CHAPTER 3

Managing Land and Water to Feed Nine Billion People and Protect Natural Systems

Climate change is already affecting the natural and managed systems—forests, wetlands, coral reefs, agriculture, fisheries—that societies depend on to provide food, fuel, and fiber, and for many other services. It will depress agricultural yields in many regions, making it harder to meet the world's growing food needs. It comes as the world faces intensified competition for land, water, biodiversity, fish, and other natural resources. At the same time, societies will be under pressure to reduce the 30 percent of greenhouse gas emissions that come from agriculture, deforestation, land-use change, and forest degradation.

To meet the competing demands and reduce vulnerability to climate change, societies will need to balance producing more from their natural resources with protecting these resources. That means managing water, land, forests, fisheries, and biodiversity more efficiently to obtain the services and products societies need without further damaging these resources through overuse, pollution, or encroachment.

Water will have to be used more efficiently. To do that, managers need to think on basin-wide scales and to devise efficient and flexible ways to allocate water among competing quantity and quality demands for human use (such as energy, agriculture, fisheries, and urban consumption) and for healthy ecosystems (such as forests, wetlands, and oceans).

Countries also need to get more from their agriculture. The rate of increase in yields for key agricultural commodities has been declining since the 1960s. Countries will have to reverse that trend if the world is to meet its food needs in the face of climate change. Models vary, but all show the need for a marked increase in productivity.[1] That increase in productivity cannot come at the expense of soil, water, or biodiversity as it has so often in the past. So countries will need to accelerate research, enhance extension services, and improve market infrastructure to get crops to market. But they also need to give farmers incentives to reduce carbon emissions from soil and deforestation. And they need to help farmers hedge against an uncertain climate by diversifying income sources and genetic traits of crops, and better integrate biodiversity into the agricultural landscape.

Key messages

Climate change will make it harder to produce enough food for the world's growing population, and will alter the timing, availability, and quality of water resources. To avoid encroaching into already-stressed ecosystems, societies will have to almost double the existing rate of agricultural productivity growth while minimizing the associated environmental damage. This requires dedicated efforts to deploy known but neglected practices, identify crop varieties able to withstand climate shocks, diversify rural livelihoods, improve management of forests, and invest in information systems. Countries will need to cooperate to manage shared water resources and fisheries and to improve food trade. Getting basic policies right matters, but new technologies and practices are also emerging. Financial incentives will help. Some countries are redirecting their agricultural subsidies to support environmental actions, and future credits for carbon stored in trees and soils could benefit emission reductions and conservation goals.

Applying climate-smart practices will hinge on managing biodiversity better—integrating natural habitats into rural landscapes, protecting wetlands, and maintaining the water storage provided by aquifers. Increasingly, countries are making use of techniques that improve soil and water productivity. But these innovations will bear fruit only if decisions are based on solid intersectoral analysis and only if users have the right incentives—stemming from policies, institutions, and market conditions.

Many natural resources cross borders. As climate change makes resources harder to manage, and growing populations increase demand, countries will need to cooperate more intensively to manage international waters, forests, and fisheries. All countries will turn more frequently to the international agricultural market and so will benefit from a number of measures—from stock management to more competitive procurement techniques to customs and port logistics—that make food trade more reliable and efficient.

Climate change also puts a premium on information about natural resources. Information—traditional and new, international and local—will have a high payoff under a more variable and more uncertain climate, where the stakes are higher and making decisions is more complicated. Information supports resource management, food production, and better trade. If societies generate information they can trust about their resources and can get it to the people who can use it, from international river basin authorities to farmers in their fields, those people can make more informed choices.

Many of these solutions, long advocated in the natural resource literature, have been frustratingly slow in coming to fruition. But three new factors, all related to climate change, could provide new incentives. First, food prices are expected to increase as a result of more climate shocks as well as from growing demand. Increasing food prices should spur innovation to increase productivity. Second, it may be possible to extend carbon markets to pay farmers to store carbon in soil. This step would create incentives to conserve forests and adopt more sustainable farming techniques. The techniques are not yet proven at the needed scale, but the potential is great, and the additional benefits for agricultural productivity and poverty reduction are substantial. At a high enough carbon price, global emission reductions from agriculture could equal reductions from the energy sector (see overview, box 8).[2] Third, countries could change the way they support agriculture. Rich countries provide $258 billion annually in agriculture support,[3] more than half of which depends only on the amount of crop produced or input used. Though politically difficult, countries are beginning to change the terms of these subsidies to encourage implementation of climate-smart practices on a large scale.

This chapter first discusses what can be done at the national level to increase productivity of agriculture and fisheries while more effectively protecting natural resources. It next discusses what can be done to support national efforts, focusing on international cooperation and the essential role of information both at the global and the local level. Then it focuses on how incentives might change to accelerate implementation of beneficial practices and to help societies balance the need for increased production with better protection of natural resources.

Put in place the fundamentals for natural resource management

An extensive literature recommends strengthening the policy and institutional conditions that influence how people manage agriculture, aquaculture, and healthy ecosystems. Several measures can increase productivity in all sectors, while protecting long-term ecological health. None of these approaches functions alone. All require the support of the others to work effectively, and any change in one can alter the whole system.

Several themes recur across sectors, climates, and income groups.

- *Innovative decision-making tools* allow users to determine the impacts of different actions on natural resources.

- *Research and development* that produce new technologies and adapt them to local conditions can improve resource management, as can *advisory services* that help users learn about the options available to them.
- *Property rights* give users incentives to protect or invest in their resources.
- *Pricing resources* in a way that reflects their full value gives incentives to use them efficiently.
- *Well-regulated markets* are important for many agricultural and natural resource functions; infrastructure is also critical so that producers can access those markets effectively.
- *Strong institutions* are important for setting and enforcing rules.
- *Information*, at all levels, permits users and managers to make better choices.

These fundamentals apply to water, agriculture, and fisheries, as discussed in this chapter.

To understand how these drivers affect the incentives of a particular community, consider farmers on the plains of the Oum Er Rbia river basin in Morocco. Engineers have designed a feasible drip irrigation system that would allow these farmers to generate higher revenue from the water they receive (by increasing yields or switching to higher-value crops). Economists have figured out that it will be profitable. Hydrologists have calculated how much water they can safely allocate to these farmers without neglecting environmental needs. Sociologists have talked to the farmers and found that 80 percent of them want to invest in this technology. Marketing specialists have talked to agroprocessors who want to buy the new crops. And the government is willing to pay for a large share. But even here, getting things moving is fiendishly difficult.

It is not worth investing in new, improved pipes between the dam and the field unless most farmers will install the drip irrigation on their fields. Yet the farmers will not put down a deposit on the drip systems until they are convinced that the new pipes will really be laid and the water will really flow. They also need information about how to use the new systems. The irrigation agency, used to providing advice to farmers, is moving toward contracting advisory services out to private firms. It will have to find, contract, and supervise these firms—tasks that require a very different set of skills. And the farmers will need to trust these new advisors as well.

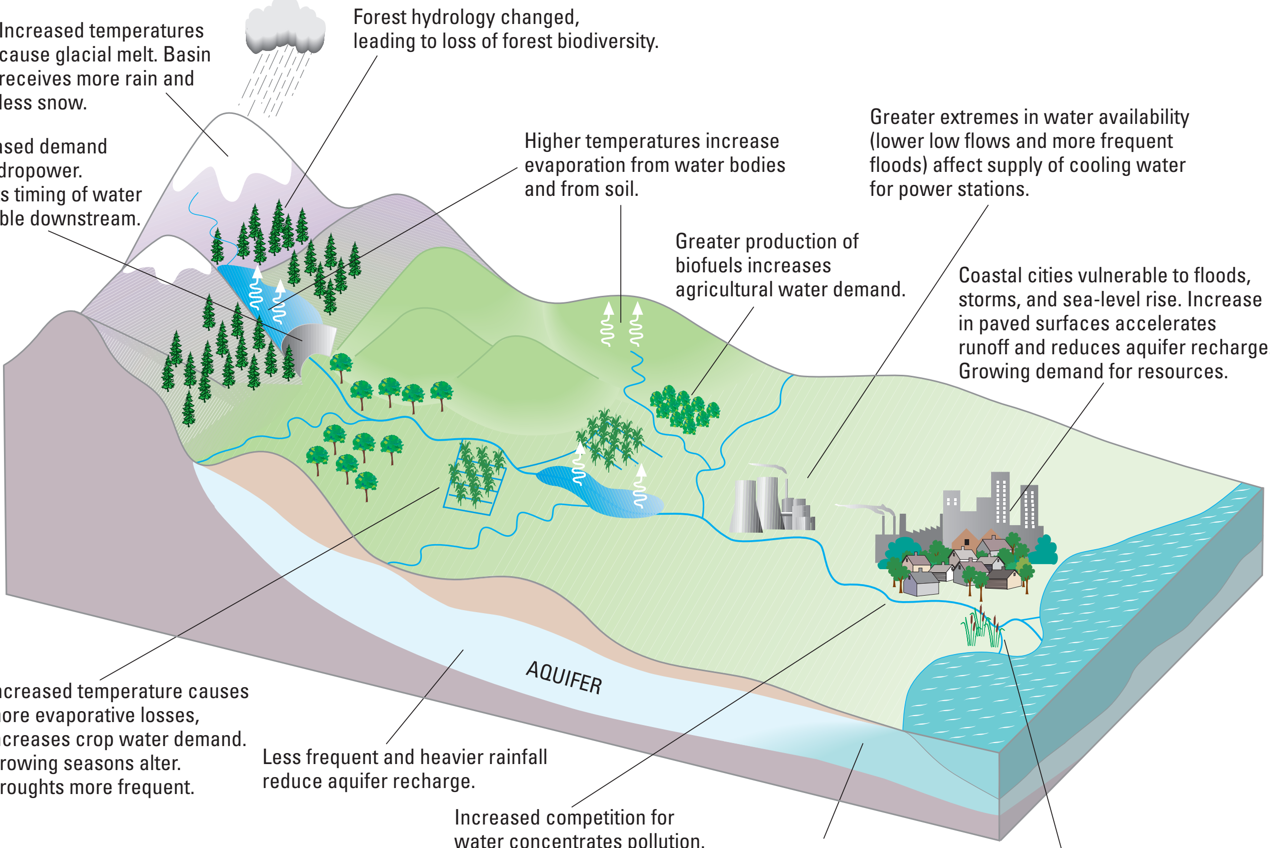
Farmers' choices of crops are determined in part by government price supports for sugar and wheat, which reduce the incentives to switch to other crops such as higher-value fruits and vegetables. If international trade agreements make it easier to ensure a reliable market for new crops, the farmers might make the switch. But without good roads, refrigerated transport, and state-of-the-art packaging facilities, the fruit and vegetables will rot before reaching their destination.

If the new advisory services are good, farmers will learn how they can get higher incomes by switching to growing fruit and vegetables for export. The extension services will also help them to organize and interact with European buyers. New infrastructure (a reliable weigh station, a cold-storage facility) will make it feasible to assume the risk of switching crops. If the farmers can get information they trust about the impacts of their actions on their aquifer, they may determine as a group to use water more responsibly. If the river basin agency has new planning tools, it can allocate water more effectively across different users' priorities, including the environment. In the long term new initiatives that set a price on soil carbon or change water allocation may provide the incentives for farmers to grow crops using different soil management techniques. Each step in the process is feasible, and in the long run will benefit every player. The challenge comes in coordinating all the efforts across multiple institutions and in persisting to see things through over a long time.

Natural resources cannot be managed separately, especially with climate change. New ways are needed to put water, agriculture, forests, and fisheries into a broader context with a web of related outcomes. In some communities, farmers have begun to moderate their fertilizer use to protect aquatic ecosystems, and fisheries managers are considering how setting catch limits for one species will affect others. These management tools appear under a wide variety of names: ecosystem-based management, integrated soil-fertility management, adaptive management, to name a few. But all share key features: they coordinate a broader range of variables (wider landscapes, longer time frames, and learning by experience) than do traditional approaches. And they stress the need for reliable information about the managed resource to ensure that recommendations are accurate, site specific, and adaptable to changing conditions. By increasing climate variability, climate change will make ecosystems' responses less predictable; resource managers will need to cope with that uncertainty with robust plans that consider the potential outcomes of multiple actions under multiple conditions.

Adaptive management (as described in chapter 2) will need to be applied at all levels of resource management. Individual farmers can monitor their soil to tailor fertilizer use to local soil, water, climate, and crop conditions without harming ecosystems. Rural communities can tailor their cropping choices to the amount of water they can safely extract from their groundwater year after year, and go back to using the aquifer only as insurance against

Figure 3.1 Climate change in a typical river basin will be felt across the hydrological cycle



Heavier rain increases erosion, siltation, and landslides.

Increased temperatures cause glacial melt. Basin receives more rain and less snow.

Forest hydrology changed, leading to loss of forest biodiversity.

Increased demand for hydropower. Affects timing of water available downstream.

Higher temperatures increase evaporation from water bodies and from soil.

Greater extremes in water availability (lower low flows and more frequent floods) affect supply of cooling water for power stations.

Greater production of biofuels increases agricultural water demand.

Coastal cities vulnerable to floods, storms, and sea-level rise. Increase in paved surfaces accelerates runoff and reduces aquifer recharge. Growing demand for resources.

Increased temperature causes more evaporative losses, increases crop water demand. Growing seasons alter. Droughts more frequent.

Less frequent and heavier rainfall reduce aquifer recharge.

Increased competition for water concentrates pollution.

Coastal aquifers vulnerable to salt-water intrusion.

Increased competition for water risks drying up wetlands. Changes in temperature, water availability, and pollution concentrations affect aquatic ecosystems.

Sources: WDR team based on World Bank, forthcoming d; Bates and others 2008.

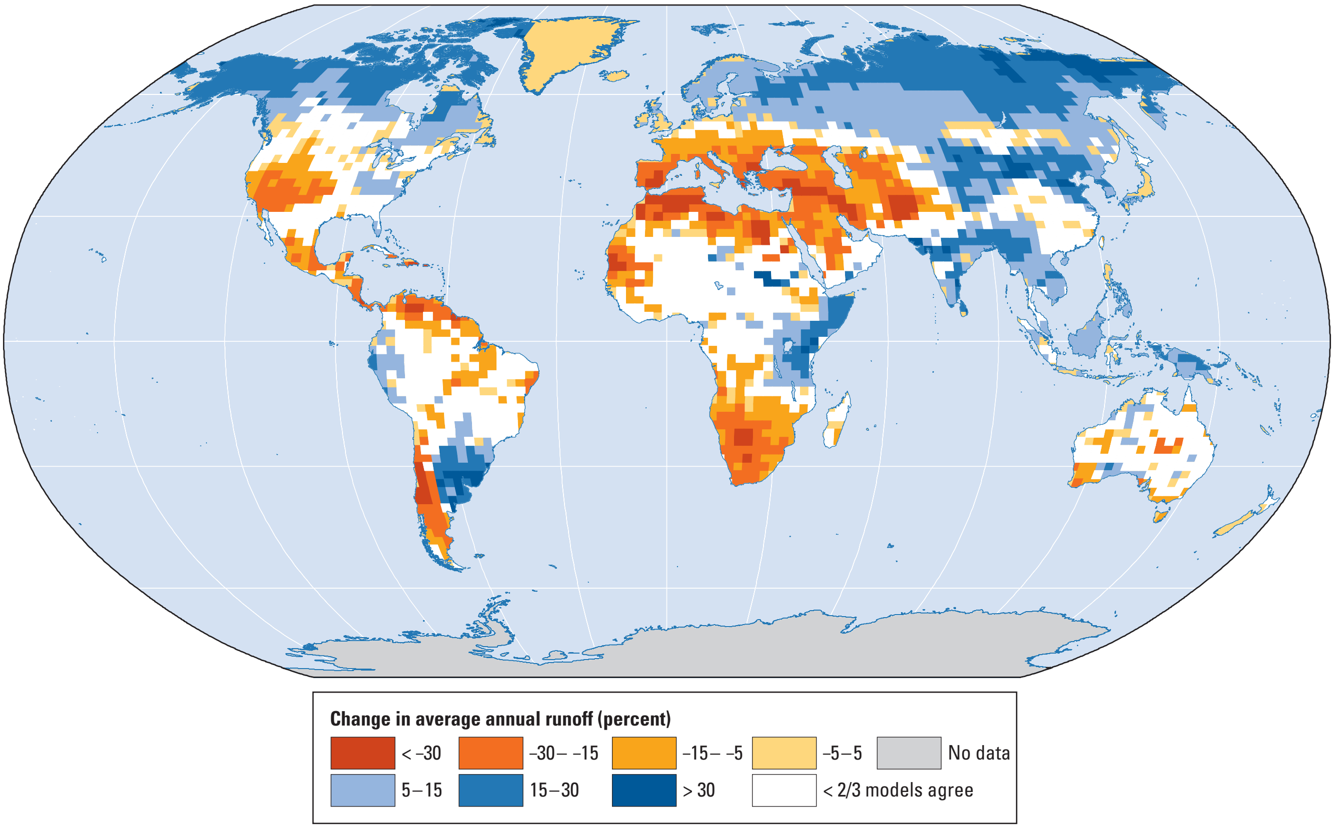
drought. And policy makers can use robust decision-making tools to forge more resilient international agreements for sharing resources. This chapter offers specifics on applying new tools and technologies to manage water, agriculture, and fisheries and advocates a systemwide approach for coping with climate change across all three sectors.

