The Greening of China's Agriculture:

A Synthesis

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Foreword

For five decades, agricultural production in China grew at a remarkable pace. Despite land and water constraints, China's agricultural output kept pace with population growth and the diversification of diets through sustained intensification. Even as agriculture's share of China's labor force fell from 60 percent in 1991 to 24 percent in 2020, agricultural productivity gains boosted food supplies. Further, the shift of agricultural labor to urban and other sectors, such as industry, transport, and energy where wages were higher, contributed to a virtuous cycle of improved incomes nationwide, including in rural communities where poverty rates were highest.

Many factors contributed to the growth of the agriculture sector, including evolving policies that granted greater autonomy to farmers, expanded the role of markets, and opened the sector to international trade; and policies that were backed by large investments in research and development, extension, and infrastructure. However, at the heart of the expansion were policies that prioritized productivity gains and promoted the use of resource-intensive technologies. Consequently, this remarkable period of agricultural growth had a significant negative impact on China's environment and natural resources, especially land and water.

Over recent decades, China's agriculture has contributed to the degradation of forests, grasslands, aquatic, and other ecosystems. Large tracts of arable land have experienced soil acidification, salinization, and other forms of degradation. Agriculture has been the country's leading source of water pollution and contributor to the depletion of groundwater resources. The sector is also a critical source of several biosecurity risks, ranging from zoonoses and unsafe food to the development of drug-resistant bacteria. Although its greenhouse gas (GHG) emissions are ranked fourth nationally after energy, industry and transport sectors, agriculture is a significant contributor to air and climate pollution. The factors contributing to agriculture's environmental footprint are wide-ranging; however, the proximate factors relate to the inappropriate and unsustainable uses of chemical agricultural inputs and irrigation water, the poor management of livestock and poultry manure as well as agricultural plastic mulch films, the over-intensive use of grasslands and aquatic resources, and the conversion of fragile terrestrial ecosystems for agricultural uses.

As the costs to the environment accumulated and became better understood, a new set of agricultural policies emerged between 2015 and 2019 with the twin goals of reducing agriculture's environmental footprint, while sustaining decades-long sector gains in output and productivity to ensure food security. One of the most comprehensive statements on the practical implications of the policy shift for agricultural policy is given in the Ministry of Agriculture and Rural Affairs' *Notice on the Implementation of the Five Major Actions for Green Agricultural Development (2017)*. The actions were designed to manage livestock, straw wastes, and plastic film; repurpose waste for use as inputs; and set aside biological reserves to restore fishery habitat.

This inflection point for Chinese agricultural policy provided the setting and motivation for a program of study initiated by the World Bank in late 2020 with three objectives. First, to synthesize the available evidence about environmental impacts attributable to China's agricultural growth. Second, to report on and evaluate the regulations and programs pertinent to China's aims of greening agricultural modernization. Third, to highlight major challenges and opportunities going forward to strengthen this overall initiative. Over the course of 2021, 16 policy and technical working papers were prepared by experts from leading Chinese universities and scientific centers and experts from the Food and Agriculture Organization, the International Food Policy Research Institute, and external universities. Findings from background papers were organized along four major themes and summarized in "*The Greening of China's Agriculture: A Compendium of Thematic Papers.*"

This Synthesis Report highlights major findings from the *Compendium*, drawing heavily on recent experiences from pilot programs launched to evaluate alternative production technologies that are less resource intensive, explore programs and incentives to restore and protect degraded ecosystems, and inform the design of efficient use of land and water resources. The Synthesis also complements a set of policy recommendations contained in "*The Greening of China's Agriculture: A Policy Brief*." More broadly, the *Synthesis*, *Policy Brief*, and the *Compendium* fit within a comprehensive review of China's efforts to reduce its agricultural environmental footprint, to improve the management of natural resources to achieve green and sustainable agricultural development, and to contribute to its ambitious goals of GHG peaking before 2030 and net zero emissions before 2060.

Based on this work the World Bank hopes to continue supporting China’s efforts to green and modernize its agricultural sector by adopting low-carbon, climate-resilient, and inclusive policies and sustainable production systems.

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Acknowledgments

Under the guidance of Mara Warwick (Country Director, China, EACCF); Martin Raiser (former Country Director, China, EACCF); Alejandro Alcala Gerez (Operations Manager, China, EACCF); Benoit Bosquet (Director, SEADR); Martien Van Nieuwkoop (Director, SAGDR); Dina Umali-Deininger (Practice Manager, SEAAG); and Yoonhee Kim (Sector Leader, SEADR), this *Greening of China's Agriculture: A Synthesis report* was prepared by a core World Bank team comprising Ladisy Komba Chengula (Lead Agriculture Economist, Task Team Leader, SEAAG); Madhur Gautam (Lead Economist, GFA12); Wendao Cao (Senior Agriculture Economist, SEAAG), and Sitaramachandra Machiraju (Senior Agriculture Economist, SEAAG). Xuan Peng (Senior Program Assistant) and Yunqing Tian (Program Assistant) provided logistic and administrative support to the team.

This report synthesizes key messages from 16 policy and technical working papers prepared by a team of Chinese researchers, academicians, and consultants. Agricultural pollution working papers were prepared by Gao Shangbin (synthesis report), Wang Quanhui (food loss and waste), Zhang Keqiang (livestock wastes), Zhang Weifeng (chemical fertilizers), Liu Yaping (pesticides), Yuyun Bi (crop residues burning), Mu Xiyan (aquaculture), and Hongyi Cai (dietary transition). Agricultural technologies and innovations working papers were prepared by Kevin Z. Chen, Yumei Zhang, and Binlei Gong (research and development; Wenbin Wu (digital agriculture); Lei Bo (agriculture water use efficiency); and Minli Yang (sustainable agricultural mechanization). Sustainable natural resource management working papers were prepared by Jin He (conservation agriculture), Chen Fu (climate-smart agriculture), and Li Changxiao (landscapes and ecosystems restoration). Similarly, the rural and agricultural policy working papers were prepared by Jikun Huang (rural transformation policy analysis), Songqing Jin and Xuwen Gao (farmland policy analysis), and Kevin Z. Chen and Zhang Yumei (producer support policy and public expenditure analysis). Yuan Mi and Zhang Wei translated the agricultural pollution working papers from Chinese to English. The working papers were edited by William J. Hardy and the synthesis report was copyedited by Avril Adrianne D. Madrid. The World Bank team is grateful for their analytical work and substantive inputs to this report.

The above policy and technical working papers were summarized into four thematic papers: (1) *Deepening Pollution Prevention and Control on China's Farms*; (2) *Restoring and Managing Agricultural Ecosystems as Climate Changes*; (3) *Greening China's Agriculture: Technology, Innovation, and Institutions*; and (4) *Incrementally Green: China's Evolving Agricultural Policy, Institutions, and Public Expenditure*. The papers were prepared courtesy of Emilie Cassou, Jock Anderson, Donald Larson, and Steven Jaffee, respectively, under the guidance of and inputs from Ladisy K. Chengula. These fairly detailed papers are published separately as a report titled *Greening of China's Agriculture: A Compendium of Thematic Papers*. Authors made every effort to present data and information from the various working papers in as coherent a manner as possible but acknowledge that some inconsistency in the information is inevitable.

During the concept and preparation stages of this report, the authors received invaluable advice and guidance from the following peer reviewers: Ulrich Schmitt (Lead Agriculture Economist, SCAAG); Sebastian Eckardt (Lead Economist, EEADR), Paola Agostini (Lead Natural Resource Management Specialist, SCAEN); William R. Sutton (Lead Agriculture Economist, SAGGL); and Svetlana Edmeades (Senior Agriculture Economist, SCAAG).

CONTENTS

Introduction

This report reviews current agricultural policies in China and their role in support of China's broader environmental goals. The policies reflect an expansion of agricultural policy objectives to better manage China's limited and overburdened natural resources. The report anchors its discussion of current policy with a description of past policies and past technology choices, emphasizing their impacts on land, water, and air. Collectively, these decisions launched a remarkable period of expansion for China's farm sector but left the country's ecosystems scarred and natural resources depleted. We review how a growing agricultural sector contributed to economic growth, poverty reduction, and the transformation of China's economy, labor markets, and farm structure, and the consequences of those changes for the sector, for new production technology choices, and for agricultural policy. We then discuss the evolution of China's broader environmental goals and link them to changes in agricultural policy designed to mitigate the effects of agricultural pollution and resource use while meeting a growing demand for agricultural products. We review the set of new greener technologies central to China's twin goals of reducing agriculture's environmental footprint and sustaining decade-long sector gains in output and productivity. We then describe challenges that policymakers and the private sector must solve to implement China's well-articulated vision of a cleaner and sustainable future for agriculture. Chief among these challenges is a need to quickly realign China's farm structure, agricultural institutions, and governing process and the skills embedded in them to accommodate a diverse set of technologies and an interconnected set of multisector goals and objectives that mark a significant departure from the past.

Broadly, this report examines the overlap between agricultural and natural resource management (NRM) policies, policies that touch on the multiple ways humans interact with their natural environment. This creates a challenge when setting out the report's scope. To manage the report's length, we emphasize the sector's impact on domestic natural resources but do not discuss fully the important impacts through trade of China's domestic food system on natural resources elsewhere. For the same reason, we emphasize efforts to support greener agricultural production technologies that limit pollution and use natural resources more efficiently but do not cover a complementary set of off-farm supply-chain technologies and food-system policies that could also limit agriculture's natural resource footprint. While Li et al. (2022), in a companion article, review the composition and degradation of China's varied landscapes, including its environmentally valuable forests and marshlands, our primary policy focus is on the sustainable management of croplands and grasslands.

The report draws on material from a collaborative program of applied research undertaken between 2020 and 2022 by several Chinese universities and research agencies, the World Bank, and international researchers from the Food and Agriculture Organization, the International Food Policy Research Institute, and Michigan State University. Some 20 background papers were prepared on topics relating to China's agricultural and environmental performance, institutions, initiatives, and policies. This work was subsequently synthesized into a set of shorter papers focused on (1) the evolution of China's agricultural sector, policies, and public expenditures; (2) agricultural innovation, including low-carbon agriculture; (3) natural resources management; and (4) agricultural pollution prevention and control. These working papers and a compendium of the four shorter papers can be found at (link to be provided once docs are uploaded).

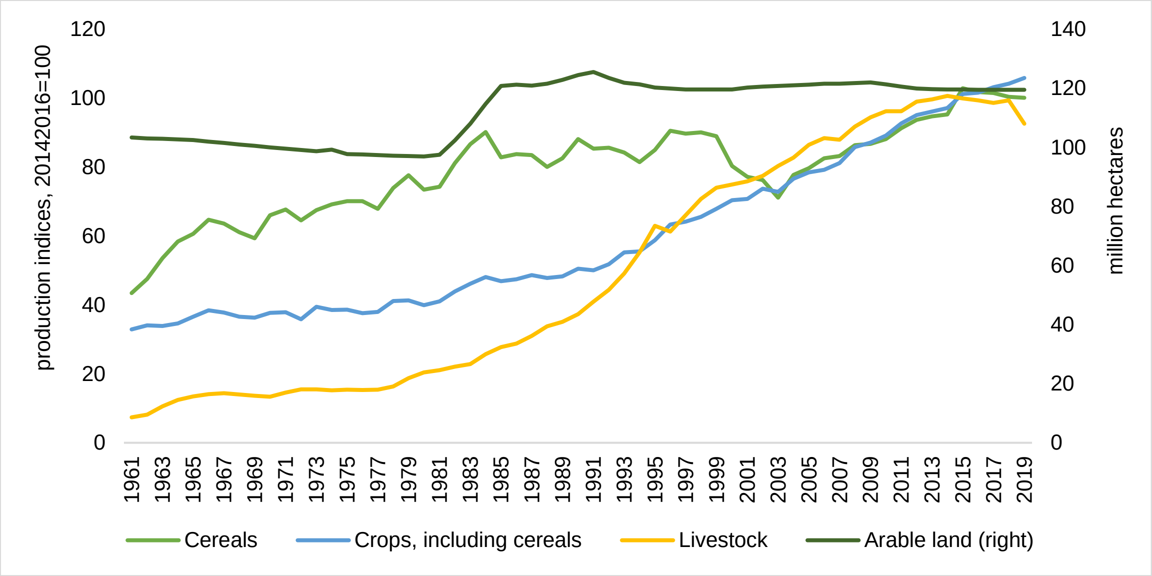
Background: Past Policies, Growth in Agriculture, and the Transformation of China's Economy

In the 50 years spanning 1970–2020, China's agricultural sector grew at a breakneck pace. Crop production increased by nearly five-fold, and livestock production grew nearly 12-fold, at sustained average growth rates of 3.5 percent and 5.9 percent per year, respectively, for five decades. Importantly, this remarkable period of expansion took place against a constrained natural resource base. China's food systems need to support 19 percent of the world's population, with only 9 percent of the world's arable land and less than 7 percent of the world's freshwater (FAO 2022; World Bank 2022a).

Boxed in by land and water constraints, China's agricultural output stayed on pace with population growth and the diversification of diets through sustained intensification. China's population grew nearly four times faster than its arable-land footprint, and crop production grew more than 16 times faster (FAO 2021; World Bank 2022a). While the country gained close to 600 million people—a 72 percent rise—and produced about 2.8 gigatons of plant food each year—a 313 percent rise—its arable land expanded by just under 20 percent. Grain output tripled in volume over this period, fruit and vegetable production was multiplied by 19, and meat and milk production grew by more than 10 times and 20 times, respectively (FAO 2021). With time, growth in land productivity was matched by labor productivity gains.

Figure 1 captures some key production dynamics for the period 1961–2019. Deeply affected by the Great Chinese Famine (1959–1961), early agricultural policies focused on achieving food security by expanding cereal production on existing farms. Later, in the early 1980s, Chinese rural communities and their leaders converted large tracts of forest and grassland into farmland, often on steep slopes, leading to erosion, land degradation, and the increased silting of streams and rivers. The conversion of forests for agricultural use was also a major cause of deforestation in China (Li et al. 2022).

Figure 1: Production per Capita Indices and Arable Land in China, 1961–2019



Source: FAO 2021

As discussed in a wide range of country and cross-country studies, productivity gains in agriculture are a powerful catalyst for poverty reduction and economic growth, and this was the case in China (World Bank 2007; Cao and Birchenall 2013; Larson, Muraoka, and Otsuka 2016;). Agriculture continued to grow rapidly, but by the late 1980s, growth in other sectors outpaced growth in agriculture, and China's economy restructured. Agriculture's share of GDP fell from more than 30 percent through the 1980s to 8 percent by

2015. Importantly, agriculture's share of China's labor force fell from 60 percent in 1991, when data were first available, to 24 percent in 2020.

Increased agricultural productivity boosted food supplies and rural incomes, and the shift of agricultural labor to other sectors, where wages were higher, led to a virtuous cycle of improved incomes, especially in rural communities where poverty rates were highest. By 2002, the number of extremely poor people, those living at USD 1.90 a day or less, had fallen by half. By 2018, the number of extremely poor people had fallen by more than 790 million (World Bank 2022b).

The shifting composition of the economy and the sectoral migration of labor were associated with an accelerated rate of urbanization. In 1970, 82 percent of China's population lived in rural areas, and, despite high rates of internal migration, about 50 percent remained in rural areas through 2010. However, with an aging rural population, the share of China's population living in rural areas fell rapidly, reaching around 38 percent in 2020, and further decreases are expected. Moreover, while China's population is still growing and is expected to grow through 2030, China's rural population may have already peaked, according to projections reported by FAO (2022). As a consequence, the agricultural labor force is both shrinking and aging. In 2021, the average age of the agricultural labor force was 46 years; two-thirds are between 40 and 60 years old, and less than 5 percent are in their thirties (Yang and Jiang 2021).

Despite the dramatic changes to the economy's sectoral composition, incomes, and labor markets, the structure of China's farms has changed little, due in part to internal migration policies (Larson et al. 2022). There is some uncertainty about the size and number of Chinese farms, and there is some evidence that farm consolidation is underway. Nevertheless, the vast majority of China's farms are small. For example, a representative survey of 4,678 farms taken by the Ministry of Science and Technology (MOST) in 2019 and 2020 suggests the average size of China's 160 million farms is about 1.25 hectares.

The shift from a farming sector characterized by abundant household labor working on small farms to a farming sector characterized by small farms and a shrinking labor force has profound implications for adopted production technologies. This is significant because adopting new, greener production technologies is crucial if China is to achieve its policy goals of using land and water resources more efficiently, reining in agricultural pollution, expanding agricultural output, and maintaining sector-wide productivity growth. As discussed later, some proven technologies are scalable and will work well on farms of any size; however, some of the technologies needed to reduce agriculture's resource footprint, especially in light of China's shrinking agricultural labor market, work best on larger farms.

Policies and Technology Choices

Two distinct periods characterize twentieth-century agricultural policies in modern China. The dividing point came with reforms that began in 1978. Prior to that time, policies promoted collective farming and communal production teams. Cereal yields and production grew, but total factor productivity did not. More than 80 percent of farmland was devoted to producing basic grains (Huang and Rozelle 2018). Rural incomes stagnated, and food availability remained low (Huang, Otsuka, and Rozelle 2008). Reforms began with a grassroots innovation in Anhui Province, where a small group of farmers took on household responsibility for production obligations in exchange for greater decision-making autonomy. Over the next few years, the approach, which became known as the household responsibility system (HRS), was piloted in poor agricultural regions and expanded quickly. The HRS was fully sanctioned in late 1981, and by 1983, more than 94 percent of agricultural households had adopted the HRS approach (Lin 1987).

The shift to a greater reliance on household decision-making initiated a steady evolution toward market-based policies, including additional reforms to land-lease markets (Jin and Deininger 2009; Gao, Huang, and Rozelle 2012; Jaffee et al. 2022), and a phased liberalization of agricultural markets, beginning with nonstrategic products in the 1980s and eventually moving to strategic crops, including grains, by the late 1990s (Rozelle and Swinnen 2004; Huang and Rozelle 2006, 2018). As part of its accession to the World Trade Organization (WTO), China significantly changed its trade institutions and policies between 2001 and 2005 (Halverson 2004; Rumbaugh and Blancher 2004; Jaffee et al. 2022).

