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The Domestic Benefits of Tropical Forests

A Critical Review Emphasizing Hydrological Functions

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Tropical forests can potentially produce hydrological benefits and yield economically valuable nontimber forest products. But the levels of these benefits are poorly understood, likely to be highly context-specific, and may often be smaller than popularly supposed. This underscores the importance of grant financing to support forest preservation that yields global or noneconomic benefits.

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Summary findings

Chomitz and Kumari critically review the literature on the net domestic (within-country) economic benefits of protecting tropical forests, focusing on hydrological benefits and the production of nontimber forest products. (The review does not consider other important classes of benefits, including global benefits of all kinds, ecological benefits which do not have instrumental economic value, and the "existence" value of forests.) Their main conclusions:

(1) The level of net domestic benefits from forest preservation is highly sensitive to the alternative land use and to local climatic, biological, geological, and economic circumstances.

When the alternative use is agroforestry or certain types of tree crops, the preservation of natural forests may yield no instrumental net domestic benefits.

(2) The hydrological benefits from forest preservation are poorly understood and likely to be highly variable. They may also be fewer than popularly assumed:

- Deforestation has *not* been shown to be associated with large-scale flooding.
- Tropical deforestation is generally associated with higher, not lower, dry season flows.
- Although it is plausible *a priori* that deforestation should affect local precipitation, the magnitude and even the direction of the effects are unknown, except in the special case of cloud forests that "harvest" passing moisture.
- The link between deforestation and downstream sediment damage is sensitive to the basic topography and geology. Where sediment transport is slow — as in large, low-gradient basins — downstream impacts may manifest themselves in the distant future, so that the net present value of damage is small. Steep basins near reservoirs or marine fisheries, on the other hand, can cause substantial damage if land cover is severely disturbed. But only a few pioneering studies have examined the economics of reservoir sedimentation, and improved models of both sediment transport and dam function are needed.

(3) The most impressive point estimates of forest value based on nontimber forest products are often based on atypical cases or faulty analysis. Where domesticated or synthetic substitutes exist, the nontimber forest product-related rents for natural forests will usually be driven toward zero.

This paper — a product of the Environment, Infrastructure, and Agriculture Division, Policy Research Department — is part of a larger effort in the department to understand the causes and consequences of land use change. Copies of the paper are available free from the World Bank, 1818 H Street NW, Washington, DC 20433. Please contact PRDEI, room N10-033, telephone 202-458-0513, fax 202-522-3230, Internet address prdei@worldbank.org. May 1996. (41 pages)

THE DOMESTIC BENEFITS OF TROPICAL FORESTS: A CRITICAL REVIEW EMPHASIZING HYDROLOGICAL FUNCTIONS

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Domestic Benefits: a Critical Review

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Table of Contents

1 Introduction and overview

Many conservation projects seek to conserve biodiversity by protecting habitats from conversion or degradation. Although often motivated by global concerns, habitat protection also yields domestic benefits. These include immediate, tangible benefits such as watershed protection, extractive products, and recreational opportunities, as well as less tangible benefits such as potential pharmaceutical royalties, or the "existence value" of habitats to local populations.

There are two rationales for quantifying the domestic benefits of habitat conservation. The first is motivational. Host countries perceive that they capture only a small proportion of the global benefits which stem from biodiversity conservation. Demonstration of palpable local benefits could help to build enthusiasm and support for biodiversity-oriented projects. Second, the magnitude of domestic benefits could influence project financing. Sufficiently large net domestic benefits could justify World Bank financing of a project on narrow economic grounds, with biodiversity conservation as a by-product. More generally, recognition of domestic benefits could shape the design of hybrid projects, with some components Bank-financed and incremental, purely biodiversity-related costs financed through the GEF.

Recently there have been a number of attempts to quantify the domestic benefits, and more broadly the total economic value of natural habitats. A particularly valuable review, on which this paper draws heavily, is Lampietti and Dixon (1994). (See also Pearce and Moran 1994) This paper's modest goal is to illustrate three themes, which in our view have been insufficiently emphasized:

1. It is not meaningful to talk of "domestic benefits" without reference to specific alternative land uses -- for both scientific and economic reasons.

2. Net benefits will generally vary widely within a site. Great care must be exercised in extrapolating point-specific benefit estimates to a larger area.

3. Our understanding of many of the underlying physical processes is weak. Nonetheless, there are relevant scientific findings, especially in hydrology, whose implications have not been well incorporated into the economic and policy literature.

In addressing these themes, this paper focuses almost exclusively on tropical moist forests. It concentrates on hydrological benefits for several reasons. First, we believed *a priori* that these benefits might in many cases be very large -- for instance, if forest preservation prevents floods in built-up areas. Second, most of the postulated hydrological effects involve externalities: land use disturbances at a particular point are felt throughout a watershed. Finally, the hydrological benefits appeared to be less well documented than other benefits. The paper also examines some issues related to nontimber forest benefits. Other classes of benefits are outlined but not discussed in depth.

To summarize our conclusions, our review cautions against expecting uniformly significant levels of net domestic benefits (narrowly construed to be instrumental economic benefits) from the preservation of tropical moist forests. There are certainly classes of domestic benefits, such as sedimentation prevention and sustainable production of nontimber forest products, which are significant and documentable. These benefits, however, are specific to limited geographic and economic circumstances -- perhaps more limited than is generally supposed. Other benefits, such as local climate regulation, are plausible and conceivably large, but subject to large scientific uncertainty. Still other supposed benefits, such as flood prevention in large watersheds, and maintenance of dry season water flow, are largely contradicted by available scientific evidence. To keep these observations in context, recall that domestic benefits are just a subclass of total economic value. Forest may be extremely valuable without yielding positive net domestic benefits.

The plan of the paper is as follows. The next section briefly sets out a conceptual framework. Section 3 reviews hydrological forest benefits, including sediment prevention, erosion prevention, flood control, water table regulation, and local climate regulation. Section 4 discusses benefits from nontimber forest products. Section 5 briefly outlines other benefits. Section 6 discusses the opportunity costs of preservation. Section 7 concludes with a summary and recommendations.

2 Conceptual framework

In this section we set out three conceptual themes which guide the subsequent review. While these themes are not novel and in fact appear to be quite obvious, we believe that they have been insufficiently emphasized in the existing literature.

2.1 *Benefits must be computed relative to an alternative land use*

There is a tendency in the literature to treat benefits of habitat protection as an absolute number irrespective of alternative land uses. This is not valid for two reasons. The first is ecological. Hydrological functions of the land are strongly regulated by ground cover, as we discuss at length below. Hence the hydrological impact of converting a natural forest to a plantation might be quite different from converting it to annual cropping.

The second reason is economic. Forest land may have alternative uses. In general, we are interested in protecting areas precisely because they are in current or future danger of being converted to an alternative use. Hence if we wish to argue that a particular area should remain protected for economic reasons, we must compare the benefit stream provided by the forest with the benefit stream which would result from the likely alternative land use. In other words, it necessary to compute the *net* benefits of forest preservation: the gross benefits less the opportunity cost.

In sum, the appropriate measure of domestic benefits from habitat preservation is simply:

Net domestic benefits = (Economic yield - external damages) under protection - (Economic yield - external damages) under alternative

While this formulation appears simple, its consistent application can help the analyst to avoid a number of pitfalls. (See the example given in section 3.2 on on-site erosion.)

2.2 *Benefit levels are highly location-specific and scale-dependent*

Habitats in general, and forests in particular, are internally quite heterogenous. Any sizeable forest area is likely to exhibit substantial internal diversity in species densities, soil types, slopes, and market access. This diversity in turn results in continuous variation over the landscape in both the physical processes underlying forest benefits, and in their economic valuation:

- forest product values depend on local density of valuable species, and on the cost of transport from extraction site to consumers
- recreational values depend on road access, species mix, and viewsheds
- hydrological values depend on slope, rainfall, soil type, position in the watershed, and proximity to dams, irrigation systems, and fisheries
- opportunity costs of preservation depend on market access and soil quality

Moreover, a variety of hydrological processes are scale dependent: the dynamics of erosion and runoff, for instance, are quite different in 100 hectare, 10,000 hectare, and million hectare watersheds. Scale dependence features also in the evaluation of markets for non-timber forest products: the price of products may decline as supply increases.

As a result of spatial heterogeneity and scale dependence, valuation estimates for a small site cannot easily be imputed to a large area. Simple scaling-up of site-specific estimates will yield inaccurate, and often biased, results.

2.3 *Many underlying physical processes are poorly understood, or poorly incorporated into the economic and policy literature*

At first blush, it might appear straightforward to assess the economic impacts of land use change. For instance, to assess benefits of sedimentation control for fisheries, one could imagine looking at the relation over time between proportion of a watershed which was converted to annual crops, and the value of downstream fish harvests. In general, however, this kind of reduced form approach has not been much used, because we usually lack sufficient data over time and space, and because there are so many other confounding variables. (We will suggest in section 7, however, that there are unexploited opportunities for careful empirical research of this type.)

The alternative is to trace out a set of physical and economic linkages, and quantify each link. For instance, the impact of land use change on fisheries is derived via:
1) relating land use change to erosion
2) relating erosion to sediment concentrations at the river's mouth
3) relating sediment concentrations to fish populations
4) relating change in fish populations to changes in the profits from fish harvests

In tracing this chain of linkages, an error at any stage compromises the overall estimate. For many hydrological effects, it is the physical linkages which are subject to the greatest uncertainty. Nonetheless, there are areas on which consensus views in the hydrological literature have not been fully incorporated into the economic and policy literature.

3 **Hydrological benefits**

We focus on hydrology for three reasons. First, hydrological functions are often cited as being among the most important benefits of forest preservation. Forests are asserted to be economically important for preventing soil erosion, maintaining water supply, preventing floods, and maintaining rainfall patterns (see for instance Botkin and Talbot 1992, p. 51; Myers 1995). Second, these assertions are often made with little supporting evidence. The claims are often seen as *a priori* plausible or even obvious, although the scientific literature has been questioning some elements of this received wisdom for at least a decade. (see Hamilton and King 1983) Only a handful of economists have attempted to measure the value of these hydrological functions, and this small literature appears not to have been fully integrated with the scientific literature on hydrology. Finally, hydrological impacts are of potentially great interest for domestic policy because they involve local externalities. That is, even if a forest area were put under private or community management, the managers would have no incentive to consider the downslope effect of their land use decisions on others in their country. But unlike global externalities, these local externalities could be addressed through local government interventions.

In this and the following section we try to sketch the possible linkages from land use change through hydrology to economic impacts. [We draw heavily on the authoritative recent survey of Bruijnzeel (1990), and earlier work by Hamilton and King (1983). Enters (1992) is also noteworthy for addressing some of the important conceptual and empirical issues]. The linkages are shown in table

1. The first column shows the possible direct hydrological results of land use change. The second column shows the potential economic impacts of the physical changes.