Produce more from water and protect it better

Climate change will make it harder to manage the world's water

People will feel many of the effects of climate change through water. The entire water cycle will be affected (figure 3.1). While the world as a whole will get wetter as warming speeds up the hydrological cycle, increased evaporation will make drought conditions more prevalent (map 3.1). Most places will experience more intense and variable precipitation, often with longer dry periods in between (map 3.2).[4] The effects on human activity and natural systems will be widespread. Areas that now depend on glaciers and snowmelt will have more fresh water initially, but supply will then decline over time.[5] The shifts may be so rapid and unpredictable that traditional agricultural and water management practices are no longer useful. This is already the case for the indigenous communities in the Cordillera Blanca in Peru, where farmers are facing such rapid changes that their traditional practices are failing. The government and scientists are starting to work with them to try to find new solutions.[6]

Map 3.1 **Water availability is projected to change dramatically by the middle of the 21st century in many parts of the world**

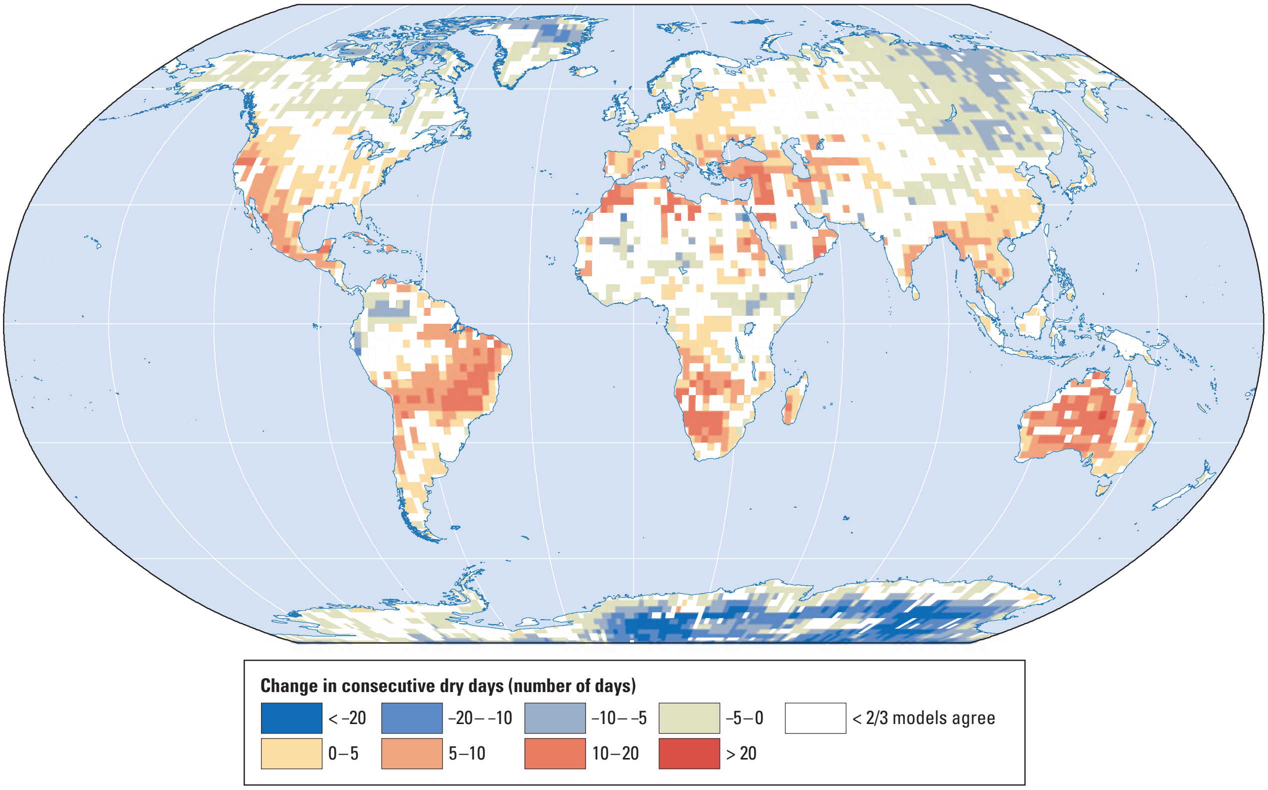


Sources: Milly and others 2008; Milly, Dunne, and Vecchia 2005.

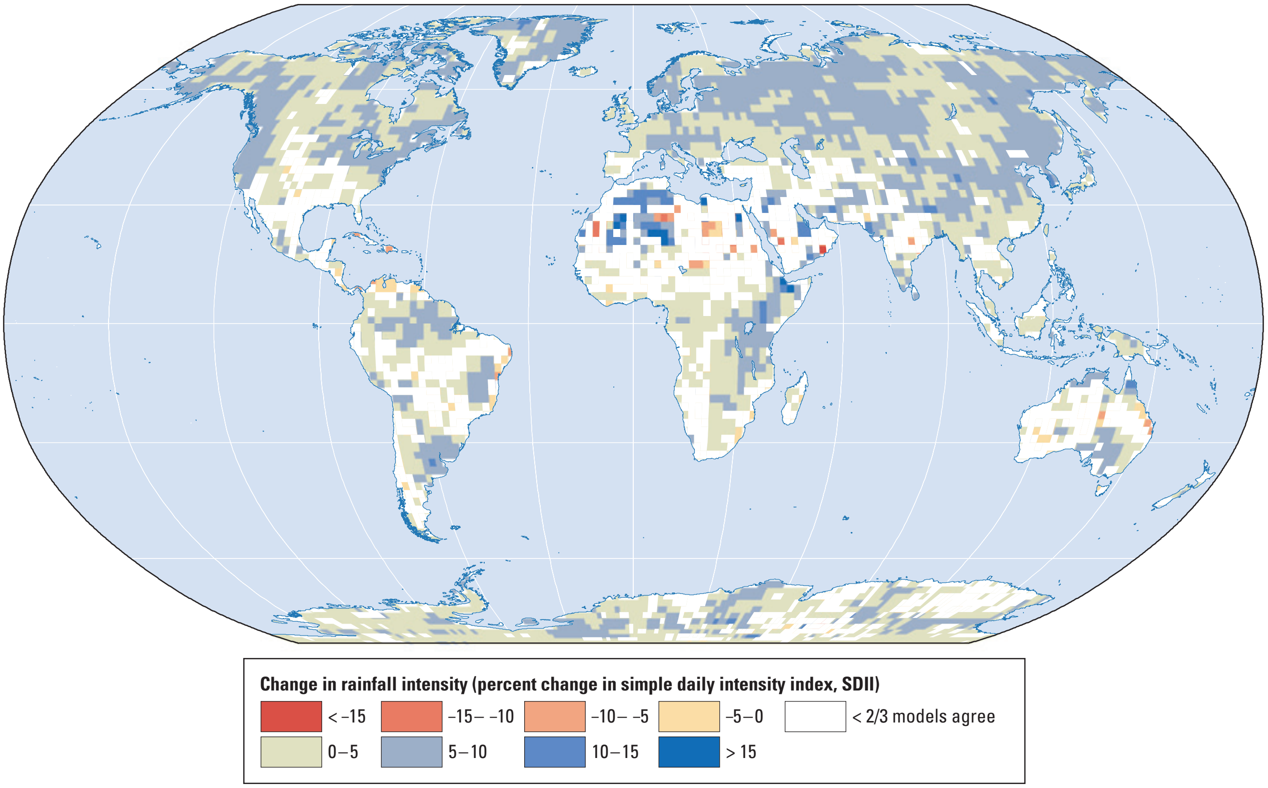
Note: The colors indicate percentage changes in annual runoff values (based on the median of 12 global climate models using the IPCC SRES A1B scenario) from 2041–2060 compared with 1900–1970. The white denotes areas where less than two-thirds of the models agree on whether runoff will increase or decrease. Runoff is equal to precipitation minus evaporation, but the values shown here are annual averages, which could mask seasonal variability in precipitation such as an increase in both floods and droughts.

Map 3.2 The world will experience both longer dry spells and more intense rainfall events

a. Longer dry spells



b. More intense rainfall



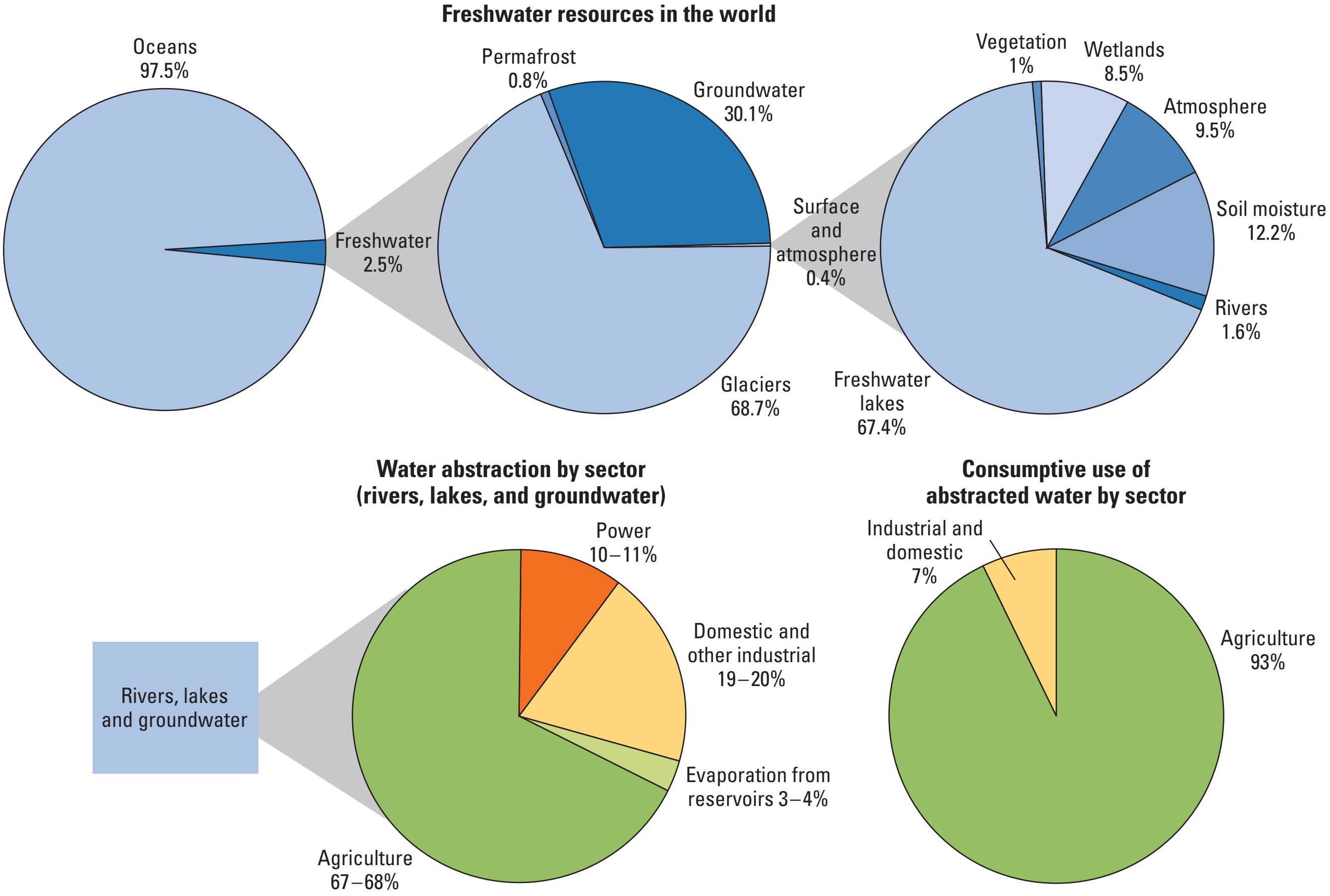
Source: The World Climate Research Program CMIP3 Multi-model Database (http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php). Analysis by the World Bank.

Note: The maps show the median change (based on 8 climate models using SRES A1B) in annual values in 2030–2049, compared with 1980–1999. A "dry" day is defined as one with precipitation less than 1millimeter whereas a "rainy" day has more than 1 millimeter. Precipitation intensity (SDII, or simple daily intensity index) is the total projected annual precipitation divided by the number of "rainy" days. White areas show areas of high model disagreement (fewer than two-thirds of the models agree on the sign of change).

Increasing knowledge about the world's water will improve management. To manage water well, it is critical to know how much water is available in any basin and what it is used for. This may sound straightforward, but it is not. The UN's World Water Development Report states: "Few countries know how much water is being used and for what purposes, the quantity and quality of water that is available and can be withdrawn without serious environmental consequences, and how much is being invested in water infrastructure."[7] Water accounting is complex. Definitions and methods vary, and confusion is common. For example, the Pacific Institute puts the Arab Republic of Egypt's annual renewable water resources in 2007 at 86.8 cubic kilometers, whereas Earthtrends reports it at 58 cubic kilometers. Both reports cite the same source of information. The confusion stems from different interpretations of the term *use* (the higher figure includes water reuse within Egypt, while the lower figure does not).[8]

The planet contains a fixed amount of water, with the form and location varying over space and time.[9] Humans have little control over most of it—saltwater in oceans, freshwater in glaciers, water in the atmosphere. Most investment concentrates on water in rivers and lakes, but soil moisture and groundwater together account for 98 percent of the world's available freshwater (figure 3.2).[10] Many people worry about how much drinking water is available,

Figure 3.2 Freshwater in rivers makes up a very small share of the water available on the planet—and agriculture dominates water use



Source: Shiklomanov 1999; Shiklomanov and Rodda 2003; Vassolo and Döll 2005.

Note: When humans use water, they affect the quantity, timing, or quality of water available for other users. Water for human use typically involves withdrawing water from lakes, rivers, or groundwater and either consuming it so that it reenters the atmospheric part of the hydrological cycle or returning it to the hydrological basin. When irrigated crops use water, it is a consumptive use—it becomes unavailable for use elsewhere in the basin. In contrast, releasing water from a dam to drive hydroelectric turbines is a nonconsumptive use because the water is available for downstream users but not necessarily at the appropriate time. Withdrawals by a city for municipal supplies are mainly nonconsumptive, but if the returning water is inadequately treated, the quality of water downstream is affected.

not realizing that agriculture dominates human water use. Each day, a person drinks 2–4 liters of water but eats food that requires 2,000–5,000 liters of water in its production.[11] These averages mask considerable variation. In some basins, industrial and urban use dominates, and more and more basins will be in that situation given the pace of urban growth.[12]

Climate change will reduce the natural water storage of snow and glaciers, which will in turn affect aquifer storage and require water managers to design and operate reservoirs differently. Water managers will have to manage the entire water cycle. They can no longer afford to concentrate on the small share of water in rivers and lakes and leave groundwater and soil moisture to be managed by landowners. Many basins will experience increased demand, reduced availability, and increased variability all at the same time. Water managers in those places will have less room to maneuver if their decisions are not robust to a variety of outcomes. Tools are available to help societies cope with these changes. They range from policy reform to decision-making protocols, from data collection technologies to new infrastructure design.