High-Yielding High-Input Cultivars

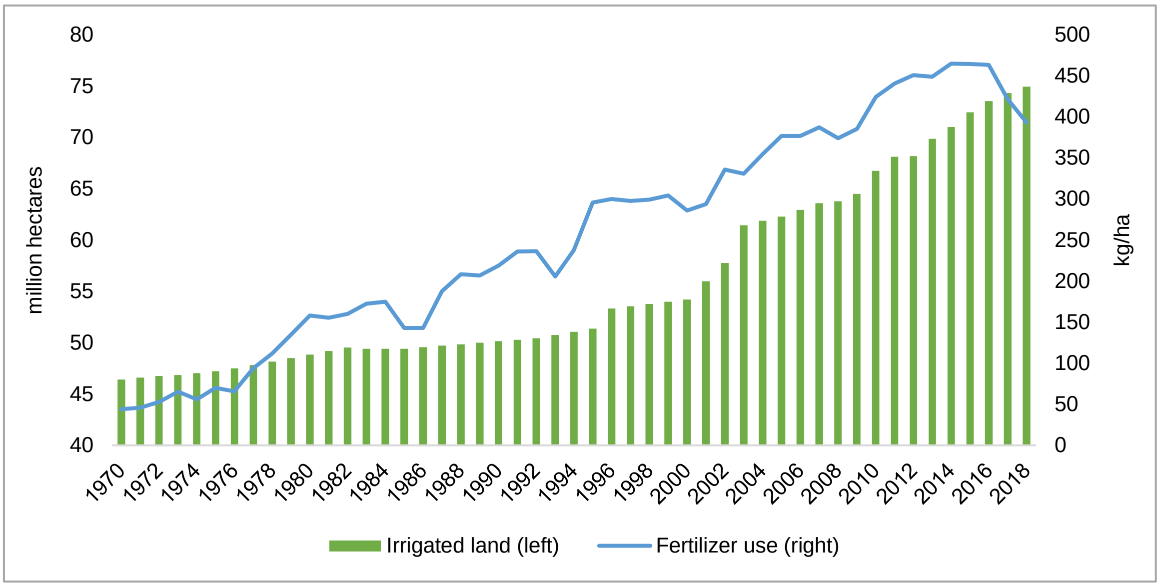
At the heart of China's initial productivity gains were a series of biological innovations in plant breeding. China pioneered the first fertilizer-responsive, semi-dwarf rice varieties in the early 1960s (Jaffee et al. 2022). Similar innovations from other research centers worldwide quickly followed and were widely adopted, launching what would become known as the Green Revolution (Evenson and Gollin 2003; Evenson 2005; Hazell 2009; Pingali 2012; Estudillo and Otsuka 2013; Otsuka and Larson 2013).

Because the innovations were largely embodied in seeds, the technology was scalable and well-suited for China's small farms. Following the introduction of the HRS, production choices devolved to the household, albeit with considerable direction at the village level and guidance from the center. In this case, incentives aligned, the new cultivars improved the productivity on smallholders' land-constrained farms, and the cultivars were promoted by public policy.

Because the new cultivars boosted yields, the technology was land-conserving (Stevenson et al. 2013); however, the technologies relied on the intensive use of chemical inputs, especially fertilizer. Soon environmental problems emerged worldwide, especially in places where multiple crops were harvested each year (Pinstrup-Andersen and Hazell 1985; Pingali and Rosegrant 1994; Rosegrant and Livernash 1996). In China, the excessive use of fertilizers and pesticides associated with this class of technology and the mismanagement of freshwater resources would place a heavy burden on all of China's ecosystems.

Yields from the new varieties were also highest on irrigated land, and, as the new technology found widespread use, irrigated cropland in China grew from 45 million hectares in 1978 to 67 million hectares by 2016 (Zhang et al. 2004; Huang and Rozelle 2018) (Figure 2). However, China's freshwater resources are limited when measured on a per capita basis. For example, in 2017, China's renewable freshwater resources were estimated at 2,015 cubic meters (m^3) per capita, less than half the average for East Asia and the Pacific countries (4,411 m^3); 35 percent of the world average (5,725 m^3); and less than a quarter of the United States average (8,668 m^3). Against this limit, the buildup in irrigation capacity had a dramatic impact on available water supplies. By 1982, the agricultural sector accounted for 88 percent of China's available water (FAO 2022).

Figure 2: Fertilizer Use and Irrigated Land in China, 1970–2018



Source: FAO 2021

The absolute size of the irrigated area burdened water supplies; however, the strain was worsened because water went largely unpriced in most irrigation systems, leading to inefficient use and sometimes waste. Further, under HRS reforms, the ownership of tubewells shifted from villages to households. This led to a wave of investment by farmers, and the share of private tubewells increased from 7 percent to 83 percent between 1983 and 2004 (T. Wang et al. 2019; Jaffee et al. 2022). Privatization gave farmers control over water resources, boosting productivity on individual farms, but creating eventual collective water basin-management problems as well. Moreover, private ownership fueled a growing groundwater market. For example, the percentage of villages on the North China Plain with active groundwater markets increased from 5 percent in 1990 to 80 percent in 2016 (Zhang et al. 2008; Jaffee et al. 2022). This gave non-owners access to irrigation as groundwater markets evolved, again boosting short-term land productivity, but because scarcity went unpriced, further eroding long-term water basin sustainability.

A growing population and economy put additional demands on water resources. Water stress levels for the country have risen from 34 percent to 44 percent since 1982. Moreover, the national indicator masks large inter-regional differences. Both surface water and groundwater resources are highly stressed in the north of the country (excluding the Song Hua River Basin), with average basin water extraction exceeding 40 percent, an internationally recognized limit for sustainable water use (Bo 2021). The highest levels of extraction per basin in Northern China have reached 118.6 percent due to overextraction of groundwater, with a cumulative regional overdraft of 100 cubic gigameters (Gm^3). The average use rate of groundwater in Northern China has reached 105.2 percent, affecting 90 percent of the North China Plain, including an annual overdraft of 6.8 Gm^3 in the Beijing-Tianjin-Hebei region.

Livestock Systems

Early on, the resources of China's small farms, and the sector in general, were mostly devoted to producing field crops. As incomes in China grew along with the demand for meat, mixed farming systems emerged, where crops and livestock were jointly produced. Livestock production from mixed farming systems expanded quickly in the 1980s, supplementing production from livestock grazing systems; later, larger-scale industrial livestock production systems would emerge (Li et al. 2008). Sustaining natural resources under each system has proven difficult.

Grassland ecosystems are the largest ecosystem type by area in China. China's grassland occupies nearly 400 million ha, accounting for nearly 42 percent of the total land area. Grasslands have an important ecological function in regulating climate, conserving water, fixing carbon, and preventing sandstorms. They are also China's traditional animal husbandry base (Li et al. 2022). In recent years, the grassland ecosystems have gradually degraded, and their functions compromised because of climate change, the development of industrialization and urbanization, the increase in population pressure, and changes in land use. Some 90 percent of grasslands in China have degraded to different degrees. Reasons for the degradation of the grassland ecosystems mainly include (1) excessive "reclamation" of grassland for cropping, driven largely by past-century large-scale grassland conversion projects (2) overgrazing and grazing of livestock on a large scale, which led to more sparse vegetation on the surface of the soil and more serious environmental degradation; and (3) overharvesting of grassland medicinal materials. In places, extreme degradation has led to desertification (Li et al. 2022).

Still, there are indications that degradation due to overgrazing has declined. The overload rate, an indicator of the number of animals grazing relative to the sustainable number of grazing animals (carrying capacity), gradually decreased from 40 percent in 2005 to 17 percent in 2013, and the average overload rate in the past 10 years was 30 percent. This is encouraging since the sheer size of the grassland ecosystems means that even small gains per unit area can accumulate to significant decarbonization of the atmosphere.

How best to manage animal waste is a primary environmental challenge for the remaining two systems. Animal manure was the major source of additional nutrients and crucial for maintaining soil fertility and crop yield in traditional farming systems; however, more convenient chemical fertilizers have displaced its use. Further, even on mixed crop-and-livestock farms, the amount of manure generated usually exceeds the amount needed. This raises the challenge of efficiently gathering animal waste from the large number of very small farms where it is produced and distributing it to the many small farms where it can be used. The waste produced at industrial livestock sites is more easily collected and managed, but none of the waste can be used on-site, and the processing and distribution systems for animal waste are underdeveloped.

A study by Jin et al. (2021) shows the underlying conundrum for the industry. Based on long-term data (1986–2017) from more than 20,000 households, the share of rural households that engaged in both crop and livestock production declined sharply from 71 percent in 1986 to 12 percent in 2017. Compared to households that only raised crops, mixed-system households applied less chemical fertilizer and more manure per cropland area. However, manure production on one-third of these household farms exceeded household needs and was disposed of in polluting ways.

Agricultural Pollution

Agriculture was still the number one contributor to water quality impairment going into the 2020s and responsible for major air pollution events that seasonally affect certain regions and major cities such as Beijing. While water and air pollution have markedly improved in some respects (Yin et al. 2020), they remain at levels that put human health, wildlife, biodiversity, and valuable ecosystem resources at risk, while also risking food output, quality, and safety. Animal production has gotten more efficient at breeding meat animals, but it is also one of the critical breeding grounds for infectious diseases, including human-transmissible (zoonotic) ones. In recent years, the industry has been responsible for mass cullings, foodborne disease, antibiotic overuse and resistance, and heightened pandemic risk.

From a domestic perspective, agricultural pollution is also considered a national food security concern. China's food supply situation has evolved dramatically in recent decades, with the national grain supply moving from a surplus situation to one of tight balance (Gao 2021). In this context, agricultural pollution has placed additional strain on domestic food supplies, which authorities sometimes perceive as being too tight for comfort. From the standpoint of food security, it concerns authorities that China is facing increasing water and other resource constraints, pressure on the expanse and quality of arable land, and rising production costs (Buisonje et al. 2016 in Gao 2021). While agriculture has no doubt been undermined by the contaminants flowing out of other sectors, its own contributions to water and soil pollution have rivaled those of households and industry. And at the local level, agriculture has been known to drive specific ecosystems, landscapes, bodies of water, and watersheds to their demise. For all of these reasons, agricultural pollution detracts from efforts to enhance not only food supply and self-sufficiency but also food and diet quality.

Even though agricultural greenhouse gas (GHG) emissions are neither the largest nor the fastest growing in the country, they will need to be reined in if China is to achieve its climate commitments. China aims for its GHG emissions to peak by 2030 and decline, on net, to zero between then and 2060. Given the urgency of the climate situation, it is notable that agriculture is the leading national source of nitrous oxide emissions and the second-largest source of methane (Climate Watch 2020), both potent GHGs whose mitigation should be prioritized. While China's success at mitigation is essential to global climate stabilization, cutting national emissions is also now a core long-term goal of China's socialist modernization (Cheng and Pan 2021). It bears emphasizing that climate stabilization will scarcely be possible if China does not address its food-related emissions. As elaborated upon in Cassou et al. (2022), China's current food-related GHG emissions would account for nearly half of the country's economy-wide target by 2050.

Agricultural Pollution Impacts

Diverse in its manifestations and consequences, the magnitude of agricultural pollution impacts can be difficult to recognize. Agricultural pollution comes from many sources and appears in many forms. Also, much of agricultural pollution is spread out over space and time, generated by multitudes of farms scattered across rural and peri-urban landscapes. In that respect, agricultural pollution broadly falls in the non-point source (NPS) pollution category, which is notoriously difficult to measure and manage. In turn, these qualities of being diverse and diffuse have made and continue to make agricultural pollution difficult to recognize in its entirety and even more difficult to characterize its impacts or measure its costs. Even so, though specific estimates of the economic impact of agricultural pollution are lacking, agriculture contributes greatly to the overall environmental problems that cost China's economy billions of dollars each year—possibly on the order of 10 percent of GDP (Maizland 2021). China's Ministry of Ecology and Environment (MEE) estimated pollution to cost the economy roughly 3.5 percent of GDP in 2010. Although that number has probably improved, further limiting agricultural pollution would likely benefit China's economy as well as its natural resource base.

Water Quality

Despite important improvements, water pollution remains a serious problem in China; and agriculture is its main driver. As of 2020, over 86 percent of China's monitored groundwater was deemed unfit for human contact by government standards (MEE 2021; China Water Risk 2021). Moreover, China's groundwater has significantly deteriorated over time; in 2011, over 40 percent of groundwater sources met minimum standards. In comparison, China's surface waters are in better condition and generally improving. In 2020, six out of seven monitored river basins had met national targets, and the worst quality waters had all been but eliminated. And yet, nearly 17 percent of surface water was still considered unsafe for human contact.

Although domestic and industrial sewage are major sources of water pollution, the farm sector is the main source of water quality impairment nationally. In 2017, the national census of pollution showed that agriculture remained responsible for more nitrogen and phosphorus emissions than other sources, including industry. The sector accounted for nearly half (47 percent) of national nitrogen emissions and over two-thirds (67 percent) of phosphorus ones (Gao 2021). Agricultural sources of excess nutrients are primarily farm-animal feces (including those generated by aquaculture operations), fertilizer, and to a lesser extent, aquaculture feed and detritus.

One of the major manifestations of agricultural pollution lies in the eutrophication of surface waters, China's leading NPS pollution problem. Eutrophication occurs when bodies of water become excessively enriched with nutrients, causing an overgrowth of aquatic plant life, resulting in the depletion of dissolved oxygen and ecosystem destabilization. Eutrophication can eventually lead to hypoxic and sometimes toxic conditions that cause ecosystem species to die off, sometimes resulting in mass fish kills. The damage in China is widespread: about 85 percent of China's monitored lakes and reservoirs suffered from eutrophication in 2018, and since the early 2000s, coastal eutrophication has also progressed rapidly (Gao 2021; Wang et al. 2021). As of 2017, the livestock and aquaculture sectors were responsible for half of the national chemical oxygen demand (COD) in surface waters, a measure of eutrophication. Brought on by eutrophication, toxic algal blooms, known as red tides, have become more frequent in parts of China, such as Fujian (Baohong et al. 2020).

Agricultural pollution has also been implicated in the impairment of drinking water quality, especially in rural areas. While the extent to which agriculture impacts health through drinking water contamination is difficult to quantify, recent evidence points to microbiological contamination being the leading problem with national drinking water, implicating the manure generated by livestock operations. Other leading threats to rural drinking water safety in China are linked to the presence of arsenic, fluoride, microorganisms, and different forms of nitrogen, the latter two also being partly of agricultural origin. In agricultural areas where an abundance of fertilizer and manure nutrients are present, it is common for nitrate concentrations in groundwater to exceed World Health Organization (WHO) drinking water standards (Zhang et al. 2015). Other warranted health concerns come from the potential presence in untreated drinking water of toxic and endocrine-disrupting substances found in pesticides, plastics, pharmaceuticals, and aquaculture chemicals.

While the vast majority of centralized drinking water sources meet basic safety requirements in China, and access to some centralized water sources is widespread, a large share of rural households, possibly one-third, draw water from decentralized and often untreated sources (Zhang et al. 2015). Moreover, according to a 2021 study that reviewed drinking water quality across provinces from 2007–18, only 51 percent of rural drinking water samples met safety standards versus 85 percent of samples drawn in urban areas (T. Wang et al. 2021).

Water pollution of agricultural and other origins has also led to the wide impairment of aquaculture and coastal waters at considerable cost to the industry. Of the 16 million hectares of natural aquaculture waters subject to monitoring in China, 74 percent exceed inorganic nitrogen limits (nitrite, nitrate, ammonia), and 67 percent exceed phosphorus limits. Significant shares also exceed limits for petroleum (40 percent), COD (17 percent), mercury (3 percent), and copper (3 percent) (Gao 2021). It is also the case that, between 2012 and 2018, nearly 1,400 major fishery pollution accidents were recorded in China, resulting in about USD 110 million (CNY 707 million) in direct economic losses and USD 12 billion (CNY 77 billion) in indirect losses (MEE and MARA 2020). Recorded accidents have declined considerably in number and size since the early 2000s, when the country was recording between 1,000 and 1,500 every year. Nonetheless, to underscore how substantial risk to the industry remains, China's exports of all seafood products amounted to a value of about USD 18 billion in 2020 (UN Comtrade 2021). Furthermore, losses due to fishery pollution accidents do not include the potential economic losses owed to missed trade opportunities and products selling at a discount compared to higher quality ones.

Land Quality

Like its water resources, China's agricultural landscapes are affected by extensive soil pollution and degradation. China's farmland is about one-fifth polluted—heavily affected by organic and inorganic pollutants—and 40 percent eroded (Gao 2021). About 15 percent of China's land is estimated to suffer from excessive nitrogen loading (Zhao et al. 2017); over 13–16 million hectares of farmland have been polluted by pesticides, according to a survey by the Chinese Academy of Sciences (Yaping 2021). Microplastics have also become ubiquitous in soils across China, the highest concentrations occurring in northern and northwest China.

Healthy soils are a foundation for productive farms and safe food, and by undermining soil health, the agriculture sector has jeopardized its own potential for success. Major agricultural sources of soil pollution include fertilizers, plastic film mulch, pesticides, and the practice of open field burning of agricultural residues. The resulting pollutants have affected the quality of soils in various ways by utilizing production techniques that cause acidification and soil hardening and disrupt the communities of microorganisms that play essential roles in ensuring gas and nutrient exchange during crop production.

The deterioration of soil quality has potentially impaired crops' uptake of soil nutrients, negatively affecting crop yields and quality. Soil acidification also enhances the potential for crops to take up pollutants present in the soil, including heavy metals from industrial runoff, thereby introducing them into the food chain. This, in turn, can put human health at risk and lead to costly market rejections and reputational risk. By the 2000s, over 15 million hectares of China's cropland were considered heavily acidified, with a pH of less than 5.5, one-fifth larger than the area affected during the 1980s (Xu et al. 2018 in Zhang 2021). While the overuse of nitrogenous fertilizer is considered the leading driver of acidification, manure-related ammonia emissions and long-term use of certain pesticides have also been implicated. Meanwhile, both the accumulation and the prolonged use of plastics on cropland are raising concerns about its possible effects on soil function and food safety. Recent studies show that microplastics (0.1–5 millimeters in size) and nanoplastics (<100 nanometers) can be taken up and accumulate in plants, potentially affecting both food safety and crop yields (Sun et al. 2020; Conti et al. 2020 in Cassou and Xu 2021). The implication is that agricultural plastics can be a source of pollution even when managed.

Air Quality

The magnitude of air pollution in China is such that even a secondary contributor such as agriculture cannot be ignored. Agricultural activities contribute to poor air quality directly and indirectly. In particular, the ammonia emitted by fertilizer and livestock manure interacts with emissions from diesel motors and other sources to contribute to the formation of health-threatening smog and urban air quality deterioration. The burning of crop straws and residues also gives rise to acute local and downwind fine particulate pollution on a seasonal basis.