Possible hydrological changes	**Possible economic impacts**
Increased sediment delivery	Siltation of reservoirs, canals, harbors
	Damage to fisheries
	improved agricultural productivity from downslope soil deposition
Erosion	Loss of productivity for downslope farmers
Increased water yield	Flood damage to crops and settlements
	Benefits to downstream water consumers
Water table change	agricultural productivity, household water consumption
Climate change	Agricultural productivity impacts from altered precipitation and temperature patterns

1 *Hydrological impacts of land use change and their economic consequences*

3.1 ***Sediment impacts***

We turn now to the first set of linkages, from land use change to river sedimentation. There are two linkages to be evaluated:

1). Under what conditions does forest removal or degradation results in increased sediment flows into rivers?

2) What is the linkage between increased sediment load and economic damage to dams, canals, harbors, or fisheries?

Below, we address each linkage in turn.

From land use change to sedimentation

There are actually two links here: from land use change to erosion, and then from erosion to sedimentation. The first of these links is relatively well understood from experimentation and observation on relatively small plots, although most attention focuses on sheet erosion as opposed to gully erosion and mass wasting (landslides). Table 2 shows the results of a review of 80 studies by Wiersum (1984), reproduced in Bruijzneel (1990, p. 117) as the best available summary. The results are quite striking. Ground cover, rather than canopy extent, is the chief determinant of erosion (Bruijnzeel, p. 118). Erosion rates are indeed low in natural forests, but are equally low in tree gardens, in the fallow phase of slash and burn cultivation, and in plantations where weeds and leaf litter are retained. Erosion rates in plots under current slash and burn cultivation are ten times as high as in natural forest. In plantations where weeds and litter have been removed, erosion is more than 100 times as great as in natural forests.[1]

LAND COVER	SURFACE EROSION, TONS/HA/YR		
	min	median	max
Natural forests	0.03	0.3	6.2
Shifting cultivation, fallow period	0.05	0.2	7.4
Plantations	0.02	0.6	6.2
Multi-storied tree gardens	0.01	0.1	0.15
Tree crops with cover crop/mulch	0.1	0.8	5.6
Shifting cultivation, cropping	0.4	2.8	70
Agricultural intercropping in young forest plantations	0.6	5.2	17.4
Tree crops, clean-weeded	1.2	48	183
Forest plantations, litter removed or burned	5.9	53	105

2 *Surface erosion rates for selected land cover types*

In many cases, erosion impacts of land use change may be the result of associated road construction, rather than the land use change itself. For instance, Hodgson and Dixon's (1988) study of logging in Palawan finds that, while logged over forest exhibits a fourfold increase in erosion rate,

[1] At first glance, the lack of protection by canopies is surprising. But even in a closed forest, about 85% of the incident rain reaches the ground, mostly via drip from the canopy. Moreover, contrary to intuition, evidence suggests that the canopy drops are sufficiently larger than the original raindrops as to be substantially more erosive (Bruijnzeel 1990, p 118).

conversion of uncut forest to road surface increase erosion by a factor of 260. Hence while roads accounted for only 3% of the surface area in the study basin, they were estimated to account for 84% of sheet erosion in the drainage basin.

Gully erosion and mass wasting are important sources of sediment, but these are more complex and less well-studied processes than sheet erosion. Gully erosion is associated with road construction, with poorly managed annual cropping, and with overgrazing. Unlike sheet erosion, which can diminish over time as disturbed land is recolonized by vegetation, gullies tend to worsen. Mass wasting can generate very large quantities of soil movement. While the removal of tree roots is thought to encourage shallow landslides, truly massive landslides appear to be associated with high slopes and extremely waterlogged soil, regardless of forest cover (Bruijzneel 1990, p 123).

While these erosion mechanisms are highly complex, it seems fair to conclude that there will be little sedimentation-related damage from conversion of natural forests to appropriately-managed plantations, agroforestry, moderate grazing, and long-fallow shifting cultivation. On the other hand, road construction, conversion to annual cropping, and plantations practicing litter removal can generate considerable erosion. To assess the potential damage from these land use changes, it is necessary to turn to the next link: from induced erosion to stream sediment and siltation.

Will changes in surface erosion induced by land cover change result in major changes in sedimentation? The answer depends on two factors. First, only a portion of eroded soil makes its way into rivers and streams; the remainder is trapped (perhaps temporarily) downslope. The sediment delivery ratio varies inversely with catchment basin size, since larger basins have more places for the sediment to get caught. The relation between basin size and sediment delivery ratio has been calibrated for the US but only scattered observations exist elsewhere. Mahmood (1987) suggests that the sediment delivery ratio declines from near 100% in 200 ha basins to around 10% in very large (million square kilometer) basins. Sediment delivery ratios of about 0.3 are often assumed for basins on the scale of hundreds of square kilometers. In addition, lower sediment delivery ratios are associated with longer sediment transport times, causing a lag between land cover change and downstream impacts. We will return to this point later.

Second, the induced sedimentation may be large or small relative to the "background" level of sedimentation[2]. Background sedimentation varies tremendously depending on local geology and on the current state of land use in the basin. It is related to existing agriculture and roads within a catchment basin, to unstable river banks, natural landslides, and to commercial dredging for sand and gravel. Enters (1992) cites a study of a small catchment basin in Northern Thailand in which

[2] One might still worry about induced sedimentation even the presence of much greater background sedimentation if: a) marginal increases in sediment load result in further damages, and b) the costs of averting induced sedimentation are smaller than those of remedying background sedimentation.

riverine erosion was found to contribute 57% of total sediment, a 2 kilometer road contributed another 34.9%, 300 ha of abandoned swidden and forest contributed 7.6%, and 10 ha. of rice fields contributed 0.5%. Bruijzneel (pp 131-133) cites two contrasting cases. The Phewa Tal catchment basin in Nepal (117 km^2) is subject to overgrazing, with average on-site erosion of about 7.6 tons/hectare per year. However, assuming a sediment delivery ratio of 0.3, this erosion contributes only about 6% of sediment inflows to the lake which drains the basin, the remainder coming from landslides. In contrast, the small Konto catchment of East Java exhibits high erosion rates from densely populated areas (21 to 26 tons/ha per year) vs forested areas (0.23 to 3.8 tons/ha depending on geology), with a high *measured* sediment delivery ratio (0.5 - 1.1) (*sic;* actual sediment delivery ratios must be less than 1).

In general, "background" levels of sedimentation tend to be underestimated, due to inadequate sampling data on sediment flows. (Mahmood 1987, Bruijnzeel 1990). Most sediment is generated during very brief episodes of rainfall or landslides. Hence low sampling rates (intervals of weeks or days instead of hours) and short sample periods (months instead of years) can result in gross underestimates of actual sedimentation rates. When this bias is not recognized, higher-than-expected siltation rates at new dams are sometimes erroneously attributed to contemporaneous land use changes.

Given the complexity of erosion and sediment transport processes, and their sensitivity to biological and geological conditions, how is it possible to calibrate the relation between land use change and sediment delivery at a watershed scale? There are two approaches. A modeling approach simulates erosion and transport over the watershed, using GIS data on precipitation, land cover, and topography. This has been done most commonly with the universal loss soil equation (USLE). The USLE is a simple multiplicative formula based on land-cover specific parameters, precipitation, and slope. It is generally poorly calibrated, especially for tropical areas, and its application outside its intended domain is often criticized. Recently, there have been efforts to build more sophisticated models which represent the physical processes of soil particle detachment, transport and deposition. (Rose 1993)

An alternative, purely empirical approach seeks to relate changes in a river's sediment load to land cover changes in the surrounding watershed. The empirical approach is an essential check on theoretical models, but it is usually hard to apply for lack of data. One exception is a study by Alford (1992) which assembled annual time series data on sediment transport, streamflow, and precipitation for the Ping River in Northern Thailand, over the period 1958-1985. Despite substantial land use change during this period[3], sediment concentration in the Ping was approximately constant. According to Alford, the near-linear relation between streamflow volume

[3] Forest cover in Chiang Mai province declined from 92% in 1973 to 73% in 1991, according to data from the Royal Thai Forestry Dept. (C. Griffiths, personal communication)

and total sediment transport "implies a sediment source within the stream channel rather than erosion from slopes contributing sediment to this channel." This somewhat surprising conclusion -- significant deforestation unaccompanied by contemporaneous increases in sedimentation -- underscores the need for many more empirical studies of this kind in order to understand the role of local geology and topography in modulating the effects of land use change on sediment delivery.

Impact on dams

Above we looked at the link between land use change and sediment generation. Next we identify and evaluate economic damages caused by river-borne sediment. Here there are three prominent classes of damage: reduction of the output and lifetime of dams; clogging of irrigation canals and siltation of harbors and navigable rivers; and damage to marine ecosystems with consequences for fisheries yield, aquaculture, and tourism. We turn first to dams, for which the literature is largest.

Siltation affects dams in a number of ways. (Mahmood 1987; Southgate and Macke 1989) First, by reducing the active storage volume of the reservoir, siltation diminishes the output of hydroelectric, irrigation, or flood control services. Second, siltation diminishes the effective life of the dam, both by advancing the date at which capacity is exhausted and by increasing the risk of a "sloughing" incident (Southgate and Macke 1989). Silt also damages turbines and increases the need for dredging to counteract sloughing.

Total costs of siltation are significant; a very rough order of magnitude estimate by Mahmood (1987) puts the world annual replacement costs of lost capacity at about $6 billion. Chunhong (1995) reports that sedimentation reduces the storage capacity of Chinese reservoirs by 2.3% annually. The relevant question, though, is the marginal impact of deforestation-related sedimentation. The impacts at a particular site will depend not only on the amount of sediment generated, but on:

- the per hectare benefits delivered by the dam
- whether the dam incorporates sediment sluices which redirect most sediment past the dam
- the timing of sediment-related damage (if not averted)

We briefly discuss some of these issues below.

<u>Per hectare benefits</u>
In principle, there could be great variance in dam benefits per hectare of watershed. Basin topography and precipitation, reservoir size, and dam configuration affect the level of irrigation, flood control, or hydroelectric services which the dam can offer. Unfortunately we cannot find a database which combines information on dam benefits and catchment area and so are unable to illustrate this obvious but potentially significant point.

Sediment avoidance: technical fixes
A variety of hardware and operational 'fixes' exist for sluicing incoming sediments past dams, or for flushing accumulated sediments out of reservoirs. Some recent hardware innovations are described in Lysne *et al.* (1995). Chunhong (1995) describes techniques used in north China for sluicing muddy water during the flood season. These techniques are not universally applicable, and typically have opportunity costs (in downtime or diminished output) in addition to capital costs. They also shift the costs of sedimentation downstream. However, to the extent that dams can minimize sedimentation using these techniques, the domestic benefits of forest preservation are reduced.

Time path of benefits
Since siltation is a gradual process, damage valuation depends crucially on the time path of reduced benefits. There are three potential time lags between initiation of land use change and diminution of dam benefits. First, the rate of land use change matters. Clearcutting, or the construction of extensive low quality logging roads, could generate substantial amounts of erosion quickly. Reductions in swidden fallowing periods, on the other hand, might take decades to make a substantial change in basin-wide erosion.