The effects of climate change on hydrological patterns mean that the past can no longer be used as a guide for future hydrological conditions. So, like other natural resource managers, water engineers are developing new tools that consider impacts across a number of scales and time frames to help evaluate tradeoffs and make choices robust to an uncertain future (box 3.1).[13]

Climate change will make applying and enforcing sound water policies even more important

Allocating water efficiently and limiting water consumption to safe levels will become increasingly important with climate change. When water is scarce, individual users can take too much, making water unavailable to others or harming ecosystems and the services they provide. When consumption in a basin exceeds the amount of water available, users must use less, and the water must be shared according to some process or principles. Policy makers have two options: they

BOX 3.1 *Robust decision making: Changing how water managers do business*

Traditional decision making under uncertainty uses probability distributions to rank different options for action, based on the envelope of risk from the past. But this approach is inadequate when decision makers do not know or cannot agree on how actions relate to consequences, how likely different events are, or how different outcomes should be evaluated. As chapter 2 shows, robust decision making is an alternative. Robust strategies are those that perform better than the alternatives across a wide range of plausible future circumstances. They are derived from computer simulation models that do not predict the future but create large ensembles of plausible futures to identify candidate robust strategies and systematically assess their performance. The process does not choose an optimal solution; instead, it finds the strategy that minimizes vulnerability to a range of possible risks.

Southern California's Inland Empire Utilities Agency has used this technique to respond to the effects of climate change on its long-term urban water management plan First, the agency derived probable regional climate projections by combining outputs from 21 climate models. Coupled with a water management simulation model, hundreds of scenarios explored assumptions about future climate change, the quantity and availability of groundwater, urban development, program costs, and the cost of importing water. Then the agency calculated the present value of costs of different ways to supply water under 200 scenarios. They rejected any strategy that gave costs above $3.75 billion over 35 years. Scenario discovery analysis concluded that the costs would be unacceptable if three things happened at the same time: large precipitation declines, large changes in the price of water imports, and reductions of natural percolation into the groundwater basin.

The goal of the process is to reduce the agency's vulnerability if those three things happen at the same time. The agency identified new management responses including increasing water-use efficiency, capturing more storm water for groundwater replenishment, water recycling, and importing more water in wet years so that in dry years more groundwater can be extracted. The agency found that, if all these actions were undertaken, the costs would almost never exceed the threshold of $3.75 billion.

Source: Groves and others 2008; Groves and Lempert 2007; Groves, Yates, and Tebaldi 2008.

can either set and enforce fixed quantities for specific users, or they can use prices to encourage users to cut back and even trade among themselves. Either way, designing and enforcing good policies require accurate information and strong institutions.

Quantitative allocations are most common, and it is difficult to do them well. South Africa has one of the most sophisticated schemes, though it is still a work in progress. Its 1998 National Water Act stipulates that water is public property and cannot be privately owned.[14] All users must register and license their water use and pay for it, including river or groundwater extracted at their own expense. *Streamflow reduction activity* is a category of water use, which means that owners of plantation forests must apply for a license just like an irrigator or a town's water utility. Only plantation forestry has so far been categorized as a streamflow reduction activity, but rainfed agriculture or water harvesting techniques could follow. Counting forestry as a water user makes land use compete squarely with other water users. The only guaranteed rights to water are for ecological reserves and to ensure that each person has at least 25 liters daily for basic human needs.[15]

Water is almost always priced below its value, giving users little incentive to use it efficiently.[16] The literature is virtually unanimous in calling for economic instruments to reduce demand.[17] Charging for water services (irrigation, drinking water, wastewater collection and treatment) can also recover the cost of providing the service and maintaining infrastructure.[18]

The role of pricing to influence demand varies for different types of water use. For municipal water, pricing tends to be effective at reducing demand, especially when combined with user outreach. When the price is high, many utilities and users fix leaks and use only what they need.[19] But because urban consumption accounts on average for only 20 percent of water abstractions, the effects on overall use are limited (figure 3.2). And because municipal use is basically nonconsumptive, the impact of reduced use in cities does little to increase availability elsewhere in the basin.

For irrigation, a consumptive use, pricing is more complex. First, the amount of water actually consumed is difficult to measure. Second, experience shows that farmers do not reduce consumption until the price is several multiples of the cost of providing the service. Yet most countries find it politically unacceptable to charge much more than is required to recover the operational costs. Third, too steep an increase in the price of surface water will encourage any farmer who can drill into an aquifer to switch to groundwater, shifting but not eliminating the problem of overuse.[20]

In most countries the state or another owner of the water charges the city utility or irrigation agency for the water extracted from the river or aquifer. This is known as bulk water. For a host of technical and political reasons few countries charge enough for bulk water to affect the way resources are allocated between competing uses.[21] Indeed, no country allocates surface water by price,[22] although Australia is moving toward such a system.[23] Although far from straightforward, fixed quotas on the combined quantity of surface and groundwater allocated to irrigation, or, better, the amount of water actually consumed (evapotranspiration), seem to be politically and administratively more realistic than pricing to limit overall consumptive use.[24]

Tradable water rights could improve water management in the long term but are not realistic short-term options in most developing countries. Tradable rights have great potential for making water allocation more efficient and for compensating people who forgo their water use.[25] Formal tradable water rights schemes are in place in Australia, Chile, South Africa, and the western United States. In Australia, evaluations indicate that trading rights has helped farmers withstand droughts and spurred innovation and investment without government intervention.

But the details of the design greatly affect the success of the venture, and establishing the necessary institutions is a lengthy process. It took decades to develop this capacity in Australia, a country with a long history of good governance, where customers were educated and accustomed to following rules, and where allocation rules were broadly in place and enforced before the rights system was established.[26] Countries that allow water trading when they do not have the institutional ability to enforce the quotas assigned to each user tend to increase overextraction considerably (box 3.2).

Climate change, which makes future water resources less predictable, complicates the already challenging task of establishing tradable water rights.[27] Even in a stable climate, sophisticated agencies find it difficult to determine in advance how much water can safely be allocated to different users, and how much should be set aside for environmental purposes.[28] By not properly accounting for certain uses (such as plantation forestry and natural vegetation) or for changes in user behavior, the schemes in Australia and Chile assigned rights for more water than was actually available. They had to undergo the painful process of reassigning or reducing the allocations.[29] Properly regulated markets for fixed quantities of water are a good long-term goal, but most developing countries need to take a number of crucial interim steps before adopting such a system.[30]

Climate change will require investing in new technologies and improving the application of existing technologies

Water storage can help with increased variability. Storage in rivers, lakes, soil, and aquifers is a key aspect of any strategy to manage variability—both for droughts (storing water for use in dry periods) and for floods (keeping storage capacity available for excess flows). Because climate change will reduce natural storage in the form of ice and snow and in aquifers (by reducing recharge), many countries will need increased artificial storage.

Water planners will need to consider storage options across the entire landscape. Water stored in soil can be used more efficiently by managing land cover, particularly by improving the productivity of rainfed agriculture. Managing groundwater, already challenging, will be more important as surface water becomes less reliable. Groundwater is a cushion for coping with unreliable public supplies and rainfall. For example, it supplies 60 percent of irrigated agriculture and 85 percent of rural drinking

BOX 3.2 *The dangers of establishing a market for water rights before the institutional structures are in place*

A review based on the Australian experience concludes that "with the benefit of hindsight and emerging experience, it is becoming clearer that . . . it is necessary to attend to many design issues. Water trading is likely to be successful unambiguously if and only if allocation and use management regimes are designed for trading and associated governance arrangements prevent over-allocation from occurring. Opposition to the development of markets without attention to design detail is justified."

Design concerns include accounting (proper assessment of the interconnected surface- and groundwater, planning for climatic shifts to drier conditions, and expanded consumption by plantation forestry because of public subsidies), and institutional issues (designing separate rules and agencies to define entitlements, manage allocations, and control the use of water; developing accurate registers early in the process; allowing unused water to be carried over from year to year; developing a private brokerage industry; and ensuring timely flow of information to all parties).

Some countries have long-standing informal water-trading arrangements. The ones that work are often based on customary practices. Farmers in Bitit, Morocco, for example, have traded water for decades, based on rules established by customary practices. The system operates from a detailed list available to the entire community, which identifies each shareholder and specifies the amount of water each is entitled to, expressed as hours of flow.

Schemes that allow trading in the absence of established and enforced water rights can worsen overexploitation. Farmers near the city of Ta'iz, in the Republic of Yemen, sell their groundwater to tankers to supply the city. Before this market existed, the farmer withdrew only as much water from the aquifer as his crops needed. By increasing the price of a unit of water, the trading increases the benefits of using groundwater. And because the farmer's extraction from his well is not controlled, there is no limit to the amount he can extract. As a result, the unregulated market accelerates the depletion of the aquifer.

Sources: CEDARE 2006; World Bank 2007b; Young and McColl, forthcoming.

water in India as well as half the drinking water received by households in Delhi. Well managed, groundwater can continue to act as a natural buffer. But it is far from well managed. In arid regions across the world, aquifers are overexploited. Up to a quarter of India's annual agricultural harvest is estimated to be at risk because of groundwater depletion.[31]

Improving groundwater management requires actions to enhance both supply (artificial recharge, accelerated natural recharge, barriers within aquifers to retard underground flows) and demand. And groundwater cannot be managed alone—it must be integrated with regulation of surface water.[32] Supply enhancing techniques are not straightforward. For example, artificial recharge is of limited use when water and suitable aquifer storage sites are not in the same places as the overstressed aquifers; 43 percent of the funds allocated for India's $6 billion artificial recharge program is likely to be spent recharging aquifers that are not overexploited.[33]

Dams will be an important part of the story of climate change and water. And they will need to be designed with built-in flexibility to deal with potential precipitation and runoff changes in their basins. Many of the best sites for dams are already exploited, yet the potential for new dams does exist, particularly in Africa. Managed well, dams provide hydropower and protect against droughts and floods. Comprehensive analyses of the economic impacts of dams are rare, but four case studies indicate positive direct economic effects and large indirect effects, with the poor sometimes benefiting disproportionately.[34] The High Dam at Aswan in Egypt, for example, has generated net annual economic benefits equivalent to 2 percent of Egypt's gross domestic product (GDP).[35] It has generated 8 billion kilowatt-hours of energy, enough to electrify all of the country's towns and villages. It has allowed the expansion of agriculture and year-round navigation (stimulating investments in Nile cruises) and has saved the country's crops and infrastructure from droughts and floods. But dams have well-known negative effects as well,[36] and the tradeoffs need to be weighed carefully. Climate change puts a premium on identifying robust designs: where countries face uncertainty about even whether their rainfall will increase or decrease, it can be cost-effective to build structures that are specifically designed to be changed in the future. As hydraulic systems increase in complexity, countries need solid hydrological, operational, economic, and financial analyses and capable institutions all the more (box 3.3).

Nonconventional technologies can increase water availability in some water-scarce regions. Water supplies can be enhanced by desalinating seawater or brackish water and reusing treated wastewater. Desalination, which accounted for less than 0.5 percent of all water use in 2004,[37] is set to become more widely used.

Technical developments, including energy-efficient filters, are causing desalination prices to fall, and pilot schemes are beginning to power desalination plants with renewable energy.[38] Depending on the

BOX 3.3 *Managing water resources within the margin of error: Tunisia*

Tunisia is a good example of the demands on water managers in countries that are approaching the limits of their resources. With only 400 cubic meters of renewable resources per capita, which are highly variable and distributed unevenly over time and space, Tunisia has a huge challenge managing its water. Yet in contrast to its Maghreb neighbors, it has withstood consecutive droughts without rationing water to farmers or resorting to supplying cities from barges. It has built dams with conduits to connect them and to transfer water between different areas of the country.

As the most promising schemes were developed, the government built additional infrastructure in more marginal areas. Rivers that flowed to the sea have been dammed even when water demand in those basins is not intense. The stored water can be pumped across the mountain range into the country's principal river basin. The new water both increases supply and dilutes the salinity in the area where water demand is highest. In addition, Tunisia treats and reuses one-third of its urban wastewater for agriculture and wetlands, and recharges aquifers artificially. Tunisian water managers now face a complex set of decisions: they must optimize water quantity, timing, quality, and energy costs, showing the importance of human capacity to manage resources so intensively.

Source: Louati 2009.

scale of the plant and the technology, desalinated water can be produced and delivered to the utility for as little as $0.50 per cubic meter. This remains more expensive than conventional sources when freshwater is available.[39] Therefore, desalinated water usually makes sense only for the highest-value uses, such as urban water supply or tourist resorts.[40] It also tends to be limited to coastal areas, because inland distribution of desalinated water adds to the costs.[41]

Producing more food without more water will not be easy, but some new approaches will help. Managing water to meet future needs will also involve making water use more efficient, particularly in agriculture, which accounts for 70 percent of freshwater withdrawals from rivers and groundwater (figure 3.2).[42]

There appears to be scope for increasing the productivity of water in rainfed agriculture, which provides livelihoods for the majority of the world's poor, generates more than half of the gross value of the world's crops, and accounts for 80 percent of the world's crop water use.[43] Options, described in the next section, include mulching, conservation tillage, and similar techniques that retain water in the soil so that less is lost to evaporation and more is available to plants. Other options involve small-scale rainwater storage, sometimes called water harvesting.

Of the various interventions to increase rainfed production, some (mulching, conservation tillage) divert some water that would otherwise evaporate unproductively. Others (water harvesting, groundwater pumps) divert some water that would otherwise have been available to users downstream. When water is plentiful, impacts on other users are imperceptible, but as water becomes scarcer, the impacts become more important. Once again, comprehensive accounting for water and integrated planning of land and water at local, watershed, and regional scales can make these interventions productive, by ensuring that the tradeoffs are properly evaluated.

Irrigated agriculture is expected to produce a greater share of the world's food in the future, as it is more resilient to climate change in all but the most water-scarce basins.[44] Crop productivity per hectare will have to increase, because there is little scope for increasing the total area under irrigation. Indeed, irrigated land is expected to increase by just 9 percent between 2000 and 2050.[45] And water productivity (in this case, agricultural output per unit of water allocated to irrigation) will also have to improve, given the increasing water demands of cities, industries, and hydropower. New technologies have the potential to increase water productivity when combined with strong policies and institutions.[46]

Getting more "crop per drop" involves a complex combination of investments and institutional changes. Countries from Armenia to Zambia are investing in new infrastructure that delivers the water efficiently from the reservoir to the crops, reducing evaporative losses. However, as the example of the Moroccan farmers described earlier indicates, the investments can work only if local institutions deliver the water reliably, farmers have a voice in decision making, and they can get the advice they need on how to make the most of the new infrastructure or technological developments. New infrastructure will help water management only if combined with strong quantitative limits on each individual's water consumption, covering both ground and surface water. Otherwise, the increased profitability of irrigation will tempt farmers to expand their cultivated area or double- or triple-crop their fields, drawing ever more water from their wells. This is good for the individual farmer, certainly, but not for the other water users in the basin.[47]

Good crop management can increase water productivity by developing varieties resistant to cold so that crops can be grown in the winter, when less water is required.[48] Growing crops in greenhouses or under shade screens also can reduce the evaporative demand of open fields, though it does increase production costs.[49] When crops die before they produce their yields, the water they have consumed is wasted. Therefore more widespread adoption of drought- and heat-tolerant varieties will increase water as well as agricultural productivity.[50]

Well-timed applications of irrigation water can also help. If farmers do not know exactly how much water is needed, they often overirrigate because a little extra water is less harmful to yields than too little water. By monitoring water intake and growth throughout the growing season, farmers can deliver the exact amount of water that their crops need and irrigate only when really necessary. Remote-sensing systems are beginning to allow farmers to see the water needs of plants with great accuracy even before the plants show signs of stress.[51] But because of the technological requirements, precision agriculture of this type is limited to a small number of the world's farmers.[52]