Air pollution remains a major public health concern in China, even though concentrations of fine particulate pollution have generally fallen since China adopted a national $PM_{2.5}$ standard in 2012—especially around Beijing (Zheng, Yan, and Zhu 2020). Between 2000 and 2016, long-term exposure to air pollution killed nearly 31 million people in China (1.5–2 million people each year) and sickened many more, according to a 2020 study published in the Proceedings of the National Academy of Sciences (Liang et al. 2020). According to a 2016 study, 83 percent of the Chinese population lived in regions that failed to meet the WHO's $PM_{2.5}$ standard—versus 32 percent of the world population (Liu et al. 2016). The problem is particularly pronounced in the northern parts of the country (Cassou et al. 2022).

Reduced air quality is associated with acute and chronic health risks, haze, and short-term warming. Exposure to fine particulate matter is also a known risk factor for cardiovascular, cancer, upper respiratory disease, and premature death (Li et al. 2020; US EPA 2021a). In addition, its inhalation can cause acute irritation of mucous membranes in the eyes, nose, and throat, causing coughing, chest distress, tearing, and bronchitis in severe cases. In China, exposure to high levels of $PM_{2.5}$ has been associated with elevated lung cancer incidence and mortality (Li et al. 2020). In parallel, ground level or tropospheric ozone, which manifests as smog, impairs visibility (increasing the risk of accidents) and increases the risk of upper respiratory disease. Long-term exposure to ozone is notably a risk factor for developing and exacerbating asthma (US EPA 2021b). In addition, both fine particulate matter and ozone are short-lived climate pollutants.

Climate Change

Although China's agricultural GHG emissions are low relative to other sectors, the sector's emissions nearly equal the emissions of the entire economy of Canada. China's agricultural sector was responsible for about 5.5 percent of China's GHG emissions, or about 667 metric tons of carbon dioxide equivalent ($MtCO_2e$), in 2019 (Climate Watch 2020; FAO 2021). Of note, this footprint excludes indirect emissions, such as those relating to fertilizer and pesticide production, as well as on-farm energy-related emissions. It is also based on what China produces domestically, not what it consumes. The sector's footprint would be larger if it included the impact of feed, meat, and dairy imports on the emissions of exporting countries, especially those experiencing tropical deforestation and landscape degradation, such as Brazil. Not counting these sources or indirect sector emissions, agriculture ranked fourth nationally, after electricity, heat, industry, and transportation.

Agriculture is also among the leading national emitters of two potent GHGs, nitrous oxide and methane, both seen as near-term mitigation priorities. Agriculture was responsible for 63 percent of China's 2018 emissions of nitrous oxide, making it the largest national contributor to emissions of this long-lived GHG with 273 times the global warming impact of CO_2. The sector's share has decreased over time (down from 80 percent in the mid-1990s) because nonagricultural emissions of nitrous oxide have been rising faster than agricultural ones. Agriculture was also responsible for 27 percent of national emissions of methane, a short-lived GHG with about 81 times the impact of CO_2 on a 20-year time horizon (or 27 times its impact over 100 years). Formerly the leading national emitter of methane, the agricultural sector has been overtaken by the energy sector, whose methane emissions are rising faster. Overall, while agriculture was responsible for only 5.5 percent of national GHG emissions in 2018, the sector accounted for nearly 38 percent of national emissions of methane and nitrous oxide (Climate Watch 2020). These potent GHGs are considered an important avenue for mitigating near-term warming while structural changes to reduce fossil fuel dependence are undertaken.

Overall, livestock (enteric fermentation and manure), synthetic fertilizer use, and rice paddies are the largest sources of agricultural GHG emissions in China, in that order. On-farm energy use comes next. When breaking down sector emissions by gas, methane leads (46 percent), followed by nitrous oxide (39 percent) and carbon dioxide (15 percent).

It is encouraging that overall agricultural GHG emissions may have peaked in China. After increasing for several decades, China's farm-related GHG emissions declined between 2016 and 2019. According to FAO (2022), GHG emissions on agricultural land peaked at 842 $MtCO_2e$ in 2016. Between then and 2019, they declined by 6 percent, returning approximately to their 2007 levels. The sector also recorded a decline in carbon intensity. That said, agricultural GHG emissions took an upward leap during the 1990s, and the increase has yet to be reversed. Meanwhile, the agricultural sector's indirect emissions have been a source of emissions growth (Zhang, Xu, and Lahr 2022). And, due to agricultural trade, emissions from domestic food consumption have outpaced emissions from domestic food production.

Unsafe Food

One of the major pathways for potentially harmful human exposure to agricultural pollutants lies in the consumption of unsafe food. Food can become unsafe when it is chemically or microbiologically contaminated, and agricultural pollution can contribute, directly and indirectly, to both. Major agricultural food contaminants include animal feces and their pathogens, drugs and heavy metals, pesticides, and plastics—most risks originating from animal agriculture.

In China and globally, foodborne disease is largely due to the microbiological contamination of livestock products. One study estimated that animal-source foods directly accounted for approximately 35 percent of the global burden of foodborne disease in 2010 (Li, Li, and Li 2019). Dairy alone is conservatively estimated to contribute 4 percent of the global burden of foodborne disease and 12 percent of the animal-source food burden (Havelaar, Grace, and Wu 2020).

In China, the potential for harmful exposure to a range of agricultural pollutants in food may be particularly pronounced with aquaculture products. A large share of China's aquaculture products is thought to contain excessive drug residues, some of which harbor co-pollutants (Mu 2021). Notably, seafood grown in polluted waters is more likely to harbor toxins and pathogens, including ones brought about by harmful algal blooms and ecosystem degradation in general. In addition, pesticide residues, including residues of chemicals banned for their high level of toxicity, such as organochlorines, are commonly found in farmed seafood products (Mu 2021). And because many of them do not easily degrade, they can accumulate in the fat of aquatic foods and later in the bodies of those who consume them, increasing the risk of antimicrobial resistance (Cassou et al. 2022).

For plant-based foods, causes for concern include cross-contamination with animal pathogens, potentially exposing consumers to agriculture-related endocrine disruptors and carcinogens. Both pesticides and the polymers and chemicals used in plastic production can have these properties. It is encouraging that routine monitoring of food products for pesticide and other residues means that an ever-increasing share of food products has come to pass food safety standards in China. For example, the Ministry of Agriculture and Rural Affairs (MARA) reports that the "pass-rate" for vegetables increased from 62 percent in 2001 to 97 percent in 2020 (MARA 2021; Yaping 2021). In contrast, a growing food safety concern lies in the ubiquitous and sometimes heavy presence of microplastics in China's agriculture. Sources of these include plastic films used in crop farming and sewage as fertilizer, often laden with nonagricultural microplastics. A growing number of studies show that worrisome substances can migrate from soils into crops and into the food chain. Evidence of the extent of this phenomenon and its health effects is still emerging.

Certainly, today, the full public health ramifications of chemicals that have been widely adopted in farming and have become ubiquitous in the food chain and environment have yet to be determined conclusively. One cause for concern comes from uncertainties surrounding the potential aggregate and cumulative effects of pollutants, including agricultural pesticides, plastics, and other chemicals, on human health. The potential chronic health impacts of pollutants in their ensemble are largely unknown today. Despite this, many scientists from different fields have observed that the safeguards in place to protect public health from potential harm are not based on the potential for environmental pollutants to act cumulatively or synergistically. This heightens the potential benefits of eliminating pollutants whose risks are known.

Wildlife, Animal Health, and Biodiversity

In aquatic environments, both wild and farmed species have been harmed by agricultural pollution, especially in the form of pesticides and eutrophication. Pesticide pollution is believed to have led to the heavy loss of frogs and fish in some parts of China and the almost complete disappearance of eels and loaches (Yaping 2021). In waters subject to nutrient pollution, eutrophication and unbalanced nitrogen-phosphorus ratios in mariculture areas have been important contributors to harmful algal blooms and an extreme decline in plankton biodiversity (Mu 2021). Pollution has been known to disrupt animals' reproductive health, development, and growth and induce abnormal behaviors (Mu 2021). Even trace amounts of pollutants can have these effects, and over time, even sublethal problems can lead certain populations to dwindle and eventually become extinct. Pesticides, for example, can lead to this outcome by affecting animals' fertility and survival rates. One consequence of eutrophication is that it favors small species (low food chain) over large ones (high food chain) less able to feed on sediment and organic detritus (Mu 2021). That said, eutrophication eventually kills off all the aquatic animals that live in an affected body of water by causing dissolved oxygen levels to decline. Since farmed species are similarly affected, the poor management of feed and fertilizer erodes the natural resource foundation of commercial aquaculture.

Wild aquatic populations have also been affected by genetic pollution introduced by aquaculture activities. Indeed, aquaculture activities have been known to introduce invasive species into bodies of water, to the detriment of native species. In China, for example, tilapia and largemouth bass have invaded the Pearl River, and crayfish have invaded most freshwater bodies across the country. Invasive species such as these tend to suppress and threaten native species quickly because of their strong competitiveness, and when they do, they can destabilize the original ecosystem, introduce new pathogens, and cause biodiversity loss. The genetic "erosion" of wild species can enhance their vulnerability to pathogens. This erosion can mainly occur when native species hybridize with introduced ones, which has been observed in scallop populations.

Agricultural pollutants such as pesticides have also taken a toll on terrestrial species in China. For example, while various stressors are believed to contribute to the decline in pollinator populations, pesticides have likely been implicated to some degree (Yaping 2021). Many pesticides used in China's fields are lethal to nontarget species, even in small doses. To illustrate, a single granule of carbofuran, an insecticide, can be lethal to small songbirds, the lethal dose being less than 1 milligram per kilogram. By the end of 2022, that pesticide will be banned.

It is telling that efforts to reduce pesticide use in China in recent years have enabled beneficial insect populations to recover in certain contexts. This has, for example, been observed in connection with pesticide control efforts in Anhui Province, where spiders have reportedly returned to rice fields, and in Zheijiang Province, where lacewings and spiders made a comeback in citrus orchards (Yaping 2021). A survey in Hunan Province showed that the number of fish, shrimp, frogs, and other animals is gradually increasing in rural areas, and the number of birds in spring is increasing rapidly (Yaping 2021).

Another major and emerging threat to wildlife health lies in plastic pollution. Large numbers of animals are ingesting and becoming entangled in plastic debris, both on land and at sea, and studies have revealed the widespread presence of potentially harmful microplastics in China's freshwater environments (Fu et al. 2020). While agricultural contributions to plastic pollution are not well known, agricultural plastics may be particularly prone to contaminating wildlife habitats in rural settings where collection infrastructure and services are often inadequate.

Air pollution is another source of stress for both fauna and flora. Ozone pollution, for which certain agricultural pollutants are a precursor, can have negative effects on species diversity, habitat quality, and water and nutrient cycles (US EPA 2021c). In addition, wildlife is not immune to the detrimental health effects of particulate pollution, to which agriculture contributes directly and indirectly.

The Link between Agricultural Pollution and Technology Choices

Multifaceted as it is, the challenge of agricultural pollution can be traced to a relatively discrete set of farming practices. It is from these broad categories of farming practices that most of the pollution problems discussed in this report stem. This section provides an overview of these—although it omits some, such as flooded rice paddy cultivation and the use of drugs in animal farming—selectively highlighting information about their scale and scope, major trends and drivers, and how they contribute to pollution.

Livestock Rearing and Waste

As the world's largest meat producer, China is by far the largest producer of manure in the world today. In 2019, the country's farmed terrestrial animals excreted an estimated 12.4 metric tons of nitrogen in the form of manure. At this rate, China generated roughly 5 percent more manure than India, 12 percent more than Brazil, 48 percent more than the European Union, and 77 percent more than the United States, the next four largest producers globally (FAO 2021). Unprocessed animal waste, particularly when exposed to the elements and released into the environment untreated, is a source of air, water, soil, and climate pollution.

Both nationally and in many local contexts, livestock waste is the leading source of nutrient pollution. In the Lake Tai or Lake Taihu catchment in Jiangsu Province, for example, livestock wastes were recognized as constituting the main causes of water eutrophication, accounting for 32 percent of total phosphorus (TP) and 23 percent of total nitrogen (TN) discharged into the catchment at one point in the past (Zhang et al. 2004 in Zhang 2021). Nationally, the 2017 census of pollution found that livestock manure (including manure from poultry) accounted for nearly half (47 percent) of national COD—again, a measure of eutrophication—and the vast majority (94 percent) of that attributable to the agricultural sector. Manure also accounted for 11 percent of national ammonia emissions, the largest share nationally.

As noted, livestock waste is also the leading source of foodborne pathogens. Food-producing animals and their manure are the major reservoirs for many foodborne pathogens such as *Campylobacter* species, non-Typhi serotypes of *Salmonella enterica*, Shiga toxin-producing strains of *Escherichia coli*, and *Listeria monocytogenes* (Heredia and Garcia 2018). It is a particular concern when manure is discharged untreated in the vicinity of drinking water sources or used to fertilize fruits, vegetables, and other food crops.

The livestock sector is also by far the leading source of agricultural GHGs in China. Its emissions account for 40 percent of emissions on agricultural land, or 47 percent of sector emissions, excluding farm-related energy emissions from the total (based on FAO 2021). Factoring in indirect emissions related to feed production, grassland degradation, and forest clearing for grazing and feed production—the latter occurring primarily in Latin America—inflates emissions from animal agriculture even further. While enteric fermentation accounts for a little over half of the livestock emissions in China, manure is responsible for most of the GHGs produced by pork and poultry, China's preferred meats.

Growth in meat and manure—or, more generally, herd size and emissions—have gone hand in hand with the livestock industry's concentration and intensification. Large-scale and intensive animal farming is thriving in China, generating not only ever-rising volumes of product but also manure and sewage every year (Gao 2021). At the same time, the fragmentation of crop and animal farming has also potentially exacerbated the problems caused by livestock waste. As of 2020, more than 70 percent of the agricultural parks in China were practicing only crop or animal production (K. Zhang 2021). Although large-scale animal farms predictably generate voluminous cesspools of manure, only a minority of livestock operations were planned in a way that reflects an intent to integrate them with crop farming.

The livestock pollution situation has not been static in China, and efforts have been made on multiple fronts to manage livestock and their wastes more sustainably in recent years. Notable advances have been made in breeding, feeding, and waste recovery and treatment technologies. Among other things, China stands out for its relatively wide adoption of biodigesters to treat animal waste. However, experience from the Netherlands, which is home to one of the world's most intensive, regulated, and modernized livestock industries, offers a cautionary tale. Despite stringent environmental regulations and support to adopt state-of-the-art practices and technologies, the livestock industry's pollution footprint continues to expand, even as the government looks to reverse its impacts.

Aquaculture and Water Management

While aquaculture is not a leading source of agricultural pollution, it is a major contributor to surface water pollution downstream of areas where the industry is highly developed, particularly in southern China. In 2017, the industry was responsible for about 6–8 percent of agricultural sector-wide nutrient emissions and COD.

Aquaculture pollution results from the industry's use of inputs and its management of used water. Inputs into aquaculture include feed, drugs, and a variety of chemicals. While these contribute to the endogenous pollution of aquaculture waters, their discharge also pollutes downstream bodies of water, potentially affecting other aquaculture operations and farms. Most inland farms regularly release large volumes of used water. In addition, the escape or release of farmed animals into the wild can cause a form of genetic pollution, impacting wildlife and ecosystems in surrounding waters.

China's aquaculture industry has scaled to the extent that it has tested or exceeded environmental carrying capacity. Between 1978 and 2019, aquaculture production in China increased 40-fold, growing about 3.5 times larger than capture fisheries' output (Mu 2021). Aquaculture is considered a source of high-quality protein and an important source of agricultural sector jobs and income (Gao 2021). For this and other reasons, the sector's development has been heavily promoted by the government since the 1980s. By 2019, the industry produced nearly 51 metric tons of seafood, over 60 percent of the world total. While this scale-up has also expanded the industry's footprint, the latter has also been widened by the development of high-density fish culture more reliant on inputs.

The aquaculture industry has not only grown but also gravitated toward intensive, large-scale, branded, and high-density production and embraced a high-input, high-output model of production (Gao 2021). As a result, China's extensive and crowded fish farms have seriously overloaded water bodies by releasing large amounts of residual feed, fertilizer, feces, dead fish, metabolites, drugs, and other chemical wastes. Aquaculture operations have contributed to widespread water quality degradation and eutrophication by overwhelming many water bodies' capacity to self-purify. China's water conservation efforts have not kept pace with the development of its aquaculture industry. Today, China's aquaculture waters are seriously polluted, endangering the quality and safety of products and dragging down the productivity of aquaculture operations.

Fertilizer Use

In large part due to policy changes discussed later, fertilizer use is in decline in China. Still, China remains the largest and among the most intensive users of these chemicals in the world. Chemical fertilizer use increased more than 75 times between 1961 and its high point of over 55 metric tons (of nutrients) in 2015 (FAO 2021). By 2019, total nutrient consumption had declined by more than 14 percent, reaching 47 metric tons. Even so, China was and remains the world's largest consumer of nitrogen, phosphate, and potash. It is also the largest producer of the first two.

Moreover, despite recent declines, China still applies more fertilizer per hectare than most other countries (NBS 2020 in W. Zhang 2021). If in 1978 China applied only 65 kilograms per hectare (kg/ha) of fertilizer on average, by 2015, it applied nearly 600 percent more, or almost 450 kg/ha. As of 2019, it applied about 11 percent less, or 400 kg/ha. But in certain provinces, the rate of fertilizer application is much higher—

reaching nearly 700 kg/ha in Beijing, the province with the highest fertilizer use intensity—although one of the smallest footprints overall (W. Zhang 2021).

A key problem with these levels of fertilizer use is that most of the nutrients applied to crops are lost to the environment. In China, some 67 percent of fertilizer nutrients may be lost to the environment every year, with far less than half of the chemicals helping crops grow (Gao 2021). While challenging soils, rainfall, and intense population pressure are important factors, high rates of fertilizer use in China are also a reflection of low fertilizer-use efficiency.

The result is that fertilizers have been a double-edged sword, increasing crop yields and output but causing serious damage to farmland, watersheds, and entire ecosystems. In the Chinese context, synthetic fertilizer is considered a cornerstone of the country's agricultural achievements over the past several decades and vital to its continued food security. But the wasteful use of fertilizer has led to wide-scale water eutrophication, soil acidification, and other problems already documented. Fertilizer use has also overtaken rice paddies as the leading source of crop-related GHG emissions in China. Meanwhile, if fertilizers contribute mainly to nutrient pollution, they are also a source of heavy metal and microplastic contamination. Indeed, fertilizers are often formulated to contain trace amounts of elements such as arsenic, cadmium, chromium, mercury, and lead, which can accumulate in soils over time. Above certain concentrations, they can impair crop health. On the other hand, recycling sewage sludge as fertilizer in China has proven to be a vehicle for microplastic pollution.

Pesticide Use

China has made significant progress moderating the use of pesticides in recent years. As of 2019, China was the third largest user of pesticides globally as well as one of its leading producers. However, it was no longer the largest or among the most intensive users of these chemicals.

