without substantial support for research and development to address the challenges.

- Cognitive failure**.** Individuals are much less likely to plan for low-probability, high-consequence risks. This cognitive failure is a known psychological phenomenon and affects the willingness of poor individuals to spend their limited income to cover these risks. In fact, the poor tend to select payouts for relatively low liability levels and for smaller magnitude events. Given this cognitive failure, it is unclear how long households will be willing to purchase index insurance if they do not experience large payouts within the first several years of purchasing index insurance. In general, the renewal rate for farm household purchasing index insurance is relatively low.

- Basis risk. Basis risk may prevent farmers from using index insurance to underwrite moderate losses. Basis risk is reduced for high-impact losses that affect a whole community; however, for moderate losses that affect only some of the individuals, basis risk is higher.

- Even if products can be delivered to rural households through government bodies or pre-existing networks, cognitive failure and basis risk may continue to discourage the poor from purchasing index insurance in the long term. Since lenders, self-help groups, and value chain members have a vested interest in smallholders having catastrophic weather insurance, these intermediaries are motivated to provide incentives to smallholders that can increase uptake. This can be done by linking products to other services such as loans or input supplies. In some cases lenders have provided increased access to credit and lower interest rates to households with index insurance who might otherwise not be able to obtain loans for lack of assets. Self-help groups might provide discounts for other services to members who sign up for catastrophic risk coverage.

Although the above aspects and experiences are listed from an index-insurance perspective, similar issues are likely to hold for (introducing) other risk-sharing tools in low-income countries.

5.2 Policy implications

From the above, various roles for governments can be derived. They largely converge with those of Cummins and mahul (2009), who, in the field of catastrophe risk financing, identify four key paths of intervention for donors and international financial institutions:

(1) Convening power, including a catalytic role in the development of efficient partnerships among countries, donors, and private markets.

(2) Promoter of public goods that permit the development of risk market infrastructure, such as data collection and management, design of risk assessment tools, awareness and education campaigns and legal and regulatory systems.
(3) Provider of technical assistance for innovative catastrophe insurance solutions, referring to a mix of index-based insurance solutions, risk-pooling vehicles (creating new business opportunities for the private reinsurance market), and risk transfer vehicles (e.g. by assisting in reinsuring weather-based crop insurance portfolios on the international reinsurance markets).
(4) Financier, in a role as seeder of initial capital and reserves, provider of contingent loans, provider of short term premium financing, and as a guarantor of future liabilities.

In their paper on scaling up index insurance, Skees et al. (2007) largely see similar roles for governments and donors although they strongly recommend for governments not to provide direct premium subsidies, as this undermines the incentives for private-sector insurance companies. Also, such subsidies are perceived to generally favor wealthier farm households and thus erode poverty-reduction objectives. Even targeted premium subsidies rarely work as planned. Also Meuwissen et al. (2008a, b) conclude that direct premium subsidies should be avoided in setting up risk-sharing tools.

5.3 Ways to go forward in the field of modeling

For risk modelers, many of the items described in 5.1 and 5.2 need to be taken for granted, i.e. they are a “condicio sine qua non”. Their work however can be important in enhancing markets and providing technical assistance. A relevant roadmap for the watershed modeling could be to:

(1) identify *probability distributions* (yields, prices) and correlations;
(2) use these as a basis for *risk layering* to identify risk retention, insurance and catastrophe layers (possibly different for social versus commercial farms and for traditional, emerging and commercial farmers);
(3) define various *risk management designs* for each layer, including issues of contract design, basis risk and trigger values;
(4) asses *farm-level effectiveness*, e.g. at first instance through safety-first methods and stochastic dominance;
(5) estimate *aggregate loss functions* in order to identify risks in the (re)insurance and catastrophe layers.

For the region under investigation, outcomes indicate which (mix of) risk management tools is expected to be effective and its related costs (if any) for governments. (Experience shows that this does not necessarily mean these tools are successful in practice.)

6. References

Angelucci, F., 2008. Weather indexes in agriculture: a review of theoretical and low income countries' experiences. FAO, AAACP paper series, no 1.

Arrow, K.J., 1992. Insurance, risk and resource allocation. In: Dionne, G. and S.E. Harrington (eds), Foundations of Insurance Economics, Readings in Economics and Finance. Heubner International Series on Risk, Insurance, and Economic Security. Kluwer Academic Publishers Group.

Arrow, K.J., 1996. The theory of risk-bearing: small and great risks. *Journal of Risk and Uncertainty* 12:103-111.

Baltussen, W.H.M., van Asseldonk, M.A.P.M, van der Meulen, H.A.B., Meuwissen, M.P.M., Valeeva, N.I., Vrolijk, H.C.J., Berndsen, R.C.D., Kort, M.B., van Lanen, R.J.M. and Poppe, K.J., 2008. Risk management instruments in agriculture; an assessment of efficacy and distortions. Agricultural Economics Research Institute (LEI), Wageningen UR, report no. 2008-054.

Barnett, B.J., 1999. USA Government natural disaster assistance: historical analysis and a proposal for the future. *Disasters: the Journal of Disaster Studies, Policy & Management* 23:139-155.

Barnett, B.J., Barrett, C.B. and Skees, J.R., 2008. Poverty traps and index-based risk transfer products. *World Development* 36, 10, 1766-85.

Berg, E. and Starp, M., 2006. Farm level risk assessment using downside risk measures. Contributed paper for presentation at the 26th International Conference of the IAAE Gold Coast, Australia, August 12-18, 2006.

Brown, C. and Hansen, J., 2008. Agricultural water management and climate risk. IRI: the International Research Institute for Climate and Society.

Browne, W.P., Skees, J.R., Swanson, L.E., Thompson, L.E. and Unnevehr, L.J., 1992. Sacred cows and hot potatoes. Agrarian myths in agricultural policy. Westview Press.

Cummins, J.D. and Mahul, O., 2009. Risk financing in developing countries; principles for public intervention. Washington D.C.: World Bank Publications.

Dercon, S., 2000. Income risk, coping strategies and safety nets. Background paper World Development Report WPS/2000.26.

Dick, W., 2009. Agricultural insurance: scope and limitations for rural risk management. Presentation held for Commodity Risk Management Group, March 5, 2009, World Bank.

Doherty, N.A., 1997. Innovations in managing catastrophe risk. *Journal of Risk and Insurance* 64:713-718.

Freeman, P.K., Keen, M. and Mani, M., 2003. Dealing with increased risk of natural disasters: challenges and options. IMF working paper WP/03/197.

Garrido, A. and Bielza, M., 2008, Evaluating EU risk management instruments: policy lessons and prospects for the future. In: Meuwissen, M.P.M., van Asseldonk, M.A.P.M. and Huirne, R.B.M. (eds), *Income stabilisation in European agriculture: design and economic impact of risk management tools*, Wageningen Academic Publishers, Wageningen, pp. 79-95.

Hardaker, J. B., Huirne, R.B.M., Anderson, J.R. and Lien, G., 2004. *Coping with risk in agriculture*, CABI Publishing, 2nd ed.

Harrington, S.E. and Niehaus, G.R., 1999. *Risk management and insurance*. Irwin McGraw-Hill, New York.

Harwood, J., Heifner, R., Coble, K., Perry, J. and Somwaru, A., 1999. Managing risk in farming; concepts, research, and analysis. USDA, ERS, Agricultural Economic Report 774.

Hazell, P.B.R., 1992. The appropriate role of agricultural insurance in developing countries. *Journal of International Development* 4(6), 567-581.

Hazell, P., Poulton, C., Wiggins, S. and Dorward, A., 2007. The future of small farms for poverty reduction and growth. IFPRI 2020 discussion paper 42.

Hirpa, A., Meuwissen, M.P.M., Lommen, W.J.M., Oude Lansink, A.G.J.M., Struik, P.C. and Tsegaye, A., 2009. Analysis of seed potato systems in Ethiopia. Results of an expert study, Business Economics, Wageningen University, The Netherlands.

Huirne, R.B.M., Hardaker, J.B. and Dijkhuizen, A.A. (eds), 1997. *Risk management strategies in agriculture: state of the art and future perspectives*. Mansholt Studies, No. 7, Wageningen University, Wageningen, The Netherlands.

Jaffee, S., Siegel, P. and Andrews, C., 2008. Rapid agricultural supply chain risk assessment; conceptual framework and guidelines for application (Volume 1). Commodity Risk Management Group, World Bank.

Kirsten, J. and Sartorius, 2002. Linking agribusiness and small-scale farmers in developing countries: is there a new role for contract farming? *Development Southern Africa* 19(4):503-529.

Koesling, M., Ebbesvik, M., Lien, G., Flaten, O., Valle, P.S. and Arntzen, H., 2004. Risk and risk management in organic and conventional cash crop farming in Norway. Food Economics – Acta Agriculturae Scandinavica, Section C, 1(4):195-206.

Martin, S. and McLeay, F., 1998. The diversity of farmers' risk management strategies in a deregulated New Zealand environment. *Journal of Agricultural Economics* 49(2):218-233.

Meuwissen, M.P.M., Huirne, R.B.M. and Hardaker, J.B., 1999. Income insurance in European agriculture. European Economy, no 2, European Commission, DG for Economic and Financial Affairs, Brussels.

Meuwissen, M.P.M., Van Asseldonk, M.A.P.M. and R.B.M. Huirne, 2003. Alternative risk financing instruments for swine epidemics. *Agricultural Systems* 75(2-3):305-322.

Meuwissen, M.P.M., Van Asseldonk, M.A.P.M., Huirne, R.B.M. and Skees, J.R., 2006. Designing epidemic livestock insurance. In: Koontz, S.R., Hoag, D.L., Thilmany, D.D., Green, J.W. and Grannis, J.L. (eds), *The Economics of Livestock Disease Insurance: Concepts, Issues and International Case Studies*, Oxfordshire, CAB International, pp. 126-140.

Meuwissen, M.P.M., Van Asseldonk, M.A.P.M. and Huirne, R.B.M., 2008a. Income stabilisation in agriculture; reflections on an EU-project. In: Meuwissen, M.P.M., Van Asseldonk, M.A.P.M. and Huirne, R.B.M. (eds), 2008. *Income stabilisation in European agriculture; design and economic impact of risk management* tools, Wageningen Academic Publishers, Wageningen, the Netherlands, pp. 17-31.

Meuwissen, M.P.M., Majewski, E., Berg, E., Poppe, K.J. and Huirne, R.B.M., 2008b. Introduction to income stabilisation issues in a changing agricultural world. In: Berg, E., Huirne, R.B.M., Majewski, E. and Meuwissen, M.P.M. (eds), 2008. *Income stabilisation in a changing agricultural world: policy and tools*, Wies Jutra, Warsaw, pp. 7-12.

MicroInsurance Agency, 2007. Micro insurance in Africa: filing the distribution gap. 3nd African Microfinance Conference, August 20-23 2007.

Miranda, M. and Vedenov, V., 2001. Innovations in agricultural and natural disaster insurance. *American Journal of Agricultural Economics* 83:650-655.

Mirza, M.M.Q., 2003. Climate change and extreme wethare events: can developing countries adapt? *Climate Policy* 3:233-248.

Niemeijer, D. Puigdefabregas, J., White, R., Lal, R., Winslow, M., Ziedler, J., Prince, S., Archer, E. and King, C., 2005. In: Ecosystems and human well-being: current state and trends. Washington D.C.: Island Press, pp. 623-662.

Palinkas, P. and Székely, C., 2008. Farmers' perceptions on risk and crisis risk management. In: Meuwissen, M.P.M., Van Asseldonk, M.A.P.M and Huirne, R.B.M. (eds), 2008. *Income stabilisation in European agriculture; design and economic impact of risk management* tools, Wageningen Academic Publishers, Wageningen, the Netherlands, pp. 97-122.

Rashid, S. and Assefa, M., 2007. Cereal price instability in Ethiopia: an examination of sources and policy options. AAEA Conference proceedings pp. 73-78.

Rejda, G.E., 1998. *Principles of risk management and insurance*. Addison Wesley.

Roberts, R.A.J., 2005. Insurance of crops in developing countries. FAO Agricultural Services Bulletin 159, Rome: FAO.

Roberts, R.A.J., 2007. Livestock and aquaculture insurance in developing countries. Rome: FAO.

Skees, J.R. and B.J. Barnett, 1999. Conceptual and practical considerations for sharing catastrophic/systematic risks. *Review of Agricultural Economics* 21:424-441.

Skees, J.R., Hartell, J. and Hao, J.Q., 2006. Weather and index-based insurance for developing countries: experience and possibilities. In: Sarris and Hallam (eds), Agricultural commodity markets and trade: new approaches to analyzing market structure and instability, Rome: Food and Agriculture Organization of the United Nations (FAO), pp. 256-281.

Skees, J.R., Murphy, A., Collier, B., McCord, M.J. and Roth, J., 2007. Scaling up index insurance; what is needed for the next big step forward? Paper prepared for Kreditanstalt für Wiederaufbau, German Financial Cooperation.

Skees, J.R. and Collier, B., 2008. The potential of weather index insurance for spurring a green revolution in Africa. Paper presented at the AGRA Policy workshop, Nairobi, Kenya, June 23-25 2008.

Skees, J.R., Barnett, B.J. and Collier, B., 2008. Agricultural insurance; background and context for climate adaptation discussions. Paper prepared for OECD expert workshop on economic aspects of adaptation, Paris, France, April 7-8, 2008.

Syroka, J., 2009. Experiences in index-based weather insurance for farmers; principles and lessons learned. Presentation held for Commodity Risk Management Group, World Bank.

Varangis, P., Larson, D. and Anderson, J.R., 2002. Agricultural markets and risks; management of the latter, not the former. Policy Research Paper 2793. World Bank.

Van Asseldonk, M.A.P.M., Meuwissen, M.P.M. and Huirne, R.B.M., 2008. Economic impact of prospective risk management instruments under alternative policy scenarios. In: Meuwissen, M.P.M., Van Asseldonk, M.A.P.M. and Huirne, R.B.M. (eds), 2008. *Income stabilisation in European agriculture; design and economic impact of risk management* tools. Wageningen Academic Publishers, Wageningen, the Netherlands, pp. 123-142.

Westover J., 2008. The record of microfinance: the effectiveness/ineffectiveness of microfinance programs as a means of alleviating poverty. *Electronic Journal of Sociology*.

Wu, J., 1999. Crop insurance, acreage decisions, and nonpoint-source pollution. *American Journal of Agricultural Economics* 81:305-320.

Annex 4

Climate Information Provision

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Contents

1. Introduction

Agriculture is the source of livelihood and sustenance for the majority of the Earth's poor and an engine of economic growth in much of the developing world. Climate risk is a challenge for agriculture everywhere, but especially for the hundreds of millions whose livelihoods depend precariously on rainfed agriculture in marginal, high-risk environments, where hunger and rural poverty have been most persistent. Climate change is expected to intensify many of the challenges facing rainfed agriculture, but in ways that can only be partially anticipated.

Improved control of water resources is a fundamental method for mitigating the impacts of a variable and changing climate. Large-scale irrigation infrastructure will not be feasible for many currently rainfed farming regions for at least the medium term. The opportunities for improving water management in such regions in the foreseeable future provide only partial control and leave substantial residual risk. Within a comprehensive package of support, improving the use of climate information holds promise for improving the efficiency of water management, and for managing residual climate risk that water control alone cannot address. This report reviews the impact that climate risk has on rainfed agriculture, and the role that climate information may play in managing that risk. It then discusses the challenges of improving climate information products and communication for rainfed farmers, with emphasis on seasonal climate forecasts. The next section summarizes ex-ante, model-based methods for estimating the potential benefits of advance climate information on rainfed agriculture. The report concludes with a brief overview of additional gaps that will need to be addressed in order to realize the potential benefits of climate information for rainfed agriculture.

2. Climate Risk and Rainfed Agriculture

2.1. Impacts on production and prices

In the tropics and sub-tropics, year-to-year climate variability affects crop production primarily by driving supply of soil moisture in rainfed agriculture, and surface water runoff and shallow groundwater recharge in irrigated agriculture. Variability of temperature can have a major impact in temperate zones, and in areas subject to heat spells above the crop's tolerance. Climate variability is often the dominant source of income and consumption risk in dryland (i.e., rainfed, dry sub-humid to arid climatic zones) agriculture in the topics (Dercon, 2002; Walker and Ryan, 1990; Zimmerman and Carter, 2003). Because biological response is nonlinear and generally concave over some range of environmental variability, climate variability tends to reduce average yields. Climate-driven fluctuations in production contribute substantially to volatility of food prices, particularly where remoteness, the nature of the commodity, transportation infrastructure, stage of market development or policy limit integration with global markets. Because market forces tend to move prices in the opposite direction to crop production fluctuations, variability in food crop prices tends to buffer farm incomes, but exacerbates food insecurity for poor net consumers.

2.2. Impacts on farmer decisions

2.2.1. Ex-post impacts and coping strategies

Climate-related disasters impact poor countries, and the relatively poor within countries, disproportionately (Carter et al., 2007; Easterly, 2001; Gaiha and Thapa, 2006). A severe, uninsured climate shock, such as a drought or flood, can have long-term livelihood consequences through direct damage to crop and livestock productivity, infrastructure, the few productive assets of the poor, and sometimes health. Vulnerable households employ a range of strategies to cope with the resulting crisis, including: liquidating productive assets, defaulting on loans, migration, withdrawing children from school to work on farm or tend livestock, severely reducing nutrient intake, and over-exploiting natural resources. Although these coping strategies help households to weather a crisis in the short term, they often sacrifice capacity to build a better life in the future (Barret and Carter, 2001; Carter and Barrett, 2006; Carter et al., 2007; Dercon, 2004; Dercon and Hoddinott, 2005; Hoddinott, 2006; McPeak and Barrett, 2001).