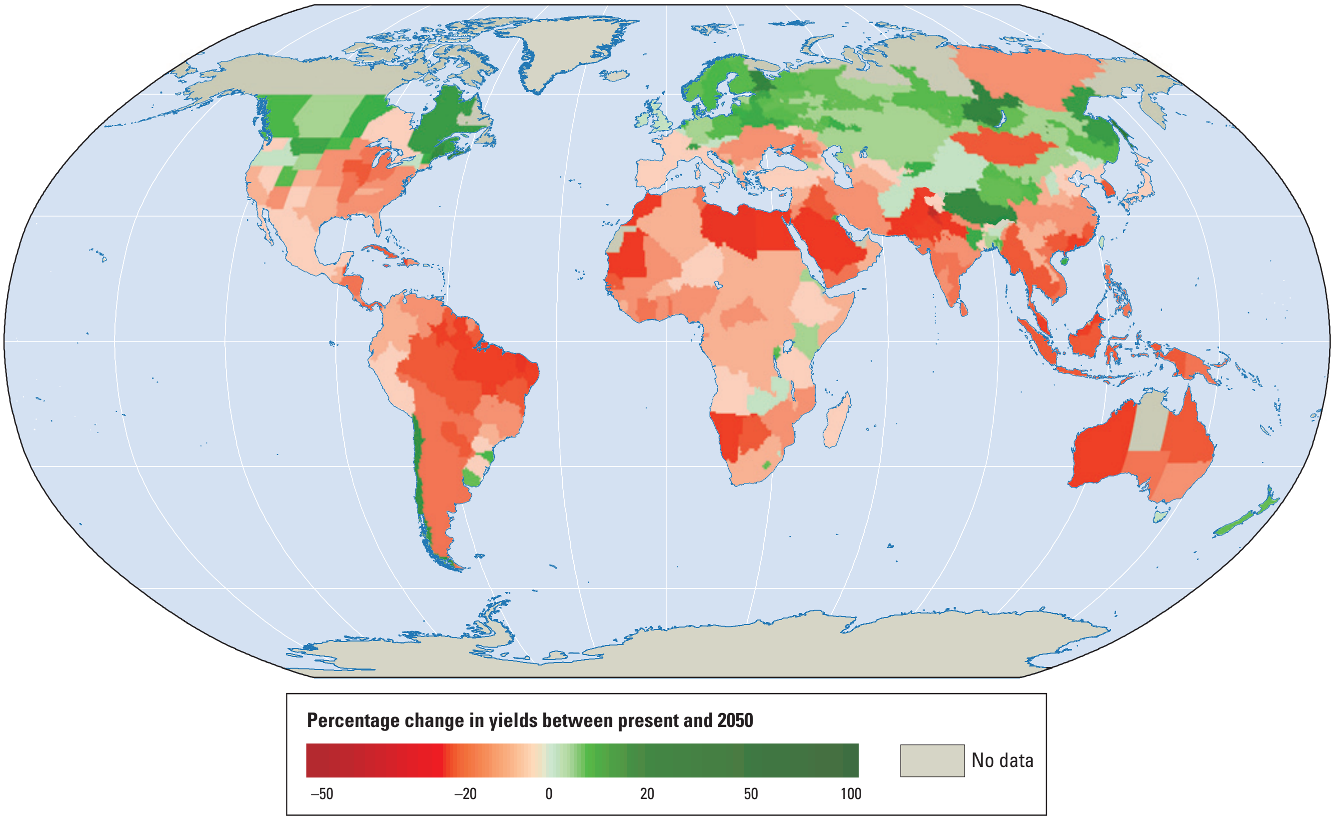
Even before this technology becomes widely available, it is possible to apply simple automated systems to help poorer farmers increase the precision of applying irrigation water. The Moroccan farmers who convert to drip irrigation under the government scheme discussed earlier will benefit from a simple technology that uses a standard irrigation formula adapted to local growing conditions. Depending on the weather in the area, the system will deliver a message to farmers' cell phones telling them how many hours they should irrigate that day. Acting on this information will allow them to avoid overirrigating.[53]

Producing more in agriculture while protecting the environment

Climate change will push societies to accelerate agricultural productivity growth

Climate change will depress agricultural yields. Climate change adds several conflicting pressures to agricultural production. It will affect agriculture directly through higher temperatures, greater crop water demand, more variable rainfall, and extreme climate events such as floods and droughts. It will increase yields in some countries but lower them in most of the developing world, reducing global average yields (map 3.3).

Map 3.3 Climate change will depress agricultural yields in most countries by 2050 given current agricultural practices and crop varieties



Source: Müller and others 2009.

Note: The figure shows the projected percentage change in yields of 11 major crops (wheat, rice, maize, millet, field pea, sugar beet, sweet potato, soybean, groundnut, sunflower, and rapeseed) from 2046 to 2055, compared with 1996–2005. The values are the mean of three emission scenarios across five global climate models, assuming no CO_2 fertilization (see note 54). Large negative yield impacts are projected in many areas that are highly dependent on agriculture.

In mid to high latitudes, local increases in temperature of only 1–3°C, along with associated carbon fertilization[54] and rainfall changes, may have small beneficial impacts on crop yields.[55] Kazakhstan, the Russian Federation, and Ukraine are all geographically positioned to benefit from these temperature increases, but they may not be able to capitalize fully on the opportunities. Since the breakup of the Soviet Union, together they have removed 23 million hectares of arable land from production, almost 90 percent of which was used for grain production.[56] Although world grain yields have been rising on average by about 1.5 percent a year since 1991, yields in Kazakhstan and Ukraine have fallen, and Russia's yields have risen only slightly. If these countries are to take advantage of the warming temperatures to increase agricultural production, they will have to build stronger institutions and better infrastructure.[57] Even if they do, extreme climate events may wipe out the improved average conditions: when the increased likelihood of extreme climate events is taken into consideration for Russia, the years with food production shortfalls are projected to triple by the 2070s.[58]

In most developing countries, climate change is projected to have an adverse effect on current agriculture. In low-latitude regions even moderate temperature increases of another 1–2°C will reduce yields of major cereals.[59] One assessment of multiple studies estimates that by the 2080s world agricultural productivity will decline 3 percent under a high-carbon-emission scenario with carbon fertilization or 16 percent without it.[60] For the developing world, the decline is projected to be even larger, with a 9 percent decline with carbon fertilization, and 21 percent without.

An analysis of 12 food-insecure regions using crop models and outputs from 20 global climate models indicates that without adaptation Asia and Africa will suffer particularly severe drops in yields by 2030. These losses will include some of the crops critical for regional food security, including wheat in South Asia, rice in Southeast Asia, and maize in southern Africa.[61] These projections are likely to underestimate the impact: models that project the effect of climate change on agriculture typically look at average changes and exclude the effects of extreme events, variability, and agricultural pests, all of which are likely to increase. Climate change will also make some land less suitable for agriculture, particularly in Africa.[62] One study projects that by 2080 land with severe climate or soil constraints in Sub-Saharan Africa will increase by 26 million to 61 million hectares.[63] That is 9–20 percent of the region's arable land.[64]

Efforts to mitigate climate change will put more pressure on land. In addition to reducing yields, climate change will put pressure on farmers and other land managers to reduce greenhouse gas emissions. In 2004 about 14 percent of global greenhouse gas emissions came from agricultural practices. This includes nitrous oxide from fertilizers; methane from livestock, rice production, and manure storage; and carbon dioxide (CO_2) from burning biomass, but excludes CO_2 emissions from soil management practices, savannah burning, and deforestation.[65] Developing regions produce the largest share of these greenhouse gas emissions, with Asia, Africa, and Latin America accounting for 80 percent of the total.

Forestry, land use, and land-use change account for another 17 percent of greenhouse gas emissions each year, three-quarters of which come from tropical deforestation.[66] The remainder is largely from draining and burning tropical peatland. About the same amount of carbon is stored in the world's peatlands as is stored in the Amazon rainforest. Both are the equivalent of about 9 years of global fossil fuel emissions. In equatorial Asia (Indonesia, Malaysia, Papua New Guinea), emissions from fires associated with peat draining and deforestation are comparable to those from fossil fuels in those countries.[67] Emissions related to livestock production are counted across several emissions categories (agriculture, forestry, waste), and overall they are estimated to contribute up to 18 percent of the global total, mostly through methane emissions from the animals, manure waste, and clearing for pasture.[68]

The cultivation of biofuels to mitigate climate change will create even more competition for land. Current estimates indicate that dedicated energy crop production takes place on only 1 percent of global arable land, but biofuel legislation in developed and developing countries supports expanding production. Global ethanol production increased from 18 billion liters a year in 2000 to 46 billion in 2007, while biodiesel production increased nearly eightfold to 8 billion liters. Land allocated to biofuels is projected to increase fourfold by 2030, with most of the growth in North America (accounting for 10 percent of arable land in 2030) and Europe (15 percent).[69] Projections indicate that only 0.4 percent of arable land in Africa and about 3 percent in Asia and Latin America will be dedicated to biofuel production by 2030.[70] Under some scenarios for mitigating climate change, projections beyond 2030 suggest that land allocated to producing biofuels by 2100 will grow to more than 2 billion hectares—a huge figure given that current cropland covers "only" 1.6 billion hectares. These scenarios project that most of the land for such large-scale biofuel production will originate from conversion of natural forests and pastureland.[71]

If demand increases rapidly, biofuels will be a significant factor in agricultural markets, increasing commodity prices. Much of the current demand for biofuel crops is spurred by government targets and subsidies and by high oil prices. Without artificial support the competitiveness of biofuels is still poor, with the exception of Brazil's sugarcane ethanol. Nor is it clear how much biofuels reduce greenhouse gas emissions because of the fossil fuels used during production and the emissions from land clearing. Despite the potential that biofuels have to decrease greenhouse gas emissions, the actual net carbon savings of current-generation biofuels is under debate, when production processes and associated land-use changes are factored in to the calculations. In addition, demand for land for biofuels already competes with biodiversity conservation. As a result, it is important to establish guidelines for expansion of biofuels so that other environmental goals are not squeezed out (box 3.4). Comprehensive life-cycle accounting for biofuels—which includes their contribution to emission reductions as well as their water and fertilizer use—may slow the pace of conversion.

Second-generation biofuels now under development, such as algae, *jatropha,* sweet sorghum, and willows, could reduce competition with agricultural land for food crops by using less land or marginal land, although some of these developments could still lead to the loss of pasture land and grassland ecosystems. Perennial crops with deeper root systems, such as switchgrass, can better combat soil and nutrient erosion, require fewer nutrient inputs, and sequester higher rates of carbon than current biofuel feedstocks.[72] But their water needs may prohibit their sustainable production in arid regions. More research is needed to improve the productivity and emission reduction potential of future generations of biofuels.

Growing populations, more carnivorous palates, and climate change will require large increases in agricultural productivity. The amount of land needed to feed the world in 2050 will depend significantly on how much meat people eat. Meat is a resource-intensive way for humans to consume protein, because it requires land for pasture and grain feed. The resource implications vary with the type of meat and how it is produced. Producing 1 kg of beef can take as much as 15,000 liters of water if it is produced in industrial feedlots in the United States (figure 3.3).[73,74] But extensive beef production in Africa requires only 146–300 liters per kilogram depending on the weather.[75] Per kilogram, beef production is also greenhouse-gas intensive, even compared with other meat production, emitting 16 kilograms of CO_2 equivalent (CO_2e) for every kilogram of meat produced (figure 3.4).[76]

Despite the resource implications, demand for meat is expected to increase as population and incomes grow. Eating more

BOX 3.4 *Palm oil, emission reductions, and avoided deforestation*

Palm oil plantations represent the convergence of many current land-use issues. Palm oil is a high-yielding crop with food and biofuel uses, and its cultivation creates opportunities for smallholders. But it infringes on tropical forests and their many benefits, including greenhouse gas mitigation. Cultivation of palm oil has tripled since 1961 to cover 13 million hectares, with most of the expansion in Indonesia and Malaysia and more than half on recently deforested lands. Recent announcements for new palm oil concessions in the Brazilian Amazon, Papua New Guinea, and Madagascar raise concerns that the trend is likely to continue.

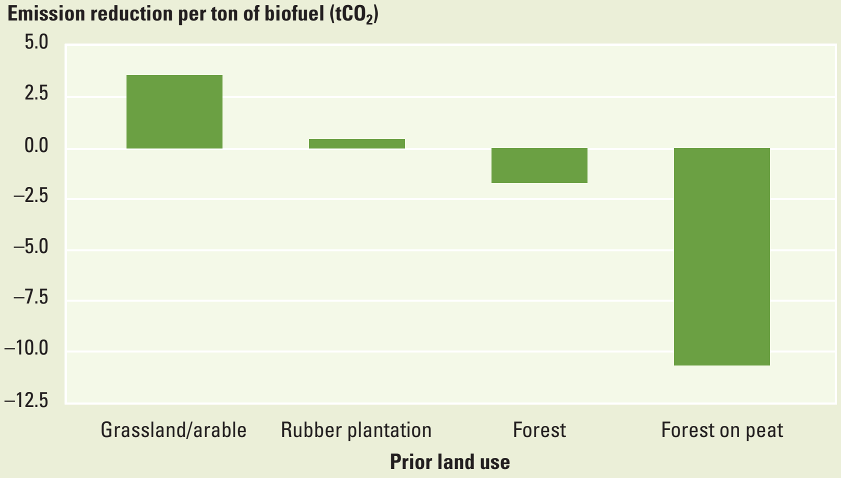
Smallholders currently manage 35 to 40 percent of the land under palm oil cultivation in Indonesia and Malaysia, providing a profitable diversification in livelihoods. However, harvested palm nuts must be delivered to mills for processing within 24 hours of harvesting, so holdings tend to cluster around mills. Thus a high proportion of the area around mills is converted to palm oil, either as large tract commercial plantations or densely clustered smallholdings. Certain landscape design practices, such as the creation of agroforestry belts to smooth the transition between palm oil plantations and forest patches, can help make the plantation landscape less inimical to biodiversity while providing further diversification for smallholders.

The mitigation value of biodiesel derived from palm oil is also questionable. Detailed life-cycle analysis shows that the net reduction in carbon emissions depends on the land cover existing before the palm oil plantation (figure). Significant emission reductions derive from plantations developed on previous grasslands and cropland, whereas net emissions will increase greatly if peatland forests are cleared for producing palm oil.

The expansion of the carbon market to include REDD (Reduced Emissions from Deforestation and forest Degradation) is an important tool to balance the relative values of palm oil production and deforestation on one hand, and forest protection on the other. This balance will be critical to ensure biodiversity protection and emission reduction.

Recent studies show that converting land to palm oil production may be between six to ten times more profitable than maintaining the land and receiving payments for carbon credits through REDD, should this mechanism be limited to the voluntary market. If REDD credits are given the same price as carbon credits traded in compliance markets, the profitability of land conservation would increase dramatically, perhaps even exceeding profits from palm oil, making agricultural conversion less attractive. Therefore, done right, REDD could realistically reduce deforestation and thereby contribute to a global mitigation effort.

Emission reductions from biodiesel derived from palm oil differ greatly according to the previous land use on the palm oil plantation site.



Source: Henson 2008.

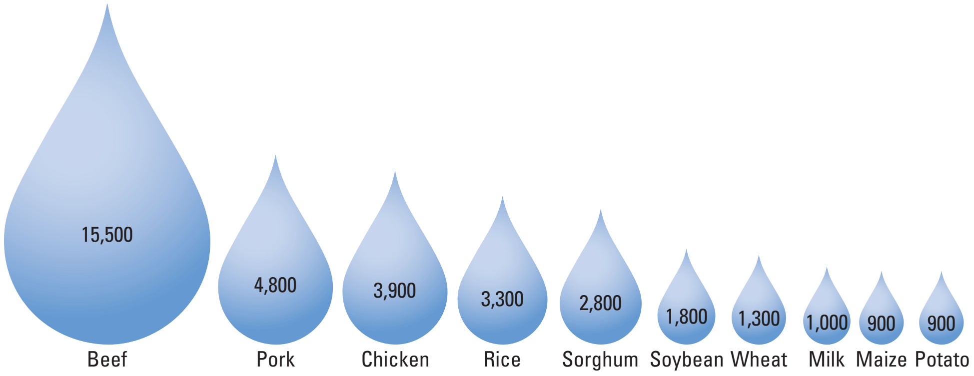
Sources: Butler, Koh, and Ghazoul, forthcoming; Henson 2008; Koh, Levang, and Ghazoul, forthcoming; Koh and Wilcove 2009; Venter and others 2009.

meat will be beneficial for poor consumers who need the protein and micronutrients.[77] But by 2050 the production of beef, poultry, pork, and milk is expected to at least double from 2000 levels to respond to the demand of larger, wealthier, and more urban populations.[78]

The world will have to meet the growing demand for food, fiber, and biofuel in a changing climate that reduces yields—while at the same time conserving ecosystems that store carbon and provide other essential services. Obtaining more land suitable for agricultural production is unlikely. Studies indicate that globally the amount of land suitable for agriculture will remain the same in 2080 as it is today,[79] because increases in suitable land in the higher latitudes will be largely offset by losses in the lower latitudes.