In both absolute and relative terms, China's pesticide use reached a peak in the early 2010s and has been in decline ever since. Overall pesticide applications made a U-turn after 2013 and, by 2019, had returned to roughly the level recorded in 2004, that is, around 273 thousand tons of active ingredients (China Agriculture and Forestry Database, FAO 2022).[1] In terms of intensity, China applied an average of 2 kg/ha of pesticide active ingredients to its cropland in 2019 (FAO 2022). In comparison, Israel, Japan, and the Republic of Korea applied in the range of 10–15 kg/ha, while rates of 4–6 kg/ha were seen in Brazil, Chile, and Malaysia, 2–4 kg/ha in the European Union (EU) and the United States, and 1–2 kg/ha in Thailand and Vietnam (FAO 2022).

Nonetheless, China's level and intensity of pesticide use remain environmental and public health concerns, especially in parts of the country where it is the most intensively used. Pesticide applications are well above the national average in fruit and vegetable producing areas, and heavy use of them is made in the south central and eastern parts of the country. The application of pesticides has also been expanding in area terms.

Part of the problem with pesticide use is that only a fraction of these intentionally toxic chemicals ends up where they are destined to go, creating a risk for nontarget organisms. In that respect, pesticide harm has likely been exacerbated by challenges with pesticide quality and application methods. One issue is that most pesticides for sale in China (around 80 percent) have been on the market for over 15 years, suggesting a likely loss of efficiency (Yaping 2021). Another issue is that more efficient application equipment, which can help mitigate losses, food contamination, and bykill, has not become the norm in China. That said, pesticides vary dramatically in their toxicity and longevity in the environment, hence their effects on nontarget organisms.

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[1] In 2022, the FAO revised China's pesticide usage numbers downward by approximately 85 percent, based on inputs from the government.

From that perspective, pesticide risks have shifted along with the mix of chemicals in use. China's pesticide use has declined not only in volume but also in toxicity, even as the uses and functions of pesticides have qualitatively shifted. Herbicides and fungicides have gained prominence relative to insecticides; and highly toxic and persistent insecticides like organochlorines were eliminated from crops in the 1980s, giving rise to more moderately hazardous substitutes. By 2021, about 80 percent of the pesticides used in China were "highly effective, low-toxicity, and slightly toxic" pesticides, according to a MARA researcher (Yaping 2021, 43).

Another problem with pesticide use—of direct concern to agriculture itself—is that it can breed pest resistance if it is not managed carefully, and in that respect, China also seems to have also made substantial progress. In the past, pesticide resistance has led to devastating pest invasions in China. In 1992, for example, the cotton bollworm invaded more than 4 million hectares (60 million mu) of cotton fields in Jiangsu, Shandong, Henan, and other provinces, causing yield losses of over 50 percent in severely affected areas, and ultimately decreasing China's national cotton production by 30 percent (Yaping 2021). Today, while pesticide resistance remains a concern, similar situations rarely occur in China as the phenomenon is subject to more careful monitoring and management.

Nonetheless, today's widely used pesticides are far from innocuous. For example, of 85 pesticides known to affect the endocrine system, about 50 are registered for use in China, including dimethoate, cypermethrin, carbofuran, triadimefon, 2,4-D, and other mainstream products (Yaping 2021).

Plastics Use

Agriculture has become a significant source of demand for plastics in China, especially short-lived ones that are quickly discarded and prone to ending up in the environment. Agricultural uses of plastics in China were estimated to fall between 2.7 and nearly 5 metric tons per year. The range is based on two separate estimations of agricultural plastics use that were carried out for this study using different methodologies (Cassou and Xu 2021; Yan et al. 2021). According to the higher estimate material flows analysis, agricultural uses of plastics accounted for nearly 8 percent of economy-wide plastic consumption and nearly one-fifth of food system plastics in 2018. Plastic films have been the largest agricultural application of plastics in China by far.

Plastic films account for over three-quarters of agricultural uses of plastic in China. According to the material flows analysis, plastic films used for mulch and greenhouses accounted for nearly 78 percent of the agricultural sector's annual demand for plastics in China in 2018. Greenhouses dominated the category in 2018, accounting for nearly half (49 percent) of agricultural plastics by weight, or nearly 2.5 Mt. Plastic mulch accounted for another 28 percent, at close to 1.5 metric tons (NBS and MEE 2019). The bottom-up study found that plastic mulch film dominated agricultural plastics use, with an annual consumption of 1.38 Mt, while that of greenhouse films was estimated at 1.03 metric tons per year (Yan et al. 2021). Other uses of plastics in agriculture are smaller but also add up; notable uses include sunblock shade cloth, insect screens, fertilizer and pesticide packaging, aquaculture feed packaging, fishing rope and net, and water piping. In all these applications, the most used polymer is polyethylene (PE).

In China, reliance on plastics is especially pronounced, where farmers have adopted plastic films to extend their growing season, retain soil moisture, and suppress weeds—particularly in cold and arid parts of the country. Indicatively, the country's largest user of agricultural plastics is Shandong Province, where rainfall is scarce and temperatures can remain low into the late spring. The province is also one of the most important vegetable and fruit production bases in China, responding to the demand of surrounding provinces, such as Beijing and Tianjin. As such, its reliance on plastic films to grow crops has become extensive.

Given China's farm labor and resource constraints, plastic film has been widely appreciated for reducing labor-intensive tasks, such as weeding and pest control, as well as for enhancing water savings and yields.

In parts of China, plastic films have to some extent, enabled farmers to overcome land, resource, and climate constraints to shift to higher-value crops or intensify production. Northern provinces have been able to scale up the cultivation of crops, such as cotton and certain fruits and vegetables, even though their cold and arid conditions are not well-suited to growing. As a substitute for glass, plastic films have also been an affordable means of scaling up greenhouse operations, enabling farmers to grow high-value food crops in partially climate-controlled conditions.

Due to their short use duration and mismanagement, agricultural films and other plastics have become notable sources of plastic waste and pollution. A key cause for concern comes from the contrast between the brevity of plastic films' useful life, and their extreme durability in most environments, bringing with it the potential to accumulate and do lasting harm. Despite progress, a significant share of agricultural plastic waste continues to be mismanaged in China, resulting in various forms of pollution and harm to wildlife. For example, while the practice is being reined in, the combustion of plastic waste on farms—practiced by an estimated 15 percent of farmers—continues to be a source of toxic air pollution and possibly soil contamination (Yan et al. 2021). It is also a problem when plastic waste is left to degrade on cropland or in natural landscapes. The leakage of plastic waste into the environment can occur at the farm level when used plastics are not fully removed from cropland but also further downstream when plastic waste is sent to open-air dumpsites or lost on its way to them. As it degrades, pieces of plastic, large and small, can be harmful and even lethal to both marine and terrestrial wildlife. Its presence in soils is also polluting farming activities and products. As already noted, plastics left to degrade in soils have also led to a degradation of soil quality, of concern regarding crop yields and food safety.

It is useful to remember that despite being the norm in certain farming systems today, the use of plastic films in farming is only a few decades old. Almost unheard of in the 1990s, over 18 million hectares of cropland were covered in plastic mulch by 2014 (NBS 2016); between 1991 and 2004, the surface covered by mulching films increased by as much as 30 percent per year (Espi et al. 2006). As of 2017, nearly 1.5 metric tons of plastic film covered an estimated 20 million hectares or 12 percent of China's farmland (China News Source 2020; Bloomberg 2017). Plastic greenhouses also surged in recent decades, and by the early 2010s, China was the largest greenhouse film user in the world, accounting for more than 90 percent of plastic greenhouse operations globally (Chang et al. 2013).

Today, however, the adoption of agricultural plastics by Chinese farms now seems largely complete, having peaked around the mid-2010s (NBS and MEE 2019). About 18 million hectares were covered in plastic films in 2018, similar to 2014. After 2016, the annual demand for plastic mulch dropped slightly, according to a China Academy of Agricultural Sciences (CAAS) study, and was back to the 2013 level in 2019 (Yan et al. 2021).

Straw Burning

Though on the decline, the practice of burning agricultural residues after harvest remains a major seasonal polluting event in parts of China. Biomass is burned worldwide to control pests and pathologies in crops, remove wastes to prepare for harvest or seeding, and produce energy (Sharratt and Auvermann 2014). In China, while agricultural burning has been controlled to a large extent since the early 2000s, the country still burns more straw than any other country (FAO 2021). According to FAO statistics, mainland China accounted for 17 percent of global open burning of agricultural residues in 2019, burning 23 percent more biomass than all of Africa and 40 percent more than India (FAO 2021). As of 2019, just under 10 percent of straw left over from growing maize, rice, wheat, and sugar cane was burned in the field, according to FAO records. These numbers do not account for the additional percentage burned as fuel.

The open burning of straw gives rise to a complex mix of air pollutants, including ones that can seriously endanger human health. These include fine particulates including $PM_{2.5}$, dioxins, polycyclic aromatic hydrocarbons (PAHs), carbon monoxide (CO), arsenic, mercury, lead, hydrochloric acid, and volatile organic compounds (VOCs) (Bi et al. 2017 in Bi 2021; Zhang et al. 2011 in Chen et al. 2017). For example, the total emissions of PAHs, known carcinogens, from the burning of corn, rice, and wheat residues in China were estimated at 1.09 gigatons in 2004 (Zhang et al. 2011). Studies carried out in China between 2000 and 2014 indicate that biomass burning activities in general (not exclusive to field burning) can account for up to about 19 percent, 25 percent, and 37 percent of fine particle emissions depending on the season (in autumn, winter, and summer, respectively) (multiple studies cited in Chen et al. 2017). The implication is that biomass burning is a major driver of particulate pollution alongside traffic and coal combustion—at least on a seasonal basis. Studies carried out in different regions of China have also found that biomass burning accounts for around 10 percent (9–13 percent) of VOCs, although its contributions can be far higher on a seasonal basis (Chen et al. 2017). One study in central China (Wuhan) showed that the burning of biomass during the autumn harvest accounted for 55 percent of VOCs and was the main source of haze during the warm season (Lyu et al. 2016 in Chen et al. 2017). Straw burning is indeed an important contributor to secondary pollutants associated with air quality impairment and climate pollution. And multiple studies have shown that smog events in North, Central, and Eastern China have been highly correlated with seasonal biomass burning (Chan and Yao 2008 in Chen et al. 2017; He et al. 2020).

Straw burning is also a source of climate pollution, particularly short-lived yet intense. The major climate forces of concern are organic aerosols—black and brown carbon—and, indirectly, tropospheric ozone. While they are not GHGs, but rather components of $PM_{2.5}$, black and brown carbon contribute directly and indirectly to near-term warming.

While burning rates have declined, the total amount of biomass burned in 2019 was 25 percent higher than in 1997, the year open burning was officially banned, albeit partially. In maize farming, the amount of biomass burned was nearly 74 percent higher in 2019 compared to 1997. In absolute terms, FAO (2022) showed that after hovering in place after the ban, burning levels resumed their climb in 2005, driven by strong increases in maize residue burning. At their peak in 2015, maize burning levels were 89 percent higher than they were the year burning was banned. In contrast, while rice and wheat residue burning levels started to creep back up a few years into the ban, they never returned to their 1997 levels. In fact, rice straw burning peaked in 1976, and wheat straw in 1991, according to FAO statistics.

Straw burning has been difficult to bring to a full stop in part because many farmers continue to view it as beneficial. Some farmers believe straw burning can quickly improve soil fertility, kill pests, eliminate weed and grass seeds, and block the inter-year or inter-season spread of pests and weeds. And while these agronomic benefits are debatable, the economic benefits are clear: straw burning is a time and cost saver for farmers. Available alternatives are generally more costly. For example, incorporating straw residues into agricultural fields takes more time and effort and requires farmers to buy or rent costly machinery. In addition, field incorporation can create nuisances when it is not done properly—notably due to limitations of available machinery. The straw that has been inadequately processed or incorporated at a shallow depth can cause soil to “clot” and interfere with subsequent planting activities. Thus, according to a MARA researcher, subsidies available for field incorporation have been unconvincing (Bi 2021). The lack of economically attractive alternatives to straw burning is also part of the equation.

Alternative Technologies

In sum, most sources of agricultural pollution stem from a small set of farming practices. Fortunately, as discussed in the next section, alternative technologies, including conservation agriculture (CA) methods, are available that, if widely adopted, could dramatically reduce agricultural pollution. A related set of smart technologies could also limit the sector’s demand for natural resources, especially freshwater. The technologies are well known and have been shown effective by researchers, and in many cases, by pilot programs implemented in China. Further, these technologies are at the center of China’s strategy to repair its natural resources and are backed by specific measures. That said, obstacles remain that could stall the widespread use of these technologies, a topic that is discussed in a later section.

The Greening of Agricultural Policy

The accumulating effects of pollution and overuse of China's natural resources from agriculture, manufacturing, and other sectors brought about policy changes. The reforms came in two parts. The first was a broad set of laws and proclamations that set out new goals and standards to safeguard natural resources at the national level, with specific provisions for agriculture. The second included mechanisms for achieving national and sectoral goals, including support for a series of experimental pilots, often designed to develop around alternative production technologies.

Though rooted in past policy proclamations, the practical goals and the implementing instruments were largely formed in a relatively short period, from 2014 to 2019, beginning with the strategic policy document, Several Opinions on Comprehensively Deepening Rural Reform and Accelerating the Promotion of High-Efficiency and Low-Carbon Agriculture, issued by the Communist Party of China (CPC) State Council in 2014. This document signaled a shift from production and productivity objectives meant to supply rapidly expanding food systems to an expanded set of objectives that included sustainability goals and environmental remediation. The vision emphasized the expanded use of new, greener technologies. China's 2021 Number One Document reaffirmed the approach, supporting agriculture's green development and accelerating the transition to high-efficiency and low-carbon agriculture. To be sure, the new policies were not intended to supplant the objective of meeting an ever-growing demand for food and other agricultural products but were instead meant to modulate the means of production to limit pollution and sustain land and water resources.

Between 2015 and 2019, China's State Council took significant steps to reset natural resources management policies and laws, issuing the Water Pollution Prevention and Control Action Plan (2015); the Action Plan for Zero Growth in Pesticide Use by 2020 (2015); a revision of the Environmental Protection Law (1980, 2015); the Pollution Prevention and Control Action Plan (2016); a revision of the Water Law (2002, 2016); a revision of Air Pollution and Control Law (2000, 2016); the Soil Pollution Prevention and Control Action Plan (2016); a revision of Pesticide Management Regulations (1997, 2017); and a revision of the Law on the Prevention and Control of Soil Contamination (2019).

The scope of China's policies on sustainable growth and development expanded significantly again in 2021 when the State Council released its Guiding Opinions on Accelerating the Establishment and Improvement of a Green and Low-Carbon Circular Development Economic System, which set the goal of slowing the growth of carbon emission so that annual emissions peak by 2030, and thereafter fall to reach a "carbon neutral" vision by 2060. That same year, the MEE and the MARA jointly formulated the Agricultural Non-Point Source Pollution Control and Supervision and Guidance Implementation Plan (Trial) to further prevent and control agricultural NPS pollution, reaffirming China's natural resource remediation goals. The goals were emphasized again when the government unveiled its National Agriculture Green Development Plan in late 2021. The plan, jointly issued by MARA, NDRC, MOST, MONR, MEE, and the State Forestry and Grassland Administration, identified resource protection, pollution control, restoration of agricultural ecology, and the development of low-carbon agricultural industrial chains as key goals to be achieved between 2021 and 2025.

Collectively, the new policies and the implementation rules influenced how water, soil, and air resources were managed and how related markets operated. However, the most crucial and direct elements affecting natural resource sustainability were the hard constraints placed on agricultural inputs.

Key Agricultural Policies, Pilots, and Their Link to Production Technologies

The added objective of the new policies was to limit agriculture's natural resource footprint by reducing the amount of water used and limiting agricultural pollution. To support those goals, implementation mechanisms were put in place to promote alternative production technologies that were also capable of sustaining output growth. In the short-term, this meant reducing the excessive use of water and chemical inputs and shifting to alternative technologies that substituted processed natural inputs, such as manure and straw, for polluting chemical inputs, such as fertilizers and plastic film. Longer term, it meant promoting another set of technologies based on digital information technologies, such as sensors and location trackers, and machinery, such as tractors and irrigation systems. Because these technologies work best at scale, programs were put in place to speed up the transformation of China's farming system, a process already underway due to the decades-long sectoral transformation of the Chinese economy and Chinese labor markets. And finally, matching programs were put in place to transform China's massive research and extension systems away from their historical role of supporting resource-intensive technologies based primarily on traditional branches of agricultural sciences to a mission in support of newer, greener technologies based on multidisciplinary innovations.

Limiting Agriculture's Natural Resource Footprint

Some key policies that limit agriculture's resource footprint reside outside of programs managed by traditional agricultural institutions. Discussed in greater detail in Li et al. (2022), the policies apply to managing broader landscapes and ecosystems and are summarized below.

The practical implications of the new national policies for agriculture are broadly outlined in the 2015 MARA document (Implementation Opinions of the Ministry of Agriculture on Preventing and Controlling Agricultural Non-Point Source Pollution), which introduced "one control, two reductions, and three basics" general requirements to promote the green transformation of China's agriculture. "One control" refers to strict controls on the total amount of water used in agriculture; "two reductions" refers to targeted reductions in fertilizer and pesticide use; and "three basics" refers to recycling goals for livestock manure, crop straw, and agricultural plastic film.

A related set of ideas appeared at the national level in 2017 when the State Council issued its Opinions on Innovating Institutions and Mechanisms to Promote Agricultural Green Development, which outlined the objective of maintaining the size and quality of existing arable land, preventing the overextraction of groundwater, pursuing net-zero growth in the use of chemical fertilizer and pesticide, and enhancing the circular use of agricultural wastes, such as straw, livestock and poultry manure, and agricultural films. Cassou et al. (2022), Larson et al. (2022), and Jaffee et al. (2022) discuss aspects of these policies in greater detail.

Landscape Policies

For the most part, policies to limit agricultural pollution focus on their impacts on cropland ecosystems, with their cascading impacts on air and water quality. Although vitally important, the cropland ecosystem accounts for just 14 percent of China's land area. Deeply connected to the protection of China's natural resources and agriculture's resource management are policies meant to protect and restore the other three ecosystems that sustain China's natural resource base.