Second, sediment transport takes time. An eroded soil particle works its way down a watershed through a process of continual redeposition and resuspension. The time between initial erosion and arrival in the reservoir depends critically on stream gradient as well as on distance. Harden (1993) notes in connection with the Paute watershed in Ecuador: "sediment eroded from agricultural lands in distant, low-gradient tributary catchments may not reach the reservoir in the next half-century, but increased sediment loads in proximal, high-gradient tributary rivers represent an immediate sedimentation hazard". Conversely, sediment has been observed to continue to flow into rivers for at least 20-30 years after source erosion stops. (Bruijnzeel 1990, Mahmood 1987).

The third lag is between the time-path of sediment entering a dam reservoir and the time path of diminished dam output. Although reservoirs are built with dead storage capacity designed specifically to catch sediment, a significant portion of sediment inflow is deposited in the active (i.e. economic) storage area. Thus one would expect that dam services would begin immediately to decline with an increase in sediment inflows. However, a simulation by Southgate and Macke (1989) found that earlier retirement accounted for 85% of the economic impact of an assumed increase in sedimentation rates.

While the processes of sediment generation and deposition are quite complex, a simple numerical example will illustrate the sensitivity of economic impacts to assumptions about the timing and discounting of sediment impacts. For heuristic purposes we assume that dam services are constant until dam retirement, and that the effect of watershed damage is to reduce the expected lifetime of the dam from 100 years to 61 years[4]. Under these assumptions and a 10% discount rate[5], the net present value of watershed protection is about 2.2% of the annual flow of dam benefits. However, a modest increase in the discount rate, to 12%, decreases the present value of watershed protection by 75%. Introduction of a 20 year lag between initiation of land use change and onset of sediment inflows decreases the present value of protection by a further 95%, to just 0.04% of the annual benefit flow[6].

In short, the benefits of extending the life of a relatively young dam will tend to occur in the distant future and therefore be highly discounted. Are there greater benefits in protecting dams that are already nearing the end of their lifetime? Sophisticated modeling of sediment deposition and dam failure would be necessary to address this question. However, if the probability of dam closure increased very rapidly past a threshold level of sedimentation, then it is conceivable that rapid deforestation in a small, sloping basin could, say, reduce the dam's expected remaining life from ten years to two. In this scenario, the benefits of watershed protection might be quite substantial, because they occur close to the present rather than in the distant, discounted future. On the other hand, the logical consequence of this argument would merely be to postpone deforestation until after the dam's shutdown. This is certainly an uncomfortable stance from a conservationist perspective, and it underlines the desirability of identifying *sustainable* streams of benefits resulting from forest preservation. The benefits of dam sediment avoidance, by definition, endure only as long as the dam itself.

Empirical studies

The theoretical bent of this discussion on dams reflects a paucity of empirical studies. We have found only four estimates of the economic impact of land use change on dam performance. These are summarized in table 3. The difficulty of gathering primary data on erosion processes is evident. None of the studies is based on retrospective studies relating actual sedimentation to actual land use changes. Only two make serious efforts to estimate the actual effect of land use change on sedimentation, and even these base their estimates on an application of the USLE and assumed sediment delivery ratios. Only one allows for a lag between project initiation and sediment impact. On the economic side, only one attempts to model in detail the process by which sediment reduces

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[4] This follows the assumptions used by Cruz *et al.* (1988) in their analysis of the Pantabangan dam, but there is no intent to represent that case.

[5] In choosing this discount rate, we are imagining that a watershed protection project is being appraised for a World Bank loan, for which there is generally a requirement of a 10% minimum rate of return.

[6] The assumption that dam life with lagged sediment delivery is=81 years is very crude, but will suffice for illustrative purpose. Also, note that a ratio of 0.04% does not necessarily imply that a watershed protection project is uneconomic -- the project's value depends on the cost of protecting the watershed, which might be relatively small.

dam life, and none incorporates the models used by dam engineers to describe the spatial patterns of sediment build-up in reservoirs (which affects the time path of dam services). Our sense is that the first problem -- the lack of hard data on erosion processes -- is the more severe.

The per-hectare benefits differ widely. The highest value by far, a NPV of over $2000/ha, refers to a subset of the interventions envisioned for the Valdesia watershed management project, namely the reforestation of the steepest slopes in the watershed. Some of the assumptions behind this estimate are open to question, and the 5% discount rate elevates the value compared to some of the other studies. Nonetheless, this example illustrates the potential for very high levels of domestic benefits in connection with protection of critical watershed areas. The Pantabangan example, in contrast, shows that under alternative conditions the benefits can be two orders of magnitude lower.

Impact on irrigation systems

Irrigation systems are subject to clogging by silt and weeds. Little data are available on the costs imposed by siltation. Magrath and Arens (1989) review sometimes conflicting evidence for Java, one of the world's most intensively irrigated areas. They report that efficient annual expenditures on silt removal are on the order of $7.9 - $26.3 million, or $0.61-$2.05 per ha, using all of Java as a denominator.

For our purposes, the question is: what proportion of this siltation is attributable to the conversion of upland areas to rainfed cropland? We are unable to find quantitative studies for Java or elsewhere. While upland areas generate much more erosion per hectare than lowland areas, upland sediments will often be intercepted by irrigation dams. This is a small side-benefit of the reservoir siltation problem discussed earlier: 90% or more of incoming sediment is trapped. However, dams may be bypassed during flood periods, when sediment loads are particularly high. According to Mahmood[7], canals are more apt to be clogged by very coarse materials. The time lag between hillside erosion of these materials and delivery to irrigation systems may be very long indeed, on the order of decades or longer.

More research or synthesis is needed to identify the sources of sediments damaging to irrigation systems. A related area is the effect of erosion-related sediments on dredging costs for harbors and navigation channels.

Impact on fish and aquatic organisms

Hodgson and Dixon (1988) present a study of the impact of sedimentation on marine life in Palawan,

[7] K. Mahmood, George Washington University. Personal communication, April 1995.

Philippines. The study is exemplary for its reliance on carefully gathered primary data and its detailed analysis. Logging in the study area resulted in the construction of highly erosion-prone roads quite close to the Manlag river, within a few kilometers of Bacuit Bay. The consequence was a very large and immediate increase in sediment load: suspended sediment load in the Manlag "were often more than 1000 mg/l" while those in a control river "rarely exceeded 10 mg/l". The increase in sediment destroyed nearly 50% of coral cover on the reef nearest the river mouth. While the sediment levels were not high enough to kill fish directly[8], coral mortality severely disrupts the ecosystems on which the fish depend. Detailed measurements at eight transect stations in Bacuit Bay established strong links from sediment deposition to loss of coral cover and coral species; and from loss of coral cover and species to loss of fish biomass. (Hodgson and Dixon, p. 41)

Hodgson and Dixon estimate the economic impact of fish and coral loss on gross revenues from fisheries and tuna revenues, and use these estimates to compute the net benefits of protecting the watershed's remaining 3700 ha of forest from logging. In their preferred scenario, over a ten year horizon, with a 10% discount rate, NPV of fisheries and tourism revenues exceed logging revenues by up to $11.8 million. However, very conservative estimates of tourism potential, downward revisions of sediment impact, and use of a 15% discount rate result in a net loss from watershed protection.

The imputed per hectare value of forest protection (under the preferred scenario) is quite high: $3200/ha. The authors acknowledge that this is an overestimate of the social gain because it is based on gross revenues from fisheries and tourism rather than net profits. It is also worth noting that Hodgson and Dixon rule out, as infeasible, interventions to reduce road-generated erosion, even though such interventions may save the loggers money. Since roads generate the bulk of all sediment, improved road-building techniques might make logging, fisheries, and tourism mutually compatible.

3.2 *Erosion and agricultural productivity losses*

We have established that deforestation can result in substantial increases in on-site erosion. Erosion causes measurable reductions in land productivity. (For reviews, see Pimentel *et al.* 1995; Bojo 1994). Can we therefore translate those productivity loss estimates directly into forest preservation benefits?

The answer is no. To see why, recall our definition of net benefits of forest preservation:

Net benefits =Benefits from forest - benefits from crops

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[8]Hodgson and Dixon cite laboratory experiments establishing a 19,000 mg/l exposure level as sufficient to kill fish by gill clogging.

Estimates of on-site losses due to erosion are:

benefits from crops (before erosion) - benefit from crops (after erosion)

Where cropping and forest are mutually exclusive land uses, estimates of on-site erosion are useful mainly for computing the opportunity cost of forest preservation.

Consider an example. A forest plot yields \$10/ha/yr in sustainable tree product production or a net present value of \$100, assuming a 10% discount rate. If deforested, the plot would yield \$200/ha in crops the first year. Due to erosion, however, that yield will decrease by \$20/yr. The net benefit of forest preservation is:

NPV of forest production - NPV of crop production =
$\$100 - (\$200+\$180/1.1 + \$160/1.1^2 + \ldots) =$
\$100-\$848=
-\$748 [Correct calculation]

An incorrect calculation would add the present value of forest production to the present value of erosion-related productivity losses. If production were sustained at \$200/ha, the NPV would be \$2000. Since the NPV with erosion is just \$848, cumulative erosion-related losses are \$1152. The incorrect computation is:

Net benefits of preservation = \$100+\$1152 =+\$1252 [Incorrect calculation]

There are however two situations in which forest preservation yields ongoing agricultural productivity benefits via erosion reduction. First, some woodlands or open forests are used for grazing or cropping. Removal of trees in order to intensify production could be self-defeating if erosion increases drastically. In this case, the net benefits expression is:

[NPV of forest products + NPV of sustainable agricultural production (no erosion)]
- NPV of agricultural production only (with erosion)

Second, deforestation could result in increased runoff and thereby increase off-site erosion -- for instance, on downslope croplands. This seems plausible and may be important in some areas, but we can find no relevant studies. On the other hand, erosion sometimes delivers valuable soils from uninhabited hillsides to farmers' fields (Enters 1992). Where this is true, forest preservation imposes external costs on those farmers. But these effects may be limited to exceptional soil conditions. We urge research attention to these issues of off-site erosion impacts.

3.3 *Impact of land use change on water yield and flooding*

Popular belief and casual empiricism link deforestation with flooding. If it were true that upslope deforestation threatens downstream cities and croplands with flood damage, then the gains to forest preservation might be quite large.

There is extensive scientific evidence linking deforestation to increases in water yield, i.e., the total volume of runoff and subsurface flows over a year. As in the case of erosion, the amount of increase depends on the type of land use change, although the differences between natural forest and tree crops seem to be more marked (Bruijnzeel 1990, pp 82-92). But increases in the *average* rate of flow do not necessarily correspond to increases in peakflow or stormflow which cause floods.

Surprisingly, the scientific literature supports a link between deforestation and flooding only at a local level -- within a drainage basin of less than about 50,000 ha. (Bruijzneel and Bremmer, 1989, p 116). In small watersheds, increases in water yield translate directly into increases in stormflow. For larger drainage basins, however, the limited number of available studies using long time series on floods show no link between deforestation and flooding. Bruijzneel (1990) cites studies of medium sized (up to 1.45 million ha) drainage basins in Taiwan and Thailand which show no effect on flooding of extensive deforestation. Bruijzneel notes, however, that in both cases much of the deforested area was not converted to permanent agriculture, and subsequently reverted to secondary forest. On the other hand, he cites three studies of India covering the period 1871-1980 which show no trend in flood frequency despite massive land use change during this period[9]. Bruijzneel and Bremmer (1989) also argue in a book-length monograph that there is no relation between Himalayan land use practices and flooding in the Ganges-Brahmaputra basin, although they do not present time-series data. Anderson *et al.* (1993) analyze eight decades of time series data on rainfall and stormflow in the Parana/Paraguay river basin and find no structural shift over that period in the relation between intense rainfall and floods, despite significant conversion of forest to pasture and cropland.