Therefore agriculture productivity (tons per hectare) will need to increase. Models vary but one study indicates that annual increases of 1.8 percent a year will be needed

Figure 3.3 Meat is much more water intensive than major crops
(liters of water per kilogram of product)



Source: Waterfootprint (https://www.waterfootprint.org), accessed May 15, 2009; Gleick 2008.

Note: Figure shows liters of water needed to produce one kilogram of product (or one liter for milk). Water use for beef production only characterizes intensive production systems.

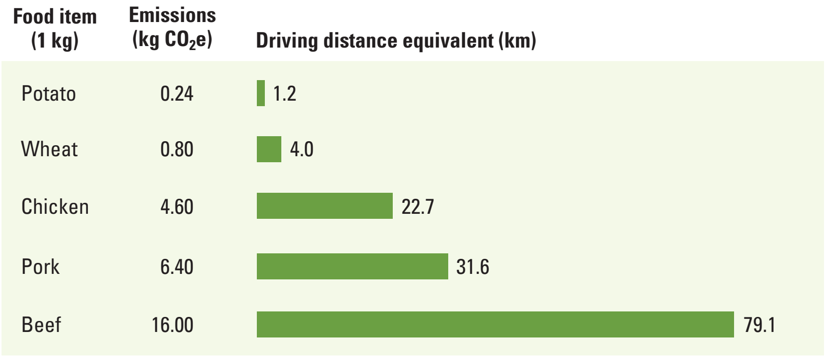
up to 2055—almost twice the 1 percent a year that would be needed under business as usual (figure 3.5).[80] This means that yields will have to more than double over 50 years. Many of the world's breadbaskets, such as North America, are approaching maximum feasible yields for major cereals,[81] so a significant portion of this yield growth will need to occur in developing countries. This means not just an acceleration of yield growth but a reversal of recent slowing: the yield growth rate for all cereals in developing countries slipped from 3.9 percent a year between 1961 and 1990 to 1.4 percent a year between 1990 and 2007.[82]

Climate change will require highly productive and diverse agricultural landscapes

Productivity gains must not come at the expense of soil, water, and biodiversity. Intensive agriculture often damages natural systems. Highly productive agriculture, such as is practiced in much of the developed world, is usually based on farms that specialize in a particular crop or animal and on the intensive use of agrochemicals. This kind of farming can damage water quality and quantity. Fertilizer runoff has increased the number of low-oxygen "dead zones" in coastal oceans exponentially since the 1960s: they now cover about 245,000 square kilometers, mostly in coastal waters of the developed world (map 3.4).[83] Intensive irrigation often causes salt to build up in soils, reducing fertility and limiting food production. Salinization currently affects between 20 million and 30 million of the world's 260 million hectares of irrigated land.[84]

Less environmentally deleterious agricultural intensification is essential, particularly considering the environmental problems associated with further extensification of agriculture. Without increased crop and livestock yields per hectare, pressure on land resources will accelerate as crop and pasture areas expand under extensive production. Since the middle of the 20th century, 680 million hectares, or 20 percent of the world's grazing lands, have been

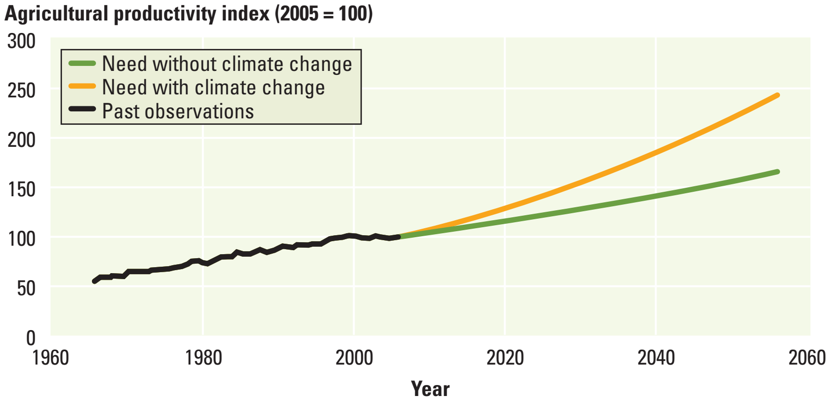
Figure 3.4 Intensive beef production is a heavy producer of greenhouse gas emissions



Source: Williams, Audsley, and Sandars 2006.

Note: The figure shows CO_2 equivalent emissions in kilograms resulting from the production (in an industrial country) of 1 kilogram of a specific product. The driving distance equivalent conveys the number of kilometers one must drive in a gasoline-powered car averaging 11.5 kilometers a liter to produce the given amount of CO_2e emissions. For example, producing 1 kilogram of beef and driving 79.1 kilometers both result in 16 kilograms of emissions.

Figure 3.5 Agricultural productivity will have to increase even more rapidly because of climate change



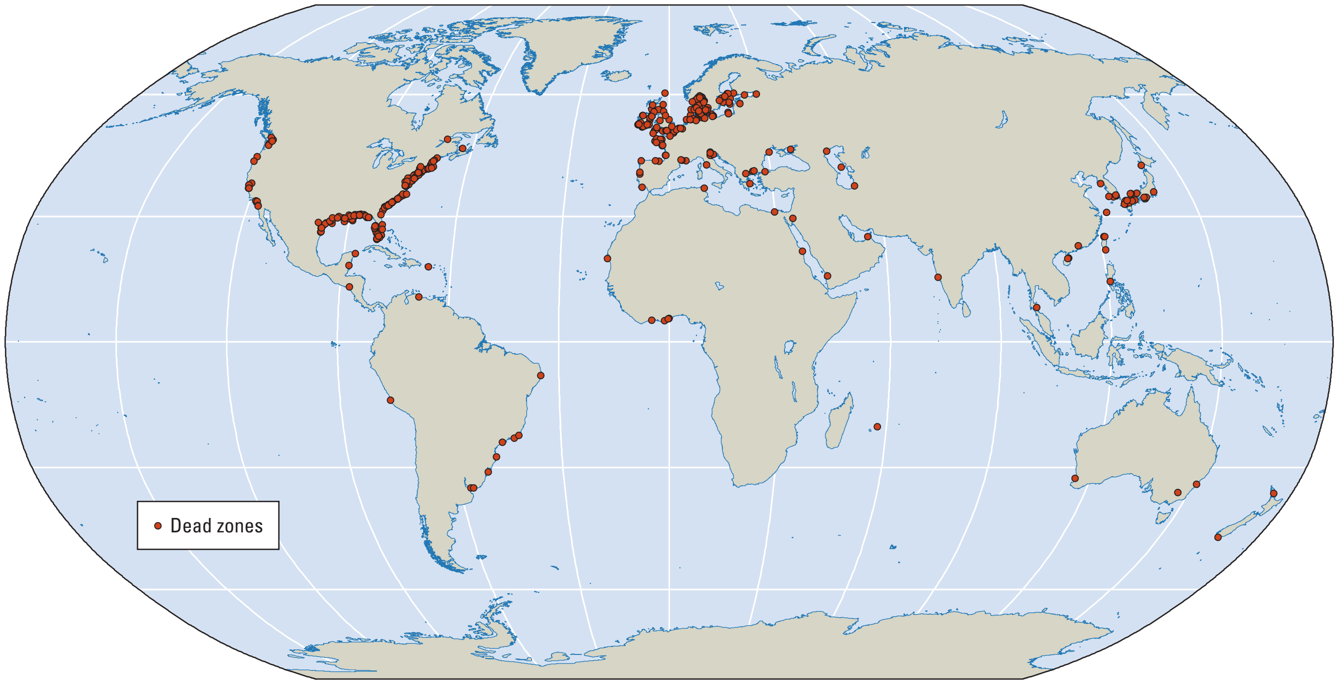
Source: Lotze-Campen and others 2009.

Note: The figure shows the required annual growth in an agricultural productivity index under two scenarios. In this index, 100 indicates productivity in 2005. The projections include all major food and feed crops. The green line represents a scenario without climate change of global population increasing to 9 billion in 2055; total calorie consumption per capita and the dietary share of animal calories increasing in proportion to rising per capita income from economic growth; further trade liberalization (doubling the share of agricultural trade in total production over the next 50 years); cropland continuing to grow at historical rates of 0.8 percent a year; and no climate change impacts. The orange line represents a scenario of climate change impacts and associated societal responses (IPCC SRES A2): no CO_2 fertilization, and agricultural trade reduced to 1995 levels (about 7 percent of total production) on the assumption that climate change-related price volatility triggers protectionism and that mitigation policy curbs the expansion of cropland (because of forest conservation activities) and increases demand for bioenergy (reaching 100 EJ [10^{18} joules] globally in 2055).

degraded.[85] Converting land for agriculture has already significantly reduced the area of many ecosystems (figure 3.6).

The Green Revolution illustrates both the immense benefits from increasing agricultural productivity and the shortcomings when technology is not supported by appropriate policies and investments to protect natural resources. New technology, coupled with investments in irrigation and rural infrastructure, drove a doubling of cereal production in Asia between 1970 and 1995. The agricultural growth and the associated decline in food prices during this time led to a near doubling of real per capita income, and the number of poor people fell from about 60 percent of the population to 30 percent, even as the population increased 60 percent.[86] Latin America also experienced significant gains. But in Africa, poor infrastructure, high transport costs, low investment in irrigation, and pricing and marketing policies that penalized farmers all impeded adoption of the new technologies.[87] Despite its overall success,

Map 3.4 Intensive agriculture in the developed world has contributed to the proliferation of dead zones



Source: Diaz and Rosenberg 2008.

Note: In the developed world intensive agriculture has often come at high environmental cost, including runoff of excess fertilizers leading to dead zones in coastal areas. Dead zones are defined as extreme hypoxic zones, that is, areas where oxygen concentrations are lower than 0.5 milliliters of oxygen per liter of water. These conditions normally lead to mass mortality of sea organisms, although in some of these zones organisms have been found that can survive at oxygen levels of 0.1 milliliter per liter of water.

the Green Revolution in many parts of Asia was accompanied by environmental damages stemming from overuse of fertilizer, pesticides, and water. Perverse subsidies and pricing and trade policies that encouraged monoculture of rice and wheat and heavy use of inputs contributed to these environmental problems.[88]

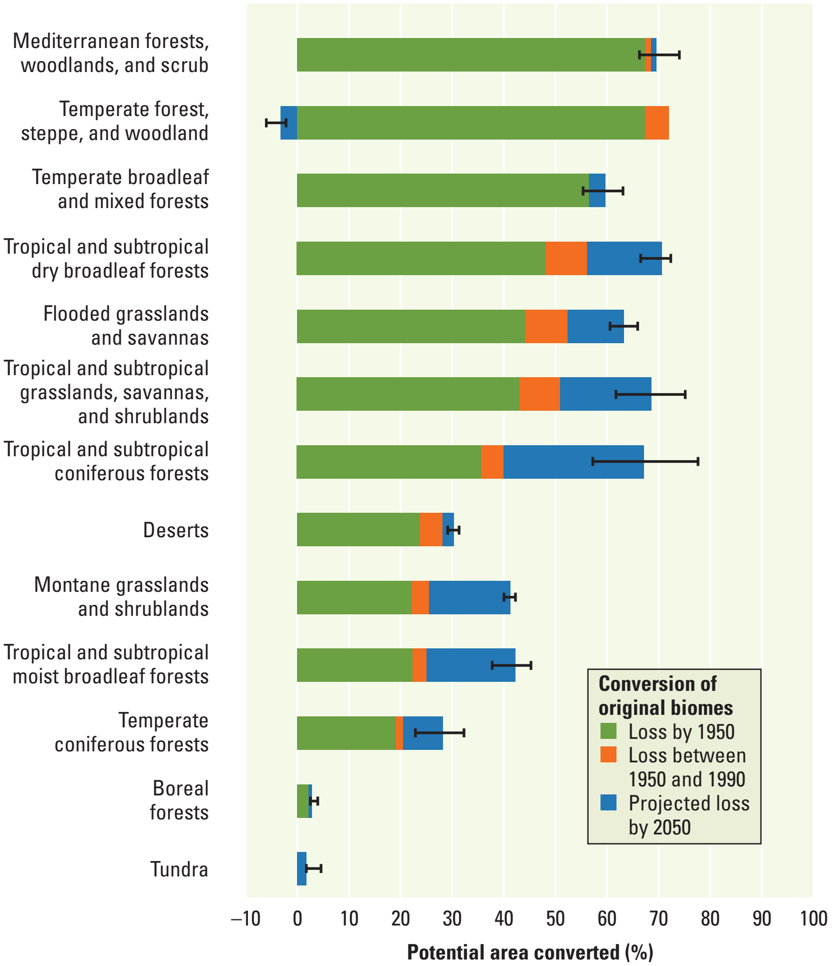
Climate-resilient farming requires diverse income sources, production choices, and genetic material. Climate change will create a less predictable world. Crops will fail more often. One way to buffer the uncertainty is to diversify on all levels (box 3.5). The first type of diversification relates to sources of income, including some outside of agriculture.[89] As farms get smaller and input prices increase, farmers will do this anyway. Indeed, in much of Asia smallholders and landless workers typically earn more than half their total household income from nonagricultural sources.[90]

A second type of diversification involves increasing the types of production on the farm. The market opportunities for crop diversification are expanding in many intensively farmed areas as a result of more open export markets and buoyant national demand in rapidly growing economies, especially in Asia and Latin America.[91] In these regions farmers may be able to diversify into livestock, horticulture, and specialized agricultural production.[92] These activities typically give high returns per unit of land and are labor intensive, which makes them suitable to small farms.

The third type of diversification involves increasing the genetic variability within individual crop varieties. Most high-yielding varieties in use on highly productive farms were bred on the assumption that the climate varied within a stable envelope; the breeders aimed for seed to be increasingly homogenous. In a changing climate, however, farmers can no longer rely on a handful of varieties that work under a narrow set of environmental conditions. Farmers will need each batch of seeds to contain genetic material able to deal with a variety of climatic conditions. Each year, some plants flourish whatever the climate that year. Over a number of years the average yields will be higher from diverse seeds than from uniform seeds, even though yields in a "normal" year may be lower.

Experiments using standard cultivation practices indicate that under increased CO_2 concentrations and higher temperatures (reflecting projections of the Intergovernmental Panel on Climate Change for 2050) older varieties of wheat or barley may grow faster and have an advantage over more modern varieties introduced in the late 20th century.[93] Furthermore, the wild relatives of today's crops contain genetic material that may be useful to make commercial crops more adaptable to changing conditions. Increased temperatures and CO_2 levels have a greater positive effect on

Figure 3.6 Ecosystems have already been extensively converted for agriculture



Source: Millennium Ecosystem Assessment 2005.

Note: The projections are based on four scenarios of how the world will approach ecosystem services and include assumptions about ecosystem management, trade liberalization, technology, and the treatment of public goods.

BOX 3.5 *Product and market diversification: An economic and ecological alternative for marginal farmers in the tropics*

Tropical areas face great challenges: the persistent poverty of rural populations, including indigenous peoples; the degradation of natural resources; the loss of biodiversity; and the consequences of climate change. The volatility of prices for tropical products on the international markets also affects local economies. Many farmers around the world have their own survival mechanisms, but efforts to improve livelihoods and address the anticipated impacts from climate change will require innovative institutions and creative methods for income generation and security.

One strategy that shows great potential for climate-smart development is agricultural and agroforestry product diversification. This strategy allows farmers to feed themselves and maintain a flow of products to sell or barter at the local market despite droughts, pests, or low prices on international markets.

Consider small coffee farms in Mexico. In 2001 and 2002 a dramatic drop in the international price of coffee pushed coffee prices in Mexico below production costs. To rescue farmers, the Veracruz state government raised the price of coffee produced in the area by establishing the "designation of origin of Veracruz" and by providing subsidies only to farmers cultivating high-quality coffee in areas more than 600 meters above sea level. Because this policy would hurt thousands of producers living in the low-quality production area below 600 meters, the government invited the Veracruzana University to find alternatives to coffee monoculture.