Forest ecosystems account for 23 percent of China's land area. Forests provide products for human beings and have historical, cultural, aesthetic, leisure, and other values. Forests have extremely important and irreplaceable roles in maintaining biodiversity, protecting the ecological environment, mitigating natural disasters, and adjusting the global carbon balance and biogeochemistry circulation. Before 1998, because of long-term excessive logging and unreasonable management of natural forests in China, natural forest resources declined sharply, and ecological functions were severely degraded, resulting in serious ecological and economic consequences. Since the catastrophic floods in 1998, China has implemented the Natural Forest Protection Program (NFPP). Starting as a pilot in 1998, the NFPP as a full-scale program has already completed its second phase (2010–2020). On July 23, 2019, the General Office of the CPC Central Committee and the General Office of the State Council issued the Plan for the Protection and Restoration of Natural Forests (PPRNF). This plan will be supported by a Natural Forest Protection and Restoration System Program, which has a long-term vision until 2050. The program started in 2021 and is an extension of the NFPP, which will continue to play a leading role in restoring the degraded forest ecosystems in China. In parallel, there are some ongoing restoration programs for degraded forest ecosystems, including the Sloping Land Conversion Program (SLCP), Desertification Combating Program around Beijing and Tianjin (DCBT), Shelterbelt Network Development Program (SNDP), Wildlife Conservation and Nature Reserve Protection Program (WCNR), and the Industrial Timberland Plantation Program (ITPP).

Grassland ecosystems account for 400 million hectares in China, nearly 42 percent of the total land area. Desertification is one of the main forms of grassland ecosystem degradation, mainly caused by wind erosion and overgrazing. Because of the large-scale desertification and degradation of grassland, surface temperatures have increased, which, in turn, further intensified the desertification and degradation of the grassland. As discussed later, the Grain for Green Project, initiated in 2000, was an early pilot designed to reduce overgrazing and restore damaged grasslands.

Since 2000, China has invested substantial resources to address grassland degradation. A revised national Grassland Law in 2002 preceded a suite of grazing restrictions and associated compensation measures, such as the Grassland Ecological Subsidy and Award Scheme (GESAS) formalized in the 12th Five-Year Plan (FYP). GESAS was rolled over in the 13th FYP with a strengthened full grazing ban and reward balance payments. In addition, the Chinese government has carried out a work plan to promote the grassland protection system (Ministry of Agriculture 2016) and the National Plan for Recuperation of Cropland, Grassland, Rivers, and Lakes (2016–2030) to conserve the grassland ecosystems.

Wetland ecosystems in China have been constantly under serious threat of degradation over the past 50 years. However, the rate of wetland loss decreased markedly, with a loss rate of 5,523 square kilometers (km^2) per year from 1978 to 1990; 2,847 km^2 per year from 1990 to 2000; and 831 km^2 per year from 2000 to 2008. From 1978 to 2000, nearly all natural wetlands (98 percent) lost were transformed into non-wetlands. During the 13th FYP period (2016–2020), the level of wetland protection and restoration in China was comprehensively improved, with an area of 2,026 km^2 of newly added wetland, and the protection share of wetlands surpassed 50 percent.

Recently, new regulations, such as the Wetland Protection and Restoration System Plan issued in 2016 and the Decree on Strengthening the Protection of Coastal Wetlands and Strictly Controlling Reclamation issued by the State Council in 2018, have helped protect and restore wetlands. Successful examples of restoration include the Yellow River Delta Wetland, the Loess Plateau River Wetland–Qianhu National Wetland Park in Shaanxi Province, and the Qilihai Wetland.

Aquatic ecosystems degradation has attracted national attention and threatens limited and already stressed freshwater supplies. Further, 21 percent of wetlands line rivers, directly linking the two systems. Pollution from rivers also flows into the ocean affecting marine ecologies.

At present, the viability of most of the rivers in China has been weakened in terms of sewage treatment and pollution dilution. Polluted rivers are usually coupled with the eutrophication of water bodies. Eutrophication is the process in which the increase in nutrients, such as nitrogen and phosphorus, makes the river change from "grass type" to "algae type." The excessive input of nutrients exceeds the threshold of self-purification of the water body, and eutrophication is further aggravated. In addition, because of the low-lying terrain of rivers, pollutants such as trace metals, fertilizers, and pesticides produced by human activities can enter the water body through surface runoff, groundwater, and other channels, making the river ecosystem a gathering place for these pollutants. Moreover, more than two-thirds of the lakes in China are polluted by nutrients such as nitrogen and phosphorus, and 10 percent of the lakes in China are being steadily eutrophied (Li et al. 2022). The annual output of freshwater fisheries in the Yangtze River Basin dropped by nearly half from 1954 to 1970, and output continues to decline.

In 2019, various departments of the State Council successfully implemented the Water Pollution Prevention and Control Action Plan (WPPCAP) and the Inshore Sea Pollution Prevention and Control Plan. Agriculture is one of the primary sources of NPS pollution in China, and steps to limit agricultural pollution, driven in part by the WPPCAP, are discussed further below. In addition, ecological protection and restoration of key ecological areas of the Yangtze and Yellow Rivers have been incorporated into nine major ecological protection and restoration projects. Importantly, by the close of 2019, the cleanup of 602 “sewage outfalls” in coastal waters across the country had been completed.

Agricultural Water Use

Although agriculture accounts for most of China’s water consumption, a revision to the Water Pollution Prevention and Control Law in 2008 put national water plans under coordinated management by 12 ministries, including the Ministry of Environmental Protection (now MEE), National Development and Reform Commission (NDRC), MOST, Ministry of Industry and Information Technology, Ministry of Finance (MOF), Ministry of Land and Resources, Ministry of Housing and Urban-Rural Development, Ministry of Transport, Ministry of Water Resources (MWR), Ministry of Agriculture (now MARA), National Health and Family Planning Commission, and State Oceanic Administration.

A significant change occurred in the 2011 national water plan, which tightened controls on water pollution and water use, introduced improved monitoring systems, and set goals for water efficiency improvements. The plan capped annual water use at 670 Gm^3 by 2020 and set a maximum extraction rate of 700 Gm^3 by 2030. According to the Water Resources Bulletin,[2] China’s total water consumption in 2020 was 581.29 Gm^3, 20.83 billion less than that in 2019, with per capita consumption of 412 m^3, equivalent to 57.2 m^3 per CNY 10,000 of GDP.

In 2016, the State Council issued the Opinions on Promoting the Comprehensive Reform of Agricultural Water Prices, laying the foundations for water pricing and markets. The policy contains three core elements. The first requires localities to clarify the irrigation quotas for major crops and improve the basic irrigation systems to adequately control and measure water use. The second is to construct reasonable water-pricing and water-fee-collection mechanisms based on delivery costs and farmers’ capacity to pay. The third is to establish a water-saving establishment and subsidy mechanism and use economic means to reward and compensate farmers for water-saving behavior. The implementation period is 10 years, which means the water pricing system should be in place by 2025.

In 2019, the National Water Conservation Action Plan aligned national goals to specific irrigation goals for agriculture. In addition to meeting flatline extraction goals for the sector overall, the plan set a goal of increasing the effective use coefficient (a technical term for the ratio of water used on the farm relative to the source water extracted) to 0.56 by 2022.

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[2] http://www.mwr.gov.cn/sj/tjgb/szygb/202107/t20210709_1528208.html

Fertilizers, Pesticides, Straw, and Plastic Film

Policies affecting this set of agricultural inputs are derived from the economy-wide laws to remediate water, air, and soil resources. For example, Article 8 of the 2015 WPPCAP sets out the goal of avoiding soil deterioration from farming methods and excessive chemical inputs, and Article 19 calls for zero growth in fertilizers and pesticides used by 2020. The 2016 Soil Pollution Prevention and Control Action Plan contains provisions to subsidize the use of low-toxicity and low residue pesticides and calls for the recycling of waste agricultural film. The 2016 Air Pollution and Control Law tightened restrictions on straw burning.

MARA's Five Major Actions

One of the most comprehensive statements on the practical implications of the policy shift for agricultural policy is given in MARA's Notice on the Implementation of the Five Major Actions for Green Agricultural Development (2017), which mandated the following five major actions.

Animal waste management. The action program charged local governments with monitoring and managing manure from large livestock and poultry operations. The program also supports pilot projects to build facilities to better manage waste and convert it into safe organic fertilizer.

Straw waste management. This program component is meant to eliminate open straw burning and utilize field wastes for feed and fertilizer.

Replacing chemical fertilizer with organic fertilizer in farming fruits, vegetables, and tea. This component aims to vigorously promote the replacement of chemical fertilizer with organic fertilizer and accelerate the promotion of using livestock and poultry farming wastes and crops straw as a resource.

Agricultural film recycling. This component is meant to control "white pollution" on farms, that is, the problem of discarded plastic ground covering, often used as an artificial mulch.

Protecting aquaculture resources. These actions are meant to establish aquatic biological reserves and restore the fishery ecological environment along rivers by better managing fish stocks and fishing fleets.

As with the rollout of the HRS reforms decades earlier, MARA's Five Major Actions Plan relies on pilots to inform a national shift in policy. For example, initially, new standards for animal waste management will only apply to large livestock and poultry operations, and the new straw treatment rules would apply, initially, only to counties in Northeast China; the use of organic fertilizers for fruit, vegetables, and tea production will be piloted in 100 key counties; the aquatic measures will be piloted on the Yangtze River; and pilots to limit plastic film waste through recycling programs in combination with an increase in the use of natural mulches involve constructing 100 demonstration centers focused on cotton, maize, and potatoes in the Northwest. The impacts of these pilots on green and low-carbon agricultural development will depend on how fast and wide the successful technologies are upscaled in China.

Transforming Research and Dissemination Institutions

China's public support efforts in science, research, and extension institutions are key elements of policy frameworks that sustained agricultural productivity growth over decades. And China's new policy framework will continue to rely on the ability of these same institutions to deliver an equally productive set of greener technologies to China's farmers.

China has the world's largest agricultural research and development (R&D) system, which is dominated by the public sector. China has 1,014 agricultural research institutes and 96 agricultural universities. The

Chinese agricultural research institutes are institutionally separated from the education system. In 2018, the number of full-time agricultural R&D workers reached 63,184, of which 78 percent were working in agricultural research institutes and the remainder in universities. China's public agricultural research institutes are decentralized, with most of its research institutes at the prefectural level. In 2018, national, provincial, and prefectural research institutes accounted for 6.9 percent, 40.4 percent, and 52.7 percent, respectively, of the total number of research institutes. MARA, the National Key R&D Program (NKP), the National Science Foundation of China (NSFC), CAAS, and the China Agricultural University (CAU) are key public stakeholders.

There have been gradual shifts in how research budgets are spent. Still, most expenditures are for crops, although the share of R&D expenditures on crops has dipped from 61.8 percent in 2002 to 57.4 percent in 2018. R&D expenditures on basic research have been growing, and their share in total agricultural R&D expenditures doubled from 2002, reaching 19.7 percent in 2018.

Several key policy documents signaled the intent to redirect technology development, adoption, and farmer support to green technologies. In 2016, the State Council issued the 13th Five-Year National Science and Technology Innovation Plan, which outlines the goal of advancing modern agricultural technology with high efficiency, safety, and ecological benefit and establishing a modern agricultural technology system characterized by informatization, biotechnology, intelligent production, and sustainable development. In 2017, the State Council issued its Opinions on Innovating Systems and Mechanisms to Promote Agricultural Green Development, which specifically commented on the structure of R&D institutions, stating the goals of building a scientific and technological innovation system to support green agricultural development; improving the mechanism of collaborative research among research institutions, universities, enterprises, and other innovative entities; and carrying out joint research on science and technology relevant to green agricultural production.

Both MARA and MOST issued plans supporting the national directives at the ministry level. In 2017, MARA issued its own 13th Five-Year Agricultural Technology Development Plan, outlining how the ministry would promote the wide application of biotechnology, information technology, and material technology in the fields of improved seed technology, efficient production, food safety, resource use, and equipment manufacturing; and gradually realize the transformation of agricultural development from being reliant on resource input to a science-and-technology-driven mode. In 2018 MARA issued the Technical Guidelines for Green Agricultural Development (2018–2030), which included support for developing the agricultural green technology innovation system and improving agricultural resource use. In 2019, MOST issued its Special Plan for Innovation-Driven Rural Revitalization and Development (2018–2022), which included programs to support agricultural science and technology innovation.

Strategic Technologies

As explained in a companion paper by Larson et al. (2022), researchers and policymakers have identified a set of available technologies that could help China meet its policy goals. For the most part, evaluations of the technologies are gleaned from academic studies; however, several are important components of pilots backed by MARA and MOST. Some of the innovations rely on sophisticated machines, while other technologies originate in more traditional agricultural sciences, such as agronomy and plant breeding. Other technologies rely on data systems that collect and distribute better data.

Irrigation

Water delivery: Pipeline technology can limit transmission losses to 5 percent or less. This can be achieved by lining channels with less expensive concrete, plastic, or clay, either completely or in areas where the channels pass over more porous soils. The benefits of doing so vary considerably, depending on local conditions. For example, for some irrigation areas supplied by groundwater, canal seepage is recovered as the water recollects underground. In other locations, canal seepage can raise soil salinity and greatly diminish soil fertility. Adding sprinkler systems, including drip irrigation systems, allows water to be delivered more frequently and in smaller quantities.

Field management: There are many ways to better manage irrigation water in the field. Some very effective approaches are simple, such as field leveling and furrow design. Irrigation systems can be operated at less than full capacity to minimize leakage, and irrigation timing can be optimized. Newer technologies, such as laser-based leveling systems, allow for more precise modifications. Agronomy-based improvements can include mulch application and deficit irrigation methods. Biology-based improvements such as drought-tolerant and water-saving varieties can also be used.

System management: Some of the most promising technologies integrate engineering components that manage water deliveries, sensors and data collection systems, and digital platforms that can be used to manage water supplies and demand. Once in place, the systems can be used to manage economic innovations, such as water pricing or water quota trading systems.

An example, described in more detail in Bo (2021), involves a pilot in the Hai River Basin, which involved the installation of and training for a computer-based platform to manage irrigation quotas for local water user associations (WUAs). The database was linked to sensors that tracked individual farmers' pumping times and water use against quota allocations. Farmers can book irrigation time slots and perform other tasks using a mobile phone. Irrigation schedules, water use, and other information were accessible to all farmers, and historical data can be used to improve the performance of the overall irrigation system.

Field Operations

Precision applications: Drip irrigation and advanced digital systems where water use is monitored and controlled at the nozzle head are available technologies that could improve water-use efficiency. A related set of innovations integrate irrigation systems to deliver fertilizer inputs. A good example is the pilot program in Huang-Huai-Hai Plain, where real-time monitoring, drip irrigation, and fertigation (fertilizers delivered through irrigation systems) have increased fertilizer use efficiency by 7–9 percent. Another approach used in pilots utilizes “side-deep” fertilization, where fertilizer is placed at the base of the plant for more efficient uptake.

Data collection, management, and dissemination: Some innovations involve making better use of information. A good example is a program to use soil testing to build customized advice on fertilizer use (WU 2021). Experimental results from CAAS across the country showed that fertilizer application based on soil testing increased yield by an average of 15.0 percent for rice, 12.6 percent for wheat, 11.4 percent for maize, 11.2 percent for soybeans, 15.3 percent for vegetables, and 16.2 percent for fruits. In the program, agriculture departments use soil tests to devise customized recommendation cards that are distributed to farmers. The current pilot encompasses nearly 128 million ha.

Another example of a piloted technology discussed more fully in Wu (2021) involves the placement of self-contained wireless field monitors that sample for pest infestations and provide early warnings to farmers when pests are detected. The system reduces pesticide applications by eliminating unwarranted applications and, when warranted, increases pesticide use efficiency by coordinating the applications among neighboring farms.

Machines and data generation: China’s agricultural policies are meant to address two seemingly separate goals, remediating the natural resources that sustain agriculture and addressing problems related to an aging and diminishing agricultural labor force. Capital-intensive machines and systems are part of what is needed to meet both goals. In addition, labor-saving investments in machines can be leveraged to collect data that inform decisions and data that other machines also use. Two examples include the precision planting machines and combine harvesters discussed in Wu (2021). In both cases, the technologies are labor-saving and have little direct impact on water or chemical input use. However, when equipped with geo-location and soil moisture measurement systems, the machines help create field maps that improve the precision of fertilizer applications and irrigation systems.

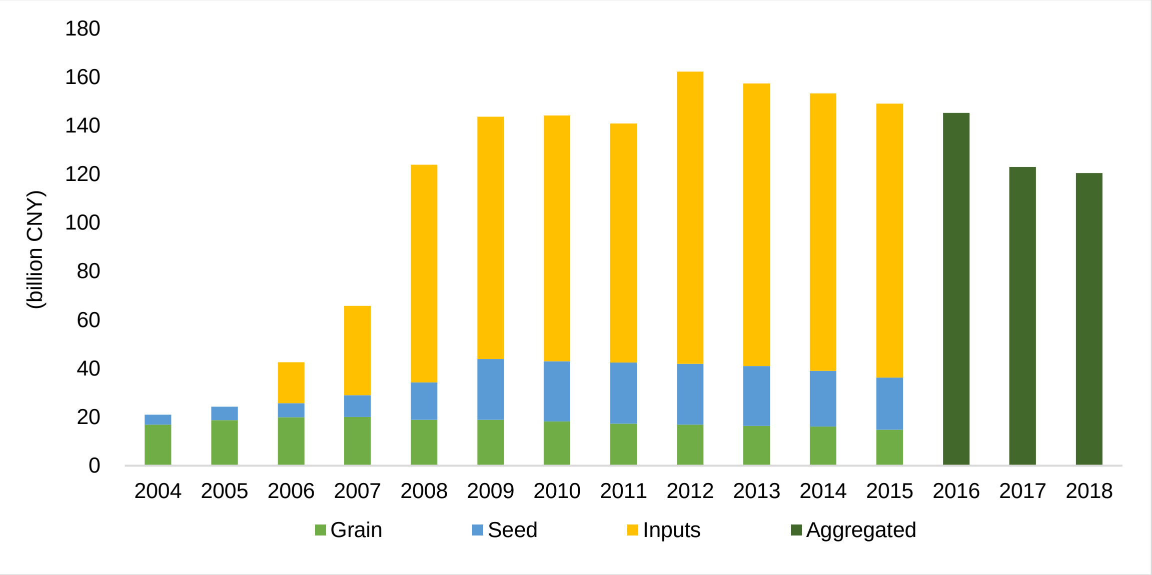
Backbone technologies: Data generation and utilization applications rely on a communications network that has been expanding rapidly in China. In 2000, less than 7 percent of the population had mobile phone service, and less than 2 percent used the internet. Mobile phones and internet access were rare in rural areas. As telecommunications infrastructure and incomes grew, and as handset and computer prices fell, mobile phone and internet use became common in most places in China. By 2020, there were more mobile service plans than people in China, and more than 70 percent of people accessed the internet (World Bank 2021). Increasingly, private platforms, such as Alibaba's Taobao, complement public platforms to provide better internet access in rural areas. These technologies link farmers and machines to platforms that gather and combine data from remote sensors on land, air, and space and location data from global positioning systems (GPS) and BeiDou (a satellite-based radio navigation system developed by the China Space Science and Technology Group), which then link farmers to markets. Improvements to communication systems, such as fiber optics and 5G, increase the speed and usefulness of these connections.