At first glance, these results seem paradoxical: how can deforestation cause flooding in small basins but not in the large basins? The hypothesis is that basin-wide flooding depends more on rainfall intensity than on land use. Most storms are small and transient. Individual sub-basins will tend to flood in sequence, as the storm passes over, rather than simultaneously. Local floods are thus averaged out over space and time. Only extremely large and long-lasting storms will affect all the tributaries of a major river at once. Storms of this magnitude would be large enough to saturate the soil's absorptive capacity, leading to rapid runoff, even if the land were still forested (Bruijnzeel and

[9] Richards and Flint (1994) estimate that forests, woodlands, and "interrupted woods" in India declined from 98.9 million ha in 1880 to 63.5 million ha in 1980.

Bremmer 1989; Bonell and Balek, 1993, pp 227-8).

Given the complexity of hydrological processes, the size of the economic damages attributable to floods, and the thinness of the scientific literature, further research would be valuable. There may, in fact, be climatic, geological, and ecological circumstances under which forest change does contribute to flooding in large basins. Furthermore, existing evidence suggests there are hydrological links between deforestation and flooding in small basins, but the economic impacts have not been quantified. To pursue this research agenda, it may be possible to identify for study river basins with the following features:

- a history of conversion of upland forests to cropland or grazing
- lowland towns or croplands subject to periodic flooding
- long time series data on stream flows, rainfall, and land use

It would be possible to compute the effect of land use change on flooding frequency, and to assess the damages caused by flooding.

3.4 *Land use change and dry season flows*

Deforestation has long been thought to result in lower water tables and reduced dry season flows of water. Plato, for instance, wrote (*Timaeus and Criteas*, quoted in Grimble *et al.* 1994, p. 1):

> There are mountains in Attica which can now keep nothing more than bees, but which were clothed not so long ago with fine trees...while the country produced bountiful pasture for cattle. The annual supply of rainfall was not then lost, as it is now, through being allowed to flow over a denuded surface to the sea. It was received by the country in all its abundance, stored in impervious potter's earth, and so was able to discharge the drainage of hills into the hollows in the form of springs or rivers with an abundant volume and wide distribution.

Similarly, Huntoon (1992) links the loss of the "green reservoirs" of hillside forests in South China to severe reductions in dry-season availability of groundwater.

According to current hydrological science, however, the effects of deforestation on dry season flows are ambiguous but likely to be counterintuitive. (Bonell and Balek 1993; Bruijnzeel 1990) This is because forest conversion has two opposing effects on the water table. First, it increases runoff and decreases infiltration of water into the ground. This by itself would lower the water table. On the other hand, trees are highly effective water pumps, removing water from the soil and transpiring it into the air. Replacement of trees by vegetation with shallow roots and lower transpiration rates (such as grass, annual crops, or early stages of secondary regrowth) therefore tends to reduce groundwater loss and raise the water table. Dozens of controlled experiments have been conducted, and they show that, contrary to the folk belief, the net immediate effect of tree removal is a *rise* in the water table, and therefore a probable *increase* in dry season flows. (Hamilton and King 1983) Similar results have been found in studies of actual conversion sites. Nepstad *et al.* (1994) compare deep-rooted evergreen forests to an adjacent degraded pasture in Pará, Amazonia. At the end of the dry season, plant-available water (in the top 8 meters of soil) was 370 mm higher in the degraded pasture.

Vincent and Kaosa-ard (1995) present a particularly interesting case study in which *re*forestation was found to *reduce* dry season flows and impose costs on downstream users. Starting in 1967, Thai authorities promoted reforestation and sedentary agriculture in deforested areas of the Mae Theng watershed. These efforts involved two water-consuming interventions: the construction of irrigation systems and the establishment of pine plantations, which transpire more water than the deciduous forests which originally covered the area. An analysis of monthly streamflow records show no change in dry season flows over 1952-1972, but a significant reduction in 1972-1991. Annual streamflows were estimated to decrease by an additional 2.9 million cubic meters each year. These reductions resulted in seasonal closure of one of Chiang Mai's water treatment plants and forced downstream farmers to switch from rice to soybeans. The marginal costs of these reductions in water availability ranged from 0.91 baht/cubic meter for agriculture to 6.99 baht for industrial water users. These results imply that upslope deforestation, while highly undesirable on many grounds, yields external benefits rather than costs for downstream water users.

Under some circumstances, however, deforestation may indeed result in reduced water tables. Bruijnzeel (1990) and Bonell and Balek (1993) point out that many forest conversion processes result in soil compaction and in gullying. Such processes include overgrazing, road construction, and the use of heavy machinery for land clearance. Compaction and gullying, in turn, increase runoff and decrease infiltration. If infiltration is reduced more than transpiration, the water table could drop[10]. Hamilton and King (1983) cite Australian studies showing severe reductions in infiltration following heavy grazing. They also cite a Fiji study finding runoff rates of 90% on grassland. They were unable to find analogous results, however, following conversion of forests to annual cropping. A different situation is described by Kumari (1994). In this case, selective logging of a peat swamp forest resulted in construction of drainage canals. Expansion of the drainage network could reduce water storage sufficiently to imperil dry season rice production in adjacent fields.

There is a troubling disjunction between the findings of careful, but limited, scientific studies, and impressionistic but compelling reports such as Huntoon's. It suggests that either the scientific studies are missing some crucial aspects of land use change, or the impressionistic studies are confounding anthropogenic effects with other climatic or hydrological changes. As in the case of flooding, it would be worthwhile to encourage additional research into the relation between forest conversion

[10] This does not explain Huntoon's reports for South China, since the deforestation resulted from felling of trees by peasants for charcoal and would therefore not be expected to result in soil compaction.

and dry season flows.

3.5 *Climate maintenance*

There is a long-standing belief that deforestation reduces rainfall. Grove (1994) provides a fascinating account of scientific and policy interest in the topic dating to the seventeenth century (see for instance Halley 1694). According to Grove, scientific opinion convinced the European colonial powers to establish tropical forest preserves with the explicit goal of maintaining rainfall, starting in the British West Indies in 1763. In the mid-nineteenth century the British Association for the Advancement of Science and the Royal Geographical Society published studies linking tropical deforestation to potentially catastrophic reductions in rainfall. Presaging modern climatology, Wilson (1865, quoted in Grove 1994) wrote:

> In our own British colonies of Barbadoes, Jamaica, Penang, and the Mauritius, the felling of forests has also been attended by a diminution of rain....The absolute necessity which exists for keeping as large a surface of the ground as possible covered with vegetation, in order to screen it from the solar rays, and thus to generate cold and humidity, that the radiation from the surface may not drive off the moisture of the rain-bearing clouds in their season, ought to compel rigid enforcement of [laws restricting deforestation and forbidding burning of grasslands in South Africa]

To the modern layman, too, it seems intuitively obvious that tropical deforestation reduces rainfall. Evapotranspiration from tropical forests accounts makes up from 20% (Southeast Asia) to 80% (Africa) of incident rainfall (Wilkie and Trexler 1993). It seems logical to expect that forest removal would break this recycling process, resulting in a drier climate.

Modern climate theory, however, introduces a host of additional complexities. Changes in land cover introduce not only changes in evapotranspiration, but also changes in albedo (surface reflectivity) and aerodynamic drag. These directly affect temperature and precipitation, but also set off a whole round of positive and negative feedback effects involving changes in cloudiness, air circulation patterns, and even plant transpiration behavior. The result is a highly non-linear, scale-dependent dynamic system, and it is no longer *a priori* clear that deforestation reduces local rainfall. Eltahir and Bras (1992) suggest, for instance, that deforestation on the scale of hundreds of square kilometers will increase convection and therefore rainfall, while deforestation on the scale of millions of square kilometers will reduce rainfall. In any case the magnitude and spatial distribution of climate impacts will be sensitive to local conditions, especially to the nature of the vegetation which replaces the forest.

Theoretical analysis of the climatic impact of land use change therefore requires sophisticated models. Over the past ten years, general circulation models (GCMs) of the earth's atmosphere have been used to analyze the effect of very large scale deforestation on global climate. A number of exercises have examined the implications of converting the entire Amazonian or Southeast Asian rainforests to savanna. These exercises might in principle be used to evaluate the domestic benefits of forest preservation for large countries such as Brazil or Indonesia. Henderson-Sellers *et al.* (1993) predict complete deforestation of the Amazon would reduce rainy season precipitation by 30%, while complete deforestation of Southeast Asia would have no impact on precipitation. Lean and Rowntree (1993), claiming improved representation of the role of the forest canopy on rainfall interception and evaporation, predict that total Amazonian deforestation would decrease local rainfall by 14%. However, 20% of Eastern Brazil would experience increases in rainfall. Dirmeyer and Shukla (1994) find that the effect of deforestation depends on the change in albedo. If the new land cover does not have an appreciably higher albedo than the old forest cover, precipitation can increase.

These results must be interpreted with extreme caution, for several reasons. First, the scale and permanence of deforestation simulated in these exercises is unrealistic. Shukla *et al.* (1990), for instance, assume conversion of the entire Amazon to degraded pasture. Many of the deforested areas in the Amazon in fact revert to secondary forest (Moran *et al.* 1994), whose climatological properties will be much closer to primary forest than to pasture. Second, despite their sophistication, GCMs omit a range of physical processes and rely on a great many assumptions about parameters. We do not know how sensitive the results are to these omissions and assumptions. Third, these models divide the planet's surface into a very coarse grid, typically using 1.8 x 2.8 or 4.5 x 7.5 degree cells. The models therefore can only be applied to deforestation processes at the scale of tens of thousands of square kilometers or above. Results at this scale cannot be generalized to deforestation patches of tens or hundreds of square kilometers. Work on more appropriate mesoscale models is still in its infancy.

Empirical work in this area is as inconclusive as the theoretical work. Bruijnzeel (1990) provides a review of the thin literature. There are a great many microstudies of temperature and soil wetness changes in small clearings but these cannot be generalized to larger scales and are useful mainly for parameterizing GCM and mesoscale models. There are a limited number of mesoscale empirical studies which try to relate changes in forest cover to changes in recorded precipitation. Meher-Homji (1988), for instance, summarizes several such studies for India which find concurrent forest loss and precipitation declines. Bruijnzeel is critical of these studies, which he finds lacking in rigor and in attention to data consistency.

Current research is just beginning to make use of remote sensing data to track both climatic and land use changes, resulting in much more rigorous studies. O'Brien (1995) gathered and checked 22 years of data from twenty climate stations in the Selva Lancondona region of Chiapas, and uses ground-truthed remote sensing data from 1979 and 1989 to track deforestation around each station. Preliminary analysis indicates that deforestation increases minimum temperature, decreases maximum temperature, and has no significant effect on precipitation. Cutrim *et al.* (1995) uses satellite data to show increases in cloudiness (not necessarily implying increased precipitation) following large scale deforestation in Rondonia.