2.2.2. Ex-ante impacts: moving target effect

The uncertainty associated with climate variability creates a moving target for management that reduces efficiency of input use and hence profitability. Crop responsiveness to fertilizer (Christianson and Vlek, 1991; Pala et al., 1996) and planting density (Anderson, 1984; Myers and Foale, 1981), and hence optimal rates and profitability of production inputs (Hansen et al., 2009; Jones et al., 2000b; Piha, 1993), vary considerably from year to year as a function of water supply. Management that is optimal for average climatic conditions can be far from optimal for growing season weather in most years. The difference between average returns to management that is optimized for the climatological distribution and returns to management that is optimized for each year of weather data (discussed further in section 5.2) provides estimates of the cost of the moving target effect for agronomic management of individual crops (Hansen et al., 2009; Jones et al., 2000a; Thornton and MacRobert, 1994).

2.2.3. Ex-ante impacts: risk aversion effect

Because farmers tend to demonstrate aversion to risk, they do not optimize management for average conditions, but for adverse conditions. In the face of climate variability, risk aversion on the part of decision makers cause substantial additional loss of opportunity beyond the “moving target effect” as a result of the precautionary strategies that vulnerable farmers employ ex ante to protect against the possibility of catastrophic loss in the event of a climatic shock. Farmers’ precautionary strategies include: selection of less risky but less profitable crops (Dercon, 1996; Morduch, 1990), under-use of fertilizers (Binswanger and Sillers, 1983; Dercon and Christiaensen, 2007; Morris et al., 2007; Simtowe, 2006), shifting household labor to less profitable off-farm activities (Rose, 2001; Rosenzweig and Stark, 1989), and avoiding investment in production assets (Barrett et al., 2007; Fafchamps, 2003) and improved technology (Barrett et al., 2004; Kebede, 1992; Marra et al., 2003). Limited evidence suggests that the opportunity costs of farmers’ ex-ante response to climate risk is substantial – perhaps greater than the ex-post cost of shocks (Elbers et al., 2007) – and is much greater for those who are relatively poor and hence least able to tolerate risk (Rosenzweig and Binswanger, 1993; Zimmerman and Carter, 2003). Although the greatest setbacks to rural livelihoods can be linked to the most damaging climatic extremes, farmers experience the ex-ante impacts of climate risk, in the form of opportunity costs in favorable and near-normal seasons, far more frequently.

2.3. Impacts on institutions

Climate risk and risk-aversion can affect the decisions of market institutions. Efforts to develop agricultural input markets in rural SSA appear to be most successful when they include policy mechanisms for controlling risk to suppliers (Kelly et al., 2003). Spatially-correlated, catastrophic losses from climatic or other shocks can exceed the reserves of an insurer or lender, and lead to financial market failures in many low-income countries (Besley, 1995; Miranda and Glauber, 1997; Poulton et al., 2006). When constraints such as climate-related risk impact institutions operating at a more aggregate scale, the impact can further constrain economic opportunities and hence reinforce poverty traps at the household level (Barrett and Swallow, 2006; Carter and Barrett, 2006).

3. Information for Managing Climate Risk in Rainfed Agriculture

3.1. The value of climate information

The economic framework for the value of information (Hilton, 1981; Johnson and Holt, 1997; Nelson and Winter, 1964) treats information as a message that alters probabilistic perceptions of stochastic events

(Chavas and Pope, 1984). The value of information is commonly defined as either: (1) the maximum price that a user would pay for the information, (2) the minimum price under market equilibrium that a provider would accept for the information, and (3) the expected improvement in economic outcome of management that incorporates the new information (Hilton, 1981). The first two definitions assume that access to information is controlled by the market. While this is certainly relevant in some contexts, climate forecasts can be, and arguably should be, a public good and a public sector responsibility. If we were to assume a competitive market for climate forecast information, the amount that a rational user would be willing to pay (definition 1) would not exceed the expected benefit of the improved decisions associated with the forecast system (definition 3). The usefulness of the first two definitions depends on either observed behavior within well-developed markets for information, or elicited perceptions under a hypothetical market. For these reasons, most studies of the value of climate information use the third definition – the difference between expected returns to optimal management that incorporates the new information, and expected returns to optimal management based on information available in the absence of the forecast system, or:

$$V_F = \mathrm{E}\{U(\Pi(\mathbf{x}^* \mid I_{new}, \theta, \mathbf{e}))\} - \mathrm{E}\{U(\Pi(\mathbf{x}^* \mid I_{old}, \theta, \mathbf{e}))\}. \qquad (1)$$

The value of a forecast system depends on the set of management options ($\mathbf{x}$); expected probability distributions conditioned on the new (I_{new}) and prior information (I_{old}); realized weather (θ) for the period of interest; economic returns (Π) as a function of weather and management; the subjective value, or "utility" (U) placed on economic outcomes; and the current state of all other variables – the "environment" ($\mathbf{e}$) – that constrain management or affect returns to management. Utility is generally omitted, although it may enter into the process of identifying optimum management $\mathbf{x}^*$. The discussion of climate forecast valuation methodology (Section 5) builds on this framework. From Eq. 1, value results only if (a) the new information leads to expectations that are closer, on average, to the actual weather realized each year, leading to (b) management that is closer to the management that is optimal for perfect information, resulting in (c) better economic outcomes. The value of climate information therefore depends on a combination of the nature of the new and prior information, farmers' ability to access and process the information, feasible decision options that are sensitive to the new information, and the sensitivity of the components of economic returns to the changes in management.

The atmosphere varies on a continuum of time scales, from sub-daily weather events to long-term climate change. Likewise, climate-sensitive agricultural decisions have a range of time horizons. To be useful and have value, the climate information must match the time horizon of the particular decisions (Table 1; (Meinke and Stone, 2005). The most important decision time scales for rainfed annual crop farmers range from a few days to the upcoming season. While longer time scales (i.e., 1-2 decades) may influence farm decisions, they are more likely to influence institutional and policy decisions (e.g., plant breeding programs, market development, investment in infrastructure) that influence options and incentives for farmers. Identifying the time horizon of climate-sensitive decisions, and mapping those made annually onto a decision calendar are useful initial steps when identifying climate information needs and opportunities to improve information services.

Table 1. Climate-sensitive agricultural decisions at a range of temporal and spatial scales (Meinke and Stone, 2005).

Farming decision	Frequency (years)
Scheduling of e.g., planting, harvest operations	Intraseasonal (> 0.2)
Tactical crop management (e.g. fertilizer, pesticide use)	Intraseasonal (0.2 – 0.5)
Crop selection (e.g. wheat or chickpeas) or herd management	Seasonal (0.5 – 1.0)
Crop sequence (e.g. long or short fallows) or stocking rates	Interannual (0.5 – 2.0)
Crop rotations (e.g. winter or summer crops)	Annual/bi-annual (1 – 2)
Crop industry (e.g. grain or cotton; native or improved pastures)	Decadal (~ 10)
Agricultural industry (e.g. crops or pastures)	Interdecadal (10 – 20)
Land use (e.g. agriculture or natural systems)	Multidecadal (20 +)
Land use and adaptation of current systems	Climate change

The potential for value is most obvious for advance information (i.e., forecasts). In the context of climate forecasts, the information in the absence of the forecast system is generally assumed to be the historic climatological distribution, although evaluating improvements relative to an existing forecast system is also relevant. Historic climate records can have value if they correct biased perceptions of the climatological distribution, for example, where a farming population is new to a region, or where decadal climate variations or climate change have shifted the distribution of climatic conditions. Similar arguments hold for monitoring information and climate change projections, but for decisions with different time horizons.

3.2. Value-added climate information

To be useful, raw climate information must be translated into impacts and management implications within the system being managed, either through subjective expertise or intuition, or through quantitative methods including statistical and process-oriented models. Value-added climate information that is relevant to rainfed agriculture includes estimates of sowing conditions, crop phenological stage, soil temperature water content, soil temperature, crop water stress, irrigation requirements, and pest and disease risk. Most of these can, in principle, be considered at climatological (i.e., probability distributions estimated with historic weather records), monitoring and predictive time frames.

Crop production is a function of dynamic, nonlinear interactions between weather, soil water and nutrient dynamics, management, and the physiology of the crop. Seasonal averages of climate variables such as rainfall accumulation therefore often correlate only weakly with crop yield, even in environments that are strongly water limited. When used properly, models that simulate the dynamic interactions between rainfall, the soil water balance, and crop growth and development tend to provide more accurate estimates of yields than can be obtained from statistical relationships with seasonal average weather.

3.3. Historic climatology

Historic meteorological time series are useful for characterizing risk, which is a prerequisite for managing climate risk. A common assumption is that, through trial and error over a period of time, farming communities tend to optimize their practices for their environments (including climate variability), goals (including risk tolerance) and constraints. If management is already optimal for the local climate, historic records would have little direct value to the farmer. However, bringing historic climate records into analyses of management practices can bring benefits where drivers such as technology, markets, demography, land quality and access to resources are changing too rapidly for farmers to adapt. Examples include analysis of optimal planting date where cropping systems have changed significantly in southern India (Gadgil et al., 2002), and in southern Zambia where conservation farming technology has eliminated a constraint to early planting (Roger Stern, Univ. Reading, pers. commun.). Historic records are also useful for detecting where climatology is not stationary due to natural multi-decadal variability or anthropogenic change, and where farming practices are no longer adapted to the current climate (Meinke and Hammer, 1995). They are essential for interpreting probabilistic seasonal climate forecasts (section 4.1, 4.2).

Historic climate records, either in the form of time series or probability distributions, are not part of the typical package of information routinely provided to farmers, for example, within agrometeorological bulletins. Exceptions include model-based decision support systems, such as Australia's *Whopper Cropper* (Nelson et al., 2002), and *YieldProphet* (Hunt et al., 2006), which provide local historic and monitored weather data, and translate it into probabilistic yield and economic outcomes. Such decision support tools allow farmers to explore the potential risks associated with alternative management strategies. They have not been used widely as a basis for adjusting farm management decisions, but have proven more effective as a basis for discussion that stimulates co-learning (between farmers and researchers) and sometimes new management heuristics (McCown, 2002).

3.4. Agricultural weather monitoring

Monitored weather conditions have obvious implications for many of the tactical, weather-sensitive rainfed farming decisions (e.g., planting, supplemental or emergency irrigation, weeding, scouting for pests and disease). Since farmers have ability to observe and interpret their own local weather, monitored weather information is not completely new information. Yet farmers can benefit when it includes quantitative, value-added information that is difficult or costly for farmers to calculate, or information about conditions in other production areas that may impact farmgate prices. *Response farming* is a system for adjusting planting and fertilizer management in response to the observed onset of rainfall, in regions where total seasonal rainfall is strongly correlated with the timing of onset (Stewart, 1991; Stewart and Faught, 1984). Response farming parallels much of the work on farm-level applications of seasonal climate forecasts, but is based on monitoring local early rainfall characteristics.

Many countries summarize and disseminate monitored agricultural weather conditions for their major agricultural regions in the form of agrometeorological bulletins. Well-designed agrometeorological bulletins provide information that is location-specific (using maps or tables by location), and interpreted for particular agricultural commodities and management decisions. They often emphasize value-added information for specific agricultural commodities and management decisions. For example, temperature is often translated into growing degree days since sowing, and current phenological stage for major crops. Cumulative precipitation and potential evapotranspiration are used to make inferences about soil moisture conditions and the moisture status of rainfed crops. Cumulative growing season information depends on monitoring sowing conditions or actual sowing progression. Presenting current or cumulative conditions along with the climatological average or other accepted "normal" conditions provides a sense of when conditions are unusual. Agrometeorological bulletins often include narrative summaries of current crop conditions, and recommendations for tactical decisions such as sowing, irrigation and pest management. Although agrometeorological bulletins emphasize monitored conditions, forecast information is sometimes included particularly in the narratives. Frequency of updates varies, but weekly and ten-daily (or "dekads") are common conventions.

3.5. Weather forecasts

Weather prediction is based on knowledge of initial atmospheric conditions. Numerical weather prediction uses dynamic models of the atmosphere to simulate its future evolution in response to detailed measurements of the atmosphere's initial state. Several operational weather forecasting centers use ensembles of many model runs with slightly different initial conditions both to improve the accuracy of forecasts, and to estimate their uncertainty. Countries with less computational and human capacity often base forecasts on their expert interpretation of model outputs from global or regional weather forecasting centers. Near real-time monitoring of cloud movements and other variables also provide information about upcoming weather, particularly at a short lead time.

Weather forecasting is classified into lead times: now-casting (≤ 2 h), very short range (≤ 12 h), short range (12 h – 3 d), and medium range (4-14 d). Forecasts at longer lead times are in the category of *climate forecasts* because they capture probability shifts in the statistics that comprise climate, and not individual weather events, although this convention is not universal. Table 2 contrasts the main features of weather and seasonal climate forecasts. Because the atmosphere is chaotic, the accuracy of weather forecasts decreases with increasing lead time. Forecasting at a weather time scale (i.e., no more than 2 weeks) is possible everywhere in the world, in contrast to seasonal forecasts. However, accuracy and maximum lead time tend to be better where frontal systems control weather (i.e., higher latitudes, winter in mid latitudes) than where local convection dominates (i.e., low latitudes, summer in mid latitudes).

Table 2. Main features of weather and seasonal climate forecasts.

Forecast	Basis	Lead time	Geographic scope	Predictand	Decisions
Weather	Initial conditions	≤ 14 days	Global, strongest in mid latitudes	Daily weather events	Tactical: irrigation, pest control, field operations
Seasonal climate	Boundary conditions	≤ 6 months	Particular locations & seasons, strongest in low latitudes	Shifts in statistics	Strategic: land and labor allocation, intensification

Now-casting involves extrapolating trajectories of observed weather based, for example, on dense networks of automatic stations (e.g., the Florida Automated Weather network, http://fawn.ifas.ufl.edu/). Agricultural application of now-casting focuses on management of damaging freezes. *Very short-range weather forecasts* extend applications to automatic triggering of irrigation. Utility at such short lead times depends on continuous broadcasting by the provider and continuous monitoring by the user, and is therefore limited to settings where ICT infrastructure and use are very well developed. *Short-* and *medium-range weather forecasts* are available in most rainfed farming regions, and can influence a wide range of farming operations and tactical decisions within the growing season. In addition to the standard forecast variables (precipitation, maximum and minimum temperature, wind), weather forecasts developed for agriculture can include additional meteorological variables (e.g., humidity, potential evaporation, bright sunshine duration, solar radiation) and derived values (e.g., soil water balance, leaf wetness, sowing conditions).

The use of weather forecasts for agriculture has a long history and is relatively well established. They are particularly relevant to day-to-day farming operations, to irrigation and pest management during the growing season, and to preparing for extreme weather events such as temperature extremes (heat waves, frosts) and damaging storms (wind, hail, flooding). Because of the short lead times involved, agricultural use of weather forecasts depends on having fast routine access generally through some form of mass media. The usefulness of weather forecasts to farmers can also be constrained by lack of spatial detail in forecasts, e.g., where specific forecast information is produced only for airports or urban centers. Relative to seasonal forecasts, weather forecasts have a longer history of use, are accessed and applied far more frequently, are often presented with more location-specific detail, and are more consistent with the time scales of farmers' indigenous forecasts. Farmers therefore generally face less difficulty in interpreting forecasts, gauging their uncertainty, and adjusting management at the weather than at the climate time scale. Agrometeorological bulletins (section 3.4) often incorporate weather forecasts to extend monitoring information several days into the future. The relevant forecast variables and value-added forecast information appropriately vary with farming system and farmer needs.

3.6. Seasonal climate forecasts

Year-to-year climate variations are influenced by interactions between the atmosphere and the more slowly-varying ocean and land surfaces, such as those associated with the El Niño-Southern Oscillation (ENSO) in the tropical Pacific. Seasonal climate forecasts are based either on statistical relationships or on dynamic general circulation models (GCMs) that model the physical processes and dynamic interactions of the global climate system in response to global sea surface temperatures (SSTs) and possibly land surface boundary forcing. Several climate prediction centers routinely issue probabilistic seasonal forecasts obtained from ensembles of GCM integrations initialized with different atmospheric conditions. Since 1997, periodic (annual or biannual) regional climate outlook forums (RCOFs) in Africa and Latin America have issued consensus seasonal climate forecasts based on combinations of statistical and dynamic models and subjective judgment, intended to benefit agriculture and other climate-sensitive. In principle, national meteorological services are charged with downscaling and interpreting RCOF consensus forecasts for the benefit of stakeholders within their countries, but in practice this is the exception rather than the rule.

Predictability of rainfall at a seasonal time scale varies substantially with location and time of year (see Fig. 1 for one indicator of predictability), and coincides with several major rainfed agriculture regions (Fig. 2). The highest predictability is found in Northeast Brazil, and a region of southeast Asia encompassing most of Indonesia and the southern Philippines. In North America, rainfall shows some predictability extends from Florida, through the Gulf states, into eastern Texas, but only in the winter and spring. In South America, the Pampas “breadbasket” region of Argentina, extending into Uruguay and southern Brazil, shows significant predictability during their summer growing season. In Asia, predictability coincides with rainfed farming areas in part of subtropical eastern China (fall-early spring) and a portion of west-central Asia (including eastern Uzbekistan, southern Kazakhstan, Tajikistan and northern Afghanistan) (winter-spring). In Africa, significant predictability coincides with cropping seasons in the October-December “short rains” in East Africa (much of Kenya, eastern Uganda and northern Tanzania), Sudano-Sahelian West Africa, and much of southern Africa. Rainfed agriculture is a major source of livelihood for all of these regions. Rainfall predictability is weak at best in the cereal belts of central and eastern Europe, and northern mid-west USA.