The diversification of productive lowland coffee lands found financial support through the UN Common Fund for Commodities, with the sponsorship and supervision of the International Coffee Organization. It started in two municipalities with a pilot group of 1,500 farmers, living in remote communities with 25–100 households.

Many of the farmers had traditionally produced coffee in a multicrop system, providing the opportunity to test in each plot different configurations of alternative woody and herbaceous species of economic and cultural value: Spanish cedar and Honduras mahogany trees (for wood and furniture), the Panama rubber tree, cinnamon, guava (as food and phytomedicine), *jatropha* (for food and biofuel), allspice, cocoa, maize, vanilla, chile, passion fruit, alongside coffee. All trees, herbs, and produce were locally familiar, except the cinnamon tree. There is a potentially large market for cinnamon, which is usually imported. The farmers are now learning which practices and configurations hold the best production potential in this innovative diversified system.

A cooperative company pooled different agricultural products in groups with similar market values but with different exposures to climate, pests, and market risks. Early results indicate that this bundling seems to work well, improving livelihoods and increasing the resilience of the communities. The company has been able to sell all product types, several of them at a better price than before the project started. And in the first two years the project introduced a million native timber trees.

Locals report that the practices have reduced erosion and improved soils, benefiting the surrounding ecosystem while buffering against potential future flooding associated with climate change.

Source: Contributed by Arturo Gomez-Pompa.

some weeds than on their cultivated relatives.[94] The genetic material of the weeds could therefore be used to enhance cultivars of commercial crops to produce more resilient varieties.[95]

Productive landscapes can integrate biodiversity. While protected areas may be the cornerstones of conservation, they will never be enough to conserve biodiversity in the face of climate change (see focus B on biodiversity). The world's reserve network roughly quadrupled between 1970 and 2007 to cover about 12 percent of Earth's land,[96] but even that is inadequate to conserve biodiversity. To adequately represent the continent's species in reserves, while capturing a large proportion of their geographic ranges, Africa would have to protect an additional 10 percent of its land, almost twice its current protection.[97] Geographically fixed and often isolated by habitat destruction, reserves are ill-equipped to accommodate species range shifts due to climate change. One study of protected areas in South Africa, Mexico, and Western Europe estimates that between 6 and 20 percent of species may be lost by 2050.[98] Moreover, existing land reserves remain under threat given future economic pressures and frequently weak regulatory and enforcement systems. In 1999 the International Union for the Conservation of Nature determined that less than a quarter of protected areas in 10 developing countries were adequately managed and that more than 10 percent of protected areas were already thoroughly degraded.[99] At least 75 percent of protected forest areas surveyed in Africa lacked long-term funding, even though international donors were involved in 94 percent of them.[100]

A landscape-scale approach to land use can encourage greater biodiversity outside protected areas, which is essential to allow for ecosystem shifts, species dispersal and the promotion of ecosystem services. The field of ecoagriculture holds promise.[101] The idea is to improve the farmland's productivity and simultaneously conserve biodiversity and improve environmental conditions on surrounding lands. Through the methods of ecoagriculture, farmers can increase their agricultural output and reduce their costs, reduce agricultural pollution, and create habitat for biodiversity (figure 3.7).

Effective policies to conserve biodiversity give farmers strong incentives to minimize conversion of natural areas to farmland and to protect or even expand high quality habitat on their land. Other options include incentives to develop ecological networks and corridors between protected areas and other habitats. Studies in North America and Europe show that lands withdrawn from conventional agricultural production (set-asides) unequivocally increase biodiversity.[102]

Agriculture practices that enhance biodiversity often have many co-benefits, such as reducing vulnerability to natural disasters, enhancing farm income and productivity, and providing resilience to climate change. During Hurricane Mitch in 1998 farms using ecoagricultural practices suffered 58 percent, 70 percent, and 99 percent less damage in Honduras, Nicaragua, and Guatemala, respectively, than farms using conventional techniques.[103] In Costa Rica, vegetative windbreaks and fence rows boosted farmers' income from pasture and coffee while also increasing bird diversity.[104] In Zambia the use of leguminous trees[105] and herbaceous cover crops in improved fallow practices increased soil fertility, suppressed weeds, and controlled erosion, thereby almost trebling annual net farm incomes.[106] Bee pollination is more effective when agricultural fields are closer to natural or seminatural habitat,[107] a finding that matters because 87 of the world's 107 leading food crops depend on animal pollinators.[108] Shade-grown coffee systems can protect crops from extreme temperature and drought.[109]

In Costa Rica, Nicaragua, and Colombia silvopastoral systems that integrate trees with pastureland are improving the sustainability of cattle production and diversifying and increasing farmers' incomes.[110] Such systems will be particularly useful as a climate-change adaptation, because trees retain their foliage in most droughts, providing fodder and shade and thus stabilizing milk and meat production. They also can improve water quality. Agricultural production and revenues can go together with

Figure 3.7 Computer simulation of integrated land use in Colombia.

Source: Photograph by Walter Galindo, from the files of Fundación CIPAV (Centro para Investigación en Sistemas Sostenibles de Producción Agropecuaria), Colombia. The photograph represents the Finca "La Sirena," in the Cordillera Central, Valle del Cauca. Arango 2003.

Note: The first photo is the real landscape. The second figure is computer generated and shows what the area would look like if farm productivity were increased by using ecoagricultural principles. The increased productivity would reduce grazing pressure on hillsides, protecting watersheds, sequester carbon through afforestation, and increase habitat for biodiversity between fields.

biodiversity conservation. Indeed, in many cases intact ecosystems generate more revenues than converted ones. In Madagascar managing a 2.2 million hectare forest over 15 years cost $97 million, when accounting for the forgone economic benefits that would have occurred if the land had been converted to agriculture. But the benefits of the well-managed forest (half of which come from watershed protection and reduced soil erosion) were valued between $150 million and $180 million over the same period.[111]

Decades of development experience show how difficult it is in practice to protect habitats for biodiversity. New schemes are however emerging to give landowners strong financial incentives to stop land conversion. These include ways to generate revenues from the services that ecosystems provide to society (see focus B), conservation easements (which pay farmers to take sensitive land out of production),[112] and tradable development rights.[113]

Climate change will require faster adoption of technologies and approaches that increase productivity, cope with climate change, and reduce emissions

Several options will need to be pursued simultaneously to increase productivity. Agricultural research and extension has been underfunded in the past decade. The share of official development assistance for agriculture dropped from 17 percent in 1980 to 4 percent in 2007,[114] despite estimates that rates of return to investment in agricultural research and extension are high (30–50 percent).[115] Public expenditures on agricultural research and development (R&D) in low- and middle-income countries have increased slowly since 1980, from $6 billion in 1981 to $10 billion in 2000 (measured in 2005 purchasing power dollars), and private investments remain a small share (6 percent) of agricultural R&D in those countries.[116] Those trends will have to be reversed if societies are to meet their food needs.

The recently concluded Integrated Assessment of Agricultural Knowledge, Science, and Technology for Development (IAASTD) showed that successful agricultural development under climate change will involve a combination of existing and new approaches.[117] First, countries can build on the traditional knowledge of farmers. Such knowledge embodies a wealth of location-specific adaptation and risk management options that can be applied more widely. Second, policies that change the relative prices that farmers face have great potential to encourage practices that will help the world adapt to climate change (by increasing productivity) and mitigate it (by reducing agricultural emissions).

Third, new or unconventional farming practices can increase productivity and reduce carbon emissions. Farmers are beginning to adopt "conservation agriculture," which includes minimum tillage (where seeds are sowed with minimum soil disturbance and residue coverage on the soil surface is at least 30 percent), crop residue retention, and crop rotations. These tillage methods can increase yields,[118] control soil erosion and runoff,[119] increase water and nutrient-use efficiency,[120] reduce production costs, and in many cases sequester carbon.[121]

In 2008, 100 million hectares, or about 6.3 percent of global arable land, were farmed with minimum tillage—about double the amount in 2001.[122] Most takeup has been in developed countries, because the technique has heavy equipment requirements and has not been modified for conditions in Asia and Africa.[123] Minimum tillage also makes the control of weeds, pests, and diseases more complex, requiring better management.[124]

Nevertheless, in the rice-wheat farming system of the Indo-Gangetic plain of India, farmers adopted zero-tillage on 1.6 million hectares in 2005.[125] In 2007–08 an estimated 20–25 percent of the wheat in two Indian states alone (Haryana and Punjab) was cultivated under minimum tillage, corresponding to 1.26 million hectares.[126] Yields increased by 5–7 percent, and costs came down by $52 a hectare.[127] About 45 percent of Brazilian cropland is farmed using these practices.[128] The use of minimum tillage will probably continue to grow, particularly if the technique becomes eligible for payments for soil carbon sequestration in a compliance carbon market.

Biotechnology could provide a transformational approach to addressing the tradeoffs between land and water stress and agricultural productivity, because it could improve crop productivity, increase crop adaptation to climatic stresses such as drought and heat, mitigate greenhouse gas emissions, reduce pesticide and herbicide applications, and modify plants for better biofuel feedstocks (box 3.6). There is, however, little likelihood of genetic modification affecting water productivity in the short term.[129]

Climate-smart farming practices improve rural livelihoods while mitigating and adapting to climate change. New crop varieties, extended crop rotations (notably for perennial crops), reduced use of fallow land, conservation tillage, cover crops, and biochar can all increase carbon storage (box 3.7). Draining rice paddies at least once during the growing season and applying rice straw waste to the soil in the off-season could reduce methane emissions by 30 percent.[130] Methane emissions from livestock can also be cut by using higher-quality feeds, more precise feeding strategies, and improved grazing practices.[131] Better pasture management alone could achieve about 30 percent of the greenhouse gas abatement potential from agriculture (1.3 gigatons of CO_2e a year by 2030 over 3 billion hectares globally).[132]

As countries intensify agricultural production, the environmental impacts of soil fertility practices will come to the fore.[133] The developed world and many places in Asia

BOX 3.6 *Biotech crops could help farmers adapt to climate change*

Conventional selection and plant breeding have produced modern varieties and major productivity gains. In the future a combination of plant breeding and selection of preferred traits through genetic techniques (genetic modification, or GM) is likely to contribute most to producing crops better adapted to pests, droughts, and other environmental stresses accompanying climate change.

A number of crops with genetically modified traits have been broadly commercialized in the last 12 years. In 2007 an estimated 114 million hectares were planted with transgenic crop varieties, mostly with insect-resistant or herbicide-tolerant traits. More than 90 percent of this acreage was planted in only four countries (Argentina, Brazil, Canada, and the United States). These technologies will significantly reduce environmental pollution, increase crop productivity, cut production costs, and reduce nitrous oxide emissions. To date successful breeding programs have produced crop varieties, including cassava and maize, that resist a number of pests and diseases, and herbicide-tolerant varieties of soybean, rapeseed, cotton, and maize are available. Farmers using insect-resistant GM crops have reduced the amount of pesticides they use and the number of active ingredients in the herbicides they apply.

Genes affecting crop yield directly and those associated with adaptation to various types of stress have been identified and are being evaluated in the field. New varieties could improve the way crops cope with unreliable water supplies and potentially improve how they convert water. Breeding plants that can survive longer periods of drought will be even more critical in adapting to climate change. Initial experiments and field testing with GM crops suggest that progress may be possible without interfering with yields during nondrought periods, a problematic tradeoff for drought-tolerant varieties developed through conventional breeding. Drought-tolerant maize is nearing commercialization in the United States and is under development for African and Asian conditions.

Nevertheless, GM crops are controversial, and public acceptance and safety must be addressed. The public is concerned about the ethics of deliberately altering genetic material as well as about potential risks to food safety and the environment, and ethical concerns. After more than 10 years of experience, there has been no documented case of negative human health impacts from GM food crops, yet popular acceptance is still limited. Environmental risks include the possibility of GM plants cross-pollinating with wild relatives, creating aggressive weeds with higher disease resistance and the rapid evolution of new pest biotypes adapted to GM plants. However, scientific evidence and 10 years of commercial use show that safeguards, when appropriate, can prevent the development of resistance in the targeted pests and the environmental harm from commercial cultivation of transgenic crops, such as gene flow to wild relatives. Crop biodiversity may decrease if a small number of GM cultivars displace traditional cultivars, but this risk also exists with conventionally bred crop varieties. Impacts on biodiversity can be reduced by introducing several varieties of a GM crop, as in India, where there are more than 110 varieties of Bt (*Bacillus thuringiensis)* cotton. Although the track record with GM crops is good, establishing science-based biosafety regulatory systems is essential so that risks and benefits can be evaluated on a case-by-case basis, comparing the potential risks with alternative technologies and taking into account the specific trait and the agroecological context for using it.

Source: Benbrook 2001; FAO 2005; Gruere, Mehta-Bhatt, and Sengupta 2008; James 2000; James 2007; James 2008; Normile 2006; Phipps and Park 2002; Rosegrant, Cline, and Valmonte-Santos 2007; World Bank 2007c.

BOX 3.7 *Biochar could sequester carbon and increase yields on a vast scale*

Scientists investigating some unusually fertile soils in the Amazon basin found that the soil was altered by ancient charcoal-making processes. The indigenous people burned wet biomass (crop residues and manure) at low temperatures in the almost complete absence of oxygen. The product was a charcoal-type solid with a very high carbon content, called biochar. Scientists have reproduced this process in modern industrial settings in several countries.

Biochar appears to be highly stable in soil. Studies on the technical and economic viability of the technique are continuing, with some results indicating that biochar may lock carbon into the soil for hundreds or even thousands of years, while others suggest that in some soils the benefits are far less. Nevertheless, biochar can sequester carbon that would otherwise be released into the atmosphere through burning or decomposition.

So biochar could have great carbon mitigation potential. To give an idea of scale, in the United States waste biomass from forestry and agriculture, plus biomass that could be grown on land that is currently idle, would provide enough material for the United States to sequester 30 percent of its fossil fuel emissions using this technique. Biochar can also increases soil fertility. It binds to nutrients and could thus help regenerate degraded lands as well as reduce the need for artificial fertilizers and thus the pollution of rivers and streams. The potential is there. But there are two challenges: to demonstrate the chemical properties and to develop mechanisms for application on a large scale.

Research is needed in a number of areas, including methodologies to measure biochar's potential for long-term carbon sequestration; environmental risk assessment; biochar's behavior in different soil types; economic viability; and the potential benefits in developing countries.

Sources: Lehmann 2007a; Lehmann 2007b; Sohi and others 2009; Wardle, Nilsson, and Zackrisson 2008; Wolf 2008.

and Latin America may reduce fertilizer use to reduce both greenhouse gas emissions and the nutrient runoff that harms aquatic ecosystems. Changing the rate and timing of fertilizer applications reduces the emissions of nitrous oxide from soil microbes. Controlled-release nitrogen[134] improves efficiency (yield per unit of nitrogen), but so far it has proved too expensive for many farmers in developing countries.[135] New biological inhibitors that reduce the volatilization of nitrogen could achieve many of the same goals more cheaply. They are likely to be popular with farmers because they involve no extra farm labor and little change in management.[136] If producers and farmers have incentives to apply new fertilizer technology and to use fertilizers efficiently, many countries could maintain agricultural growth even as they reduce emissions and water pollution.

In Sub-Saharan Africa, by contrast, natural soil fertility is low, and countries cannot avoid using more inorganic fertilizer. Integrated adaptive management programs with site-specific testing and monitoring can reduce the risk of overfertilizing. But such programs are still rare in most developing countries because there has not been enough public investment in the research, extension, and information services necessary for effective implementation—a recurring theme of this chapter.

Part of achieving the necessary increase in agricultural productivity in the developing world, sound fertilizer policy includes measures to make fertilizers affordable to the poor.[137] It also includes broader programs, such as the Farm Inputs Promotion program in Kenya that works with local companies and subsidiaries of international seed companies to improve agricultural inputs (by formulating fertilizers using locally available minerals, providing improved seed varieties, and distributing fertilizer in rural areas) and to promote sound agronomic practices (correct fertilizer placement, soil management, and effective weed and pest control).