In sum, it is plausible that deforestation affects local climate, but the magnitude (and indeed sign) of the effect remains to be demonstrated. Given the potential significance economic significance of climatic effects, this should be an early priority for research.

3.6 *Summary*

The hydrological benefits of forest preservation are less well understood, and probably smaller on average, than is generally supposed. Forest preservation does not appear to avert catastrophic, large scale flooding and generally is not an instrument for protecting critical dry season flows of water. It may play a role in maintaining local climate, but the magnitude and incidence of this benefit is unknown.

The primary documented hydrological benefits of forest preservation are in sedimentation prevention. These benefits will be greatest when all of the following criteria hold:

- the alternative land use involves annual cropping, heavy grazing, or road construction
- the forest area at risk is close to reservoirs, towns, or coral reefs
- the area at risk is steep, its geology is conducive to erosion, and it is in a watershed with high-gradient streams and rivers.

The criteria are commonsensical, but illustrate the point that watershed benefits are not homogenous across forests or even within a forest. At the extremes, forest preservation directly around a reservoir is quite valuable for sedimentation prevention. Forest preservation on mild slopes far from any reservoir will yield little economic benefits from sediment prevention.

4 Nontimber forest products

There is a rapidly growing literature on the valuation of tropical nontimber forest products such as fruits, nuts, latex, resins, medicines, and animals. Godoy *et al.* (1993) survey 24 valuation estimates[11], reporting annual per-hectare forest values ranging from \$.75 to \$422, with a median of about \$50 . Without undertaking an exhaustive review, we will argue that, as a group, these studies give an exaggerated impression of the level of domestic benefits which would be realized by

[11] A similar list is given in Lampietti and Dixon (1995)

protecting a typical "natural"[12] forest.

There are four reasons why these estimates give an overly optimistic impression of NTFP values:

- failure to distinguish between agroforestry and pure extraction.
- failure to account for extraction costs
- failure to allow for spatial variation in product density or extraction rate
- failure to allow for long-term competitive supply

We discuss each of these problems in turn.

The distinction between agroforestry and extraction

Non-timber forest products can be produced at different levels of intensivity, with higher intensivity associated with greater disturbance to the original ecosystem. At one pole is the ideal of an extractive reserve, where extractors harvest products from an otherwise undisturbed forest. One notch up in intensivity, extractors may artificially enrich the forest with desired plant species. Still more intensive are a range of agroforestry techniques that replace the primary forest with a carefully manipulated multispecies gardens. At the other pole, many forest products such as latex can be produced in monocultural plantations.

If we are interested in the domestic benefits of preserving "natural" ecosystems, then we must restrict our attention to valuation estimates based on purely extractive values. Agroforestry systems typically generate higher values per hectare, because commercial species densities are greater and extraction and processing costs are lower. While these systems are attractive for many reasons, including their relatively high degree of biodiversity, they are not the same as the ecosystems they replace. Agroforestry valuations should therefore not be used to justify natural forest preservation. For instance, Alcorn (1989) describes an agroforestry system which involves coffee planting, and thinning of undesirable plant species, and which only makes economic sense when practiced in close proximity to swidden agriculture. The agroforestry component generates a high per-hectare valuation, but it is not meaningful to apply this valuation to undisturbed forest areas.

On the other hand, it is worth stressing that agroforestry systems may have both high biodiversity and high economic benefits relative to other land uses. This is true of 'jungle rubber', a Sumatran land use system in which swidden farmers create rubber-rich secondary forests. After the rubber trees reach maturity (at around the tenth year of regrowth) they yield about 600 kg/ha/year of dry-

[12] Almost all forests have been subject to some human influence at some time. We use the term "natural" to distinguish old growth forests from recently disturbed, or manipulated, forests.

equivalent rubber (van Noordwijk *et al.*1995, p. 88) with no inputs aside from labor (current rubber prices are about $1.60/kg). Extraction can continue for twenty years or more before another cycle of clearing. Since the owners' share in share-tapping arrangements is 1/3, this implies substantial per hectare rents. At the same time, ecological studies show fairly high levels of species richness. Michon and de Foresta (in press), for instance, report that sample jungle rubber sites had 92 tree species, 97 lianas, and 28 epiphyte species vs. 171, 89, and 63 in primary forest (and compared to 1,1, and 2 in monoculture plantations). Thiollay (1995) estimates that jungle rubber supports about 137 bird species (45% of them characteristic of primary forests) vs. 241 in the primary forest. Moreover, these agroforests should closely resemble primary forests in their hydrological properties. Thus agroforests may in some cases offer both net domestic economic benefits and global or nonmarket benefits relative to competing land uses.

Allowing for extraction costs

Conceptually, the per-hectare value of a forest for NTFP production is equivalent to the rent that would be paid for the right to harvest that hectare. Clearly that rent is less than the final value of the NTFP in the marketplace. It is necessary to deduct the costs of extraction and transport. This elementary point has been made many times in the literature, and it is important to apply it to Godoy *et al.*'s list. For instance, the highest documented value based on actual extraction rates is the Chopra (1993) estimate of $117-$144/ha/year for fuelwood, fodder, and miscellaneous products from Indian tropical deciduous forests. In the absence of market prices for these goods, Chopra values them either by their cost of extraction or by the price of substitute commodities. For instance, labor valued at $18.87 to $24.17 per ha is used to gather fuelwood, whose equivalent in softcoke would cost $9.50 to $17.33. Chopra concludes that the value of forests for fuelwood must lie between $9.50 and $24.17. But these figures mean that villagers are expending labor worth more than $18.87 in order to produce fuelwood worth less than $17.33. Clearly the estimates need revision, but the main implication is that the net value of the forest for firewood production is close to zero. Similarly, Chopra estimates labor expenditures of $66.67/ha to produce miscellaneous products such as lacquer and dyes. To get the value of the forest in producing these goods, however, we must subtract $66.67 from the price paid to the collectors.

Spatial variation

Forests tend to be large and heterogenous. It is therefore inappropriate to take a per hectare value estimate for a small plot and attribute it to the forest as a whole, let alone to any other forest. This point again is obvious, but is almost universally ignored in practice.

Three difficulties arise in generalizing small-plot estimates. First, transport costs will be important for some NTFP. Açai fruit, for instance, spoils within 24 hours of harvesting if not refrigerated. Given the costs of transporting bulky or perishable goods through the forest, the "forest-gate" price will fall off rapidly with distance from the road and from the market. Large portions of the forest will not be economically exploitable for this class of commodities, and will have zero value. On the other hand, high-value, less perishable commodities such as rubber will have a broad economic range.

Second, the density of exploitable species can vary dramatically within and between forests. Noteworthy cases of NTFP extraction tend to be found in sites with unusually high densities of exploitable species. For instance, two of the highest per hectare values cited in Godoy *et al.* (1993) (Anderson and Ioris 1992, Anderson and Jardim 1989) refer to oligarchic forests (Peters 1992) near the mouth of the Amazon. These forests are dominated by just a few, highly commercial, species. While interesting and locally important, they are quite atypical of tropical rainforests, whose hallmark is very high diversity and thus very low densities for any individual species.

Third, consumption of some NTFPs may tap only a small fraction of the potential supplying area. For instance, the most important NTFP described by Grimes *et al.*(1994) in their Ecuadorian case study is a resin derived from a *Protium* tree. Harvesting *Protium* yielded an average potential net return (after collection, transport and marketing) of $61/ha/year for the three forest plots surveyed. However, the resin is used exclusively for finishing local ceramic handicrafts, which are presumably in limited demand. We surmise that the total number of hectares subject to *Protium* harvesting is a small fraction of the total area from which the tree could be economically harvested[13]. If so, it would be a gross error to apply the $61/ha value to the entire range of the species. The same situation may apply to very high value medicinal plant products.

Proper estimation of forest values for NTFP production requires GIS technologies. Spatial data on species distributions and populations, road networks, and markets can be combined with estimates of transport costs to derive net values per hectare. Eade (1994) is a pioneering example of this kind of work, though it does not yet incorporate transport costs. The GIS-based work by Magrath *et al.*(1995) on valuing agricultural land could also be applied to the valuation of NTFPs.

Long run competitive supply

There is an emerging consensus that, for most commercially attractive products, pure extractive reserves cannot compete with synthetic or domesticated substitutes (Richards, 1993; Browder 1992, Homma 1992). Many NTFPs follow a lifecycle in which they start out as extractive products, achieve a world market and a high price, and then undergo domestication in intensive plantation or

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[13] What then sustains the $61/ha net return? Why doesn't competition drive these returns toward 0? Either the producing plots are to some extent, perhaps informally, privatized, and the return reflects the opportunity cost of the land; or the $61 figure includes returns to the expertise of the collector, who knows how and where to find NTFPs; or in fact all economically exploitable areas are being harvested, and the $61 measurement is based on inframarginal plots.

agroforestry systems. Intensive cultivation greatly reduces labor, land, and capital costs, permits product standardization, facilitates processing, assures reliability of supply, and takes advantage of economies of scale in marketing. This drives the supply price of the product below the viable level for extractive supply. The prime example is rubber. In the early part of this century, Brazilian rubber prices (and extraction volumes) collapsed as Malaysian plantations came on-line. In recent years, the celebrated extractive rubber reserves have been supported by subsidies. Currently, extractivists in the Chico Mendes Extractive Reserve are being driven out of business by lower priced latex produced by plantations in Sao Paulo state. Labor productivity in the plantations is approximately 10 times as high as that in the Reserve (Brooke 1995).

The implications for forest valuation are inescapable. Lower-cost domesticated or synthetic substitutes greatly reduce, and possibly completely eliminate, the rents from extractive reserves. Only in the case of NTFPs which are resistant to domestication can we hope to maintain significant private forest values based on commercially valuable NTFPs.

The foregoing gloomy statement requires some qualification and expansion. First, the oligarchic forests mentioned above may be able to compete with plantations, especially with some small interventions such as pruning (Anderson and Jardim). Second, as noted earlier, agroforestry systems such as jungle rubber may in some cases be able to compete with plantations, while also preserving some biodiversity. They are not, however, perfect substitutes for the forests from which they are derived. Third, and most important, the success of large-scale NTFP plantations increases the *global* urgency of preserving genetic diversity within the commercial NTFP species. This may often be best accomplished through *in situ* preservation of the forests to which the NTFP are native. The implication is that the global benefits of forest preservation may increase even as the domestic benefits decline.

5 Other benefits

We have focused this paper on forest benefits from hydrological functions and nontimber products. For the sake of completeness, we briefly mention here some other potentially important benefits, but defer to others a thorough treatment.

The use of forests for *recreation* remains a largely unexplored and unquantified source of domestic benefits. Many national parks and private ecotourism lodges already attract substantial numbers of visitors. Standard techniques exist for valuing recreational benefits using information about visitors' travel costs, but these have rarely been applied to tropical forest sites. A notable exception is Kramer *et al.* (1995), which applies contingent valuation and travel cost techniques to derive the benefits of Mantadia National Park, Madagascar, to foreign visitors. The estimates range from about $100 to $250/ha, depending on the technique used. Generalizing data of this sort is however difficult; the results are likely to be quite site-specific and depend heavily on the rate of growth of ecotourism over coming decades. Recreation does however seem to hold potential as a major source of value for forest preservation.