Seasonal climate forecasts match the period between the many climate-sensitive decisions that must be made prior to planting, and harvest when outcomes of those decisions are realized. Within a comprehensive package of support and an enabling environment, skillful seasonal forecasts can therefore provide opportunity for farmers to adopt improved technology, intensify production, replenish soil nutrients and invest in more profitable enterprises when conditions are favorable or near average; and to more effectively protect their families and farms against the long-term consequences of adverse extremes.

Seasonal climate forecasts have been the subject of more research than other types and time scales of climate information for agriculture, yet this has had little impact on the design or communication of seasonal forecasts for agriculture. With a few exceptions (e.g., Australia), institutional support for agricultural use of seasonal forecasts remains underdeveloped.

4. Improving Rural Climate Information Services

While all of the types and time scales of climate information discussed in section 2 are relevant for managing rainfed agriculture, the communication issues surrounding seasonal forecasts warrant special attention. First, effective use of seasonal forecasts requires understanding their probabilistic nature and implications for production and management. Yet seasonal forecasts are experienced only once each year (at a given lead time and for a given growing season), so learning purely from personal experience can be very slow and costly. Short-term weather forecasts, on the other hand, are experienced frequently enough that users can quickly develop at least an intuitive understanding of their accuracy, and rules of thumb for applying the information to management. Second, the use of historic records, monitoring and weather forecasts are older and more established. They are often either accessible through existing services (e.g., weather forecasts, agrometeorological bulletins) or part of indigenous knowledge of how to "read the sky." Finally, the communication, perception and use of seasonal forecasts have been the subject of considerable research, which provides general insights about the challenges of communicating climate information effectively. Yet with few exceptions, this research has had very little impact on the design or communication of operational seasonal forecasts, suggesting that there is considerable unrealized potential. The most frequently reported obstacles to successful use of seasonal climate forecasts by farmers are associated with communication – either inequitable access; or mismatch between farmers' needs and the scale, content, format, or accuracy of available forecasts (e.g., Archer, 2003; Ingram et al., 2002; Klopper and Bartman, 2001; Ngugi, 2002; O'Brien et al., 2000; Phillips, 2003; Ziervogel, 2004). Adoption rates and reported benefits have been fairly high in pilot projects in Zimbabwe, southern India and Burkina Faso, where extended interaction between smallholder farmers and researchers overcame some of the communication barriers (Huda et al., 2004; Meinke et al., 2006; Patt et al., 2005; Roncoli et al., 2009).

4.1. Improving utility of forecast information products

Experience in a range of contexts (e.g., Childs et al., 1991; Ingram et al., 2002; Jochec et al., 2001; Klopper and Bartman, 2001; Letson et al., 2001; Madden and Hayes, 2000; Nelson and Finan, 2000; Ngugi, 2002; O'Brien et al., 2000; Phillips and McIntyre, 2000; Podestá et al., 2002; Ziervogel, 2001) reveals that farmers can best use climate forecast information when it: (a) is interpreted at a local scale; (b) includes information about timing (e.g., rainy season onset, risk of dry spells) beyond seasonal climatic means; (c) expresses accuracy in transparent, probabilistic terms; and (d) can be interpreted in terms of agricultural impacts and management implications. In contrast, available seasonal climate forecast products typically express rainfall and sometimes temperature averaged in time over three or more months, and aggregated over large subjectively-defined regions or at the scale of the GCM grid cells (on the order of 1000-10,000 km^2). A common convention represents the uncertainty of the forecast as probability shifts of the climatological tercile categories (Fig. 3). The tercile categories (i.e., wettest, middle and driest third of past years) are described in qualitative terms as "above-normal," "normal" and "below-normal." However, the probabilistic information is often collapsed into a deterministic forecast of the most probable tercile category by the time forecast information reaches farmers.

4.1.1. Downscaling in space

Until recently, the coarse spatial scale of operational seasonal forecasts was assumed to represent a fundamental constraint imposed by the climate system, and occasionally used to argue that forecasts should target only institutional decision makers who operate at similar large spatial scales, and not farmers. Limited published evidence and much more unpublished experience at the IRI suggests that it is feasible to provide forecasts at individual stations with only modest loss of skill where forecasts are skillful at an aggregate scale (e.g., Gong et al., 2003; Mishra et al., 2008; Moron et al., 2006; Ndiaye et al., 2008; Robertson et al., Submitted). Statistical methods for downscaling forecasts to a stations scale have been embodied in tools such as the Climate Predictability Tool (CPT, http://iri.columbia.edu/outreach/software/), and are simple, quick and flexible enough to use routinely for forecasts targeting farmers.

4.1.2. "Weather within climate"

Farmers frequently request information beyond the three-month average climate anomalies typically forecast, including characteristics such as rainy season onset, dry spell distributions and harvest conditions (Ingram et al., 2002; Nelson and Finan, 2000; O'Brien et al., 2000; Phillips and McIntyre, 2000). Total rainfall for a season is the product of frequency (i.e., number of days with rainfall) and mean intensity (i.e., rainfall amount). Because rainfall occurrence is spatially more coherent (i.e., correlated among neighboring stations) than the amount of rain during a rain day, most of the predictability of seasonal rainfall total at a small scale is due to the predictability of the frequency of days with rain (Hansen and Indeje, 2004; Mishra et al., 2008; Moron et al., 2006; Moron et al., 2007; Robertson et al., In press). Farmers participating in workshops in Kenya said that they found probabilistic seasonal forecasts of numbers of wet days to be useful. Limited evidence suggests that the predictability of rainfall frequency leads to a degree of predictability of dry spells (Ndiaye et al., 2008; Robertson et al., In press; Sun et al., 2007) – with obvious relevance to the soil water balance and its effects on crops and pastures.

The timing of the onset of growing season rainfall is critical for dryland (i.e., dry sub-humid to arid) agriculture in tropical and sub-tropical regions. Credible skill at forecasting onset using seasonal forecast methods has been demonstrated in Indonesia (Moron et al., In press-b; Robertson et al., In press) and The Philippines (Moron et al., In press-a). Unfortunately, the timing of growing season onset appears to have little or no predictability at a long lead time in most locations where it has been explored.

4.1.3. Probability formats

While all meteorological forecasts have some degree of uncertainty, expressing the uncertainty of forecasts in probabilistic terms is particularly important for low-probability, high-impact events, and for predictions at a seasonal lead-time at which a substantial portion of variability is inherently unpredictable. In both cases, decision makers do not experience predictions or predicted outcomes often enough to gauge their accuracy from experience, creating a need to package forecasts with information about their accuracy in transparent, probabilistic terms.

Simple event probabilities, estimated simply as historic relative frequency, are the appropriate way to express uncertainty about high-impact meteorological events when the primary concern is about whether the event occurs and not its intensity.

Forecasts of continuous quantities (e.g., precipitation, temperature) are appropriately expressed mathematically or graphically either as a cumulative distribution function (CDF) (Fig. 4a) or a probability density function (PDF) (Fig. 4c). The bell curve or histograms associated with a PDF may be more familiar to many from exposure in school. However, we favor the CDF over the PDF. First, a CDF graph explicitly relates probabilities and climatic thresholds. Either may be of interest to farm decision making. Second, it is relatively easy to show how a CDF is derived from a time series. Probability of exceedance (POE, also known as the complementary cumulative distribution function, or CCDF) is simply the inverse of a cumulative distribution function (POE = 1-CDF) (Fig. 4b). Some evidence suggests that probability of exceeding a particular threshold (i.e., POE) may be easier to understand than probability of an outcome below a threshold (i.e., a CDF) (L. Dalgleish, Univ. Queensland, pers. commun.).

Probabilistic climate forecasts can also be presented as categorical (or discrete, not to be confused with “deterministic”). The climatological distribution is divided into categories such as above and below median, or terciles (e.g., the wettest, middle and driest third of past years), and then the forecast is expressed as a shift from the probabilities that define the categories. Categorical probability formats lend themselves well to maps. Color coding represents the probability associated with a particular category (e.g., above-median, or dominant tercile category). Probability shifts can be represented independent of the fine-scale spatial variability of climatological quantities. Categorical probabilistic formats are now standard for forecasts produced and distributed by international forecast centers such as the IRI, regional climate outlook forums in Africa and Latin America, and many farmer-oriented climate application programs such as in eastern Australia. Proponents argue that categorical probability formats are easier for farmers to interpret (Clewett et al., 2000; Hayman, 2000). However, there is evidence that many people have difficulty interpreting existing categorical probabilistic formats (O'Brien et al., 2000), and prefer probability of exceedance and time-series graphs to categorical formats (tercile shifts and box plots) (Breuer et al., 2000). Ambiguous or inconsistent interpretations of forecast categories can contribute to misunderstanding (Fischhoff, 1994; O'Brien et al., 2000; Patt and Schrag, 2003). The loss of information that results from categorizing a cumulative distribution, ambiguous or inconsistent interpretations of forecast categories, the arbitrary nature of thresholds embodied in category boundaries, and evidence of difficulties in interpreting categorical probabilistic presentations of forecast information (Coventry, 2001; Fischhoff, 1994; Gigerenzer and Hoffrage, 1995; McCrea et al., 2005; O'Brien et al., 2000; Patt and Schrag, 2003) are arguments for presenting seasonal forecasts as continuous distributions. Unfortunately, because most studies have focused on categorical probability formats, we know far less about how farmers and other decision makers perceive and interpret continuous probability formats.

Based on a combination of published research, discussions with farmers primarily in India, primary research in Florida (Hansen et al., 2004) and Kenya (Hansen et al., 2007), I recommend presenting seasonal forecasts as a shifted probability of exceedance (or CCDF), along with historic time series of observations and hindcasts. Probability of exceedance, the y-axis, is likely to be understood more easily if expressed as a relative frequency (e.g., number of years with at least this much rain) (Gigerenzer and Hoffrage, 1995). A time series of observations and hindcasts based on an operational forecast model is a useful complement to forecast distribution formats, as it (a) reduces some of the mystery behind probability formats, (b) provides a bridge between farmers' experience with variability and more formal probability formats, and (c) allows the farmers to intuitively evaluate the forecast system's uncertainty based on past performance. The resulting transparency helps shift the object of trust from the forecast provider to the farmers' own evaluation of the data. These formats fit within the training process discussed in section 4.2.3. For precipitation, I recommending including, as a minimum, rainfall frequency along with seasonal total. The forecast distributions can be derived either from analogs, from hindcast residuals, or from appropriately calibrated GCM ensembles (Hansen et al., 2006).

4.2. Communicating probabilistic climate information

For the risk-averse farmer, understanding the uncertainty of a forecast in probabilistic terms is a prerequisite for appropriate response. Distortion can easily occur anywhere in the forecast generation, distribution, interpretation, and application process. Underestimating uncertainty can lead to excessive responses that are inconsistent with decision makers' risk tolerance (Hammer et al., 2001; Hansen, 2001; Hansen and Selvaraju, 2001), and can damage the credibility of the forecast provider (Changnon, 2002; Nicholls and Kestin, 1998; Orlove and Tosteson, 1999). On the other hand, under-confidence in forecasts due to inflated perception of forecast uncertainty will reduce the value of a forecast through under-response and missed opportunity (e.g., Hammer et al., 2001), although the costs of such missed opportunity have received less attention than the costs of misinterpretation and misuse of forecasts.

4.2.1. Cognitive challenges

Much of neoclassical economics is built on the assumption that decision makers are rational, meaning that they interpret available information and make decisions that optimally advance their goals. Since Simon's (1957) seminal work first recognized the cognitive limitations to purely rational decision making, behavioral psychology has identified several widespread departures from rational decision making in response to probabilistic information (e.g., Gilovich et al., 2002; Tversky and Kahneman, 1974). Some affect ability to interpret probabilistic information. For example, *anchoring* refers to our tendency to rely too heavily on an initial piece of information, and resist modifying an initial conclusion as additional information comes available. *Availability bias* refers to the tendency regard as most likely the experiences we can recall most readily or scenarios we can envision most vividly – which tend to be those that are associated with the strongest emotions. *Recency bias* is a variation of the availability bias that gives greatest weight to more recent experiences, which can be recalled most readily. A second set leads to decisions that are inconsistent with one's goals. For example, *framing effects* occur when presenting the same decision problem in different ways (e.g., probability of deaths vs. probability of preventing deaths) leads to different decisions. *Loss aversion* (also referred to as *regret aversion*) is a particular framing effect that reflects a tendency to give greater weight to an outcome when it is expressed as a loss, relative to an baseline position that may be quite arbitrary, than when it expressed equivalently as a gain. The resulting asymmetry between perceived loss and perceived gain is the basis for prospect theory (Kahneman and Tversky, 1979) – the major alternative to expected utility theory (section 5.5). The existence of these and many other systematic cognitive challenges seems to suggest that people are inherently poor intuitive statisticians, and will face rather fundamental difficulties in using probabilistic climate information effectively (Nicholls, 1999; Stern and Easterling, 1999). Fortunately, there is some evidence that the cognitive challenges are not intractable, and can be greatly reduced when probabilistic climate information is expressed as natural frequencies (section 4.1.3); when the information can be related to decision makers' experience with climate fluctuations and climate-sensitive decisions (section 4.2.2); and when understanding and use are reinforced by appropriate training, interaction with experts and group interactions. Note that several cognitive biases are described primarily for discrete stochastic events, and therefore seem to apply more to probabilistic statements about occurrence of climatic extremes (e.g., flooding, storms, landslides) than to seasonal forecasts of continuous variables (e.g., cumulative precipitation, mean temperature).

4.2.2. Analytical and experiential processing

Probabilistic information about stochastic drivers such as climate variability can be obtained in two ways: from their own repeated experience or from statistical descriptions. The two sources of information are processed in distinctly different ways. Experiential processing relates current situations to memories of past experiences, applies heuristics (i.e., rules-of-thumb) to decisions, and is strongly influenced by the emotions that memories or current experience elicit. In contrast, analytical processing applies learned rules of logic to abstract symbols that represent sets of possible probabilistic outcomes. They tend to reflect opposite biases with low-probability events, which tend to be over-weighted when based on statistical description and under-weighted when based on personal experience. The two processing modes can lead to substantially different choices under the same risk or uncertainty. Evidence suggests that information that is processed experientially tends to reduce some cognitive biases and lead to more rational decisions (Chu and Chu, 1990; Hertwig and Ortmann, 2002; Koehler, 1996).

The difference in how people process description-based vs. experience-based information has important implications for the challenge of communicating climate information to farmers (Hansen et al., 2004; Marx et al., 2007). First, much of the experimental evidence of fundamental difficulties in processing probabilistic information is in the context of analytical processing of statistical information. Because farmers in rainfed environments, on the other hand, routinely make climate-sensitive livelihood decisions based on probabilistic information in the form of repeated direct experience with weather fluctuations, they may have less difficulty processing probabilistic forecast information than some of the behavioral psychology research suggests for individuals who lack this experience base. Second, Marx et al. (2007) suggest that communication of climate forecasts can be improved by bringing together both the analytical and experiential modes of processing.

4.2.3. Improving understanding

We developed a process that appears to help farmers in several contexts to interpret and respond to probabilistic climate forecasts in a manner that is consistent with the way they interpret and make decisions in the face of climate variability in the absence of seasonal forecasts. It seeks to combine the strengths of the analytical and experiential processing modes. By communicating forecast information in a transparent manner and not as a "black box," it also seeks to shift the focus of trust from the information provider to the data and the process. The logical progression was initially developed as a short, self-directed tutorial, and tested with farmers in Florida, USA (Hansen et al., 2004). The approach was well received, and had a significant positive influence on stated willingness to change management conditions based on ENSO state. We expanded the approach and applied it in a two workshops with 20 farmers each in two locations in Kenya (Hansen et al., 2007). When farmers in breakout groups were presented with hypothetical forecasts, they were able to interpret the forecasts and identify a range of management responses that were consistent with the forecasts.

The first step involves relating measured time series to farmers' experience, by eliciting their collective memory of qualitative rainfall conditions, then allowing them to plot observed quantities and validate them against their collective memory. Second, on a blank graph with quantity (e.g., seasonal rainfall) on the x-axis and frequency (e.g., "Years with at least this much rain") on the y-axis, allow farmers to convert the time series of observations into frequency, sorting from lowest to highest (if using probability of exceedance). Gigerenzer and Hoffrage (1995) found that expressing probabilistic information as natural frequencies rather than as equivalent probability eliminates some of the biases that seem to plague the interpretation and use of probabilistic information. Third, changed the y-axis from frequency to probability and discuss what it means to interpret past relative frequency as future probability. Fourth, discuss implications of shifts in the probability distribution, using analogies of locations that farmers identified as somewhat wetter (dryer) to aid understanding of shifts to the right (left). Fifth, repeat the procedure for analog (e.g., El Niño or La Niña) years. Where rural communities are already aware of El Niño and La Niña, this helps convey the notion that a forecast is a shift of the climatological distribution, even if operational forecasts are more complicated or not based strictly on ENSO. Sixth, provide an opportunity (e.g., in breakout groups) for farmers to relate forecast distributions to decisions. Allowing farmers to brainstorm among themselves about potential management responses to either hypothetical or actual forecasts reinforces both appropriate interpretation and relevance.