Evolving Budget Priorities

The evolution of agricultural policies described above was linked to an evolution in government spending. A good starting point to understand that evolution is 2004 (Jaffee et al. 2022). That year, prompted by concern about farmer incomes and a growing gap between rural and urban incomes, the Chinese government began to phase out all agricultural taxes and fees, which were used to partially support the provision of local public goods and services and, sometimes, to pay for local administration and management. In 2000, the total taxes on agricultural commodities, including grain and non-grain commodities, reached CNY 43 billion, and the fees collected from agriculture totaled CNY 16.3 billion. These two together accounted for 4.4 percent of the government's fiscal revenue that year. By 2016, agricultural taxes and fees had been eliminated in all provinces.

Programs to deliver direct payments to farmers began at the same time. The subsidies started with the "direct grain subsidy" and the "quality seed subsidy" in 2004. When domestic chemical fertilizer and fuel prices rose with international prices in 2005–06, a new aggregate subsidy program named the "agricultural input aggregate subsidy" was started in 2006. Almost all farmers received subsidies. The total amount of the three major subsidies reached a peak of CNY 162.2 billion (at 2018 prices) in 2012 (Figure 3). While not shown in the figure, China also started an agricultural machinery subsidy in 2006, which grew to more than CNY 23 billion by 2014.

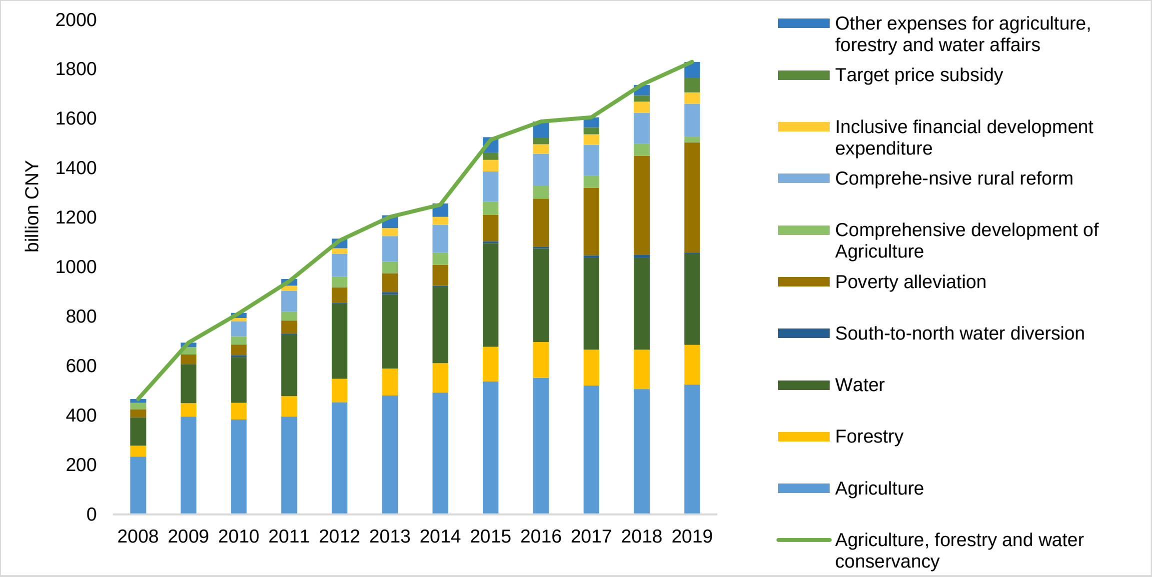
Figure 3. Major Agricultural Subsidies in 2004–18 (billion CNY in 2018 prices)



It is important to note that input subsidies comprised the largest share of direct subsidy payments, even as policies were being put in place to rein in excessive fertilizer and pesticide use. More recently, subsidies to farmers have been more supportive of policies to promote greener technologies. For example, in 2016, direct subsidies to farmers for agricultural insurance, soil conservation, and grassland ecology protection reached CNY 15.8 billion, CNY 0.8 billion, and CNY 19 billion, respectively.

As more fully explained in Jaffee et al. (2022), total public expenditures on agriculture, forestry, and water conservancy (AFW) grew and changed in composition, largely reflecting concerns over rural welfare. In real terms (2010 prices), the AFW budget grew by 13.2 percent (Figure 4) per year between 2008 and 2019, increasing from CNY 466.1 billion in 2008 to a total of CNY 1.83 trillion in 2019. The share of AFW expenditures in total government spending grew from 6.8 percent in 2007 to 9.7 percent in 2020. As shown in the figure, most of the growth originated in new programs related to poverty alleviation, comprehensive rural reform, and inclusive financial development.

Figure 4: National Public Expenditures on Agriculture, Forestry, and Water Conservancy, 2008–19



Source: Final budget sheets of the MOF, various years

While the expenditures on AFW increased over time, and their growth rate exceeded that of national total public expenditures, they extended well beyond conventional agricultural programs to also include items related to south-to-north water diversion.

Dedicated spending on "traditional agriculture" represented about half of the total in 2008 but less than one-third by 2019, as the biggest increases in spending have occurred for water resources and poverty alleviation. The expenditures on water conservancy included not only expenditures on water conservancy activities and drinking water for rural households and livestock but also on developing water conservancy facilities and south-to-north water diversion programs largely unrelated to agriculture. These expenditures constituted 17 percent to 22 percent of the total expenditures on AFW.

Poverty alleviation funds increased most rapidly, growing from CNY 33 billion in 2008 to CNY 445 billion by 2019. The share of poverty alleviation funds in total AFW expenditures increased from 7.0 percent in 2008 to 24.3 percent in 2019. The largest component of poverty alleviation expenditures, almost one-third, was spent on improving rural infrastructure. Other poverty alleviation spending targeted agricultural production in very poor locations, social development and rural education programs, and programs providing low-interest loans.

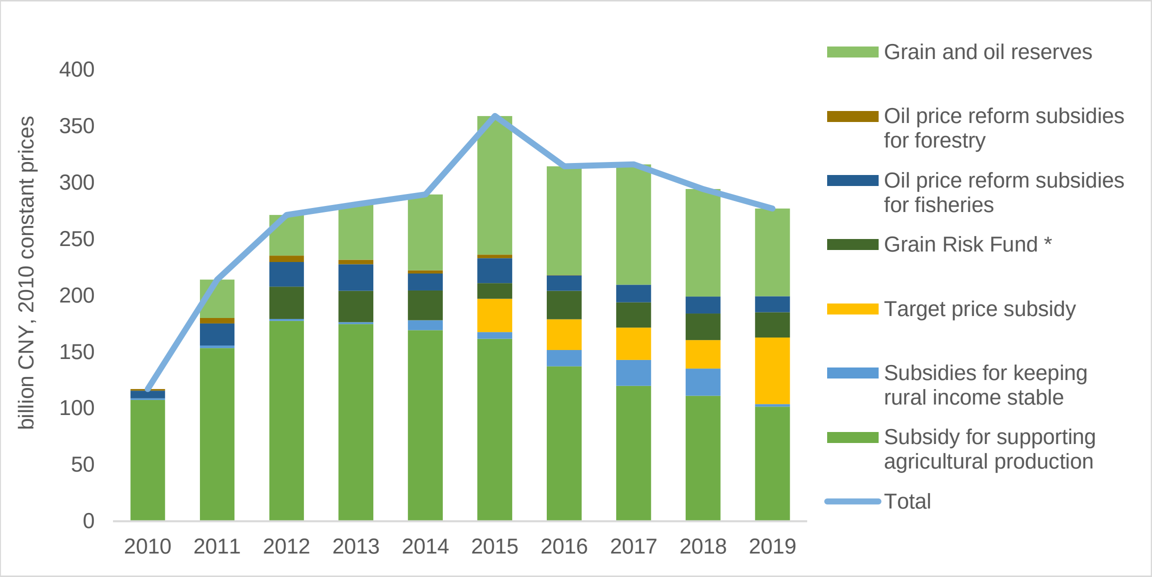
As analyzed in detail by Chen and Zhang (2022), the changing composition of AFW spending has been accompanied by other structural shifts. The bulk of spending now occurs at the local level, with most of the central government's expenditures on AFW involving transfers to the local government. Central government spending on AFW now accounts for only 1.4 percent of total central government spending (down from 2.7 percent in 2007), while 11.1 percent of total local government spending is related to AFW (up from 8.1 percent in 2007). Transfer payments from the central government are used to equalize payments across regions plus re-enforce selected areas of national priorities. Ongoing reforms are geared toward improving the fiscal system, clarifying the responsibilities of central and local governments, and improving performance evaluation.

Support for Production and General Services

China's public expenditures on agricultural production follow the typical dichotomy between direct and general support for public services. Direct support for agricultural production includes agricultural production support subsidies, subsidies for stabilizing farmers' incomes, targeted price subsidies, food risk funds, subsidies for fisheries and forestry, and grain and oilseed reserves. General financial support for agricultural public services includes science and technology and extension services, pest control, quality and safety of agricultural products, disaster prevention and relief, irrigation and water conservancy, rural road construction, drinking water for rural households and livestock, rural infrastructure construction, comprehensive agricultural development and inclusive financial development expenditures, agricultural structure adjustment subsidies, and agricultural organizations and industrialization management. Taken together, expenditure support of both types (direct and general support) increased from CNY 324.3 billion in 2010 to CNY 646.7 billion in 2019, with an average annual growth rate of 8.0 percent.

Public expenditures for direct support to agricultural production have fallen in recent years, driven mostly by the decline in direct farmer subsidies already discussed. To a degree, the decline in direct payments has been offset by expenditures on programs meant to support and stabilize farm incomes (Figure 5). New programs include expenditures for grain and oil reserves, subsidies related to oil price reforms, and commodity price support. Still, since 2015, expenditure on direct support for agricultural production has declined from CNY 360 billion to CNY 277.1 billion in 2019.

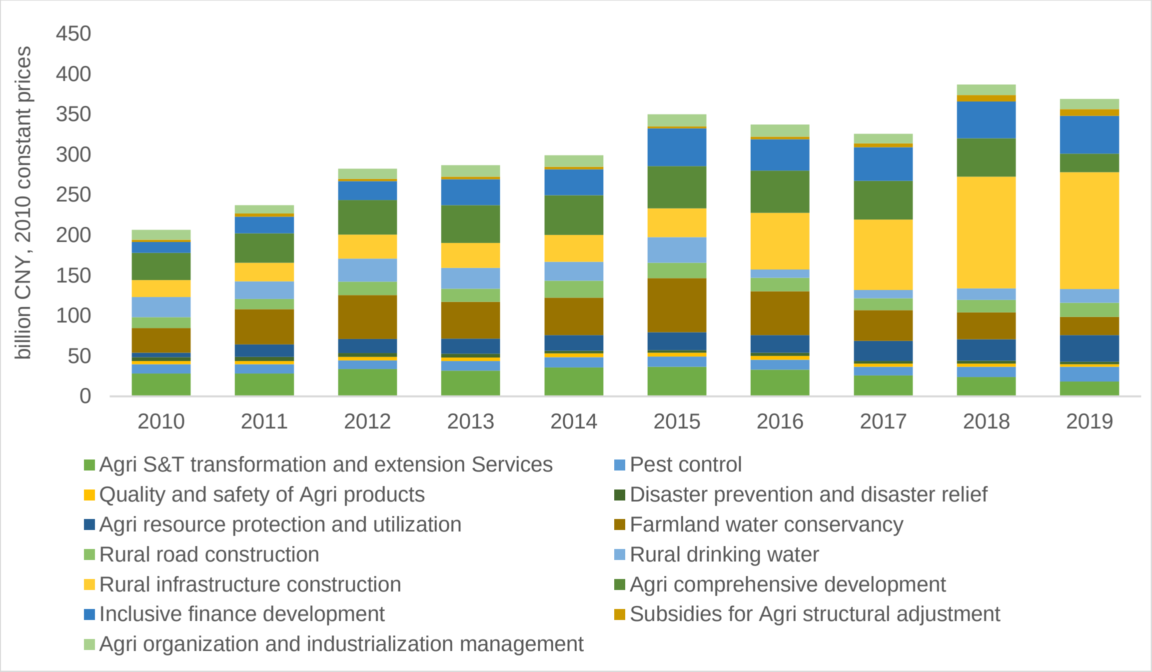
Figure 5: Public Expenditures on Direct Support for Agricultural Production in China



Source: Final budget sheets of the MOF, various years

Public expenditures on general public services are decoupled from specific agricultural products and income support and include eight subcategories summarized in Figure 6. Most of the increase in spending this past decade has pertained to infrastructure development, including farmland water conservancy in poor areas, rural roads, and drinking water for people and livestock in rural areas. Because of the national strategy of poverty alleviation, expenditures on rural infrastructure increased dramatically, from CNY 36 billion in 2015 to CNY 145 billion in 2019. Expenditures on inclusive financial development also increased. More than half of that spending has gone for agricultural insurance subsidies. The agricultural structural adjustment subsidy has been deployed to support shifts from grain to non-grain crops; to restore farmland polluted by heavy metals; and to support shifts in the organization of production, including involving cooperatives and leading enterprises.

Figure 6: Public Expenditures on Agricultural General Public Services in China, 2010–19



Source: Final budget sheets of the MOF, various years

China has invested heavily in its agricultural research system. Based on 2010 constant prices, China's public agricultural R&D expenditures increased from CNY 2.73 billion in 2002 to CNY 21.43 billion in 2018, with an average annual growth rate of 12.9 percent, faster than national public expenditures. Specifically, in 2018 the R&D expenditures of agricultural research institutes and agricultural universities were CNY 15.9 billion and CNY 5.53 billion, respectively. The R&D expenditures of agricultural universities and research institutes reached annual growth rates of 14.1 percent and 12.5 percent from 2002 to 2018, respectively.

Expenditures to Limit Agriculture's Resource Footprint

China has an extended history of soil and land conservation projects, which usually rely on agroforestry management. Examples of these include the state-level shelter-forest systems that have been implemented in many regions in China since the 1970s, including northern ecological protection schemes, water source conservation of the Yangtze River, and the coastal-shelter forests for the middle and lower reaches of the Yangtze River. In the 1980s, the intercropping method of forest-rubber-tea was developed in Hainan Province and the south of Yunnan Province. The middle and lower reaches of the Yangtze River saw the development of co-cultivation systems for pine tree and tea, Chinese tallow tree and tea, and paulownia and tea in the hilly region. Later, a more complex co-cultivation system, such as forest-fish-agriculture, was developed in the wetlands of the Lixia River area in Jiangsu Province. In the 1990s, contour hedgerow technology was developed in mountainous and hilly areas of Southwest China. Across many regions of China, other intercropping methods were also developed, such as forest-ginseng in Northeast China, fruit-grain in Northern China, and forest-crude medicinal plants and forest-grass in various regions, resulting in an improved ecological environment and benefiting farmers' income.

Landscapes

Another set of successful programs was aimed at remediating the impact of earlier conversions of grasslands and forests to agriculture. Jaffee et al. (2022) discussed in greater detail the influential Grain for Green program, which was piloted in 1999 and extended nationally in 2002. It provided cash and in-kind subsidies to farmers to convert fragile agricultural land into forests or pastures and provided income for resource management. A related program, Green for Grain, was started in 2003 and provided grants to farmers for grassland conversion. By 2011, the program expanded to include subsidies for farmers to restore the ecological integrity of grasslands by introducing seasonal breaks in grazing. The Natural Forest Conservation Project was piloted in 1998 and launched in 2000 and aimed to protect and rehabilitate natural forests. As discussed in earlier sections, other important programs were designed to protect grasslands, croplands, and water resources through better land-resource management.

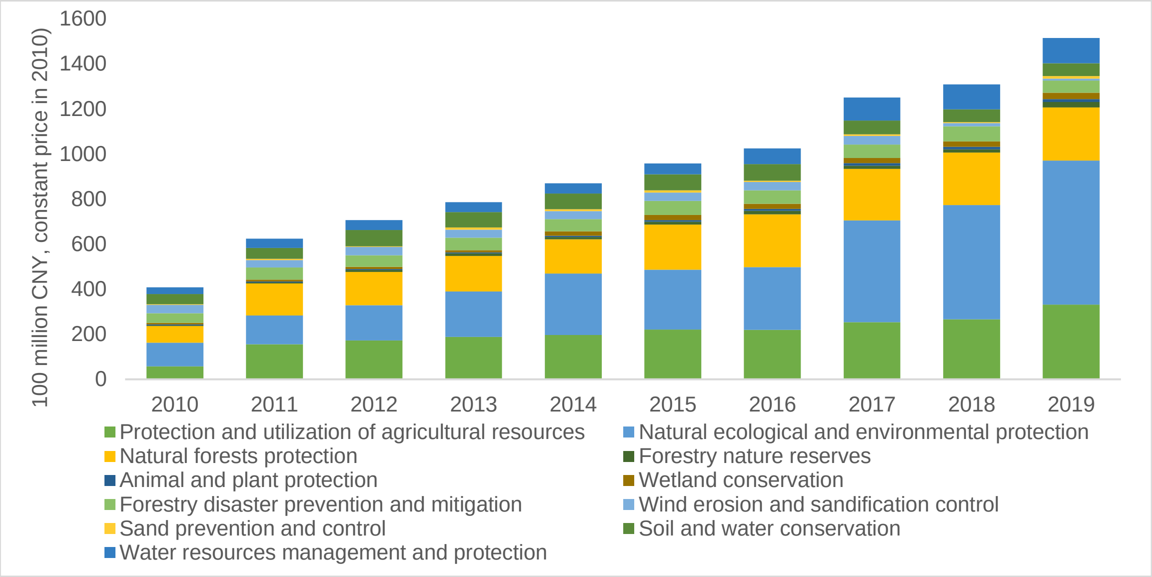
Although funding for the programs has slowly waned since 2015, annual expenditures, mostly in the form of direct subsidies or payments for environmental services, were substantial during the past decade, averaging between CYN 40 to CNY 50 billion between 2010 and 2018.

Environmental Services

Far more substantial than these direct subsidies have been expenditures supporting general public eco-environmental services. Consistent with the pivot in policy, spending for environmental services increased sharply from CNY 41.1 billion in 2010 to CNY 151.5 billion in 2019, an average annual growth rate of 15.6 percent. Except for expenditures on wind erosion and desertification control, subcategories of these expenditures displayed an increasing trend.