Timber can be harvested sustainably or via a one-time unsustainable harvest followed by abandonment. Following the framework of section 2, the latter is the opportunity cost of the former. That is, consistency demands that if sustainable output of timber products is counted as a benefit, the foregone opportunity to "liquidate" (Kishor and Constantino 1993) all commercially marketable timber is a cost. Since the private returns to liquidation generally exceed the private present value of sustainable management (see Kishor and Constantino 1993 for data from Costa Rica), including the benefits and opportunity costs of timber products will generally depress the total net domestic benefits of a forest plot.

Appropriable rights in biodiversity are extremely difficult to value. The possibility of domestic benefits arises from GATT and the Convention on Biodiversity, which appear to grant nations property rights in biochemicals found within their borders. Forest preservation may therefore have the option value of potentially yielding profitable pharmaceutical or agricultural products. Bioprospecting is still in its infancy, and there is relatively little data to use for imputing these option values. It is likely that the *total* value of products derivable from biodiversity is quite high. However, a simple probabilistic model of Simpson *et al.* (1995) suggests that even under extremely optimistic assumptions the option value of a *marginal* hectare of habitats extremely small, on the order of $1/ha. The low value arises from redundancy in genetic information among hectares of similar habitats. Moreover, once the organisms on a particular plot have been screened for possible uses, the option value of preserving the plot drops dramatically.

Existence (nonuse) values of forest preservation may be high, although they may be spread out over a very large area of forest. Kramer *et al.* 1995 present the results of a contingent valuation survey for the US which attempted to elicit these values. Households were asked their willingness to make a one-time contribution to a notional fund to preserve 5% (110 million ha) of the world's remaining rainforests. Total US willingness to pay was estimated to be on the order of $2.1 to $2.8 billion, or about $19 to $25/ha. More work needs to be done to test the sensitivity of these results to alternative payment schemes (e.g. annual payments instead of one-time payments), different sizes and characteristics of habitats to be preserved, non-US populations, and so on.

Carbon sequestration values There is a growing literature on the potential value of forest preservation as a means of slowing global warming. Some very high per-hectare values of forest maintenance have been suggested. Converting these global benefits into domestic benefits, however, requires the emergence of a global market for carbon sequestration services.

6 Opportunity costs of preservation

In the preceding sections we looked briefly at the sustainable benefit streams associated with forest preservation. These must be thought of as "gross" benefits. The existence of a threat to a forest tract usually implies an economic motive for forest conversion or degradation -- typically, conversion to agriculture. The potential benefits of agricultural or silvicultural conversion are the opportunity costs of preservation. Following the conceptual framework of section 2, these opportunity costs have to be deducted from gross forest benefits to yield the net domestic benefits of preservation.

Opportunity costs are highly sensitive to land characteristics. The returns to agricultural use of a plot depend on the physical characteristics of the land, the current vegetation, market access, and land tenure. Physical characteristics such as slope, drainage, and soil fertility determine the land's relative physical productivity for different crops, the need for inputs, and the degree to which output can be sustained over time. Local density of commercial tree species will also affect the net cost of clearing; in some cases the value of timber may outweigh the benefits from agriculture. Market access -- the cost of off and on road (or river) transport to the nearest market -- determines the potential farmgate price of crops or cattle and their inputs. Land tenure and ownership, together with land-related tax and subsidy rules, affect the incentives to invest in land preparation and in perennial crops.

Figure 1, based on a statistical analysis by Chomitz and Gray (1995) illustrates the sensitivity of opportunity cost to land characteristics. It shows the probability of cultivation in Belize as a function of three variables: kilometers to the nearest road; subsequent on-road distance to the nearest town; and an index of soil quality, where "good land" has low slope and high nitrogen, "bad land" has high slope and low nitrogen. In Belize's low population density context, the results are striking: cultivation is unlikely, and opportunity costs therefore low, on virtually all poor soils, and on good soils not close to markets or roads.

Two practical techniques, with different informational requirements, can be applied to the task of estimating the opportunity cost of land -- that is, the foregone benefits of conversion[14]. Magrath *et al.* (1995) use farm budgets and a land capabilities assessment to impute land values in West Kalimantan. The land capabilities assessment divides the province into 1682 polygons and assesses the suitability of each polygon for a variety of crops. Magrath *et al.* apply standard productivity, input price, and output price data to the preferred crop for each polygon to impute per hectare profits. (For lack of data, however, no adjustments are made for the cost of transporting crops to markets,

[14] Kramer *et al.* (1995) examine a different opportunity cost scenario. The establishment of Mantadia National Park in Madagascar would lead to the exclusion of current land users, who derive income from shifting cultivation of rice and extraction of fuelwood and minor forest products. Based on a household survey, the present value of this production is about $57/ha.

or for benefits from timber marketing.) The result are quite striking: much of West Kalimantan's land has little value for agricultural production. Of the province's 14.65 million hectares, 3.7 million have an opportunity cost of less than US $0.20/ha per year (1991 prices). About 95% of the province has an agricultural opportunity cost of less than $2/ha per year. Were transport costs factored in, the opportunity costs would be far lower.

Chomitz and Gray (1995) use a slightly different GIS technique to address the same question for areas where land use maps are available but detailed farm budgets are not. Rather than explicitly compute land values based on assumed crop productivity, they derive implicit land values for Belize by modeling land use. The implicit rents to commercial cropping and to semi-subsistence cropping are each expressed as functions of land and soil characteristics, distance to the nearest road, and on-road distance to market. Land is assumed to go to the use with the highest rent, subject to tenure or regulatory constraints. Using GIS data from about 2000 sample points, the model then estimates coefficients for each of the two rent functions so as to best reproduce actual land use. These coefficients in turn can be used to impute land value at each point. By construction, these land values incorporate transport costs and soil-related productivity differentials. To calibrate these imputed rents, however, one would need observations on farmgate prices of outputs and inputs.

Given spatial data on opportunity costs, net domestic benefits would be computed by overlaying spatial data on gross benefits (e.g. nontimber forest product values) and computing net benefits at each point. We are not yet in a position to present a worked example of this. We can, however, begin to sketch out some possible scenarios:

Scenario 1: an area which enjoys relatively good soils and close proximity to a developing market. Market proximity confers high value on extractive products such as fruits and medicinal plants. The recreation value is also high, yielding a relatively high value for gross forest benefits. But the land's agricultural potential and proximity to market makes it ideal for the production of high-value fruits and vegetables, so that the opportunity costs of forest preservation are high. If the value of cultivated crops is high enough, the net domestic benefits of preservation might be negative, even though the "gross" benefits are high.

Scenario 2: the forest plot is far from the market and has poor agricultural potential, but it drains directly to offshore coral reefs. If the plot were under pressure for clearance by low-return, short-fallow shifting cultivation, the resulting sedimentation would threaten offshore fisheries and tourism. In this case the net domestic benefits of preservation are relatively high.

Scenario 3: a logged-over forest area whose utility is low for commercial agriculture, but which offers no commercially valuable forest products and serves no critical hydrological function. The principal threat is from low-value, subsistence-oriented shifting cultivation. Here the net domestic benefits of preservation may be negative, but very small in absolute magnitude. Hence preservation, if desirable on the basis of global benefits, may be accomplished in principle at comparatively small social cost (Here "social cost" is used in the welfare economics sense. The social acceptability of preservation would depend on the nature of the burdens imposed on and compensation offered to the postulated subsistence farmers.)

7 Conclusions

We conclude that:

1) The level of net domestic benefits from forest preservation is highly sensitive to the alternative land use, and to local climatic, biological, geological, and economic circumstances. When the alternative use is agroforestry or forest plantations (depending on the management system), there may be no net domestic benefits to natural forest preservation. On the other hand, some agroforests may offer both biodiversity benefits and net domestic economic benefits relative to other land uses.

2) The prospects for economically significant hydrological benefits from forest preservation appear to be smaller than popularly supposed.

- Deforestation has not been shown to be associated with large-scale flooding.
- In general, deforestation has not been shown to be associated with diminished dry season flows; on the contrary, it is usually associated with greater flows.
- While it is *a priori* plausible that deforestation should affect local precipitation, the magnitude and even the direction of the effects are not known, except in the special case of cloud forests which "harvest" passing moisture.
- The link between deforestation and downstream sediment damage is sensitive to the basin topography and geology. Where sediment transport is slow -- as in large, low-gradient basins -- downstream impacts may occur far in the future, so that the net present value of damages is small.

3) Measurement of forest benefits from minor forest products is still rudimentary. Current valuation exercises tend to be point specific and not generalizable to significant forest areas. The most impressive per-hectare estimates of forest value are mostly not generalizable for one of the following reasons: a) They are based on inventories of saleable products rather than actual extraction; b) Value is based on gross market prices rather than prices net of extraction and transport costs; c) The case study describes agroforestry products rather than true extractive products; d) The case study describes products of unusual forests dominated by a few commercial species rather than a typical species rich rain forest. The prospects for basing forest values on

extractivist production of commercial, world-market NTFPs are undercut by competition from domesticated or synthetic substitutes. Locally important NTFPs may accord substantial value to certain local forest areas.

4) Domestic and international ecotourism can potentially confer substantial value on certain forests. There is insufficient data to assess the extent of forest area which might be able to support such tourism, or to calculate the net per-hectare benefits.

We stress again that 'net domestic benefits' refers only to quantifiable domestic economic benefits. Forest preservation can yield substantial global or ecological benefits.
Also, these conclusions apply only to tropical moist forests. It may be the case that for other ecosystems, such as wetlands, the links between land use change and economic benefits are both better understood and stronger.

Implications for conservation and development projects

This paper provides criteria for identifying projects with good prospects for yielding net domestic benefits. There are three main sources of domestic benefits: hydrological benefits, extractive benefits, and recreational benefits.

Section 3.7 summarized some simple criteria for projects with a high likelihood of substantial <u>hydrological benefits</u>:

- they avert erosion-generating changes such as road-building, annual cropping, or overgrazing
- affected watersheds impinge directly on reservoirs or coral reefs
- affected watersheds are small, steep, and erosion-prone.

In contrast, projects which discourage conversion of forests to plantations, or which affect remote watersheds far from reservoirs or coastal fisheries, will provide much lower levels of economically tangible hydrological benefits. The less tangible ecological benefits may, however, be profound.

The brief discussion of extractive benefits points to three kinds of forests whose preservation will yield significant, sustainable <u>extractive benefits</u>:

- natural or manipulated forests with very high densities of commercially important trees
- forests yielding commercial products for which there are no close synthetic or domesticated substitutes-- provided that these resources are protected from overexploitation
- forests providing locally consumed products (e.g., fuelwood, foods, and medicines) -- provided that these resources are protected from overexploitation

<u>Ecotourism</u> appears to have potential for conferring significant domestic value on large tracts of forest. This value is not intrinsic, however, and depends on design and implementation of

economically and ecologically sensible ecotourism programs. Much work needs to be done, however, to establish the feasibility of such programs.