A review of other published experiences leads to three additional suggestions to improve understanding of climate information. First exploit the benefits of a group process. There is growing evidence that group interaction among farmers contributes a great deal to understanding of climate forecast information, and to willingness and ability to act on that information (Marx et al., 2007; Roncoli et al., 2009). Second, provide accelerated experience through decision games. Well-designed games that link real or imaginary payouts to decisions and sampled probabilistic outcomes allow farmers to experience, in a short time, a number of imaginary forecasts, decisions, climatic outcomes, and imaginary or real payouts. Third, incorporate culturally-relevant indigenous forecasts, and analogies of decisions under uncertainty into the climate communication process.

4.3. Models for delivering climate information

Several models have been tried, in many contexts, for delivering climate information to rural communities. While most of the examples I'm aware of, including the sample discussed below, demonstrate innovations that could be useful in other contexts, I don't consider any to be sufficient as a model of best practice generally. Importantly, none of them gives balanced attention to information at the weather and the climate time scales. Some of the factors that seem to favor success are shared responsibility by agricultural and climate institutions, involvement of multidisciplinary teams of agricultural experts, substantive farm participation, and a mechanism for farmer feedback to influence practice. However, there seem to be few examples of rural climate services that are supported with credible evidence of use and benefit, and unfortunately no attempts to synthesize evidence of what has worked across several climate information delivery mechanisms. Sivakumar (2006) and Weiss et al. (2000) provide brief global overviews of efforts to deliver climate information to the farming community.

The opportunities and challenges are different for information at the weather and climate time scales. The decisions (e.g., irrigation, pest management, field operation scheduling) that are sensitive to weather monitoring and forecast information tend to have short lead times and be repeated frequently throughout the growing season. Because of the need for rapid and frequent dissemination, media (e.g., radio, television, internet, mobile phone) must play a prominent role in the delivery of weather information. Information at climate time scales (e.g., historic variability, seasonal forecasts, climate change projections) is particularly relevant to strategic decisions made near the beginning of the growing season (e.g., allocation of land, labor and capital among alternative enterprises or management strategies) or less frequently (e.g., capital investments, significant changes to the farming system). It is updated less frequently, and tends to be more challenging to understand and us, than information at the weather time scale. The speed of media is likely to be less important, and face-to-face learning is likely to be more important for information at climate than at weather time scales.

4.3.1. Regional Climate Outlook Forums

Regional climate outlook forums (RCOF) are the primary internationally coordinated mechanism for producing and delivering seasonal climate forecasts in Africa and Latin America. With backing from the WMO, NOAA, several donors, and international climate centers such as the IRI, the RCOFs bring national meteorological services (NMS) and a set of users from a region together to develop, distribute and discuss potential application of a consensus forecast of rainfall and sometimes other variables for the coming season. In Africa, the RCOFs are meant to climate information tailored to the needs of farmers, according to WMO Secretary-General Michel Jarraud (14 May 2008 statement to the UN Commission on Sustainable Development). The RCOFs have shaped, and typify, the way seasonal forecasts are provided in many developing countries. They generally express forecasts as very coarse scale maps of tercile probability shifts (section 4.1). Although NMSs are charged with downscaling RCOF consensus forecasts, and tailoring them to the needs of stakeholders within their countries, forecasts often reach national stakeholders in essentially the form, format and scale, although probabilistic information is sometimes collapsed into a deterministic forecast of the most probable tercile category. The RCOFs made important early contributions to public awareness, dialog between NMS and other stakeholders, technical capacity of NMS and regional climate centers, and sustaining forecast production and dissemination. However, designing RCOFs as a climate-led “a hub for activation and coordination of regional climate forecasting and applications activities…” (Basher, 2001, p. 13) gave the agricultural sector little influence over the design of RCOF products (at a cost to salience) and little ownership of the process (at a cost to legitimacy) (Cash et al., 2006; Hansen et al., 2007). Although agricultural stakeholders who take the initiative to attend the RCOFs access and seem to use the resulting information, the RCOFs generally fall short as a delivery mechanism for smallholder agriculture.

4.3.2. Media and ICT

Radio, television, mobile phones and internet have the potential provide information very quickly to a large audience. Newspaper, radio and television are traditional mechanisms for transmitting current weather observations and weather forecasts to the general public, including agricultural stakeholders. The relative importance of the various forms of media varies greatly by region. In Africa, rural radio has been the lowest cost vehicle for delivering climate information to rural communities at a large scale. However, the proliferation of mobile phone use over the past half decade is opening new opportunities for low-cost, timely delivery of information tailored to farmers’ needs and locations.

As part of its aggressive campaign to reach out to the agricultural sector, the Provincial Meteorological Office in Zambia’s Southern Province developed a weekly radio program, “Cuulu Cibomba Ku Ninkila” (“an ant hill that only softens by continued hammering”) (Durton Nanja, Provincial Meteorologist, pers. commun.). The program includes a range of topics (e.g., seasonal outlooks, the start and end of the rainy season, critical crop development stages, conservation farming, marketing) at the interface of agriculture and climate, information briefs in the form of “advertisements,” and drama that uses humor to reinforce concepts and motivate response.

Initiated in 1997 by the African Center for Meteorological Applications for Development (ACMAD), RANET (Radio and Internet for the Communication of Hydro-Meteorological and Climate Related Information) combines digital satellite technology, weather and climate information, low-cost community-owned radio stations, and wind-up radio receivers, to provide climate and other information to remote communities in several African countries (Boulahya et al., 2005). With support from the

WorldSpace Foundation, WorldSpace digital radio provides capability to send radio and one-way Internet anywhere within Africa and now much of Asia, to users with a special, low-cost WorldSpace receiver, adapter card, and Windows-based computer. RANET continues to operate in several African countries, although it seems to be much less active than in the first half of the decade.

Kenya's National Farmer's Information Service (NAFIS) (http://www.nafis.go.ke), launched in 2008, is designed to provide a targeted 4.5 million farmers with timely access to news and information, including weather, through mobile phones. Agricultural extension officers can update information content through the internet, which farmers can access directly through the web, or by phone translated into interactive voice response.

The internet has significant advantages over traditional forms of media because of its ability to present very detailed and customizable information through a combination of text, images, audio and video. India is investing in rural internet infrastructure at an unprecedented scale. The M.S. Swaminathan Research Foundation and others promote "Village Knowledge Centers" as a means to provide information to rural communities and to empower the women who are trained to operate them. Women from the rural community are trained to develop content, operate, and help interpret web-based information at village internet kiosks. It is an attractive model for delivering timely and locally-relevant climate information to agricultural stakeholders (Rengalakshmi, 2007).

The Virtual Academy for the Semi-Arid Tropics (VASAT) (http://vasat.icrisat.ac.in) is consortium, coordinated by ICRISAT and operating in South Asia and West and Central Africa, that develops and delivers web content and web-based access to experts, designed to equip rural communities to better manage drought. VASAT emphasizes creating demand-driven content that can be easily accessed, understood and applied by rural stakeholders; and trains "community animators" in partner organizations and multi-disciplinary professionals.

In many regions, particularly sub-Saharan Africa, the potential for internet-based delivery of climate information is currently constrained by the poor state of infrastructure and high cost. However, FANRPAN is looking closely at this model for southern Africa (Lindiwi Sibanda statement to the UN-CSD, http://www.un.org/esa/sustdev/csd/csd16/statements/technology_9may_africa.pdf).

4.3.3. Facilitated farmer workshops

Face-to-face group interaction, facilitated by someone who understands climate information and opportunities to manage climate risk, appears to be the most effective method for communicating information at a climate time scale in a way that farmers can use. A workshop setting allows a facilitator to use a combination of visual and narrative methods to present local forecast and historic climate information. Workshop-based interactions also provide a mechanism for evaluating and improving climate information products and communication protocols, and for informing agricultural research about farmers' climate-related problems. Sustained farmer-researcher and farmer-farmer interaction, and attention to communication issues seem to be common factors among the few pilot studies that have reported at least moderately high adoption of seasonal forecasts among smallholder farmers (Huda et al., 2004; Meinke et al., 2006; Patt et al., 2005; Roncoli et al., 2009).

The WMO has been promoting and facilitating "Roving Seminars on Weather, Climate, and Farmers," with the objectives of: (a) informing farmers about weather and climate risk management, (b) increasing interactions between farmers and national meteorological services, (c) raising farmers' awareness of advances in climate information, and (d) soliciting feedback to improve products and services (http://www.wmo.int/pages/prog/wcp/agm/roving_seminars/index_en.html). The seminars have been piloted in India, West Africa and Ethiopia. In Andhra Pradesh, India, the seminars led farmers to record daily weather time-series data from the local media (newspapers, radio and television). In West Africa, a series of one-day seminars in Mali, Burkina Faso, Mauritania, Niger and Senegal, supported by the State Agency for Meteorology in Spain and WMO, built on prior experience in Mali. Participating farmers received rain gauge so they could monitor and record their on-farm rainfall. The 2-day seminar in Tegray, Ethiopia, targeted agricultural extension agents and regional meteorologists in addition to farmers, and built largely on Mali's experience with agrometeorological services. Outcomes included a set of recommendations for strengthening agrometeorological information services in Ethiopia.

Climate Field Schools (CFS) in Indonesia (http://www.agrometeorology.org/topics/accounts-of-operational-agrometeorology/climate-field-schools-in-indonesia-coping-with-climate-change-and-beyond) are based on the experiences of Farmer Field Schools developed initially to support integrated pest management. Their goal is to enhance farmers' knowledge about the use of climate information for decision making. The curriculum covers the principles of response farming; the implications of climate for management of soil, water, planting date, pests and diseases; and adaptation to climate change. CFS were piloted initially in Indramayu, West Java, in 2005-2006, with the involvement of the Ministry of Agriculture, the NMS, Bogor Agricultural University, and the Asian Disaster Preparedness Center (Bangkok). Questions from alumni farmers about water management in rice prompted participatory research that further refined the CFS curriculum. The CFS process is being sustained and gradually scaled up elsewhere in the country.

Facilitated radio listening groups combine the benefits of media-based dissemination and facilitated group interaction. They also provide a potential mechanism to obtain feedback to improve content. A research project in Uganda provided insights in how to design useful radio messages about climate, and evidence of understanding and use by radio listening groups (Orlove and Roncoli, 2006; Phillips and Orlove, 2004).

Delivering climate information and supporting its use fits well within the role of agricultural extension. One of the goals of our work on farmer workshops in Eastern Province, Kenya (section 4.2.3), was to develop principles that could provide a basis for training agricultural extension officers to support the delivery and use of climate information. Unfortunately many government agricultural extension services eroded or were dismantled as a result of structural reform policies in the 1990s. Where agricultural extension services are non-functional or weak, agribusiness and NGOs may have potential to serve as communication intermediaries. In our experience in southern Zambia, the Dunavant cotton company appeared to be the most comprehensive source of technical, financial and market support for smallholder rainfed farmers. However, experience with another cotton parastatal in Burkina Faso suggests that there is some risk that agribusinesses could manipulate the delivery or interpretation of information to protect their interests (Ingram et al., 2002).

4.3.4. India's Agrometeorology Advisory Service

India is attempting to provide useful climate information to a range of agricultural stakeholders in a systematic manner at probably the largest scale. The National Center for Medium Range Weather Forecasting (NCMRWF), in collaboration with the Indian Meteorological Department (IMD) and national and state agricultural institutions, developed an Agrometeorological Advisory Service (AAS) that delivers medium-range (3-10 day) forecasts and management recommendations to farmers through a nation-wide network of 127 AAS Units (Rathore and Maini, 2008). At each Unit, an interdisciplinary group prepares a bi-weekly bulletin containing monitored and forecast weather information, crop conditions, weather-based and crop-specific advice, and early warning information for their agro-climatic zone. The information is disseminated to farmers through mass media (radio, newspaper), agricultural extension; and in some cases phone, poster and hand delivery. Groups of participating farmers provided a feedback mechanism to improve products, and a basis for evaluating impact. Operational responsibility for the AAS was transferred to IMD in 2007, after successful pilot demonstration and encouraging economic impact evaluation.

4.3.5. Mali's Agrometeorological Information Service

Through an effort launched in 1982, with support from Switzerland and technical support from the AGRHYMET Regional Center, Mali has pioneered what is widely considered the most comprehensive agrometeorological information service in sub-Saharan Africa (Hellmuth et al., 2007). Multidisciplinary working groups representing meteorological, agricultural and development agencies and the media helped bridge a divide between development and climate communities that has frustrated efforts elsewhere in Africa. Ten-day bulletins, disseminated by several means, provide monitored weather, crop and water conditions; and crop, livestock, pest and market information and advice. Short-range (1-3 days) weather forecasts are broadcast by radio. The multidisciplinary working groups consult seasonal forecasts, but do not provide the information directly to farmers. A set of participating farmers tests and refines services, disseminates information to the broader rural population, and evaluates impacts. On-farm evaluations showed substantial apparent yield and income benefits. The resulting evidence suggests that the information service has contributed to improved farm management, fostered adoption of new technologies, and stimulated demand for additional information.

5. Estimating Value of Advance Climate Information

5.1. Ex-ante and Ex-post valuation

Ex ante assessment seeks to assess the potential outcomes of an innovation in advance of its adoption, while ex post assessment seeks to assess outcomes following adoption. Because the use of seasonal climate forecasts within agriculture is a relatively new innovation, ex ante methods are, in most cases, the only way to estimate their benefits. Pilot studies have compiled some evidence of use of forecasts for farm decisions, but have generally not tried to quantify the resulting production or livelihood benefits. Even after farmers learn to use forecast information routinely, ex post assessment of benefits would require multiple years due to the stochastic nature of climate variability and forecast responses – longer than typical funding cycles allow. Furthermore, there are few, if any, regions in the developing world where rural communities have had access to operational climate information tailored to their needs for sufficient time to allow ex post assessment of use and benefits.

Ex-ante valuation can provide at least preliminary answers to questions such as: How do we evaluate potential, recommended or observed management responses to forecast information? How do we identify what decision option is best for a given forecast? How do we factor the inherent uncertainty of a seasonal climate forecast into recommendations? How do we attribute economic value to a forecast system or compare alternative forecast systems in a particular decision context?

5.2. Retrospective analysis

In the case of a seasonal climate forecast system *F*, the value of information (Eq. 1) is

$$V_F = \mathrm{E}\{U(\Pi(\mathbf{x}^* \mid F, \theta, \mathbf{e}))\} - \mathrm{E}\{U(\Pi(\mathbf{x}^* \mid \Theta, \theta, \mathbf{e}))\}, \qquad (2)$$

where *F* is the forecast distribution. The other variables are defined in section 3.1. In practice, we cannot know the full distribution of climatic or economic outcomes. However, potential value of a forecast system for particular decisions can be estimated by sampling hindcasts (i.e., past predictions) and realized weather in what is sometimes referred to as "retrospective analysis." Approximating the expected values in Eq. 2 by sampling *n* years of available past weather observations and hindcasts gives:

$$V_F \cong n^{-1}\sum_{i=1}^{n} U(\Pi(\mathbf{x}^* \mid F_i, \theta_i, \mathbf{e})) - n^{-1}\sum_{i=1}^{n} U(\Pi(\mathbf{x}^* \mid \Theta, \theta_i, \mathbf{e})). \tag{3}$$

Because each forecast F_i, potentially yields a different optimal strategy $\mathbf{x}_i$*, but there is only one optimal strategy in the absence of forecasts under these assumptions, $\mathbf{x}^*|\Theta$ and $\mathbf{x}^*|F$ are sometimes referred to as fixed and flexible strategies. For a skillful forecast system, forecasts F_i are closer, when averaged among all years i, than the climatological distribution Θ to realized weather θ_i, and hence forecast-based management strategies $\mathbf{x}^*|F_i$ are closer than climatology-based management $\mathbf{x}^*|\Theta$ to the management strategies $\mathbf{x}^*|\theta_i$ that are optimal for realized weather. The more skillful the forecast system, the closer the forecast-based management strategy is to the value of perfect foreknowledge of growing season weather,

$$V_{perfect} \cong n^{-1}\sum_{i=1}^{n} U(\Pi(\mathbf{x}^* \mid \theta_i, \theta_i, \mathbf{e})) - n^{-1}\sum_{i=1}^{n} U(\Pi(\mathbf{x}^* \mid \Theta, \theta_i, \mathbf{e})),$$

the upper limit of value of forecast information.

In the case where forecasts are expressed as probability of falling within a few categories (e.g., ENSO phase) rather than as continuous distributions (see section 4.1.3), some authors sum or integrate over forecast categories rather than over years, and then estimate expected economic returns as averages weighted by the historic frequencies of the forecast categories (e.g., Hill and Mjelde, 2002; Messina et al., 1999; Meza et al., 2008). This is equivalent to the more general formulation expressed in Eq. 3.

This general formulation (Eq. 3) must be adapted for different decision problems, and for analysis at different system levels (section 5.3). Retrospective analysis based on adaptations of Eq. 3 offers a flexible framework for estimating the potential value of a forecast system or improvements to an existing forecast system under a wide range of assumptions about the system being managed, the decision set, decision criteria, the forecast system, any perception biases or communication failures, and policy interventions that target any of these determinants of value. It requires a means to estimate economic outcomes as a function of weather and management using, e.g., simulation models or statistical production functions (section 5.4), and a means to identify management strategies that are optimal for forecasts and climatology.