Most of the activity categories denoted in Figure 7 are self-explanatory, but there are a few exceptions. Public expenditures on natural ecological and environmental protection, including ecological protection, ecological restoration, rural environmental protection, and biosafety management, exhibited a significant growth from CNY 10.4 billion in 2010 to CNY 63.9 billion in 2019, with an average annual growth rate of 22.3 percent. As discussed, a key element of current agricultural policies is to limit pollution stemming from fertilizers, pesticides, plastics, manure, and straw burning. Rural environmental protection refers to targeted agricultural and rural environmental protection and pollution control activities, including comprehensive rural environmental management (that is, domestic waste treatment, sewage treatment, and rural drinking water source monitoring and protection);, environmental protection in small towns (that is, environmental protection capacity building and environmental infrastructure development, beautiful towns, and building of eco-villages); prevention of agricultural NPS pollution (that is, agrochemicals, manure and carcasses of livestock, and soil pollution); environmental monitoring and supervision of agricultural production areas; organic food production base construction and management, comprehensive use of agricultural wastes, and rural environmental protection capacity building.

Figure 7: Eco-Conservation Public Service Expenditures in China, 2010–19



Source: Final budget sheets of the MOF, various years

In many areas of broad landscape protection or restoration, it is difficult to identify national-level indicators of the impact and efficacy of some programs as these are likely to be strongly influenced by local conditions. Some impacts can be more readily illustrated at the provincial or localized level.

Achievements, Challenges, and Market Innovations

As discussed, China's current agricultural policies set out to both maintain production and productivity gains in the sector while protecting and remediating the natural resources that sustain agriculture. This section reviews some early achievements resulting from the policies, ongoing challenges, and market innovations that are integral to the ultimate success of current policies.

Achievements

Zero growth in the use of chemical fertilizer and pesticide. Nitrogen fertilizer use decreased from 23.8 metric tons in 2012 to 19.3 metric tons in 2019, a compound annual decrease of 2.31 percent and a cumulative decrease of 18.95 percent. The amount of potash fertilizer and phosphate fertilizer used dropped from 6.40 metric tons to 8.43 metric tons in 2015 to 5.61 metric tons and 6.82 metric tons, respectively, in 2019, with a compound annual decrease of 0.84 percent and 2.02 percent and a cumulative decrease of 7.3 percent and 16.8 percent, respectively. In 2019, pesticides use had returned to around its 2004 level after falling for six consecutive years.

Promoting the use of livestock and poultry manure resources. Pilots focused on large livestock, and poultry operations have been launched to construct manure treatment and resource use facilities. The pilots also explored using livestock and poultry manure resources as an alternative to chemical fertilizers. In 2020, the national comprehensive use rate of livestock and poultry manure surpassed 75 percent, and the supporting rate of manure treatment facilities for large-scale farms surpassed 95 percent (Wu 2021).

The comprehensive use of crop straw. The government has launched several pilot programs to experiment with technologies that recover straw during harvesting and systems to store and distribute straw resources to farms. Since 2015, the central government has allocated CNY 800 million each year to implement a soil organic matter improvement subsidy project to encourage and support farmers to return straw to the field. At the same time, 17 types of machines related to the comprehensive use of straw were added to the agricultural machinery purchase subsidy program. In 2017, the area of straw return reached 50 million ha, and the area of picked and bundled straw exceeded 670,000 ha, effectively improving soil quality, which positively affects farmland conservation. As of 2020, the comprehensive use rate of straw exceeded 85 percent (Wu 2021).

The recycling rate of waste agricultural film has increased significantly. In 2019, the use of agricultural film nationwide was about 2.41 metric tons, a decrease of 2.38 percent from the previous year. Furthermore, the coverage and use of plastic mulch films across China have achieved negative growth, the recycling rate of agricultural film has reached 80 percent, and "white pollution" in key areas has been greatly diminished.

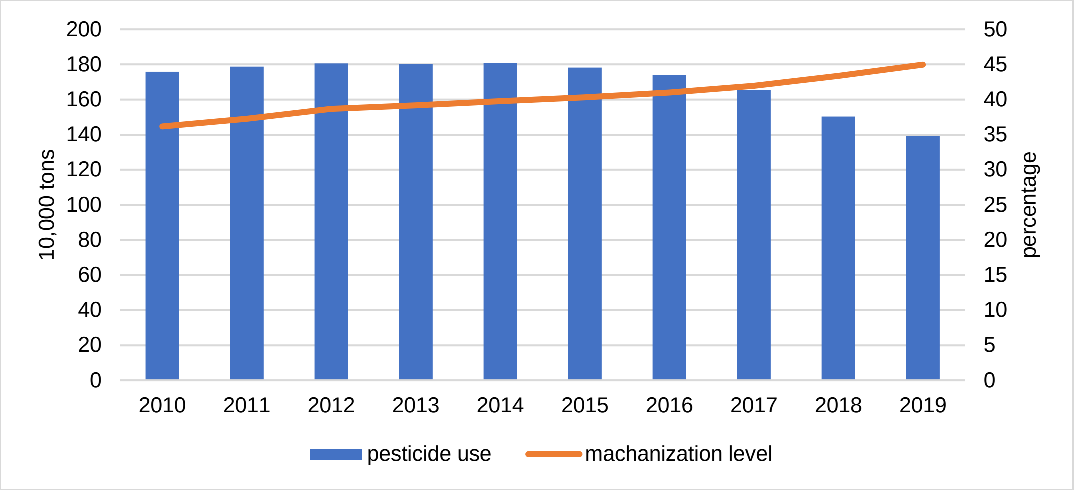
Expanding the backbone for digital agriculture. The "information into villages and households" project has been implemented in 18 provinces. There are more than 70,000 business sites. As of 2021, more than 30,000 drones have been used during the spring plowing period in China. More than 20,000 tractors are now equipped with the BeiDou navigation satellite system, and more than 20,000 machines are equipped with precision systems.

Mechanization. In the first three quarters of 2020, large-tractor production reached 47,500 units, already an increase over 2019. At the same time, the total power of agricultural machinery mainly used for various activities for agriculture, forestry, animal husbandry, and fishery reached 1.027 billion kilowatt-hours, an annualized increase of 2.3 percent. Moreover, the national comprehensive mechanization rate of crop cultivation and harvesting increased from 64 percent in 2015 to 70 percent in 2019.

New intelligent machines and systems have facilitated production technologies that lessen agriculture's natural resource footprint, including low-fragmentation maize grain harvesting, CA soil management, straw returning, cotton picking with residual film recovery, mechanized transplanting of rice and synchronous side-deep fertilization, and waste disposal for livestock and poultry.

In 2019, CA adoption areas reached 8.2 million ha, mechanized straw returning areas reached 54.3 million ha, and straw picking and baling areas reached 8.8 million ha. Figure 8 shows trends in mechanization and pesticide use from 2010 to 2019, depicting a decrease in pesticide use associated with increased mechanization.

Figure 8: Trends in Mechanization and Pesticide Use



Source: Yang and Jiang (2021). Note: Pesticide use is expressed in tons of product.

Challenges and Innovations

Economies of Scale

As discussed, for decades, agricultural policies have relied on resource-intensive technologies that are well-suited to small farms operated by labor-abundant households. Faced with severe resource constraints and a shrinking and aging agricultural labor force, current agricultural policies promote a switch to alternative technologies. The portfolio of technologies needed to address natural resource constraints is mixed and includes important innovations based on agronomy and innovations from animal and plant breeding research. However, many precision technologies that rely on smart machines, irrigation systems, and data platforms are best suited for larger farms. Consequently, achieving economies of scale is central to China's current policy goals.

Moreover, there is strong empirical evidence that increased farm scale addresses both problems. Using a nationally representative rural household survey from China, Wu et al. (2018) found that a 1-percent increase in farm size was associated with a 0.3-percent and a 0.5-percent decrease in per hectare fertilizer and pesticide use, respectively.

International experience shows that land consolidation occurs slowly in places where most farms are initially small; however, features of China's land and internal migration institutions have likely placed additional constraints on the pace of land consolidation. By law, households in China must register as rural *hukou* or urban hukou. Under the already mentioned Household Contract Responsibility System (HCRS), rural communities allocate land among village households (rural hukou). Households can work the allocated land, transfer the land to family members, transfer the use rights to others, or return the land to the village collective. Because urban incomes are higher than rural incomes, many younger members of rural households move from rural communities to take jobs in other sectors, often as temporary workers (Zou, Mishra, and Luo 2018). Even though surveys show that less than 9 percent of rural migrant workers showed a willingness to return to their rural communities to farm, rural workers who have not been formally reclassified under hukou are usually unwilling to relinquish their land-use rights since they do not receive urban hukou benefits (Meng 2012; Yang 2013).

The ongoing restructuring of rural labor markets has an additional impact on agricultural land. Research shows that local sectoral migration, in the form of full- and part-time off-farm work in rural areas, increases land abandonment. One recent study, based on national data, suggests that, on average, a 10-percent increase in off-farm income in a rural community leads to a 3–5 percent abandonment of land farmed by the community (Xu et al. 2019).

Market Innovations to Achieve Scale

Although the process of land consolidation is slow in China, other market innovations have allowed China's small farms to achieve it through market innovations, including the use of fee-based service providers for mechanization and farm management services and land trusts.

Machine hire services. International experience shows that owners of large farms have better access to capital than smallholders. For a fee, hire services allow smallholder farmers to access capital-intensive farm machinery without making large upfront investments. Often, hire services are set up by independent companies, but there is an increasing trend for farmers to collectively invest in hire-services cooperatives. The size of the mechanized service market is astonishingly large. In 2019, for example, about 41 million farming households used machines provided by more than 192,000 agricultural machinery service providers. The total income of agricultural mechanization hire services reached CNY 473 billion (Yang and Jiang 2021).

Advisory and technical services. Larger farms often benefit from more highly skilled management and are sometimes better informed about available technologies. Traditionally, public extension agents provide information to farmers individually or in small groups, a practice that may favor larger farms. Digital technologies can extend the capacity of agents and provide more timely information "on demand." For example, relying on county-level soil testing and a formula fertilization expert system, Mingguang City in Anhui Province, provides one-click fertilizer ordering through a mobile app, thus combining expert advice as an add-on service to fertilizer customers.

Small-scale farmers with less interest in learning new technologies and farmers with less capacity to apply new techniques can hire firms to provide advice and manage input applications. Although the public sector is still the primary provider of agricultural technology extension in China, the private sector and social organizations have made significant progress in the past decade. The services have played an important role in promoting soil testing and fertilizer application, green pest control, and other advanced production technologies, increasing the efficiency of reduced levels of chemical inputs. By the end of 2020, national specialized service organizations reached 93,000 farms, and coverage of the three major grain crops reached 41.9 percent, 8.9 percentage points higher than in 2015.

Aggregated land management structures. A more comprehensive solution is to transfer operational rights to an aggregating entity. Wang and Zhang (2017) provide examples for four types of transfers currently used to consolidate land holdings in China: (1) from farmers to a collective; (2) from farmers to a collective and then to leasehold farms; (3) from farmers to leasehold farms; and (4) from farmer to farmer. In all cases, the goal of the transfer is to achieve a greater operational scale. In the simplest case, farmers trade operational rights for scattered plots to build a farm of contiguous plots. In this case, the farm size does not change, but farms are compact and better suited for mechanization. In the other cases, land operations are transferred to potentially larger farms, either managed by the village collective or by a leaseholder. In the latter case, the use-right transfers, but not the land itself, can be managed either by the collective (case 1) or through a separate structure, such as a land trust (case 3). This approach results in larger, more compact farms better suited for mechanization and marketing. In all cases, contracted services can be hired to achieve additional scale economies.

Market Innovations to Manage Resources

Water. As more fully described in Bo (2021), the government of China clarified use rights with allocations for agriculture, municipalities, conservation, and other uses. In addition, as described earlier, capital investments have been made to better transport, monitor, and manage water for irrigation. In a growing number of WUAs, water is managed by allocating quotas. Traditionally, water has been freely provided, although water resource fees are sometimes assessed to cover the costs of maintaining wells and irrigation systems. However, while the notion that the water itself has an underlying resource value (as a production input with alternative uses) is largely acknowledged, water pricing mechanisms are at an exploratory stage and limited to pilots.

Water taxes. One experimental approach is to apply a tax on water used in excess of a prescribed quota. The approach was first piloted in Hebei Province in 2016 and was extended to nine additional jurisdictions in 2017: Beijing, Tianjin, Shanxi, Inner Mongolia, Shandong, Henan, Sichuan, Shaanxi, and Ningxia. The terms of the pilot are described in the Interim Measures for the Pilot Reform of Water Resource Tax, jointly issued by the MOF, the State Administration of Taxation (SAT), and the MWR in 2016, and the Implementation Measures for Expanding the Pilot Program of Water Resources Tax Reform issued in 2017.

Lessons learned from the pilots suggest that pricing water generates water conservation. For example, in the Hebei pilot, a local steel company invested in its own water treatment facility, saving 14.6 million m^3 of water annually. In many places in the pilot regions, groundwater had been severely overexploited, which led authorities to set groundwater's average water tax rate at 4.6 times the rate for surface water. In response, the structure of water use by enterprises has begun to change. Some enterprises have decreased groundwater use, transferred to surface water, and actively switched to unconventional water sources (rainwater, reclaimed water, seawater, atmospheric water, mine water, brackish water, etc.). In the first half of 2018, the amount of groundwater extracted in the overexploited areas of the nine pilot provinces decreased by 9.28 percent on a year-by-year basis (Bo 2021).

Trading water rights. China is also experimenting with trading water rights, which would help with price discovery. Bo (2021) provides three examples: regional water rights trading, water extraction permit trading, and irrigation water users' water rights trading.

Regional water rights trading occurs between administrative regions within the same river basin or between basins when the trading partners are local governments. This can become complex in larger river basins that include multiple provinces. The most recent example in Hetao Irrigation District, Ningxia, involves a 25-year lease of 120 million m^3 of water rights to 40 industrial enterprises in Ordos City and Alxa League at a price of CNY 15 per m^3 for 25 years (Bo 2021).

The procedures for the remaining two types of water trading are well established, but lessons from ongoing pilots are yet to be gathered. In the case of water extraction permit trading, entities with the right to draw water (including industry, agriculture, and water users other than urban public water supply enterprises) that have saved water through product or industry structural adjustment, process innovation, or water-saving techniques, may trade extraction rights with other qualified units or individuals, provided the selling parties have not exceeded their extraction quota, and the right has not expired (Bo 2021). Irrigation water users' water rights trading covers water rights traded among users within WUAs or between WUAs within an irrigation system.

Straw and Plastic Film Innovations

Transforming straw from a source of pollution to a natural resource requires the creation of value chains that collect, store, and transfer straw. Pilots suggest that the process entails innovative applications of agronomy, advances in farm machinery, and establishing distribution networks.

Ongoing farm pilots described more fully in Wu (2021) explore several combinations of agronomy and machine technologies, including deep plowing of maize stalks in the Northeast alpine region, deep plowing of cotton stalks in the arid areas of the Northwest, maize stalks covered by rotary tillage in Huang-Huai-Hai area, low-tillage and no-tillage straw mulch return model in the Loess Plateau, rice and wheat straw smashing and rotary tillage return model in the Yangtze River Basin, rapid decay of straw return model in South China, straw-feed-fertilizer combined planting and breeding model, straw-methane-fertilizer energy ecological model, straw-bacteria-fertilizer substrate use model, and straw-charcoal-fertilizer return to soil model. Mechanization innovations include improvements in crop-combine equipment to crush straw, return it to the field, and pick up and bundle it. Other innovations involve the design of specialized machines to facilitate straw storage and transportation and machines integrated into straw field treatment systems (Wu 2021).

Straw management and plastic film management are closely related; mulch from collected straw can serve as an alternative to plastic film, and straw and used film are often collected from the same or neighboring fields. Consequently, some pilots are underway to work with both materials. In general, however, the pilots operate independently. Agricultural film pilots are especially focused on dry farming areas, such as Gansu, Ningxia, and Xinjiang, where experimentation with thick film, mechanized picking, and specialized recycling are taking place and starting to show promise. As of the end of 2017, the number of residual film recycling machines in Gansu surpassed 10,000, and the mechanized recycling area reached 1.47 million ha, accounting for nearly 80 percent of the total film-covered area. The number of residual film recycling machines in Xinjiang was nearly 20,000, and the mechanized recycling area was approximately 1.4 million ha, accounting for 60 percent of the total covered area. Ningxia has more than 1,300 residual film recycling machines, following the technical model of "mechanized film mulching planting-company acquisition of residual film-mechanized residual film recovery operation-granulation production and sales," which is based on the government promotion plus enterprise drive, plus farmer participation, plus market operation mode. By 2017, 217 residual film recycling stations and 29 residual film granulation processing enterprises had been established in central and southern Ningxia, recovering 15,200 tons of residual film, bringing the residual film recycling rate to 90 percent (Wu 2021).

The Challenge of Adjusting Knowledge Institutions and Skills to Support New Technologies

To summarize from earlier sections, the technologies that have fueled China's decades-long trajectory of productivity growth in agriculture have been based on the successful development and applications of agricultural sciences, especially agronomy and plant and animal breeding. Moreover, the technologies were developed with smallholders in mind. The new set of technologies needed to remediate and conserve China's natural resources and to adjust to a shifting labor force are more multidisciplinary, and additional skill sets are required for farmers and for the research and extension services that support them.

Research and Extension

The expanded multidisciplinary nature of the new green technologies has implications for how the goals of China’s formidable research and extension network are managed. Currently, the development of green agricultural technologies is promoted by MOST and MARA. However, the technologies touch on air, water, and land resources, and the goals and regulations motivating the shift in technologies involve other ministries, chiefly the MNR, MEE, and MWR. Coordination among key ministries can also help guide the next round of green technologies. Technologies that use data currently siloed in separate agencies and about natural resources managed in separate ministries are perhaps the best illustrations of how coordination among the ministries is needed.

Funding for research still follows classifications associated with traditional agricultural technologies, and support for agricultural green technology research mainly relies on established funding systems, such as the modern agricultural industrial technology system and the NKP, even though many agricultural green technologies draw on interdisciplinary fields. However, to a degree, the limits of this legacy structure may be offset by private sector research into green agricultural technologies since private agricultural research, in general, is growing rapidly (Chai et al. 2019). Still, the extent of private green technology funding remains unclear. Moreover, the government has begun to develop targeted programs. CAU established the National Academy of Agricultural Green Development and the College of Agricultural Green Development in 2018 and four cross-research and training platforms to carry out high-end skill education and scientific research. CAU also developed a new mode of technology transfer for empowering smallholder farmers—Science and Technology Backyard (STB)—in 2009.