A project with potential hydrological, extractive, or recreational benefits faces one more hurdle to establish net domestic benefits: the opportunity costs of preservation. Many forest areas are under threat precisely because there are high returns to conversion. These opportunity costs must be weighed against the direct benefits in order to compute net domestic benefits.

Implications for policy

The most important policy conclusion is a cautionary one. Net domestic benefits of forest preservation are poorly understood. Existing evidence suggests that these benefits are highly variable, and are not always large. We should therefore be cautious about reliance on domestic economic benefits as a rationale for conservation -- and especially as a rationale for funding forest preservation via market rate loans. There are undoubtably forest preservation projects for which this rationale is clearly justified, and these should be vigorously pursued. For many projects, however, we may well find that net domestic benefits either do not exist or cannot be quantified with sufficient rigor to support a market-rate loan or a convincing cost/benefit analysis. Hence the domestic benefits argument -- save your forests because they bring palpable economic benefits to your country -- cannot be the mainstay of forest preservation. For many, possibly most, tropical forests, the more compelling rationale for preservation is based on global values.

The hopeful converse, however, is that the net domestic *costs* of forest preservation may also be small. The argument is: save your forests because the out-of-pocket costs of doing so are small, and the noneconomic benefits are large. Many biodiverse, carbon-rich forest areas are poorly suited for agriculture because of isolation and poor soils. These areas can be preserved through a three pronged strategy. First, it is essential to keep the opportunity costs of preservation low by directing regional development towards more economically promising districts. Above all, uneconomic road-building should be avoided in these areas. Once roads are in place, the opportunity costs of preservation can increase substantially. Second, where pressures for logging are politically and economically irresistible, low-impact techniques can be required as a condition for access. This would entail also the disabling of main access roads after the completion of logging. Third, direct and ongoing compensation can be paid, or alternative livelihoods set up, for land users or stakeholders who would otherwise convert the forest to other uses.

Recommendations for research

There are a number of areas where our knowledge base appears to be very thin. Almost all of the needed research is interdisciplinary in nature. Because the issues are so wide ranging, it would be worthwhile to convene a National Research Council-style committee of prominent scholars from the range of relevant disciplines, including ecology, hydrology, meteorology, agronomy, economics, engineering, and others. With its broad expertise and knowledge, this committee would be able to set research priorities and devise appropriate research strategies.

Following are some areas where there may be good payoffs to research, either in demonstrating the existence of domestic benefits or in refining the criteria for identifying where domestic benefits are present.

1) Land cover change and regional climate change

The effect of land cover change on regional climate are very poorly understood. If these effects are large -- as seems plausible in tropical Africa where most rainfall derives from evapotranspiration -- then the domestic benefits of forest preservation may be quite large.

More work is needed on refining meso-scale climatic models. Also, it may be possible to look empirically at the effect of land use changes on local climate. To do so requires a very broad sample across time and space, because of the prevalence of "noise" and decades-long trends in weather data. It may however be possible to assemble the necessary data. Thomson (1995) for instance, while not addressing land use issues, identified 16 weather stations in the tropics with more than a century of data and less than 5% missing data; another 18 stations were available below 23° S, and 188 above 23° N. Century long time series on land use have been compiled from historical records at the provincial level for South and Southeast Asia. (Richards and Flint, 1994). It may also be possible to construct a broader data set by using satellite data describing land cover changes over much of the tropics for the last two decades; this would expand the number of weather stations which could be included in the sample. The ongoing LAMBADA (Large-scale Atmospheric Moisture Balance of Amazonia using Data Assimilation) experiment in Brazil may provide a variety of useful hydrological data which can be linked with land use change information. In the near future, the Tropical Rainfall Measuring Mission satellite will be a potentially important source of information.

2) Land cover changes, flooding, and sediment delivery

There are only a handful of studies which attempt to relate land use change to flooding in large basins. These cannot possibly cover the full range of possible land use changes and watershed types. As in the case of climate change, it is attractive to look for historical data which will allow us to look directly at the impact of land use change on flooding. Similarly, long time series on riverine sediment loads may help calibrate the relationship between land use change and sediment delivery. In many parts of the world there may be good times series on river flows and sediment loads. Matching these data with land use change information will be challenging, but again remote sensing data can provide information back to the early 1970's.

Additionally, it would be possible and desirable to monitor the impacts of ongoing land use changes. Remote-sensing based land cover monitoring could be linked with continuous river monitoring in sets of similar watersheds. For reliable results in a short period of time it will be necessary to monitor a fair number of watersheds, some of which must be undergoing rapid change. This is because of the large natural variance in water yield and sediment flow. A single large storm or large landslide event can skew annual averages for a watershed far above normal levels.

3) Sedimentation and dam benefits

Existing studies of the effect of sediment on dam operations have employed simplistic models of dam operations. Quite sophisticated models of reservoir sedimentation exist and can be used to model the time path of dam benefits under different sediment inflow scenarios (see for instance Cogollo and Villela 1988). This is important because failure to take account of early sedimentation of active storage may lead to underestimates of the economic impact of reservoir sedimentation. More work is also needed on the economic impacts of sediment on irrigation systems, river navigation, and drinking water supply.

4) Ecotourism demand

Ecotourism is much discussed, but there is a paucity of hard economic analysis on its prospects. By now, however, there are a number of successful ecotourism sites, and it should be possible to develop some rough estimates of: a) 'carrying capacity' per hectare of forest -- how many ecotourists can be supported without jeopardizing the resource; b) the net revenues possible per hectare; c) the prospective worldwide annual demand for such tourism. Doing this properly would require conducting a survey of ecotourism sites, and analyzing primary or secondary household travel data. There is also a need for household-survey based work in developing countries to measure local demand for natural habitats as recreation sites.

8 Bibliography

Alcorn, J. (1989). "An economic analysis of Huastec Mayan agroforestry management". In J.G. Browder, ed., *Fragile Lands of Latin America: Strategies for Sustainable Development.* Boulder: Westview.

Alford, Donald. (1992) "Streamflow and sediment transport from mountain watersheds of the Chao Phraya Basin, Northern Thailand: A reconnaissance study". *Mountain Research and Development, 12*, no. 3 (Aug 1992), pp 257-268.

Anderson, A.B. and E.M. Ioris. (1992) "The logic of extraction: resource management and income generation by extractive producers in the Amazon estuary". in K.H. Redford and C. Padoch, eds., *Conservation of neotropical forests: working from traditional resource use,* pp 175-199. New York: Columbia University Press.

Anderson, A.B., and M.A.G. Jardim. (1989) "Costs and Benefits of floodplain forest management by rural inhabitants in the Amazon estuary: A case study of açaí palm production." in J. Browder, ed., *Fragile Lands in Latin America: the Search for Sustainable Uses.* Boulder: Westview.

Anderson, Robert J., Jr., Nelson da Franca Ribeiro dos Santos, and Henry F. Diaz. (1993). *An Analysis of Flooding in theParana/Paraguay River Basin.* World Bank: Latin America Technical Department Dissemination note no. 5.

Bojö, Jan. (1994) "The Costs of Land Degradation from a National Perspective: An Assessment of African Evidence". Prepared for the 8th Internatinal Soil Conservation Conference, New Delhi, Dec. 1994. World Bank, Africa Technical Department.

Bosch,J.M. and J.D.Hewlett (1982) "A Review of Catchment Experiments to Determine the Effect of Vegetation Changes on Water Yield and Evapotranspiration". *Hydrology, 55*(3): 3-23.

Bonell, Michael, Maynard M. Hufschmidt and John S. Gladwell, eds. (1993) *Hydrology and Water Management in the Humid Tropics: Hydrological Research Issues and Strategies for Water Management.* Cambridge: Cambridge University Press.

Botkin, Daniel B. and Lee M. Talbot. (1992) "Biological Diversity and Forests", in Narendra P. Sharma, ed., *Managing the World's Forests:Looking for Balance between Conservation and Development.* Dubuque: Kendall-Hunt.

Brooke, James. (1995) "Rubber Trees Being Planted in Brazil, the Source". *The New York Times,* July 9, p. 14.

Browder, J. ed. (1989). *Fragile Lands in Latin America: the Search for Sustainable Uses.* Boulder: Westview.

Bruijnzeel,L.A. (1989) "Deforestation and Dry Season Flow in theTropics: A Closer Look". *Journal of Tropical Forest Science, 1*:229-243.

Bruijnzeel,L.A. (1990) *Hydrology of Moist Tropical Forests and Effects of Conversion: A State of the Knowledge Review.* Amsterdam: Netherland Committee for the International Hydrological Programme of UNESCO.

Bruijnzeel, L.A. with C.N. Bremmer. (1989) *Highland-Lowland Interactions in the Ganges Brahmaputra River Basin: A Review of Published Literature.* ICIMOD Occasional Paper No. 11. Kathmandu: International Center for Integrated Mountain Development.

Briones, N.D. (1991) "Estimating Erosion Costs: A Philippine Case Study in the Lower Agno River Watershed". In Easter,K.W.,J.A.Dixon and M.M.Hufschmidt (eds) Watershed Resources Management- Studies from Asia and the Pacific. ISEAS EnvironmentDevelopment Series, Singapore.

Chomitz, Kenneth M. and David A. Gray. (1995) *Roads, Land, Markets and Deforestation: A Spatial Analysis of Land Use in Belize.* World Bank, Policy Research Department, Working Paper no. 1444.

Chopra, Kanchan (1993). "The Value of Non-timber Forest Products: An Estimation for Tropical Deciduous Forests in India". *Economic Botany, 47(3)* (July-September), 251-258.

Chuhong, Hu (1995). "Controlling reservoir sedimentation in China". *Hydropower and Dams*, March 1995, pp. 50-52.

Cogollo, P.R.J., and S.M. Villela (1988). "Mathematical model for reservoir silting" In *Sediment Budget,* pp 43-52. International Association of Hydrological Sciences Publication no. 178. Wallingford, Oxfordshire: IAHS Press.

Cruz, W., H.A.Francisco and Z.T.Conway (1988) "The On-site and Downstream Costs of Soil Erosion in the Magat and Pantabangan Watershed". *Journal of Philippines Development*, *26*(25,1): 85-111.

Cutrim, Elen, David W. Martin and Robert Rabin (1995). "Enhancement of Cumulus Clouds over

Deforested Lands in Amazonia". *Bulletin of the American Meteorological Society,* November 1995.

Dirmeyer, P. A., and J. Shukla (1994) Albedo as a modulator of climate response to tropical deforestation. Journal of Geophysical Research.

Dyhr-Nielsen,M. (1986) "Hydrological Effect of Deforestation in the Chao Phraya Basin in Thailand". Paper presented at the International Symposium on Tropical Forest Hydrology and Application, Chiangmai, Thailand, 11-14 June.

Eade, Jeremy. (1995) *Natural Capital in Space: Mapping and Modelling the Environmental Assets of the Rio Bravo Conservation Area, Belize.* MSc. Dissertation, Department of Geography, University of Edinburgh.

Eltahir, E.A.B. and R.L. Bras. (1992) "On the response of the tropical atmosphere to large-scale deforestation". *Quarterly Journal of the Royal Meteorological Society, 119,* pp 779-793.