5.3. Levels of analysis

Although the preceding discussion lays the groundwork for retrospective decision analysis, its application must be in the context of a particular set of decisions within a well-defined system operating in a particular environment. Agricultural systems are hierarchical. Although agriculture is studied at scales ranging from cellular to global, decision making emerges at the level of the enterprise, where agroecosystem processes and management of farm resources combine. Decisions such as management of crops and livestock can sometimes be analyzed at the enterprise level without explicitly considering whole-farm economics. Other decisions, such as allocation of farm land or family labor among competing enterprises, are explicitly farm-level and require farm-level analysis. While an individual farmer's decisions will generally have a negligible influence on market prices, large-scale adoption of production-related decisions may alter prices substantially, requiring a market-level analysis. We consider the enterprise and farm levels in more detail later.

Meza et al. (2008) provide a recent review of ex-ante, model-based studies of the value of seasonal forecasts for agriculture. Of the 58 analyses (from 33 publications) that they reviewed, most (43) are at the enterprise level, 10 are at a farm level, and 6 include at least elements at a market level. The majority of studies focused on agronomic crops grown under rainfed conditions. A few considered irrigated horticultural crops, and two addressed livestock. While many of the forecast value estimates were under \$10 ha^{-1} y^{-1}, high potential forecast values (approaching \$1000 ha^{-1} y^{-1}) were associated with high-value horticultural crops.

Table 3 Levels of analysis of climate forecast value

Level	Types of decisions	Objective functions	Optimization framework	Prices	Constraints
Enterprise	Intensification, input use, timing	Gross margin, risk efficiency	Unconstrained optimization of a production function	Exogenous	Production function
Farm	Resource allocation, timing	Farm or household income, expected utility	Constrained optimization	Exogenous	Land, labor, possibly capital
Market	Extent of adoption		Economic equilibrium modeling	Endogenous	Market equilibria

5.4. Translating climate into production outcomes

In rainfed agriculture, climate variations and climate-sensitive decisions impact economic outcomes primarily through crop or animal production. Analysis of the value of climate information for rainfed agriculture requires estimation of yield and/or income response to climate and to the management decisions under consideration. Where the focus is on crop management, crop × weather × management × soil (if inference across locations is needed) interactions must be estimated. Yield and/or income response to climate can be estimated either from statistical production functions or from dynamic crop simulation models integrated with climate forecasts. Statistical (generally econometric) and dynamic simulation modeling approaches can also be used to characterize baseline risk, i.e., distributions of outcomes under climate risk and current management. Each method has strengths and limitations. The brief discussion below does not attempt to capture the extensive literature on either econometric or agricultural simulation modeling methodology for characterizing risk and modeling the interactive response of agricultural production to weather and management.

5.4.1. Statistical modeling

The ability to estimate crop × weather × management interactions statistically depends on sufficient empirical data at the appropriate scale and across a sufficient range of climate variability to fit statistical production functions. Modeling risk (e.g., yield distributions) statistically is easier. However, there is no consensus about the form of distribution that is appropriate for yield response to weather variability. For rainfed conditions, this can be explained in part by the competing effects of the tendency for seasonal rainfall statistics to be positively skewed, and the tendency of crop response to rainfall to be nonlinear and concave, which would lead to negative skewness under a symmetrical (i.e., non-skewed) distribution of seasonal rainfall.

Because of their widespread availability and relatively long duration, official historic production statistics are often the best source of information about crop × weather interactions. Production statistics at an aggregate reporting district scale also tend to underestimate variability at a field or farm scale due to the imperfect correlation among fields within the district (Lobell et al., 2007; Rudstrom et al., 2002). Multi-year variety trials and farm yield records potentially provide information at a field scale, but are not widely available. Aggregate production statistics do not provide direct information about management interactions with crops and weather.

Non-climatic factors, such as changes in technology, land use, soil quality, and market influences on production intensity, influence district-scale yields and production. The simplest approach for dealing with these confounding factors is to de-trend the time series. A non-parametric smoothing function, such as a LOWESS or a spectral smoothing filter, is suited for de-trending, as it is designed to separate high-frequency (primarily climate) and low-frequency (primarily non-climatic drivers) signals. Furthermore, there is no clear theoretical basis for assuming that a trend should follow any particular functional form.

If the variance about the trend is constant, analyses of yield distributions or the effect of climate variables should be based on anomalies (i.e., observed – trend). When the standard deviation increases in proportion to the trend, analyzing ratios (i.e., observed / trend) stabilizes the variability of the data.

Where changes in technology or land use have significantly altered yield distributions, stochastic production functions (Chen et al., 2004; Just and Pope, 1978) can capture the effect of those factors on yield variability. Fitting crop × weather × management production functions generally requires either long-term experiments, or extensive and detailed surveys of farmer practices and yields.

5.4.2. Crop simulation modeling

Because they explicitly model the dynamic process underlying interactions, crop simulation models have the potential to provide more realistic and robust representation of the interactions between climate and management that are the source of value from seasonal forecasts. Regionally-adapted and tested crop simulation models allow one to quickly explore the production outcomes of a range of decision alternatives under a wide range of climatic conditions, and therefore crop × weather × management × soil interactions. Crop simulation models explicitly account for weather effects, but do not capture all determinants of actual farm yields or all relevant management options. It may therefore be useful to combine simulation modeling with statistical methods to calibrate crop model output or incorporate factors that the crop model does not account for. For example, a regression model can be used to adjust simulated yields to eliminate biases relative to an observed, de-trended time series of yields (Hansen and Jones, 2000). Additional predictor variables could be incorporated to account for processes (e.g., increasing pest and disease pressure as the season progresses) that crop models don’t capture.

A standard method to characterize production risk is to run a suitable, well-validated agricultural simulation model with many realizations of weather data either from historic observations or a stochastic weather model parameterized from observations. Use of stochastic weather generators requires caution, as many systematically under-represent year-to-year variability (Katz and Parlange, 1998; Wilks, 1999), and it may mask an inadequate sample of observed weather (used to parameterize the weather generator), giving a false sense of confidence in the resulting distribution.

Most published ex-ante studies of the value of forecast information for rainfed farming, and all I’m aware of at the enterprise level, incorporate agricultural simulation modeling (Meza et al., 2008) to capture crop or livestock interactions with weather and management. Nearly all incorporate use the analog method to incorporate climate forecast into simulated crop yields and (through enterprise budgeting) economic returns. (An exception is Hansen et al. (2009), who used a crop simulation model and stochastic disaggregation approach to estimate the potential value of forecasts from a GCM for maize management in two locations in Kenya.) The analog method samples weather data all years that fall within the current predictor category – usually ENSO phase (El Niño, neutral or La Niña) – to estimate simulate mean or probability distributions of outcomes. Although the approach is simple, it discards information, is prone to artificial skill and inflated value, and does not incorporate the state-of-the-art in climate prediction (Hansen et al., 2006). Several methods are now available (reviewed in Hansen et al., 2006) for linking crop simulation models with dynamic climate model output.

5.5. Decision criteria

Ex ante decision analysis requires some simplifying assumptions about how decision makers make decisions. The simplest assumption is expected profit maximization, constrained by whatever resource limitations or other factors limit the range of viable options.

Assuming that balancing the tradeoff between returns (i.e., mean level of livelihood) and risk (i.e., stability of livelihood) is among the farmers’ important goals, attitude toward risk is a key element the use of climate information. The standard framework in economics for accounting for risk attitudes assumes that the decision maker seeks to maximize the expected value of a utility function, and conforms to a set of axioms (ordering, transitivity, continuity, independence) (Anderson et al., 1977; von Neumann and Morgenstern, 1944) that define "rational" decision making in the face of risk. Utility U is a unitless measure of subjective value of, or preference placed on, different returns Π or levels of wealth W (e.g., stored grain, livestock or money), although economists generally focus on wealth, $W = W_0 + \Pi$, on the assumption that initial resource endowment W_0 conditions one's attitude toward risky decisions. Increasing U implies that decision makers prefer more rather than less. The shape of U embodies risk preferences: concave U implies aversion to risk (most people, including smallholder farmers), linear U implies risk neutrality (profit maximizers), and convex U implies risk seeking (gamblers). An economic interpretation attributes risk aversion to decreasing marginal utility of wealth. For example, a person in need of transportation is likely to benefit less from a second or third car than from a single car. Degree of risk aversion is related to the degree of curvature of U. Absolute risk aversion, $R_a(W) = -U''(W) / U'(W)$, is generally thought to decrease with increasing W.

A trivial example illustrates the key concepts of expected utility. In this example, a game involving a single toss of a coin creates a risky scenario with two equally-probable wealth outcomes, W_1 and W_2 (Fig. 5). Here the expected outcome $E(W)$ is the simple average, $(W_1+W_2)/2$. The vertical axis shows utility associated with each outcome, and with the expected outcome. The expected utility, $E(U(W))$, is less than the utility of the expected outcome, $U(E(W))$, due to the concavity of U. Because the scale of a utility function is arbitrary, it is useful to transform expected utility back to units of W. This transformation yields the *certainty equivalent*, $W_{CE} = U^{-1}(E(U(W)))$, the certain outcome that is equivalent, in terms of decision maker preferences, to the full distribution of outcomes associated with a risky prospect. The certainty equivalent can be regarded as a subjective value of a probabilistic economic outcome. Maximizing W_{CE} is equivalent to maximizing $E(U(W))$. A *risk premium*, $RP = E(W)-W_{CE}$, is the maximum amount that the decision maker would be willing to pay to eliminate the risk associated with the scenario.

The realism of forecast valuation studies can be improved by eliciting decision options and decision criteria from the farmers. Jochec et al. (2001) used focus groups of ranchers in West Texas, USA, to elicit factors that influence stocking rate decisions. They modeled the benefits of seasonal forecasts for stocking rate decisions and involved ranchers in evaluating the results, but did not use the process to explore a wider set of management responses. Bert et al. (2006) incorporated maize management responses to ENSO-based forecasts, elicited from farmer advisors in the Pampas region of Argentina, into model-based analysis of forecast value, and compared results with profit-maximizing strategies.

5.6. Enterprise-level analysis

In agricultural economics, an enterprise normally refers to an individual crop or herd that is managed as a unit, although other fields of economics may equate "enterprise" with a farm or other type of firm. A diversified farm contains a portfolio of production enterprises. The enterprise is the lowest managed level in the hierarchy of agricultural systems, and in many ways the simplest to analyze. The focus is generally on biological response to management; and on production costs and commodity prices. Results are typically expressed on a unit area basis. Because of the simplifications involved in enterprise-level analyses is that results can be interpreted relatively easily across farmers employing similar technology under similar environmental (i.e., soil, weather, economic) environmental conditions, and are therefore useful for fairly broad-based management recommendations.

Typical steps in an enterprise-level analysis of forecast value include:

- Identify the decision problem and a range of viable decision options;
- Implement a method for estimating production response to weather × management interactions using simulation modeling or perhaps a statistical production function;
- Develop a realistic enterprise budget;
- Develop a stochastic budget that accounts for climate variability;
- Identify and evaluate optimum strategies for climatology and for each hindcast or forecast category.

An enterprise budget calculates gross margin π as gross receipts less variable production costs, in monetary units per unit area (e.g., \$ ha^{-1}). In the case of a crop enterprise; with farmgate price P; yield y a function of management $\mathbf{x}$, weather θ and initial conditions $\mathbf{e}$; and variable costs $C_{\mathbf{x}}$, gross margin is calculated as:

$$\pi = P\ y(\mathbf{x},\theta,\mathbf{e}) - C_{\mathbf{x}}. \tag{4}$$

Variable costs are generally,

$$\begin{aligned} C_{\mathbf{x}} = & \sum \text{unit area costs} \\ & + \sum \text{per plant costs} * \text{planting density} \\ & + \sum \text{unit labor costs} * \text{labor use} \\ & + \sum \text{unit harvest \& processing costs} * \text{yield.} \end{aligned} \tag{5}$$

Costs that vary with specific management decisions under consideration should be factored into the cost. Other costs can be lumped together on a unit area basis.

Eq. 3 is adapted for a crop enterprise by substituting Eq. 4 for the utility and income terms, yielding,

$$V_F \cong n^{-1}\sum_{i=1}^{n}\left(P_T\ y(\mathbf{x}^* \mid F_i, \theta_i, \mathbf{e}_T) - C_{\mathbf{x}^*|F_i}\right) - n^{-1}\sum_{i=1}^{n}\left(P_T\ y(\mathbf{x}^* \mid \Theta, \theta_i, \mathbf{e}_T) - C_{\mathbf{x}^*|\Theta}\right), \tag{6}$$

where P_T is expected crop price, y is crop yield, $\mathbf{x}$ is a vector of management variables, $\mathbf{x}^*$ is the management strategy that maximizes expected gross margin (Eq. 4), $C_{\mathbf{x}}$ is cost of production associated with management strategy $\mathbf{x}$, F represents a particular hindcast or the forecast system, Θ is the climatological distribution, θ_i is observed weather in year i, T is the current year, n is the number of historic years sampled, and $\mathbf{e}_T$ represents the current value of other environmental variables – limited in this case to initial soil moisture and N conditions. For each year of weather data, crop yield is determined as a function of observed weather and of management optimized for either the hindcast or the climatological distribution. Equation 6 applies the enterprise budget to every past year of weather data – a process sometimes referred to as "stochastic budgeting." Because nearly all published studies (Meza et al., 2008) assume that forecasts are expressed in terms of a small number of categories (e.g., ENSO phases), the value of information is typically expressed as a an average among forecast categories, weighted by the relative frequency of each forecast category, rather than the more general form in Eq. 6. A recent exception is (Hansen et al., 2009), who analyzed the potential value of continuous forecasts, based on a GCM, for maize management in Kenya.

Simulating yield response, $y(\mathbf{x}, \theta, \mathbf{e})$, to management, observed weather and initial conditions is relatively straightforward. Identifying optimal crop management $\mathbf{x}^*$ is more intensive, as it requires estimating yields and calculating gross margins for the range of management options under consideration. Optimal management must be identified for the climatological distribution, and for each hindcast. The simplest approach is to simply simulate yields for a range of management strategies that encompass the optima expected under the range of forecasts. This requires selecting a discrete set of options for continuous management variables such as fertilizer amounts. The number of combinations that must be simulated increases geometrically as the range of management options increases. If simulation time would be excessive due to the number of management combinations or the speed of the simulation, it may be more efficient to embed the simulation model into a search algorithm to identify $\mathbf{x}^*$ for the climatological distribution and for each hindcast. Because of the complex response surfaces that crop simulation models tend to produce, relatively slow but robust search algorithms, such as simulated annealing or genetic algorithms, must be used instead of the more efficient gradient search algorithms (Royce et al., 2001). Alternatively, a hybrid approach involving fitting a production function to simulated response to management, allows analytical solution by differentiation, but is limited to reasonably well-behaved response surfaces of low dimensionality.

There are two clear limitations to enterprise-level analysis of the value of forecast information. First, it does not account for resource constraints, such as limited access to capital for purchased production inputs, or limited supply and competing demands for household labor. This is a greater concern for relatively poor smallholder farmers who cannot access financial services or labor markets. Second, for a diversified farming system, it is not possible to account for risk and the risk tolerance of farmers at an enterprise level. This is because imperfect covariance of income from different enterprises results in farm income that is more stable, on average, than the income streams from individual farm enterprises. Therefore enterprise analyses generally either assume risk neutrality (most published studies), or identify sets of management strategies that are risk efficient and hence preferable under some range of household risk exposure and range of risk preferences (Mjelde and Cochran, 1988).

5.7. Farm-level analysis

Since farm-level analysis considers the portfolio of production enterprises, it can account properly for climate-related risk, for the effect of diversification on income and consumption risk, and for farmers' risk tolerance. For a diversified farm, the variability (e.g., CV) of household income tends to be much lower than the average variability of individual production enterprises due to the imperfect correlation of the various income streams. Where it is part of the livelihood portfolio, non-farm income also tends to buffer farm household income. Consumption tends to be less variable than income due, for example, to savings, credit, food stocks and formal and informal insurance.

Many farm-level decisions have to do with allocation of limited resources. Resource allocation decisions include allocation of farm land among crops, livestock and other uses; and how to allocate household labor among farm activities, and between farm and non-farm employment. Farm decisions also include asset management, such as marketing strategy; borrowing; purchasing, leasing (in or out) or selling land or equipment; or hiring permanent or seasonal labor. Constrained optimization (or "mathematical programming") provides a flexible framework for such decisions. Standard texts on mathematical programming, such as Hazell and Norton (1986), provide useful guidance and examples for structuring constrained optimization models to capture some of the complexities of diversified farming systems and the factors that constrain farm decisions. Representing a complex, diversified farming system in a realistic manner may require primary data collection and interaction with farmers. The resulting model's ability to predict farmers resource allocation decisions is a minimum test of its validity. A reasonable strategy is to start with a simple model with minimal sets of activities and constraints, then refine it incrementally until it captures the salient features of the decision problem and predicts actual decisions adequately. So far, most published farm-level analyses of forecast value have assumed a very simple structure, allocated available land among enterprises without considering other constraints or the many other complexities of realistic smallholder farming systems (Meza et al., 2008).

Early work on farm-level economic modeling emphasized linear programming largely because the simplex algorithm provided efficient and robust solutions with limited computing power. Extensions of linear programming to handle risk required either rather ad-hoc decision rules (e.g., MOTAD) to accommodate the constraints of linear programming, or restrictive assumptions about preferences or the distribution of incomes (e.g., quadratic programming). The availability of good nonlinear solvers makes direct maximization of a nonlinear utility function quite practical (Lambert and McCarl, 1985).