Nevertheless, China’s extension services were built over time to deliver information and training based on earlier technologies. And like the research institutions, they currently lack the interdisciplinary skills needed to fully promote the new set of technologies. In addition, the large network of researchers and extension services is decentralized, so a repurposing of existing institutions will require action by a broad coalition of agency administrators and public funders.

Farmers and Service Providers

As discussed, China’s population is aging, and its rural population is aging faster. Liao et al. (2019) report survey data from 2015, showing that 18.5 percent of the rural population was over 60 years old, compared to the national average of 16.2 percent. Between 1982 and 2015, as labor shifted from agriculture to other sectors, the rural population over 60 years old increased by 237 percent, compared to 192 percent in the city. Between 1990 and 2010, the average age of agricultural labor increased by 8.2 years (Liao et al. 2019). According to a 2017 survey, the average age of China's agricultural labor force is 46 years old, among whom 67.5 percent are between 40 and 60 years old, while only 4.8 percent were born in the 1980s (Yang and Jiang 2021).

The shrinking labor force affects farmers working in the field and crucially impacts the technical, business, and service industries. For example, the average age of members of agricultural mechanization cooperatives in China is still over 46 years old, and many chairpersons are more than 50 years old. Talent shortages are especially acute in the central and western regions, remote mountainous areas, and impoverished areas (Yang and Jiang 2021).

With mechanization, the needed number of next-generation Chinese farmers and service providers will decline; however, the smaller group that remains in rural areas will need a different and more diverse set of skills. As discussed, part of the solution will come from changes in the curricula of current college and university programs; and in the content of services delivered by private and public extension and service providers. In addition, cooperatives and hire services are actively recruiting young, college-educated staff.

Yang and Jiang (2021) highlight efforts by the China Association of Agricultural Mechanization to recruit well-trained staff, especially college-educated women, a group that has been underrepresented in the past.

The Challenge of Fully Aligning Agricultural Policies with Related National Priorities

To date, policies and pilots aimed at remediating agriculture's impacts on the environment have focused on making more efficient use of water resources and adopting field technologies that reduce agricultural pollution. Still, as Cassou et al. (2022) emphasized, additional and complementary pathways can help China achieve its domestic environmental objectives and provide leadership in addressing global environmental concerns. In the case of water-use policy, China has already reformed domestic institutions to align agricultural policies with multisectoral objectives, and similar progress has been made with respect to air, water, and land pollution objectives. Similar opportunities are available if agricultural policies are more closely aligned with nutritional objectives and if national environmental objectives are incorporated into agricultural trade policies.

Nutrition Policy

Decades of economic growth and a steep decline in poverty have transformed nutritional policy goals in China. Early efforts focused on addressing food insecurity proved successful. For example, recent national surveys show that the prevalence of underweight and stunting among young children fell from 78 percent and 80 percent in 1990 to 4 percent and 10 percent in 2020; mortality rates for children under 5 years old fell by 73 percent during the same period. Still, as is the case in many countries, income growth has triggered an unhealthy shift in diets and, with it, a rise in malnutrition and chronic diseases. For example, the prevalence of hypertension, diabetes, and elevated cholesterol stands at 25 percent, 10 percent, and 40 percent, respectively, and has been rising for years (Gao et al. 2021).

The shift in nutritional challenges, from undernourishment to malnourishment, is reflected in nutrition policy. The goals laid out in the China Nutrition Improvement Action Plan (1997–2000) emphasized ensuring adequate food supply to reduce the prevalence of hunger, undernourishment, protein insufficiencies, and micronutrient deficiencies. Since then, increasing emphasis has been placed on promoting healthy diets. A key element has been the issuance of dietary guidelines. First issued in 1989, the guidelines were revised in 1997, 2007, and 2016. Importantly, the most recent guidelines recommend limiting the daily consumption of meat to 75 grams (Gao et al. 2021; Sheng et al. 2021).

Overall, animal-source foods contribute disproportionately to diet-related health risks, and studies show that diets limiting meat consumption can improve health outcomes in China. For example, using data from the China Health and Nutrition Survey, Zhen et al. (2018) show that a traditional Chinese diet of rice, vegetables, with small portions of poultry, pork, and fish reduces obesity among children and teenagers, compared to an emerging urban diet with high intake of highly processed wheat and meat. Sheng et al. (2021) estimate that 1.15 million deaths could be avoided by 2030 if the population adhered to the Chinese Dietary Guidelines.

Programs that successfully convince consumers to adopt diets that are healthier and lower in animal-source food could pay an environmental dividend as well. For example, studies show that converting from current diets to a plant-based diet could cut the carbon footprint of China's food system significantly, possibly in half, on a per capita basis, by 2050 (WWF 2020, Springmann et al. 2020, Kim et al. 2020). Tilting diets away from meat and dairy would also buy time to put in place lessons from pilots on how to manage animal waste, a major source of water pollution.

Agricultural Trade Policy

China's agricultural trade with the rest of the world has grown rapidly over the past decades, and China is increasingly driving land-use change and environmental outcomes in many exporting countries. For example, Chinese demand for dairy products has impacted land use in New Zealand (Bai et al. 2018 in Mosnier et al. 2019), and Chinese timber imports are a major driver of deforestation in Southeast Asia (Mosnier et al. 2019). China's beef and feed imports are also linked to land-use change in the Brazilian Amazon and Cerrado. In 2020, Brazil supplied 43 percent of China's meat imports, according to the consultancy SAFRAS and Mercado (Phillips and Standaert 2021). Of those, roughly 70 percent came from the Cerrado and 20 percent from the Amazon, one-half and one-fifth, respectively, of which have been cleared (primarily for agriculture) (Phillips and Standaert 2021). China's imports have, in fact, been recognized as a threat to needed global GHG mitigation efforts. However, environmental protection considerations have not significantly influenced trade patterns to date.

Going forward, adapting China's trade policy to recognize environmental impacts could be game-changing at a global level. Highlighting the environmental significance of countries of origin, one study found that a 50 percent reduction in animal products targeting the highest-impact producers would achieve a 20 percent reduction in global GHGs (Poore and Nemecek 2018). Recognizing the breadth of global food system impacts and global food trade, the EU recently made commitments to apply more stringent environmental standards—relating especially to deforestation—to food crossing its borders. In parallel, shifting the domestic geography of food production has been proposed as one of the strategies that could help bring food production within environmental boundaries at the national and provincial levels in China.

In parallel, China may be able to work with authorities and private sector actors in supplier countries to help raise their environmental performance, for example, by building upon the provision regarding the legality of timber in the latest revision of the Forest Law and gradually expanding the provision to cover other commodities. China could also, for example, help incentivize and support improvements in production practices by becoming involved in sustainable supply chain initiatives (such as commodity "roundtables") and jurisdiction-level approaches to mitigating agriculture-driven forest loss and degradation. And in countries where Chinese companies have invested in farming and agro-processing ventures, it could initiate public-private partnerships and technical assistance programs. Through such initiatives, China could help establish environmental standards and timetables for compliance with them while also bringing Chinese experience in sustainable agricultural practices to bear.

Adaptation and Carbon Markets

China warmed by 1.2°C between1960 and 2010, with stronger warming occurring in the North (Piao et al. 2010). From 1951 to 2020, temperatures rose an average of 0.26°C per decade, a warming rate that exceeded the average global rate. Further, 9 out of 10 hottest years since 1900 occurred after 2000 (CMA 2021). The average temperature of 10.7°C in 2021 was the highest on record since 1961 and around 1°C higher than usual, based on calculations by the China Meteorological Administration (CMA 2021). Modeling suggests that warming will continue, with average temperatures increasing between 1 and 5 degrees by 2100. Summer warming is expected to speed up evapotranspiration, placing additional stress on water resources. Glaciers are losing mass and will continue to do so, a process that has boosted available freshwater resources in the short run but threatens future supplies. Since 1960, rainfall has declined in the drier regions of northeastern China and has increased in the wetter regions to the south (Piao et al. 2010).

There is evidence that warming temperatures have already constrained agricultural productivity in China, although to date, the impacts of climate change on agriculture have been mixed and dwarfed by productivity gains from improved production technologies (Piao et al. 2010; Chen and Gong 2021). Warming temperatures appear to have boosted rice yields in the northeast and allowed an expansion of rice production to the north while warming temperatures slowed yield gains in wheat and maize in some regions (Piao et al. 2006; You et al. 2009; Tao et al. 2008; Wang et al. 2008). In recent years, the geographic range of pests has expanded, losses to drought and flooding have steadily grown, and extended heatwaves have punished crops and workers (Piao et al. 2010).

Looking forward, the anticipated impacts of climate change on China's agriculture are associated with high levels of uncertainty. Under optimistic scenarios, gains from climate change will offset losses at the national level, supported in part by uncertain carbon-fertilization effects. Under more pessimistic scenarios, declining glacial runoff, declining rainfall to the north, and more frequent extreme weather events threaten China's food systems. Regardless of average outcomes, most modelers expect that the future effects of climate change will be spatially diverse and disruptive.

Until recently, agricultural policy and climate change adaptation policies remained largely independent. Early relevant policy was driven by responses to increasingly frequent natural disasters. For example, China began offering subsidized crop insurance in 2007. The insurance covers all major crops in China; by 2012, 42 percent of the sown area was insured. In 2010, the Ordinance on Relief of Natural Disasters established strategic reserves, including grain reserves (Chen, Yin, and Jian 2021).

In 2013, existing policies were consolidated into a unified approach to climate change adaptation when the NDRC, the MOF, MARA, and eight other ministries jointly issued the National Climate Change Adaptation Strategy. The document directly addressed agricultural adaptation to climate change and emphasized the need to strengthen agricultural monitoring and early warning systems and enhance the resilience of agriculture to climate change threats. Adaptation was emphasized most recently in China's Nationally Determined Contribution, a climate action plan submitted to the United Nations Framework Convention on Climate Change (UNFCCC) in October 2021, and the National Strategy on Climate Change Adaptation 2035, issued in June 2022 by MEE, MOST, NDRC, and other ministries.

China is currently rolling out pilot-tested technologies that are more resource efficient, less polluting, and more productive. Finding technologies that are also climate change-resilient complicates that task, especially since the local impacts of climate change are hard to foresee. Still, because China is large with diverse climates, production technologies designed to work well under current climatic conditions in some places may be transferable to other places as local climates change. Further, steps taken now to improve water-use efficiency and protect underground aquifers, as well as research into cultivars that are heat- and drought-resistant, will build future resilience.

Viewing previously disparate projects through the lens of climate change adaptation points to complementary links between agricultural policy and environmental policy. For example, though originally motivated by different concerns, programs designed to address immediate threats to natural resources through land-use changes can also build resilience against future climate change threats, and their expansion can be key elements of China's adaptation strategy. Important examples include the landscape projects already discussed. Another example is the Three-North Shelterbelt Program (TNSP), begun in 1978 to slow desertification by reclaiming land through afforestation and now covers 13 provinces. The TNSP region includes 1.6 10^6 km^2 of arid and semi-arid land in 13 provinces. By 2015, afforested lands sequestered 684.02 gigatons of carbon (Wang et al. 2010; Chu et al. 2019).

These projects fit into a broader class of nature-based solutions (NbS) to climate change that generate mitigation benefits through carbon sequestration and adaptation benefits, such as protections for soil fertility and water catchments. Wang et al. (2014) note that the mitigation potential of NbS projects in China is large, upwards of 768 $MtCO_2e$ per year by 2030 (Table 1). Significant sources include nutrient management, forest management, afforestation, and grazing land management, all of which are also important for restoring agriculture's natural resource foundation.

Table 1: Estimates of annual sequestration potential from different NbS

	Mitigation potential ($MtCO_2e$/year)	
Year	**2030**	**2060**
Nutrient management	137	198
Forest management	380	228
Afforestation	99	49
Grazing land management	152	152
Total	768	627

Source: Wang et al. (2014); World Bank (2022)

A recent World Bank study (2022) notes that carbon financing could provide supplemental funding to speed the expansion of NbS projects, which would help China reach its GHG emission goals and bolster climate-change resilience in key ecosystems. China already operates the world's largest emission trading system, which could be modified to permit the sale of carbon sequestered through NbS-based projects. This is not without challenges, as NbS mitigation projects face measurement challenges and the potential for reversibility. Still, UNFCCC-certified methods to account for and monitor agricultural and land-use mitigation impacts can be found among the many projects financed under the Kyoto Protocol's Clean Development Mechanism (Larson, Dinar, and Frisbie 2011).

Summary and Conclusion

The government of China has launched a new set of agricultural policies designed to remediate and better manage the natural resources that sustain the sector while also promoting growth through continued productivity gains. Much of the damage done by agriculture to China's natural resources stems from well-understood actions: past conversion of forests and grasslands to cropland, the inefficiency of irrigation systems, the use of polluting inputs, the mismanagement of livestock and poultry manure, and the open field burning of crop straw, and the new policies include specific measures to address these sources of degradation.

The policies have already proven successful in significant ways. China has expanded programs that reconvert cropland in ecologically vulnerable areas to grassland and forests. Chemical fertilizer and pesticide use are declining, and irrigation systems are gaining efficiency. The practice of burning crop straw, a major source of air pollution, is in decline. Early pilots to recover and recycle plastic film in agricultural fields are showing promise. Backbone systems needed to deliver information to farmers and farm equipment have been extended to include most rural areas.

Markets that help deliver on environmental goals are emerging. Progress has been made to clarify users' water rights and establish institutions to price water and trade water rights. In pilots, a better set of technologies for delivering, monitoring, and managing water use, in combination with water pricing incentives, like taxes for above-quota water use, have improved water-use efficiencies. Moreover, trading platforms are being established to reallocate water consumption among competing sectors more efficiently. For-hire services are expanding to provide small farms with better access to green technology machinery and advice.

Still, the twin goals of productivity growth and resource remediation create latent inconsistencies for legacy policy instruments that proved effective in the past but are at odds with the new overarching environmental objectives. Further, the rollout of greener policies and technologies is taking place on shifting grounds, driven by forces already in play. Crucial trends that complicate China's current green agricultural policies and initiatives include: (1) a declining rural population with aging farmers working small farms; (2) a growing and more prosperous population with an increasing preference for animal protein; and (3) the accelerating impacts of climate change. Taken together, the expansion of goals and underlying trends complicate policymaking and require an evolution in implementation instruments and institutions to assure support for both goals. These circumstances also call for aligning agricultural policies with those of other sectors.

The way forward is clearest for matching the rollout of green technologies with shifting rural demographics, a challenge stemming from the first of the three trends. Through emerging mechanisms, such as land trusts or land collectives, compact areas suitable for mechanization and unified management can be aggregated from smallholder plots without weakening the rights of individual farmers or displacing households. In turn, these arrangements complement a growing set of businesses offering hire services for smart machines and advisory services. Taken together, the innovations can speed the adoption of greener technologies best suited for larger farms years before demographics eventually drive land consolidation and a looming shortage of rural labor drives mechanization. That said, the new land institutions and hire services introduce a potential shift in the autonomy and bargaining power of millions of rural farming households, which points to the need to temper the transition with equity protections.

The second trend is far from new. Population growth and growing incomes are decades-long trends that will continue to exert pressure on China's natural resources by boosting the demand for food, especially meat and dairy. This creates the risk that, as the rollout of cleaner technologies takes place, gains in resource efficiency will be swamped by growth in production. This is especially true in the case of efforts to better manage livestock waste.

In the face of this trend, two pathways are available to gain time for cleaner technologies to displace polluting ones. The first falls within the range of traditional agricultural policy and entails replacing legacy incentives that encourage fertilizer use and promote livestock production with incentives to adopt greener technologies. The second path entails moving beyond traditional agricultural policy to integrate the goals of health and nutrition policies, which promote healthy diets that are less meat-intensive than current western diets. Paradoxically, the same wealth trends that increase meat demand can support this alignment since wealthier and better-educated consumers also tend to pay closer attention to the health impacts of the food they consume (Gossard and York 2003; Zhou et al. 2017; Cai, Xie, and Aguilar 2017; Katare et al. 2020).

Among the three trends, climate change presents the greatest challenge to current agricultural policy goals, in large part because its local impacts are hard to predict. This complicates green technology adoption since any technology switch designed to lessen the impacts of agriculture on local resources must take place against an evolving set of local climatic conditions that will shift cropping patterns and alter local resource availability. Implicitly, this means that the technologies chosen to meet stated productivity and environmental goals, and the fixed investments that accompany them, should be robust under evolving climatic conditions. In turn, this creates another area of potential conflict among legacy policy instruments, an expanded set of policy objectives, and opportunities for aligning agricultural policy with climate change policy.

Examples of legacy policy instruments ill-suited to current policy goals are the subsidies given for agricultural insurance and the use of grain reserves. Originally envisioned as ways to support the sector and consumers in the face of periodic natural disasters, the programs create incentives to farm marginal lands, a practice that can undermine the resilience of the sector to climate change (Quiggin and Anderson 1979; Hazell 1992; Skees et al. 2002; Larson, Anderson, and Varangis 2004; McLeman and Smit 2006; Wu, Goodwin, and Coble 2020). Recent evidence from China also shows how the insurance program undermines on-farm efforts to manage pests, a problem expected to worsen as the climate warms (Feng, Han, and Qiu 2021).

Alternatively, linking agricultural policies more closely to climate change programs can generate co-benefits since better managing forests and grazing lands and recycling plant and animal waste can boost agricultural productivity, sequester carbon, reduce GHG emissions, and enhance ecosystem resilience. Taking an additional step by incorporating nature-based solutions from agriculture into China's large carbon markets could leverage private capital in support of public sector goals.

The expanded set of agricultural policy goals, which incorporate aspects of land, water, and air resource management; and climate change mitigation and adaptation strategies, drive a need to update key agricultural institutions. For decades, agricultural policies focused on the production and productivity gains, and the important field technologies promoted to support those goals were rooted in the agricultural sciences, a past policy that is embodied in the training of current agricultural researchers, in available extension services, and in the knowledge base of China's farmers. Looking ahead, emerging green technologies are based on a more diverse set of sciences. Their successful development, promotion, and adoption will crucially depend on the rapid expansion of the skillset of China's large and decentralized research and extension network. A limited range of reforms are underway in the public sector, and a growth in private researchers and service providers will help. Still, time is key, given the expanding pressures on China's agricultural sector and natural resource base.

These same forces challenge agricultural policymakers, who must find a practical way to oversee policy design and implementation that is comprehensive enough to be effective and streamlined enough to be well managed. For decades, most decisions related to agricultural policy implementation and the direction and dissemination of research could be adequately managed by the MARA and MOST. Going forward, coordination among various ministries will be needed, especially MNR, MEE, and MWR. Already, water policy implementation decisions are coordinated across ministries and agencies, and this may provide a model for an expanded set of decisions related to the agricultural sector.

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