Produce more and protect better in fisheries and aquaculture

Marine ecosystems will have to cope with stresses as least as great as those on land

The oceans have absorbed about half the anthropogenic emissions released since 1800,[138] and more than 80 percent of the heat of global warming.[139] The result is a warming, acidifying ocean, changing at an unprecedented pace with impacts across the aquatic realm (see focus A on the science of climate change).[140]

Ecosystem-based management can help coordinate an effective response to fisheries in crisis. Even without climate change, between 25 and 30 percent of marine fish stocks are overexploited, depleted, or recovering from depletion—and are thus yielding less than their maximum potential. About 50 percent of stocks are fully exploited and producing catches at or close to their maximum sustainable limits, with no room for further expansion. The proportion of underexploited or moderately exploited stocks declined from 40 percent in the mid-1970s to 20 percent in 2007.[141] It may be possible to get more value from the fish caught—for example, by reducing the fish caught unintentionally, estimated at one-quarter of the world fish catch.[142] It is likely that the maximum potential of fisheries in the world's oceans has been reached, and only more sustainable practices can maintain the productivity of the sector.[143]

Ecosystem-based management, which considers an entire ecosystem rather than a particular species or site and recognizes humans as integral elements in the system, can effectively protect the structure, functioning, and key processes of coastal and marine ecosystems.[144] Policies include coastal management, area-based management, marine protected areas, limits on fishing effort and gear, licensing, zoning, and coastal law enforcement. Managing marine ecosystems effectively also involves managing activities on land to minimize the eutrophication episodes that stress marine ecosystems, such as coral reefs, in many parts of the world.[145] The economic value of coral reefs can be many times that of the agriculture that caused the problems.[146]

The developing world already has some success stories. A program at Danajon Bank reef in the central Philippines has begun increasing fish biomass over the historical level.[147] Indeed, some developing countries implement ecosystem-based management more effectively than many developed countries.[148]

Climate change will create new pressures—an expected increase in food prices, increased demand for fish protein, and the need to protect marine ecosystems—that could prompt governments to implement long-advocated reforms. These include reducing catch to sustainable levels, and getting rid of perverse subsidies, which fuel the overcapacity of fishing fleets.[149] The annual number of newly built fishing vessels is less than 10 percent of the level in the late 1980s, but overcapacity is still a problem.[150] The global cost of poor governance of marine capture fisheries is an estimated $50 billion a year.[151] Rights-based catch shares can provide individual and community incentives for sustainable harvests. These schemes can grant rights to various forms of dedicated access, including community-based fishing, as well as impose individual fishing quotas.[152]

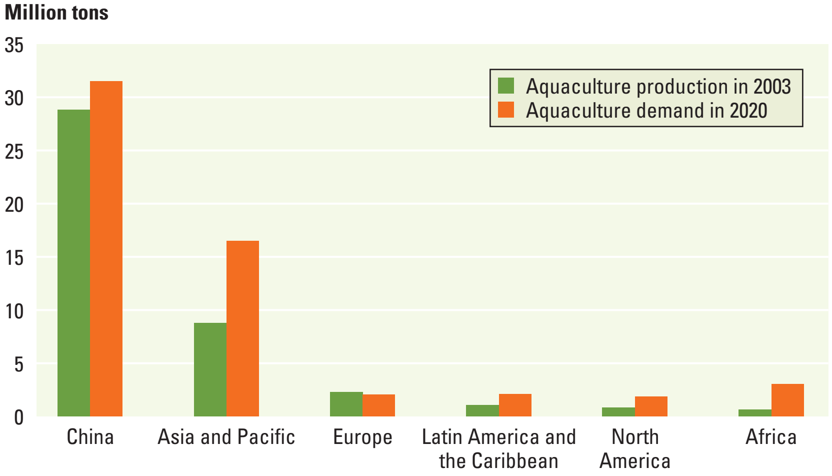
Aquaculture will help meet growing demand for food

Fish and shellfish currently supply about 8 percent of the world animal protein consumed.[153] With the world population growing by about 78 million people a year,[154] fish and shellfish production must grow by about 2.2 million metric tons every year to maintain current consumption of 29 kilograms per person each year.[155] If capture fish stocks fail to recover, only aquaculture will be able to fill the future demand.[156]

Aquaculture contributed 46 percent of the world's fish food supply in 2006,[157] with average annual growth (7 percent) outpacing population growth over the last decades. Productivity has increased by an order of magnitude for some species, driving down prices and expanding product markets.[158] Developing countries, mostly in the Asia-Pacific region, dominate production. Of the fish eaten in China, 90 percent comes from aquaculture.[159]

Demand for fish from aquaculture is projected to increase (figure 3.8), but climate change will affect aquaculture operations worldwide. Rising seas, more severe storms, and saltwater intrusion in the main river deltas of the tropics will damage aquaculture, which is based on species with limited saline tolerance, such as catfish in the

Figure 3.8 Demand for fish from aquaculture will increase, particularly in Asia and Africa



Source: De Silva and Soto 2009.

Mekong Delta. Higher water temperatures in temperate zones may exceed the optimal temperature range of cultivated organisms. And as temperatures rise, diseases affecting aquaculture are expected to increase both in incidence and impact.[160]

Aquaculture is expected to grow at a rate of 4.5 percent a year between 2010 and 2030.[161] But sustainable growth for the sector entails overcoming two major obstacles. First is the extensive use of fish proteins and oils as fishmeal, which keeps the pressure on capture fisheries.[162] The growth in aquaculture will have to come from species not dependent on feed derived from fishmeal; today, 40 percent of aquaculture depends on industrial feeds, much from marine and coastal ecosystems, which are already stressed.[163] Plant-based aquaculture feeds (such as oil-seed-based feed) are promising,[164] and some operations have completely replaced fishmeal with plant-based feeds in the diets of herbivorous and omnivorous fish, without compromising growth or yields.[165] The emphasis on cultivating herbivorous and omnivorous species—currently about 7 percent of total production—makes sense for resource efficiency.[166] For example, production of one kilogram of salmon, marine finfish, or shrimp in aquaculture systems is highly resource-intensive, requiring between 2.5–5 kilograms of wild fish as feed for one kilogram of food produced.[167]

Second, aquaculture can cause environmental problems. Coastal aquaculture has been responsible for 20 to 50 percent of the loss of mangroves worldwide;[168] further losses compromise climate resiliency of the ecosystems and make coastal populations more vulnerable to tropical storms. Aquaculture also can result in the discharge of wastes into marine ecosystems that in some areas contributes to eutrophication. New effluent management techniques—such as recirculation of water,[169] better calibration of feed, and integrated and polyculturing in which complementary organisms are raised together to reduce wastes[170]—can lessen the environmental impacts. So can appropriate aquaculture development in underexploited bodies of water, such as rice paddies, irrigation canals, and seasonal ponds. Integrated agriculture-aquaculture schemes promote recycling of nutrients, so that wastes from aquaculture can become an input (fertilizer) for agriculture and vice-versa, thereby optimizing resource use and reducing pollution.[171] These systems have diversified income and provided protein for households in many parts of Asia, Latin America, and Sub-Saharan Africa.[172]

Building flexible international agreements

Managing natural resources in order to cope with climate change entails better international collaboration. It also demands more reliable international food trade so that countries are better placed to cope with climate shocks and reduced agricultural potential.

Countries that share watercourses will need to agree on how to manage them

About one-fifth of the world's renewable freshwater resources cross or form international borders, and in some regions, particularly in developing countries, the share is far higher. However, only 1 percent of such waters is covered by any kind of treaty.[173] Moreover, few of the existing treaties on international watercourses encompass all the countries touching the watercourse in question.[174] The United Nations Convention on the Law of the Non-Navigational

Uses of International Watercourses, which was adopted by the UN General Assembly in 1997, has yet to command sufficient ratifications to enter into force.[175]

Cooperation among riparian countries is essential to address water challenges caused by climate change. Such cooperation can be achieved only through inclusive agreements that make all the riparian countries responsible for the joint management and sharing of the watercourse and that are designed to address increased variability from both droughts and floods. Typically water agreements are based on allocating fixed quantities of water to each party; climate change makes this concept problematic. Allocations based on percentages of flow volume would better address variability. Even better would be a "benefit- sharing" approach, where the focus is not on water volumes but on the economic, social, political, and environmental values derived from water use.[176]

Countries will need to work together to better manage fisheries

Fish is the most international of food commodities. One-third of global fish production is traded internationally, the highest ratio for any primary commodity.[177] As their fish stocks have declined, European, North American, and many Asian nations have begun importing more fish from developing countries.[178] This increased demand, combined with the overcapitalization of some fishing fleets (the European fleet is 40 percent larger than the fish stocks can accommodate), is spreading the depletion of marine resources to the southern Mediterranean, West Africa, and South America. And despite the multibillion dollar-a-year international trade in fisheries, developing countries receive relatively little in fees from foreign fishing fleets operating in their waters. Even in the rich tuna fishery of the western Pacific, small island developing states receive only about 4 percent of the value of the tuna taken.[179] By modifying the distribution of fish stocks, changing food webs, and disrupting the physiology of already stressed fish species, climate change will only make things worse.[180] Fleets facing further declines in stocks may venture even farther afield, and new agreements on resource sharing will need to be negotiated.

To facilitate adaptation and regulate fishery rights, it is important to develop international resource management regimes, both legal and institutional, and associated monitoring systems. Such agreements might be facilitated by strengthening regional fisheries management organizations.[181] The Benguela Current's Large Marine Ecosystem Programme is a promising development. Running along the west coast of Angola, Namibia, and South Africa, the Benguela ecosystem is one of the most highly productive in the world, supporting a reservoir of biodiversity including fish, seabirds, and sea mammals. Within the ecosystem there is already evidence that climate change is shifting the ranges of some key commercial species poleward from the tropics.[182] This shift compounds existing stresses from overfishing, diamond mining, and oil and gas extraction. Angola, Namibia, and South Africa established the Benguela Current Commission in 2006, the first such institute created for a large marine ecosystem. The three countries committed to integrated management of the fishery in order to adapt to climate change.[183]

More reliable trade in agricultural commodities will help countries experiencing unexpected weather extremes

Even if farmers, businesses, governments, and water managers dramatically increase the productivity of land and water, some parts of the world will not have enough water to always grow all of their food. Deciding how much food to import and how much to grow domestically has implications for agricultural productivity and water management (box 3.8). Seeking food self-sufficiency when resource endowments and growth potential are inadequate will impose heavy economic and environmental costs.

Many countries already import a large share of their food—most Arab countries import at least half of the food calories they consume—and increasingly harsh conditions mean that all countries need to prepare

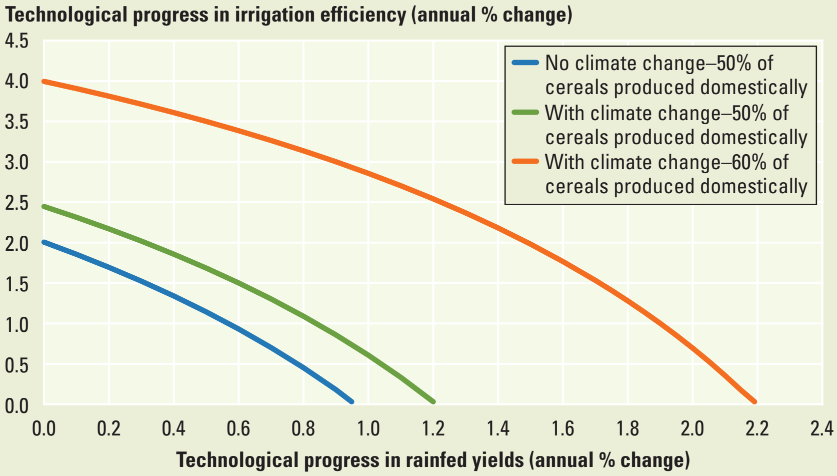
BOX 3.8 *Policy makers in Morocco face stark tradeoffs on cereal imports*

Morocco, with severe water constraints and a growing population, imports half its cereals. Even without climate change, if it wishes to maintain cereal imports at no more than 50 percent of demand without increasing water use, Morocco would have to make technical improvements to achieve a combination of two options: either 2 percent more output per unit of water allocated to irrigated cereals or 1 percent more output per unit of land in rainfed areas (blue line in figure).

Adding in the effects of higher temperatures and reduced precipitation makes the task more challenging: technological progress will need to be 22–33 percent faster than without climate change (depending on the policy instruments selected) (green line in figure). But if the country wants more protection against domestic climate shocks to agriculture and against market price shocks and decides to increase the share of its consumption produced domestically from 50 percent to 60 percent, it has to increase water efficiency every year by 4 percent in irrigated agriculture, or by 2.2 percent in rainfed areas, or any combination in between (orange line). In other words, a robust response to climate change could require Morocco to implement technical improvements between 100 percent and 140 percent faster than it would have had to without climate change. Reducing net imports could only be achieved if Morocco made much higher efficiency gains domestically.

Source: World Bank, forthcoming a.

Achieving cereal self-sufficiency without increasing water use in Morocco



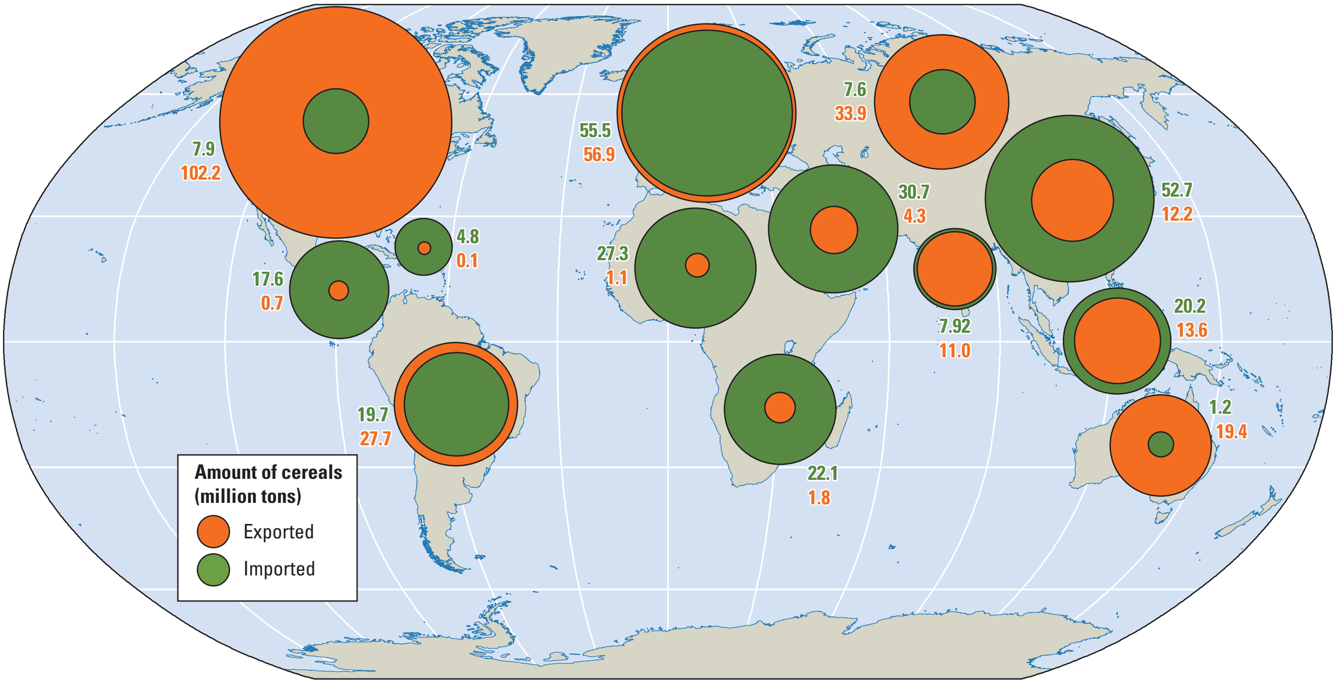
for failure of domestic crops.[184] Climate change will make today's arid countries drier, compounding the increased demand from growing income and populations. Therefore, more people will live in regions that consistently import a large share of their food every year. In addition, more people will live in countries that experience shocks to domestic agriculture, as climate change increases the likelihood and severity of extreme climate events. Several global scenarios project a 10–40 percent increase in net imports by developing countries as a result of climate change.[185] Trade in cereals is projected to more than double in volume by 2050, and trade in meat products to more than quadruple.[186] And most of the increased dependence on food imports will come in developing countries.[187]

As the sharp rise of food prices in 2008 illustrated, the global food market is volatile. Why did the prices spike? First, grain markets are thin: only 18 percent of world wheat and 6 percent of world rice are exported. The rest is consumed where it is grown.[188] And only a few countries export grain (map 3.5). In thin markets, small shifts in either supply or demand can make a big difference in price. Second, per capita global food stocks were at one of the lowest levels on record. Third, as the market for biofuel increased, some farmers shifted out of food production, contributing significantly to increases in world food prices.