A constrained optimization model includes an objective function that is to be maximized or minimized, and a matrix (or "tableau") with activities (e.g., production of a particular crop with a particular intensity of management) as columns, available resources as rows, and a matrix of technical coefficients that identify the amount of each resource required by a unit (e.g., a hectare) of each activity. The resources broadly include land, labor and capital. In addition to farm production enterprises, activities can include such things as consumption, marketing, storage and leisure.

A basic formulation for allocating farm land among crop enterprises to maximize expected nonlinear utility of wealth at the end of in the upcoming growing season is (Lambert and McCarl, 1985):

$$
\begin{aligned}
&\max_{\mathbf{x}} \mathrm{E}\{U(W_F)\} = \sum_{i=1}^{n} U(W_0 + \sum_{j=1}^{m} x_j \pi_{ij}) / n \\
&\text{subject to:} \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad (7)\\
&\quad \mathbf{A} \cdot \mathbf{x} \le \mathbf{b}, \\
&\quad \mathbf{x} \ge \mathbf{0},
\end{aligned}
$$

where U is utility for climate year i, W_0 is initial wealth, **x** is the vector of areas allocated to each crop enterprise x_j, π_{ij} is gross margin (Eq. 4) for crop j and year i, n is the number of years, m is the number of crop enterprises, **A** is a matrix of technical coefficients and **b** is a vector of farm resource constraints b_k. Gross margins, B_{ij}, from the jth crop enterprise are calculated from constant production costs and prices, and yields simulated with a crop simulation model using the ith year of daily weather data. Aversion to risk is encapsulated in the degree of curvature of a nonlinear utility function, U, which depends on farmer wealth, W (section 5.5). As with an enterprise-level analysis, yields and gross margins are estimated for each activity and each historic year of weather data. Stochastic budget results (i.e., each π_{ij}) must be linked dynamically to the nonlinear objective function through **x** before **x** can be optimized. Hardaker et al. (1991, 2004) discuss how to structure a mathematical programming model for direct expected utility maximization, and for alternative approaches for accounting for risk in mathematical programming models for farm planning.

The solution **x*** and resulting whole-farm income fits directly into Eq. 3. As with enterprise-level analysis, estimating forecast value requires solving the model for the climatological distribution and for each hindcast. Applications I'm aware of (reviewed in Meza et al., 2008) have used analog years with a small number of forecast categories. In these cases, the model is solved for the gross margins calculated for the subset of weather years falling into each individual forecast category.

5.8. Adoption and market-level analysis

Changes in management by one farmer will generally not impact prices. However, because of market equilibrium, large-scale changes in land allocation or crop management in response to widespread adoption of seasonal forecasts could have substantial impact on commodity prices and hence on farmer incomes. Widespread changes in crop mix have much greater potential price impacts than changes in management of existing crops.

At its simplest, market equilibrium can be analyzed for a single commodity in a single region. However, input and output markets are interconnected. General equilibrium modeling attempts to capture market equilibria across an entire economy. Partial equilibrium models focus on one or a few commodities, and assume that the prices of substitutes and complements are constant. Economic equilibrium models provide estimates of impacts in the forum of economic surplus, separately for producers and for consumers. The implementation of equilibrium modeling methods is beyond the scope of this report.

Several studies (reviewed in Meza et al., 2008) have used economic equilibrium modeling to estimate the potential value of climate forecasts at aggregated levels, assuming complete adoption. Similar to other improvements in agricultural technology, these studies generally show that widespread use of forecasts for agriculture would improve the welfare of consumers (through lower prices) and overall welfare of society. In most cases, these studies suggest that lower prices would outweigh the production benefits, leading to a reduction in producer surplus. However, in a study of the implications of forecasts for international wheat trade, Hill et al. (2004) found that producers would consistently benefit from complete adoption.

Two studies examined the effect of degree of adoption on the value of forecast information. For tomato growers in Florida, USA, Messina et al. (2006) showed that the information has a high potential value for the first farmers who use it, but that the value decreases due to reduced equilibrium market prices as more farmers adopt forecasts. With 100% adoption, forecasts have negative value to producers if they act independently, but producers can retain substantial value if they coordinate their responses to forecasts optimally. Rubas et al. (2008) examined the adoption of the use of seasonal climate forecasts in multiple countries throughout an international wheat trade model. They also found that early adopters would benefit the most, and that after 60 to 95% adoption there would be no further inventive for producers to respond to forecasts.

Any generalization that widespread adoption of climate information would reduce farmers' welfare should be viewed with caution. There are several mechanisms by which increases in production potentially benefit rural households, including improving their own food consumption, increasing agricultural employment opportunities and wages in the adopting region, stimulating growth in the local non-farm rural economy, increasing opportunities for livelihood through migration, and lowering food prices for farmers who are net buyers (Hazell, 2003).

6. Priorities for Scaling Up Climate Information Services for Rainfed Agriculture

The current state of climate information services is quite variable across the developing world. I suggest a few very broad generalizations that have implications for where to prioritize investment in scaling up climate information services for rainfed agriculture:

- Most countries routinely distribute agrometeorological bulletins that package relevant information about monitored weather, crop conditions; and sometimes weather forecasts and management recommendations. The World AgroMeteorolgical Information Service (WAMIS) has links to many (http://www.wamis.org). This is a primary resource for farmers and other decision-makers, but has little to offer at lead times longer than tactical decisions.
- Current mechanisms for packing and communicating forecasts at a seasonal lead time are woefully inadequate, and generally don't build on the state of knowledge about farmers' information needs.
- Current climate change scenarios are probably not adequate for routine use for farm-level planning because of their coarse spatial scale, time scales that don't match most strategic agricultural decisions, and particularly inadequate quantification of uncertainty.
- Gaps (in space and in time) in basic weather observations limit the usefulness of climate information for management at the farm level.
- The policy of many countries restricts access to historic weather observations by farmers and other agricultural stakeholders, which further limits the usefulness of other forms of climate information.
- Coordination between agricultural and climate institutions is often poor or lacking.

Sub-Saharan Africa faces particular challenges, but also offers unique opportunities to intervene. Relative to other continents and regions, sub-Saharan Africa as a whole has the least growth in agricultural production, the least development of irrigation, the highest proportion of the population dependent on rainfed agriculture, the most frequent and severe weather-related humanitarian crises, and possibly the least developed institutional support for improving the welfare of the rural population. A multi-stakeholder, cross-sectoral assessment of the use of climate information in Africa describes inadequate use of climate information, across sectors and from local to policy levels (with a few noteworthy exceptions), relative to the scale of the development challenge. The report concluded that merely improving the supply in climate data or observing infrastructure would have little impact on development because the present gap results from "market atrophy" associated with long-term interaction between ineffective demand by development stakeholders and inadequate supply of relevant climate information services (IRI, 2006). Several gaps need to be addressed in parallel if climate information is to contribute significantly to efforts to improve rainfed agriculture at the scale of the challenge.

6.1. National meteorological services

Structural reform policies in the 1990s encouraged national meteorological services (NMS) to raise revenues to supplement shrinking public funds. The unfortunate impact in many cases included: (a) treating data as a source of revenue for NMS rather than a public good, (b) prioritizing commercial aviation over other sectors such as agriculture, and (c) reducing the capacity of NMS to provide services to agriculture. Where this has happened, NMS need to be realigned, resourced and trained as providers of services for development and participants – but not leaders – in the development process. Restrictive data policy has marginalized NMS, and often forced the agriculture sector to either invest in redundant climate observing infrastructure and services, or make due with woefully inadequate information products and services. As a matter of national policy, meteorological data should be treated as a free public good and a resource for sustainable development.

6.2. Climate data

Rain gauge coverage over most of Africa is seriously inadequate and reporting of observations has been declining (Washington, 2006). Data rescue is needed to digitize older paper archives, and in some cases, to locate records that may reside in former colonial powers. Satellite remote sensing provides a complementary source of rainfall estimates with complete spatial coverage. Merging station and satellite data on a daily time step has potential to fill gaps in space and time. Current satellite-based rainfall data products are limited by their by their short duration, and often by coarse spatial and temporal (monthly or 10-daily) resolution. The longer available satellite rainfall products combine data based on different sensors, and are calibrated with varying amounts of station data. These constraints can be largely overcome. METEOSAT geostationary satellite images extend back to 1978, with full spatial coverage of Africa at a frequency of at least two images per hour and a spatial resolution of roughly 3-6 km. Removing the substantial biases in satellite rainfall estimates requires local calibration, ideally using the full set of quality-controlled stations that each country maintains and not the small fraction (on a continent-wide basis) of observations that are made freely available. Where data are sparse, data rescue; and the development of moderately high-resolution, spatially and temporally complete, daily merged station-satellite meteorological data sets is a relatively low-cost immediate investment opportunity with very high potential benefits.

6.3. Climate change information

The current generation (i.e., those used in the 4th IPCC assessment) is useful to raise awareness and motivate greenhouse gas mitigation policy, but has limited usefulness for adaptation at a local scale. Their 50-100 year time scales do not match the time frame of most viable agricultural decisions (with the exception of large-scale infrastructure) that would impact vulnerability to climate change (Table 1). Furthermore, while some degree of warming can be detected and anticipated in the majority of the developing world, projected trends in precipitation have a high degree of uncertainty at a regional scale, and even higher but generally uncharacterized uncertainty at a local scale. Near-term (roughly 1-3 decades) climate change is far more relevant for agricultural adaptation. The sources of uncertainty are different at the near-term (i.e., natural low-frequency variability; ocean heat profile) and longer-term (i.e., economic development pathways and resulting atmospheric composition). Emerging research on near-term climate change should be accelerated, and emphasize quantification of uncertainty at multiple scales.

6.4. Delivery mechanisms

Effective and timely information delivery is a particular challenge in the case of smallholder farmers due to their large numbers, remoteness, poor state of rural communication infrastructure, and weakness of many national agricultural extension systems in developing countries. These challenges tend to be greater in sub-Saharan Africa than in other developing regions. Many developing countries face a tremendous need to invest in rural climate information services, and particularly in effective mechanisms to make relevant information and guidance readily accessible to smallholder rainfed farmers. The ideal combination of delivery mechanisms (discussed further in section 4.3) is likely to vary with context, but generally include some combination of human interaction, mass media and ICT. Climate information services should ideally be integrated as a routine part of agricultural extension services where they are functional; underpinned by training for intermediaries and by agricultural research. Agricultural extension services (and their non-governmental and private sector counterparts) should be revitalized, resourced, trained, and engaged to provide climate and early warning information, and to foster and guide effective management responses. Group interaction, facilitated by agricultural extension, prior to each growing season, provides a valuable opportunity to review recent climate records, discuss decisions and outcomes from the previous season, present downscaled forecasts for the upcoming season, explore management implications, and advocate for other areas of technical and institutional support that would enable farmers to better manage risk. Investment in rural communication infrastructure (radio, internet) is also needed reach rural communities with information at the weather time scale, and to streamline information transfer to communication intermediaries (e.g., district agricultural offices).

6.5. Evidence

Evidence of development impact for rural climate information services is needed to mobilize sustained political, financial and institutional support. A weak body of evidence relative to other agricultural development interventions is due to: (a) newness of seasonal prediction, (b) lag time required to quantify impact particularly in the face of a stochastic driver, (c) widespread institutional failures that have constrained use beyond pilot projects, (d) neglect of impact assessment for established agrometeorological information services and by proponents of seasonal forecasts, and (e) early studies that identified, but didn’t seek to overcome, constraints to using existing operational products. Pilot studies that address known barriers to accessing and using multiple forms of climate information for agricultural management should be oriented toward providing credible, quantitative evidence of their use and value.

Figures

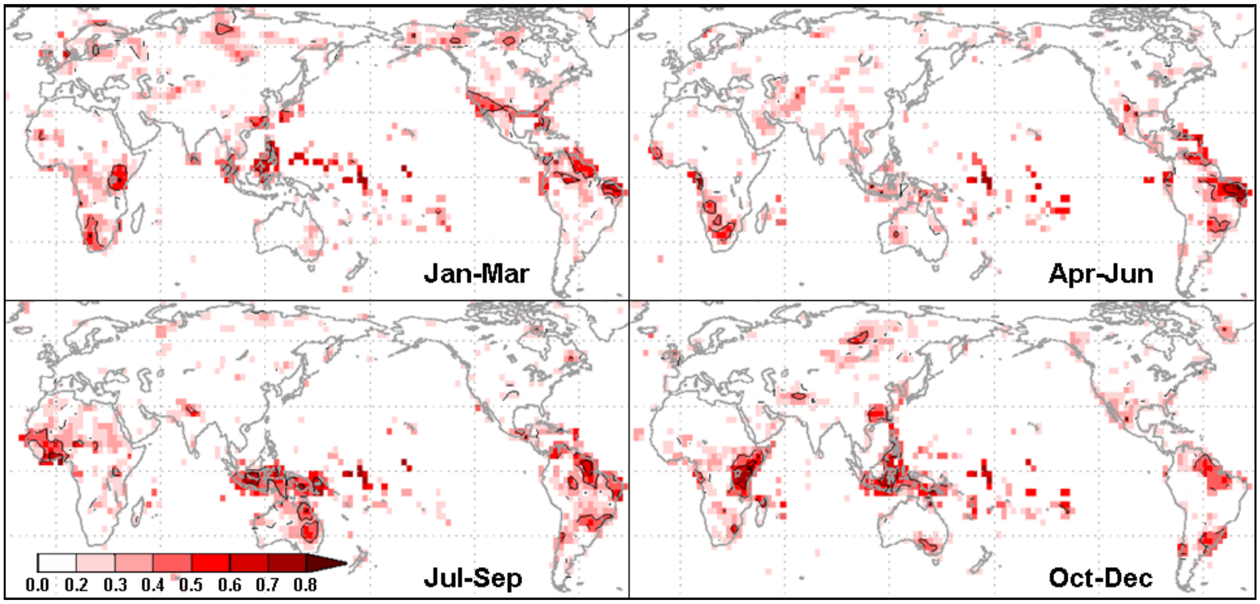

Figure 1. Correlations of observed rainfall with ECHAM 4.5 simulated with observed global SST fields (IRI).

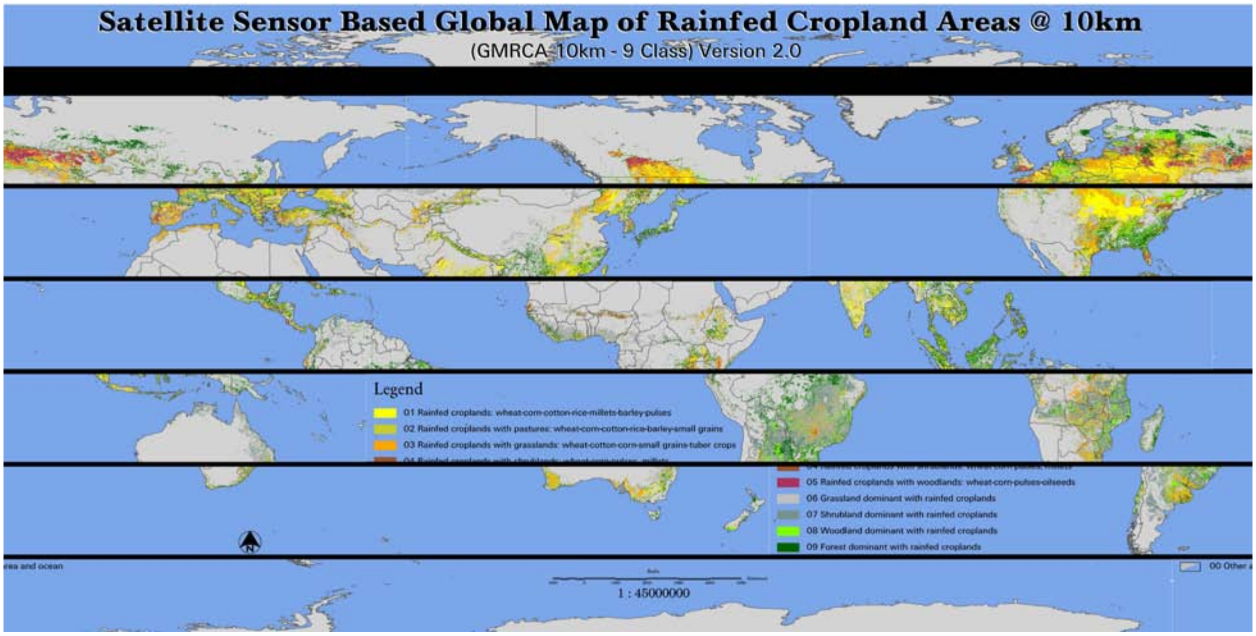

Figure 2. High-resolution estimates of global rainfed crop land areas (IWMI).