Enters, Thomas. (1992) *Land Degradation and Resource Conservation in the Highlands of Northern Thailand: The Limits to Economic Evaluations.* Ph.D. thesis, Australian National University.

Godoy, Ricardo, Ruben Lubowski, and Anil Markandya (1993). "A Method for the Economic Valuation of Non-timber Tropical Forest Products". *Economic Botany, 47*, no. 3, pp 220-233.

Grimble, R.J., J. Aglionby and J. Quan (1994) *Tree Resources and Environmental Policy: A Stakeholder Approach.* NRI Socio-economic Series 7. Chatham, UK: Natural Resources Institute.

Grimes, Alicia *et al.* (1994) "Valuing the Rain Forest: The Economic Value of Nontimber Forest Products in Ecuador". *Ambio, 23, no. 7*: 405-410.

Grove, Richard H. (1994) "A Historical Review of Early Institutional and Conservationist Responses to Fears of Artificially Induced Global Climate Change: the Deforestation-Desiccation Discourse 1500-1860". *Chemosphere, 29*, no. 5, pp 1001-1013.

Halley, Edmund (1694). "An Account of the Watry Circulation of the Sea, and of the Cause of Springs", *Philosophical Transactions of the Royal Society, 142*, no. 7, pp 468-72.

Hamilton,L.S. (1987) "What are the Impacts of Deforestation in the Himalaya on the Ganges-Brahmaputra Lowlands and Delta? Relations between Assumptions and Facts". *Mountain Research and Development*, 7: 256-263.

Hamilton,L.S. and P.N.King (1983) *Tropical Forested Watersheds:Hydrologic and Soils Response to Major Uses or Conversions.* Westview Press, Boulder, Colorado.

Harden,C.P. (1993) Land Use, Soil Erosion, and Reservoir Sedimentation in an Andean Drainage Basin in Ecuador. *Mountain Research and Development* , *13*(2): 177-184.

Henderson-Sellers, A., R.E. Dickinson, T.B. Durbridge, P.J. Kennedy, K. McGuffie, and A. J. Pittman (1993). "Tropical Deforestation: Modeling Local to Regional-Scale Climate Change. *Journal of Geophysical Research, 98*, D4, pp 7289-7315.

Hodgson, G. and J.A.Dixon (1988) *Logging versus Fisheries and Tourism in Palawan: An Environmental and Economic Analysis.* EAPI Occasional Paper No. 7. East-West Center, Honolulu.

Huntoon, Peter W. (1992). "Hydrogeologic Characteristics and Deforestation of the Stone Forest Karst Aquifers of South China". *Ground Water 30*, no.2 (March-April), pp 167-176.

Johnson,S.H.III and S.Kolavalli (1984) Physical and Economic Impacts of Sedimentation on Fishing Activities: Nam Pong Basin, Northeast Thailand. *Water International* Vol.9: 185-188.

Kishor, Nalin, and Luis F. Constantino (1993) *Forest Management and Comnpeting Land Uses: An Economic Analysis for Costa Rica.* World Bank, Latin America Technical Department.

Kramer, Randall A., Narendra Sharma, and Mohan Munasinghe (1995) *Valuing Tropical Forests: Methodology and a Case Study of Madagascar.* World Bank Environment Paper no. 13.

Kumari,K. (1994) *Sustainable Forest Management in Peninsular Malaysia: Towards a Total Economic Valuation Approach.* Ph.D.thesis. University of East Anglia, Norwich, United Kingdom.

Lampietti, Julian A. and John A. Dixon (1995) *To See the Forest for the Trees: A Guide to Non-timber Forest Benefits.* Environment Department, World Bank.

Lean, J. and P.R. Rowntree (1993). A GCM simulation of the impact of Amazonian deforestation on climate using an improved canopy representation. *Quarterly Journal of the Royal Meteorological Society, 119*, 511 (April 1), 509-530.

Lysne, D.K., N.R.B. Olsen, H. Støle, and T. Jacobsen (1995). "Sediment control: recent developments for headworks". *Hydropower and Dams,* March 1995, pp. 46-49.

Magrath,W. B. and P.Arens (1989) *The Costs of Soil Erosion on Java: A Natural Resource Accounting Approach.* Environment Department Working Paper No. 18. Washington D.C.

Magrath, W.B., Charles Peters, Nalin Kishor and Puneet Kishor (1995) *The Economic Supply of Biodiversity in West Kalimantan: Preliminary Results.* World Bank, Asia Technical Department.

Mahmood, K. (1987) *Reservoir Sedimentation: Impact, Extent, and Mitigation.* World Bank Technical Paper no. 71.

Meher-Homji, V.M. (1988)."Effects of Forests on Precipitation in India" in Evan R.C. Reynolds and Frank B. Thompson, eds, *Forests, Climate, and Hydrology: Regional Impacts.* Tokyo: United Nations University.

Michon, Geneviève and Hubert de Foresta. (in press) "Forest resource management and biodiversity conservation: the Indonesian agroforest model"in *Proceedings, IUCN Workshop on Biodiversity Conservation outside protected areas, Madrid March 1994.*

Moran, Emilio F. Eduardo Brondizio, Paul Mausel, and You Wu, 1994. "Integrating Amazonian Vegetation, Land-use, and Satellite Data". *BioScience 44*, no. 5, 329-338.

Myers, Norman (1995). "The World's Forests: Need for a Policy Appraisal". *Science, 268* (12 May 1995), pp. 82-83.

Nepstad, Daniel C. and Stephan Schwarzman, eds. (1992) *Non-timber Products from Tropical Forests: Evaluation of a Conservation and Development Strategy.* Advances in Economic Botany, vol. 9. N.Y.: The New York Botanical Garden.

O'Brien, Karen L. (1995, forthcoming). "Deforestation and cimate change in the Selva Lacandona of Chiapas, Mexico . *Nordisk Geografisk Tidsskrift.*

Pearce, David and Dominic Moran (1994). *The Economic Value of Biodiversity.* London: Earthscan.

Pereira,H.C. (1973) *Land Use and Water Resources in Temperate and Tropical Climates.* Cambridge: University Press, London.

Pimentel, David, *et al.* (1995) "Environmental and Economic Costs of Soil Erosion and Conservation Benefits. *Science, 267* (24 Feb), 1117-1122.

Qian,W.C. (1983) "Effects of Deforestation on Flood Characteristics with Particular Reference to Hainan Island, China". International Association of Hydrological Sciences
Publication Vol.140: 249-258.

Richards, E. M. (1993) *Commercialization of Non-timber Forest Products in Amazonia.* NRI Socioeconomic series no. 2. Chatham, UK: Natural Resources Institute.

Richards, J.F. and E.P. Flint. (1994) *Historic Land Use and Carbon Estimates for South and Southeast Asia 1880-1980.* Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory. Environmental Sciences Division, Publication No. 4174.

Rose, C.W. (1993) "Erosion and Sedimentation" . In Bonell, Hufschmidt and Gladwell (1993), *q.v.*

Ruitenbeek, H.J. (1989) *Social Cost-Benefit Analysis of the Korup Project, Cameroon.* Prepared for WWF UK and the Republic of Cameroon.

Ruitenbeek, H.J. (1990) *Economic Analysis of Tropical Forest Conservation Initiatives: Examples from West Africa.* Godalming, Surrey: World Wide Fund for Nature.

Shukla, J., C. Nobre and P. Sellers. (1990) "Amazon Deforestation and Climate Change". *Science, 247* (16 March), 1322-1325.

Simpson, R. David, Roger A. Sedjo, and John W. Reid. (1995) "Valuing Biodiversity for Use in Pharmaceutical Research." *Journal of Political Economy.*

Southgate, Douglas and Robert Macke. 1989. "The Downstream Benefits of Soil Conservation in Third World Hydroelectric Watersheds. *Land Economics 65* (1), 38-48.

Thiollay, Jean-Marc (1995) "The Role of Traditional Agroforests in the Conservation of Rain Forest Bird Diversity in Sumatra". *Conservation Biology 9* (2), pp 335-353.

Thomson, David J. (1995) "The Seasons, Global Temperature, and Precession". *Science, 268* (7 April), pp 59-68.

Tobias, Dave and Robert Mendelsohn (1991). "Valuing Ecotourism in a Tropical Rain-Forest Reserve". *Ambio, 20* (no. 2), April 1991, pp 91-93.

van Noordwijk *et al.*, eds. (1995) *Alternatives to Slash-and-burn in Indonesia: Summary Report of Phase 1.* ASB-Indonesia Report no. 4. Bogor: ICRAF-SE Asia.

Veloz,J.A., D.D,Southgate, F.J.Hitzhusen and R.D.Macgregor (1985) The Economics of Erosion Control in a Subtropical Watershed: A Dominican Case. *Land Economics, 61*: 145-155.

Vincent, Jeffrey R., Mingsarn Kaosa-ard *et al.* (1995, forthcoming). "Policy Brief: The Economics of Watershed Protection: A Case Study of the Mae Teng River". Cambridge MA: Harvard Institute for International Development.

Wiersum, K.F. (1984) "Surface Erosion under Various Tropical Agroforestry Systems". C.L. O'Loughlin and A.J.Pearce (eds) *Proceedings, Symposium on Effects of Forest Land Use on Erosion and Slope Stability*. IUFRO, Vienna and East-West Centre, Hawaii.

Wilkie, David S. and Mark C. Trexler (1993). "Biogeophysical Setting and Global Climate Change". In *Central Africa: Global Climate Change and Development, Technical Report.* Washington: Biodiversity Support Program.

Table 3

Study Reference	Site	Watershed Area (ha);	Intervention	Basis for impact on sediment	Basis for economic valuation	Real discount rate	Present value of Intervention , $/ha
Briones, 1991	Lower Agno, Philippines	39304 ha	Gully control, 'vegetation management' in already-deforested area	Assumes 49.9% reduction in natural sediment inflow. No method or data presented to support estimates of sediment reduction. Assumes 10 yr lag in effect of vegetation management	Allocates a proportion of sediment to active storage, assumes benefits proportional to active storage applies unit values for irrigation, hydroelectric services	10% 15%	$234-$586 $68-$218
Cruz *et al.*	Pantabangan, Philippines	91650 ha	Ex post analysis of conversion of forest to grasslands, croplands	Estimates of erosion rates by slope and land cover class (from USLE?); sediment delivery ratio assumed=.3	Linear decline in hydroelectric and irrigation services with sediment input; dam retired when dead storage filled is filled	15%	$15 (*ex post* analysis)
Southgate and Macke (1989)	Paute, Ecuador	518600 ha (from Harden)	structural measures to keep sediment out of waterways; protection of remaining forests; reforestation	Without project sediment loads grow at 4% (pure assumption); with project sedimentation rate not given	Simulation of decline in firm and non-firm power, dredging costs; endogenous dam retirement decision	6%	$54

Veloz *et al.*	Valdesia, Dominican Republic	2350 ha (slope class >50%)	reforestation of crop and rangeland	based on USLE	Sedimentation reduces dam lifetime but does not reduce pre-shutdown flow of services; no allowance for time lag in sediment reduction	5%	DR$3446= USD $2063 at market exchange rates

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