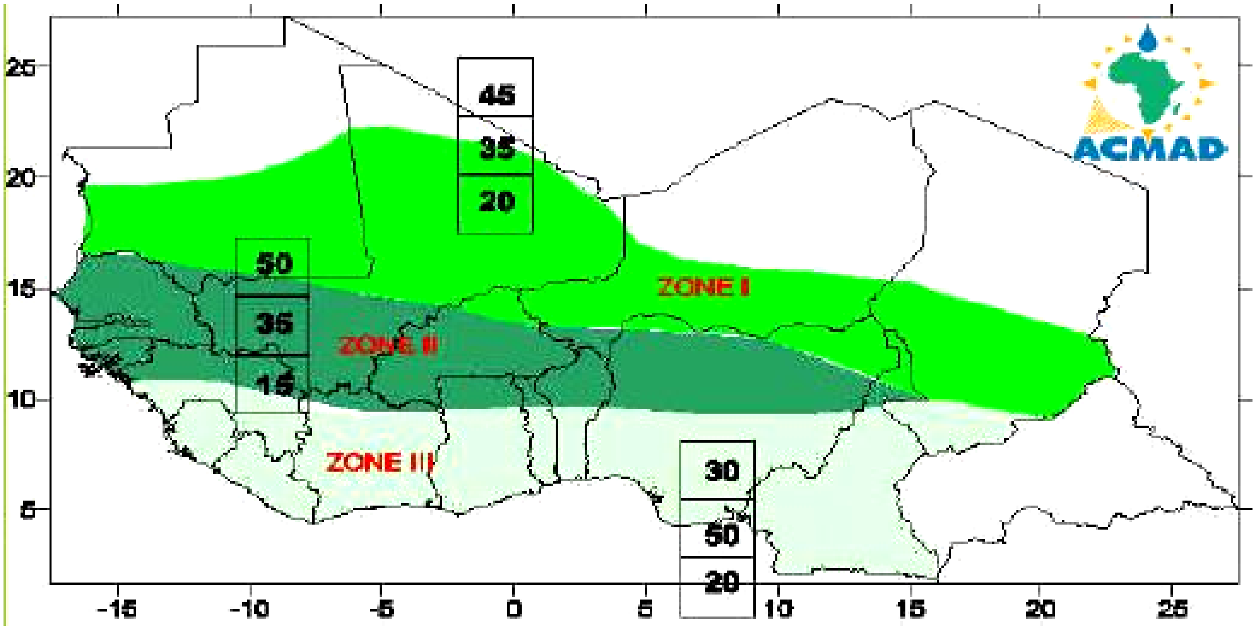

Figure 3. June 27, 2008 update of July-September seasonal rainfall forecast for West Africa (ACMAD). Numbers represent the probability that rainfall total in the upcoming season will be within the wettest (top number), middle (middle number) and driest (bottom number) terciles.

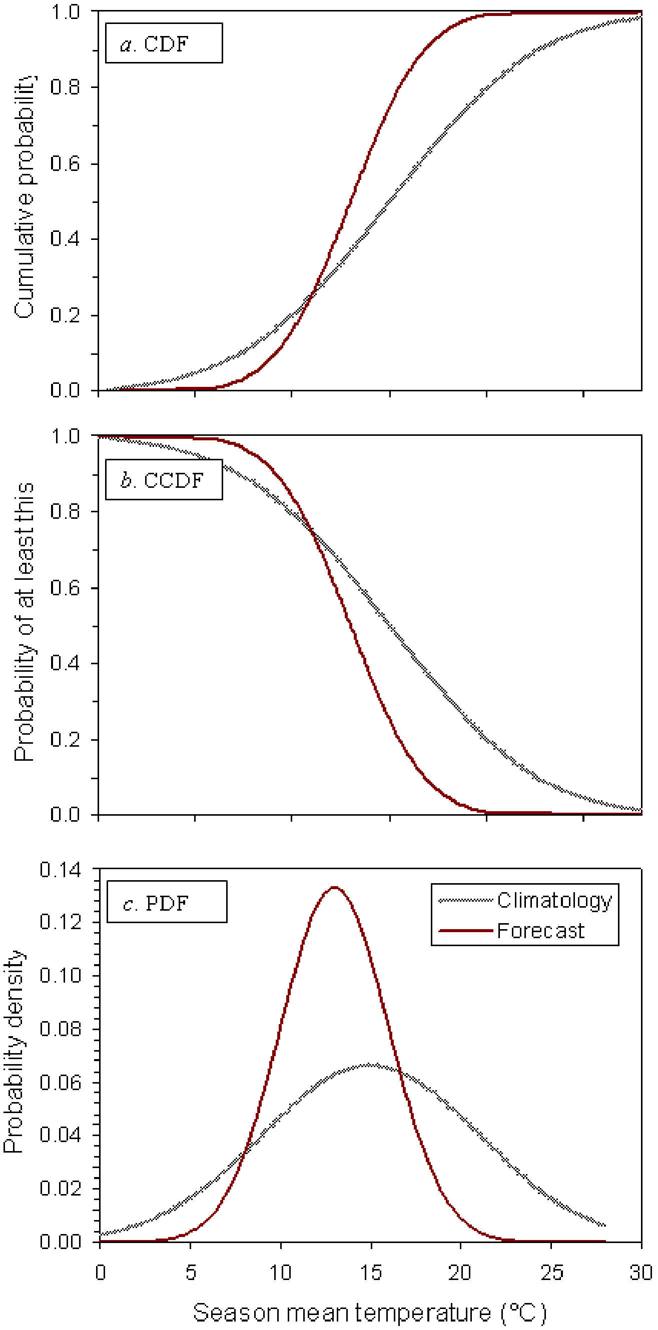

Figure 4. Hypothetical temperature forecast expressed as shifted cumulative distribution (a), probability of exceedance (b) and probability density (c).

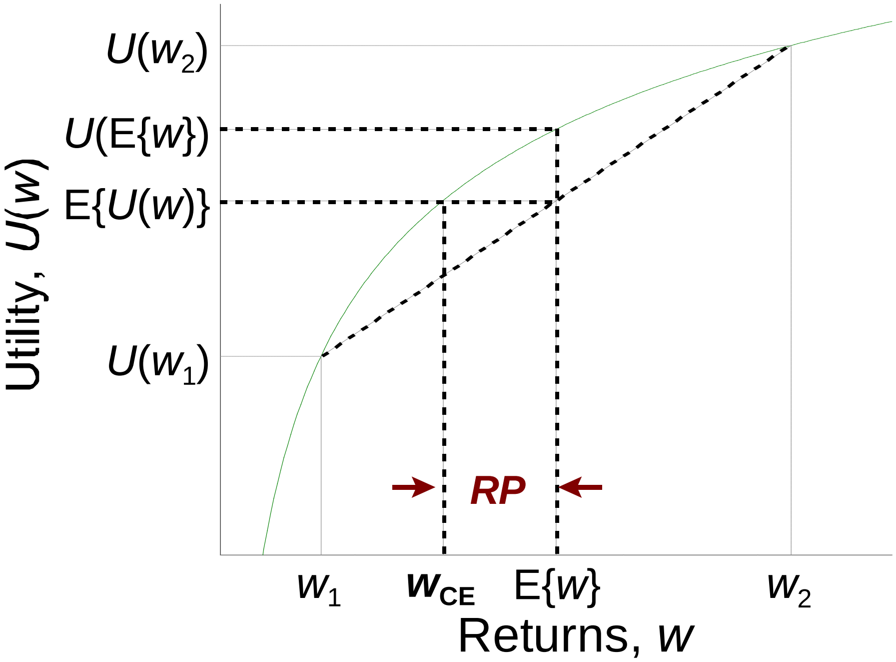

Figure 5. Illustration of expected utility concepts for a risk-averse decision maker faced with two equally-probable outcomes.

References

Anderson, J.R., Dillon, J.L. and Hardaker, J.B., 1977. Agricultural Decision Analysis. Iowa State University Press, Ames, Iowa, USA.

Anderson, W.K., 1984. Plant populations for triticale in a Mediterranean environment. Field Crops Research, 8: 281-295.

Archer, E.R.M., 2003. Identifying underserved end-user groups in the provision of climate information. Bulletin of the American Meteorological Society, 84: 1525-1532.

Barret, C.B. and Carter, M.R., 2001. Can't Get Ahead For Falling Behind: Development Policy, Poverty, and Relief Traps. Choices, Winter 2001-2002: 35-38.

Barrett, C.B. et al., 2007. Poverty Traps and Climate Risk: Limitations and Opportunities of Index-Based Risk Financing, International Research Institute for Climate and Society, Palisades, New York.

Barrett , C.B., Moser, C.M., McHugh, O.V. and Barison, J., 2004. Better Technology, Better Plots or Better Farmers? Identifying Changes In Productivity And Risk Among Malagasy Rice Farmers. American Journal of Agricultural Economics, 86: 869-888.

Barrett, C.B. and Swallow, B.M., 2006. Fractal poverty traps. World Development, 34: 1-15.

Basher, R., C. Clark, M. Dilley, and M. Harrison (Editor), 2001. Coping with Climate: A Way Forward. Summary and Proposals for Action. International Research Institute for Climate Prediction, Palisades, New York.

Bert, F., Satorre, E.H., Toranzo, F.R. and Podestá, G.P., 2006. Climatic information and decision-making in maize production systems of the Argentinean Pampas. Agricultural Systems, 88: 180-204.

Besley, T., 1995. Property Rights and Investment Incentives: Theory and Evidence from Ghana. Journal of Political Economy, 103: 903–937.

Binswanger, H. and Sillers, D.A., 1983. Technological priorities for farming in Sub-Saharan Africa. World Bank Research Observer, 3: 81-98.

Boulahya, M., Stewart-Cerda, M., Pratt, M. and Sponberg, K., 2005. Climate, communications, and innovative technologies: potential impacts and sustainability of new radio and internet linkages in rural African communities. Climatic Change, 70: 299-310.

Breuer, N. et al., 2000. Potential use of long range climate forecasts by livestock producers in north central Florida, Univeristy of Florida, Miami, Florida, USA.

Carter, M.R. and Barrett, C.B., 2006. The economics of poverty traps and persistent poverty: an asset-based approach. Journal of Development Studies, 42: 178-199.

Carter, M.R., Little, P.D., Mogues, T. and Negatu, W., 2007. Poverty traps and natural disasters in Ethiopia and Honduras. World Development, 35: 835-856.

Cash, D.W., Borck, J.C. and Patt, A., G., 2006. Countering the loading dock approach to linking science and decision making: comparative analysis of El Nino/Southern Oscillation (ENSO) forecasting systems. Science, Technology & Human Values, 31: 465-494.

Changnon, S.A., 2002. Impacts of the Midwestern drought forecasts of 2000. Journal of Applied Meteorology, 41: 1042-1052.

Chavas, J.P. and Pope, R.D., 1984. Information: its measurement and valuation. . American Journal of Agricultural Economics, 66: 705-710.

Chen, C., McCarl, B.A. and Schimmelpfennig, D.E., 2004. Yield variability as influenced by climate: a statistical investigation. Climatic Change, 66: 239-261.

Childs, I.R.W., Hastings, P.A. and Auliciems, A., 1991. The acceptance of long-range weather forecasts: A question of perception? Australian Meteorological Magazine, 39(2): 105-112.

Christianson, C.B. and Vlek, P.L.G., 1991. Alleviating soil fertility constraints to food production in West Africa: efficiency of nitrogen fertilizers applied to food crops. Fertilizer Research, 29: 21-33.

Chu, Y.P. and Chu, R.L., 1990. The subsidence of preference reversals in simplified and market-like experimental settings: a note. American Economic Review, 80: 902-911.

Clewett, J.F. et al., 2000. Building knowledge and skills to use seasonal climate forecasts in property management planning. In: G.L. Hammer, N. Nicholls and C. Mitchell (Editors), Applications of Seasonal Climate Forecasting in Agricultural and Natural Ecosystems: The Australian Experience. . Kluwer Academic Publishers Dordrecht, The Netherlands pp. 291-307.

Coventry, W., 2001. Getting the odds across - A better way. Climag, 5: 14, 16.

Dercon, S., 1996. Risk, crop choice, and savings: evidence from Tanzania. Economic Development and Cultural Change, 44(3): 485-513.

Dercon, S., 2002. Income Risk, Coping Strategies, and Safety Nets. The World Bank Research Observer, 17(2): 141-166.

Dercon, S., 2004. Growth and shocks: evidence from rural Ethiopia. Journal of Development Economics, 74: 309-329.

Dercon, S. and Christiaensen, L., 2007. Consumption risk, technology adoption and poverty traps: evidence from Ethiopia World Bank Policy Research Working Paper 4257, World Bank, Washington, DC.

Dercon, S. and Hoddinott, J., 2005. Health, Shocks and Poverty Persistence. In: S. Dercon (Editor), Insurance Against Poverty. Oxford University Press, Oxford, UK.

Easterly, W., 2001. The Elusive Quest for Growth. MIT Press, Cambridge, Mass, USA.

Elbers, C., Gunning, J.W. and Kinsey, B., 2007. Growth and risk: methodology and micro evidence. World Bank Economic Review, 21: 1-20.

Everingham, Y.L. et al., 2002. Enhanced risk management and decision-making capability across the sugarcane industry value chain based on seasonal climate forecasts. Agricultural Systems, 74: 459-477.

Fafchamps, M., 2003. Rural Poverty, Risk and Development. Edward Elgar Publishing, Glos, UK.

Fischhoff, B., 1994. What forecasts (seem to) mean. International Journal of Forecasting, 10: 387-403.

Gadgil, S., Rao, P.R.S. and Rao, K.N., 2002. Use of climate information for farm-level decision making: rainfed groundnut in southern India. Agicultural Systems, 74(3): 431-457.

Gaiha, R. and Thapa, G., 2006. Natural Disasters, Vulnerability and Mortalities – A Cross-Country Analysis, International Fund for Agricultural Development, Rome.

Gigerenzer, G. and Hoffrage, U., 1995. How to improve Bayesian reasoning without instruction: Frequency formats. Psychological Review, 102: 684-704.

Gilovich, T., Griffin, D. and Kahneman, D. (Editors), 2002. Heuristics and Biases: The Psychology of Intuitive Judgment. Cambridge University Press, New York.

Gong, X., Barnston, A. and Ward, M., 2003. The effect of spatial aggregation on the skill of seasonal precipitation forecasts. Journal of Climate, 16: 3059-3071.

Hammer, G.L. et al., 2001. Advances in application of climate prediction in agriculture. Agricultural Systems, 70: 515-553.

Hansen, J.W., 2001. Applying climate prediction in a risk management framework: farm land allocation in the Argentine Pampas., Proceedings of the Twenty-Fifth Annual Climate Diagnostics & Prediction Workshop, Palisades, New York, 23-27 October 2000. U.S. Department of Commerce. , pp. 181-184.

Hansen, J.W., Baethgen, W., Osgood, D., Ceccato, P. and Ngugi, R.K., 2007. Innovations in climate risk management: protecting and building rural livelihoods in a variable and changing climate. Journal of Semi-Arid Tropical Agricultural Research, 4(1).

Hansen, J.W., Challinor, A., Ines, A.V.M., Wheeler, T. and Moron, V., 2006. Translating climate forecasts into agricultural terms: advances and challenges. Climate Research, 33: 27-41.

Hansen, J.W. and Indeje, M., 2004. Linking dynamic seasonal climate forecasts with crop simulation for maize yield prediction in semi-arid Kenya. Agricultural and Forest Meteorology, 125: 143-157.

Hansen, J.W. and Jones, J.W., 2000. Scaling-up crop models for climate variability applications. Agricultural Systems, 65: 43-72.

Hansen, J.W., Marx, S. and Weber, E., 2004. The Role of Climate Perceptions, Expectations, and Forecasts in Farmer Decision Making: The Argentine Pampas and South Florida, International Research Institute for Climate and Society, Palisades, New York.

Hansen, J.W., Mishra, A., Rao, K.P.C., Indeje, M. and Ngugi, R.K., 2009. Potential value of GCM-based seasonal rainfall forecasts for maize management in semi-arid Kenya. Agricultural Systems, DOI:10.1016/j.agsy.2009.03.005.

Hansen, J.W. and Selvaraju, R., 2001. Why do farmers need to understand climate forecast uncertainty?, Proceedings of the Workshop on Communication of Climate Forecast Information. IRI-CW/01/4. International Research Institute for Climate Prediction Palisades, New York., pp. 7-9.

Hardaker, J.B., Huirne, R.B.M., Anderson, J.R. and Lien, G., 2004. Coping with Risk in Agriculture. CABI Publishing, Wallingford.

Hardaker, J.B., Pandey, S. and Patten, L.H., 1991. Farm planning under uncertainty: a review of alternative programming models. Review of Marketing and Agricultural Economics, 59: 9-22.

Hayman, P.T., 2000. Communicating probabilities to farmers: Pie charts and chocolate wheels. In: P.R. J. (Editor), A Manual of Tools for Participatory R&D in Dryland Cropping Areas. . Rural Industries Research and Development Corporation Canberra, Australia pp. 133-136. .

Hazell, P.B.R., 2003. The Impact of Agricultural Research on the Poor: A Review of the State of Knowledge. In: S. Mathur and D. Pachico (Editors), Agricultural Research and Poverty Reduction: Some Issues and Evidence. Economic and Impact Series 2. CIAT, Cali, Colombia, pp. 43-57.

Hazell, P.B.R. and Norton, R.D., 1986. Mathematical Programming for Economic Analysis in Agriculture. Macmillan, New York.

Hellmuth, M.E., Moorhead, A., Thomson, M.C. and Williams, J. (Editors), 2007. Climate Risk Management in Africa: Learning from Practice. Climate and Society Series. International Research Institute for Climate and Society, Columbia University, New York.

Hertwig, R. and Ortmann, A., 2002. Experimental practices in economics: a methodological challenge for psychologists. Behavioral and Brain Sciences, 24: 383-451.

Hill, H.H.S. and Mjelde, J.W., 2002. Challenges and opportunities provided by seasonal climate forecasts: a literature review. Journal of Agricultural and Applied Economics, 34: 603-632.

Hill, H.S.J. et al., 2004. Implications of seasonal climate forecasts on world wheat trade: a stochastic, dynamic analysis. Canadian Journal of Agricultural Economics, 52: 289-312.

Hilton, R.W., 1981. The determinants of information value: synthesizing some general results. Management Science, 27(1): 57-64.

Hoddinott, J., 2006. Shocks and their consequences across and within households in rural Zimbabwe. Journal of Development Studies, 42: 301-321.

Huda, A.K.S. et al., 2004. Experiences of using seasonal climate information with farmers in Tamil Nadu, India. In: A.K.S. Huda and R.G. Packham (Editors), Using Seasonal Climate Forecasting in Agriculture: a Participatory Decision-making Approach. ACIAR Technical Report. Australian Centre for International Agricultural Research, Canberra.

Hunt, J.R. et al., 2006. Yield Prophet®: An online crop simulation service, 13th Australian Agronomy Conference. Australian Society of Agronomy.

Ingram, K.T., Roncoli, M.C. and Kirshen, P.H., 2002. Opportunities and constraints for farmers of west Africa to use seasonal precipitation forecasts with Burkina Faso as a case study. Agricultural Systems, 74(3): 331-349.

IRI, 2006. A Gap Analysis for the Implementation of the Global Climate Observing System Programme in Africa, International Research Institute for Climate and Society, Palisades, New York.

Jochec, K.G., Mjelde, J.W., Lee, A.C. and Conner, J.R., 2001. Use of seasonal climate forecasts in rangeland-based livestock operations in West Texas. Journal of Applied Meteorology, 40: 1629-1630.

Johnson, S.R. and Holt, M.T., 1997. Economic Value of Weather and Climate Forcasts. In: R.W. Katz and A.H. Murphey (Editors), The value of weather information. Cambrige University Press, Cambrige, UK, pp. 75-107.

Jones, J.W., Hansen, J.W., Royce, F.S. and Messina, C.D., 2000a. Potential benefits of climate forecasting to agriculture. Agriculture, Ecosystems and Environment, 82: 169-184.

Jones, J.W., Hansen, J.W., Royce, F.S. and Messina, C.D., 2000b. Potential benefits of climate forecasting to agriculture. . Agriculture, Ecosystems and Environment 82: 169-184.

Just, R.E. and Pope, R.D., 1978. Stochastic Specification of Production Function and Economic Implications. Journal of Econometrics, 7: 67-86.

Kahneman, D. and Tversky, A., 1979. Prospect Theory: An analysis of decision under risk. . Econometrica, 47: 263-291.

Katz, R.W. and Parlange, M.B., 1998. Overdispersion phenomenon in stochastic modeling of precipitation. Journal of Climate, 11: 591-601.

Kebede, Y., 1992. Risk behavior and new agricultural technologies: the case of producers in the central highlands of Ethiopia. Quarterly Journal of International Agriculture, 31: 269-284.

Kelly, V., Adesina, A.A. and Gordon, A., 2003. Expanding access to agricultural inputs in Africa: a review of recent market development experience. Food Policy, 28: 379-404.

Klopper, E. and Bartman, A., 2001. The use of seasonal forecasts among commercial farmers in South Africa during the late 1990s. Water South Africa.

Koehler, J.J., 1996. The base rate fallacy reconsidered: descriptive, normative, and methodological challenges. Behavioral and Brain Sciences, 19: 1-53.

Lambert, D.K. and McCarl, B.A., 1985. Risk modeling using direct solution of nonlinear approximations of the utility function. American Journal of Agricultural Economics, 67: 846-852.

Lazar, C. and Genovese, G. (Editors), 2004. Methodology of the MARS Crop Yield Forecasting System. EUR 21291 EN/1. EC Joint Research Center, Ispra, Italy.

Letson, D. et al., 2001. User perspectives of climate forecasts: crop producers in Pergamino, Argentina. Climate Research, 19: 57-67.

Lobell, D.B., Ortiz-Monasterio, J.I. and Falcon, W.P., 2007. Yield uncertainty at the field scale evaluated with multi-year satellite data. Agricultural Systems, 92: 76-90.

Madden, B. and Hayes, G., 2000. Building dairy farmer demand for climate information, Proceedings of the Conference on Managing Australian Climate Variability. Albury, NSW, Australia, 23–25 October 2000.

Marra, M., Pannell, D.J. and Ghadim, A.K.A., 2003. The economics of risk, uncertainty and learning in the adoption of new agricultural technologies: where are we on the learning curve? Agricultural Systems, 75: 215-234.

Marx, S.M. et al., 2007. Communication and mental processes: Experiential and analytic processing of uncertain climate information. Global Environmental Change, 17: 47-58.

McCown, R.L., 2002. Changing systems for supporting farmers' decisions: problems, paradigms, and prospects. Agricultural Systems, 74: 179-220.

McCrea, R., Dalgleish, L. and Coventry, W., 2005. Encouraging use of seasonal climate forecasts by farmers. International Journal of Climatology, 25: 1127-1137.

McPeak, J.G. and Barrett, C.B., 2001. Differential risk exposure and stochastic poverty traps among East African pastoralists. American Journal of Agricultural Economics, 83: 674-679.

Meinke, H. and Hammer, G.L., 1995. Climatic risk to peanut production: a simulation study for Northern Australia. Australian Journal of Agricultural Research, 35: 777-780.

Meinke, H. et al., 2006. Actionable climate knowledge: from analysis to synthesis. Climate Research, 33: 101-110.

Meinke, H. and Stone, R.C., 2005. Seasonal and inter-annual climate forecasting: the new tool for increased preparedness to climate variability and change in agricultural planning and operations. Climatic Change, 70: 221-253.

Messina, C.D., Hansen, J.W. and Hall, A.J., 1999. Land allocation conditioned on El Niño-Southern Oscillation phases in the Pampas of Argentina. . Agricultural Systems, 60: 197-212.

Messina, C.D., Letson, D. and Jones, J.W., 2006. Tailoring management of tomato production to ENSO phase at different scales in Florida. Transactions of the American Society of Agricultural and Biological Engineers, 49: 1993-2003.

Meza, F.J., Hansen, J.W. and Osgood, D., 2008. Economic value of seasonal climate forecasts for agriculture: review of ex ante assessments and recommendations for future research. Journal of Applied Meteorology and Climatology, 47: 1269-1286.

Miranda, M.J. and Glauber, J.W., 1997. Systemic risk, reinsurance, and the failure of crop insurance markets. American Journal of Agricultural Economics, 79: 206-215.

Mishra, A. et al., 2008. Sorghum yield prediction from seasonal rainfall forecasts in Burkina Faso. Agric. For. Meteorol., 148: 1798-1814.

Mjelde, J.W. and Cochran, M.J., 1988. Obtaining lower and upper bounds on the value of seasonal climate forecasts as a function of risk preferences. Western Journal of Agricultural Economics, 13: 285-293.

Morduch, J., 1990. Risk, Production and Savings: Theory and Evidence from Indian Households, Harvard Univ., Dept. of Economics, Cambridge, Mass.

Moron, V. et al., In press-a. Spatio-temporal variability and predictability of summer monsoon onset over the Philippines. Climate Dynamics.

Moron, V., Robertson, A.W. and Boer, R., In press-b. Spatial coherence and seasonal predictability of monsoon onset over Indonesia. Journal of Climate.

Moron, V., Robertson, A.W. and Ward, M.N., 2006. Seasonal predictability and spatial coherence of rainfall characteristics in the tropical setting of Senegal. Monthly Weather Review, 134: 3248-3262.

Moron, V., Robertson, A.W. and Ward, M.N., 2007. Spatial coherence of tropical rainfall at regional scale. Journal of Climate, 20: 5244-5263.

Morris, M., Kelly, V.A., Kopicki, R. and Byerlee, D., 2007. Fertilizer Use in African Agriculture: Lessons Learned and Good Practice Guidelines, World Bank, Washington, DC.

Myers, R.J.K. and Foale, M.A., 1981. Row spacing and population density in grain sorghum -- a simple analysis. Field Crops Research, 4: 147-154.

Ndiaye, O., Hansen, J.W. and Robertson, A., 2008. Prediction of Rainfall Frequency and Related Quantities in West Africa. Report prepared for the International Federation of the Red Cross – West Africa, International Research Institute for Climate and Society.

Nelson, D. and Finan, T., 2000. The emergence of a climate anthropology in Northeast Brazil. Practicing Anthropologist, 22(4): 6–10.

Nelson, R.A., Holzworth, D.P., Hammer, G.L. and Hayman, P.T., 2002. Infusing the use of seasonal climate forecasting into crop management practice in North East Australia using discussion support software. Agricultural Systems, 74(3): 393-414.

Nelson, R.R. and Winter, S.G., 1964. A case study in the economics of information and coordination: The weather forecasting system. Quarterly Journal of Economics, 78: 420-441.

Ngugi, R.K., 2002. Climate Forecast Information: The Status, Needs and Expectations Among Smallholder Agro-pastoralists in Machakos District, Kenya. No. 02-04, IRI, Columbia Earth Institute, Columbia University, Palisades, NY.

Nicholls, N., 1999. Cognitive illusions, heuristics, and climate prediction. Bulletin of the American Meteorological Society, 80: 1385-1397.

Nicholls, N. and Kestin, T., 1998. Communicating climate. Climatic Change, 40: 417-420.

O'Brien, K., Sygna, L., Otto Naess, L., Kingamkono, R. and Hochobeb, B., 2000. Is information enough? User responses to seasonal climate forecasts in Southern Africa. 2000:3 Center for International Climate and Environment Research (CICERO) Oslo, Norway. .

Orlove, B.S. and Roncoli, C., 2006. Integration of Climate Information from Multiple Sources through Group Discussion in Ugandan Farm Communities, Center for Research on Environmental Decisions, Columbia University, New York.

Orlove, B.S. and Tosteson, J.L., 1999. The application of seasonal to interannual climate forecasts based on El Niño-Southern Oscillation (ENSO) events: Lessons from Australia, Brazil, Ethiopia, Peru and Zimbabwe, Institute of International Studies, University of California, Berkeley.

Pala, M., Matar, A. and Mazid, A., 1996. Assessment of the effects of environmental factors on the response of wheat to fertilizer in on-farm trials in Northern Syria. Experimental Agriculture, 32: 339-349.

Patt, A., Suarez, P. and Gwata, C., 2005. Effects of seasonal climate forecasts and participatory workshops among subsistence farmers in Zimbabwe. Proceedings of the National Academy of Sciences, 102: 12623-12628.

Patt, A.G. and Schrag, D.P., 2003. Using specific language to describe risk and probability. Climatic Change, 61: 17-30.

Phillips, J. and McIntyre, B., 2000. ENSO and interannual rainfall variability in Uganda: implications for agricultural management. International Journal of Climatology, 20: 171-182.

Phillips, J. and Orlove, B.S., 2004. Improving climate forecast communications for farm management in Uganda. Final Report to NOAA Office of Global Programs.

Phillips, J.G., 2003. Determinants of forecast use among communal farmers in Zimbabwe. In: J.J. O'Brien and C. Vogel (Editors), Coping with Climate Variability: The Use of Seasonal Climate Forecasts in Southern Africa. Ashgate Publishing, Abingdon, pp. 110-126.

Piha, M., 1993. Optimising fertiliser use and practical rainfall capture in a semi-arid environment with variable rainfall. Experimental Agriculture, 29: 405-415.

Podestá, G.P. et al., 2002. Use of ENSO-related climate information in agricultural decision making in Argentina: A pilot experience. Agricultural Systems, 74: 371-392.

Poulton, C., Kydd, J. and Dorward, A., 2006. Overcoming market constraints on pro-poor agricultural growth in sub-Saharan Africa. Development Policy Review, 24: 243-277.

Rathore L.S.and Maini,, P., 2008. Economic Impact Assessment of Agro-Meteorological Advisory Service of NCMRWF. Report no. NMRF/PR/01/2008. NCMRWF, Ministry of Earth Sciences, Government of India, Noida, Uttar Pradesh, India, 104 pp.

Rengalakshmi, R., 2007. Localized Climate Forecasting System: Seasonal Climate and Weather Prediction for Farm Level Decision-making. In: M.V.K. Sivakumar and J.W. Hansen (Editors), Climate Prediction and Agriculture: Advances and Challenges. Springer, Berlin, pp. 129-134.

Robertson, A.W., Ines, A.V.M. and Hansen, J.W., Submitted. Downscaling of seasonal precipitation for crop simulation. J. Appl. Meteor. & Climatol..

Robertson, A.W., Moron, V. and Swarinoto, Y., In press. Seasonal predictability of daily rainfall statistics over Indramayu district, Indonesia. International Journal of Climatology.

Roncoli, C. et al., 2009. From accessing to assessing forecasts: an end-to-end study of participatory climate forecast dissemination in Burkina Faso (West Africa). Climatic Change, 92: 433-460.

Rose, E., 2001. Ex ante and ex post labor supply response to risk in a low-income area. Journal of Development Economics, 64: 371-388.

Rosenzweig, M.R. and Binswanger, H.P., 1993. Wealth, Weather Risk and the Composition and Profitability of Agricultural Investments. The Economic Journal, 103(416): 56-78.

Rosenzweig, M.R. and Stark, O., 1989. Consumption smoothing, migration and marriage. Journal of Political Economy, 97: 905-926.

Royce, F.S., Jones, J.W. and Hansen, J.W., 2001. Model-based optimization of crop management for climate forecast applications. Transactions of the American Society of Agricultural Engineers, 44: 1319-1327.

Rubas, D.J., Mjelde, J.W., Love, H.A. and Rosenthal, W., 2008. How adoption rates, timing, and ceilings affect the value of ENSO-based climate forecasts Climatic Change, 86: 235-256.

Rudstrom, M., Popp, M., Manning, P. and Gbur, E., 2002. Data aggregation issues for crop yield risk analysis. Canadian Journal of Agricultural Economics, 50: 185-200.

Simon, H.A., 1957. Models of Man. Wiley, New York.

Simtowe, F.P., 2006. Can risk-aversion towards fertilizer explain part of the non-adoption puzzle for hybrid maize? Empirical evidence from Malawi. Journal of Applied Sciences, 6: 1490-1498.

Sivakumar, M.V.K., 2006. Dissemination and communication of agrometeorological information -- global perspectives. Meteorological Applications, 13: 21-30.

Stern, P.C. and Easterling, W.E., 1999. Making Climate Forecasts Matter. National Academy Press, Washington, DC.

Stewart, J.I., 1991. Principles and performance of response farming. In: R.C. Muchow and J.A. Bellamy (Editors), Climatic risk in crop production: models and management for the semiarid tropics and subtropics. CAB International, Wallingford, UK.

Stewart, J.I. and Faught, W.A., 1984. Response farming of maize and beans at Katumani, Machakos district, Kenya: recommendations, yield expectations, and economic benefits. East African Agricultural and Forestry Journal, 44: 29-51.

Stone, R.C. and Meinke, H., 2005. Operational seasonal forecasting of crop performance. Phil. Trans. R. Soc. B., 360: 2109-2124.

Sun, L., Li, H., Ward, M.N. and Moncunill, D.F., 2007. Climate variability and corn yields in semiarid Ceará, Brazil. Journal of Applied Meteorology and Climatology, 46: 226-240.

Thornton, P.K. and MacRobert, J.F., 1994. The value of information concerning near-optimal nitrogen fertilizer scheduling. Agricultural Systems, 45: 315-330.

Traoré, S.B. et al., 2006. A review of agrometeorological monitoring tools and methods used in the West African Sahel. In: R.P. Motha, M.V.K. Sivakumar and M. Bernardi (Editors), Strengthening Operational Agrometeorological Services at the National Level. Proceedings of the Inter-Regional Workshop, 22-26 March 2004. Technical Bulletin WAOB-2006-1 and AGM-9, WMO/TD No.1277. USDA, Washington, DC; WMO, Geneva, and FAO, Rome, Manila, Philippines, pp. 209-220.

Tversky, A. and Kahneman, D., 1974. Judgment under uncertainty: heuristics and biases. Science, 185: 1124-1131.

USDA, 1999. Understanding USDA crop forecasts. USDA Miscellaneous Publication No. 1554, National Agricultural Statistics Service, US Department of Agriculture, Washington, DC.

von Neumann, J. and Morgenstern, O., 1944. Theory of Games and Economic Behavior. Princeton University Press, Princeton, Mass., USA.

Walker, T.S. and Ryan, J.G., 1990. Village and Household Economies in India’s Semiarid Tropics. Johns Hopkins University Press, Baltimore.

Washington, R., Harrison, M., Conway, D., Black, E., Challinor, A., Grimes, D., Jones, R., Morse, A., Kay, G. and Todd, M, 2006. African climate change: taking the shorter route. Bull. Amer. Meteor. Soc., 87: 1355-1366.

Weiss, A., Crowder, L.V. and Bernardi, M., 2000. Communicating agrometeorological information to farming communities. Agricultural and Forest Meteorology, 103: 185-196.

Wilks, D.S., 1999. Interannual variability and extreme-value characteristics of several stochastic daily precipitation models. Agricultural and Forest Meteorology, 93: 153-169.

Ziervogel, G., 2001. Global science, local problems: Seasonal climate forecast use in a Basotho village, southern Africa, 2001 Open Meeting of the International Human Dimensions of Global Change Community, October 6-8, Rio de Janeiro, Brazil.

Ziervogel, G., 2004. Targeting seasonal climate forecasts for integration into household level decisions: the case of small farmers in Lesotho. The Geographical Journal, 170: 6-21.

Zimmerman, F.J. and Carter, M.R., 2003. Asset smoothing, consumption smoothing and the reproduction of inequality under risk and subsistence constraints. Journal of Development Economics, 71: 233-260.