When countries do not trust international markets, they respond to price hikes in ways that can make things worse. In 2008 many countries restricted exports or controlled prices to try to minimize the effects of higher prices on their own populations, including Argentina, India, Kazakhstan, Pakistan, Russia, Ukraine, and Vietnam. India banned exports of rice and pulses, and Argentina raised export taxes on beef, maize, soybeans, and wheat.[189]

Export bans or high export tariffs make the international market smaller and more volatile. For example, export restrictions on

Map 3.5 World grain trade depends on exports from a few countries



Source: FAO 2009c.
Note: Annual exports and imports are based on the average over four years (2002–2006).

rice in India affect Bangladeshi consumers adversely and dampen the incentives for rice farmers in India to invest in agriculture, a long-term driver of growth. In addition, export bans stimulate the formation of cartels, undermine trust in trade, and encourage protectionism. Domestic price controls can also backfire by diverting resources from those who need them most and by reducing incentives for farmers to produce more food.

Countries can take measures to improve access to markets

Countries can take unilateral action to improve their access to international food markets, a particularly important step for small countries whose actions do not affect the market but that nonetheless import a large share of their food. One of the simplest ways is to improve procurement methods. Sophisticated measures for issuing tenders to import food, such as electronic tendering and bidding and advanced credit and hedging products, could all help governments get a better deal. Another option would be to relax national laws that prohibit multinational procurement so that small countries can group together for economies of scale.[190]

A third measure is active management of stocks. Countries need robust national stockpiling and the latest instruments in risk hedging, combining small physical stockpiles with virtual stockpiles purchased through futures and options. Models indicate that futures and options could have saved Egypt between 5 and 24 percent of the roughly $2.7 billion it spent purchasing wheat between November 2007 and October 2008, when prices were soaring.[191] Global collective action in managing stocks would also help prevent extreme price spikes. A small physical food reserve could allow a smooth response to food emergencies. An international coordinated global food reserve could reduce pressures to achieve grain self-sufficiency. And an innovative virtual reserve could prevent market price spikes and keep prices closer to levels suggested by long-run market fundamentals without putting the coordinated global reserves at risk.[192]

Weatherproofing transport services is also critical to ensure year-round access to markets, particularly in countries such as Ethiopia, with high variability in regional rainfall. Increased investments in improving logistics in the supply chain—roads, ports, customs facilities, wholesale markets, weighbridges, and warehouses—would help get more food to consumers at a lower price. But institutional infrastructure is also needed. Transparency, predictability, and honesty in customs and warehousing are as important as the facilities.

Importing countries can also invest in various parts of the supply chain in producing countries. It may also be possible, and indeed less risky, to focus on supply chain infrastructure or agricultural research and development in the producing countries.

International rules to regulate trade will remain an important part of the picture

The World Trade Organization's Doha Development Agenda sought to eliminate trade barriers and improve market access for developing countries. But negotiations were suspended in 2008. One study concludes there would be a potential loss of at least $1.1 trillion in world trade if world leaders fail to conclude the Doha Round.[193] Completing this agreement would be a key first step in improving international food trade. Key measures include pulling down effective tariff rates and reducing agricultural subsidies and protection by developed countries.[194]

Reliable information is fundamental for good natural resource management

Investments in weather and climate services pay for themselves many times over, yet these services are sorely lacking in the developing world

Typically the ratio of the economic benefits to the costs of national meteorological services is in the range of 5–10 to 1,[195] and a 2006 estimate suggests it could be 69 to 1 in China.[196] Weather and climate services can ameliorate the impacts of extreme events to some degree (see chapters 2 and 7). According to the United Nations International Strategy for Disaster Reduction, advance flood warnings can reduce flood damage by up to 35 percent.[197] Much of the developing world, particularly in Africa, urgently needs better monitoring and forecasting systems for both weather and hydrological change (map 3.6). According to the World Meteorological Organization, Africa has only one weather station per 26,000 square kilometers—one-eighth the recommended minimum.[198] Data rescue and archiving will also be important because long records of high-quality data are necessary to fully understand climate variability. Many of the world's climate datasets contain digital data back to the 1940s, but only a few have digital archives of all available data before then.[199]

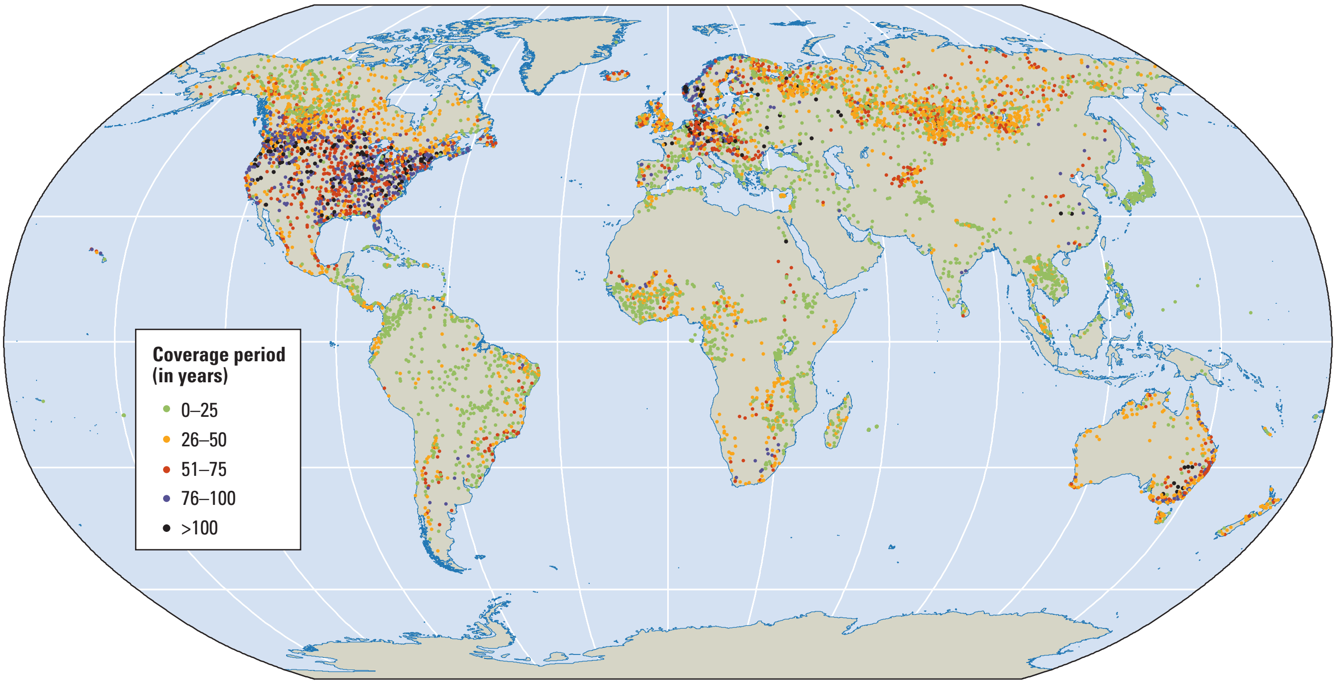
Better forecasts would improve decision making

In Bangladesh the forecasts for precipitation extend only to one to three days; longer forecasts would allow farmers time to modify planting, harvesting, and fertilizer applications, especially in rainfed cropping areas where food crises can last for many months. There have been significant improvements in seasonal climate forecasts (how precipitation and temperature over the course of a few months will vary from the norm), particularly in the tropics and in areas affected by the El Niño Southern Oscillation (ENSO).[200] The onset of monsoon rainfall in Indonesia and the Philippines and the number of rainy days in a season in parts of Africa, Brazil, India, and Southeast Asia can now be predicted with greater precision.[201] ENSO-based seasonal forecasts in South America, South Asia, and Africa have good potential for improving agricultural production and food security.[202] For example, in Zimbabwe subsistence farmers increased yields (ranging from 17 percent in good rainfall years to 3 percent in poor rainfall years) when they used seasonal forecasts to modify the timing or variety of the crops planted.[203]

New remote-sensing and monitoring technologies hold great promise for sustainability

One reason that policy makers have found it so difficult to curb the overexploitation of

Map 3.6 Developed countries have more data collection points and longer time series of water monitoring data



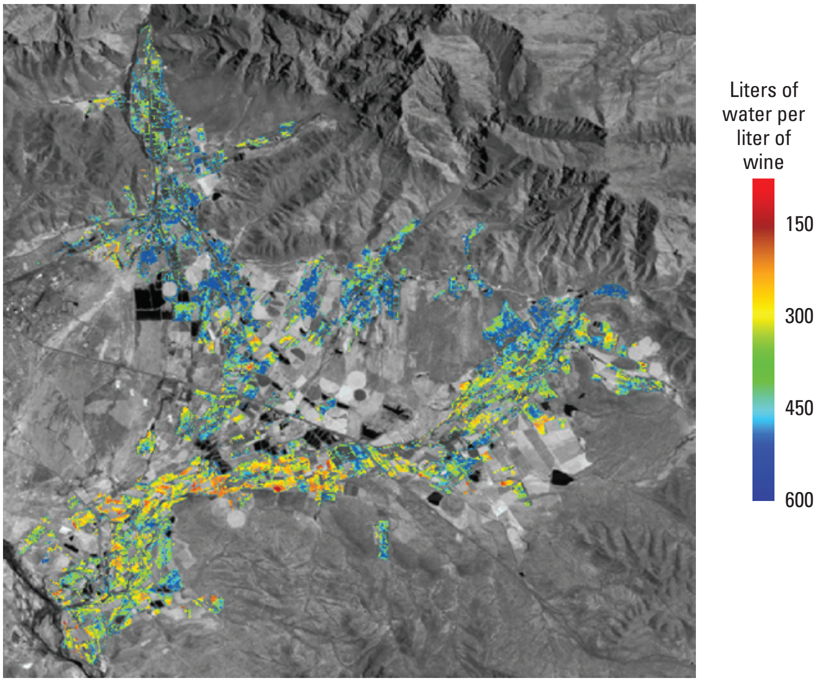
Source: Dataset for global distribution and time series coverage was provided by the Global Runoff Data Center.
Note: The map shows the discharge monitoring stations that provide information on river runoff.

land and water and their related ecosystems is that neither the managers nor the users of the resources have accurate and timely information. They don't know how much of the resource is present, how much is being used, or how their actions will affect quantities in the future. But new remote-sensing technologies are beginning to fill some of that gap, informing decisions about more efficient allocations of water and helping with enforcement of water limits.

One of the most promising applications of remote sensing measures water's productivity.[204] When thermal images from satellites are combined with field data on crop types and linked to maps from geographic information systems, scientists can measure yields on any geographic scale (the farm, the basin, or the country). That allows water managers to make better decisions about water allocations and to target advisory services to the farmers with lowest water productivity. It also guides important investment decisions—say, between increasing the productivity of rainfed or irrigated agriculture. And it can help managers measure the actual results of investments in irrigation water-saving techniques, difficult in the past (figure 3.9).

Until recently, measuring groundwater consumption was difficult and expensive in all countries, and it simply was not done in many developing countries. Taking inventories of hundreds of thousands of private wells and installing and reading meters was too costly. But new remote-sensing technology can measure total evaporation and transpiration from a geographic area. If the surface water applied to that area through precipitation and surface-water irrigation deliveries is known, the net consumption of groundwater can be imputed.[205] Various countries are experimenting with using information from new remote-sensing technologies to enforce groundwater limits, including those Moroccan farmers who are considering converting to drip irrigation (discussed at the beginning of the chapter). Options for enforcement include pumps that shut off automatically when the farmer exceeds the evapotranspiration limit and systems that simultaneously send text messages to farmers' cell phones, warning them

Figure 3.9 Remote-sensing techniques are used in the vineyards of Worcester (West Cape, South Africa) to gauge water productivity



Source: Water Watch, www.waterwatch.nl (accessed May 1, 2009).

Note: Farmers whose fields are red are using one-fourth as much water per liter of wine than those whose fields are shown in blue. In addition to gauging water productivity, governments can also use these techniques to target the activities of advisory and enforcement services.

they are about to exceed their allocation of groundwater, and alert inspectors to monitor those particular farms.[206]

Digital maps created from remote-sensing information will help resource managers at many levels. Using information from remote sensing to create digital maps of all of Africa's soils will be very useful for sustainable land management. Current soil maps are 10–30 years old and generally not digitized, making them inadequate to inform policies to address soil fertility and erosion. An international consortium is using the latest technologies to prepare a digitized global map, starting with the African continent.[207] Satellite imagery and new applications now allow scientists to measure streamflow, soil moisture and water storage (lakes, reservoirs, aquifers, snow, and ice) and to forecast floods. They also make it possible to show crop yields, crop stress, CO_2 uptake, species composition and richness, land cover and land-cover change (such as deforestation), and primary productivity. They can even map the spread of individual invasive plant species.[208] The scales vary, as does the timing of updates. But rapid advances allow managers to measure with a precision and regularity undreamed of only a few years ago. Depending on the satellite and weather conditions, the data can be available daily or even every 15 minutes.

Research and development will be necessary to take full advantage of these new information technologies. There is great scope for applying new technologies and information systems to manage natural resource issues associated with climate change. Investments in satellite data for natural resource management can pay off in the long run. But the potential is far from being met, especially in the poorest countries. A study in the Netherlands concluded that additional investments in satellite observations for water quality management (eutrophication, algal blooms, turbidity), including the capital costs of the satellite, has a 75 percent probability of producing financial benefits.[209] Research and development of these tools and their application in developing countries are thus ripe for public and private investment.[210]

More reliable information can empower communities and change the governance of natural resources

Natural resource management often requires governments to set and enforce laws, limits, or prices. Political and socioeconomic pressures make this very difficult, especially where formal institutions are weak. But when resource users have the right information about the impacts of their actions, they can bypass governments and work together to reduce overexploitation, often increasing their revenues. Making a strong economic case for reform can help, as in a recent study that highlighted the global cost of poor governance in marine capture fisheries.[211]

India offers several examples of better information resulting in more efficient agricultural production and welfare gains. In the state of Madhya Pradesh a subsidiary of Indian Tobacco Company (ITC) developed a system called eChoupals to lower its procurement cost and improve the quality of soybeans that it received from farmers. The eChoupals are village Internet kiosks run by local entrepreneurs who provide price information on soybean futures to farmers and enable them to sell their produce directly to ITC, bypassing the middlemen and wholesale market yards (*mandis*). Through the eChoupals ITC spends less per ton of produce, and farmers immediately know the price they will receive, reducing waste and inefficiency. The payback period for the initial capital cost of developing the kiosks is about four to six years.[212]

A project sponsored by the UN's Food and Agriculture Organization in Andhra Pradesh, India, has dramatically reduced the overexploitation of aquifers. It used low-tech and low-cost approaches to enable communities to assess the state of their own resources. Rather than use expensive equipment and specialist hydrogeologists, the project brought in sociologists and psychologists to assess how best to motivate the villagers to cut current water consumption. It created "barefoot hydrogeologists," to teach local people about the aquifer that sustained their livelihoods (figure 3.10). These non-specialist, often illiterate, farmers are generating such good data that they even sell it to the government hydrogeological services. Through this project, awareness of the impacts of their actions, social regulation, and information about new crop varieties and techniques led the villagers to agree to change crops and adopt practices to reduce evaporative losses.

With almost 1 million farmers, the project is entirely self-regulating, and there are no financial incentives or penalties for noncompliance. Participating villages have reduced withdrawals, while withdrawals from neighboring villages continue to increase. For an undertaking of this scale, the cost is remarkably low—$2,000 a year for each of the 65 villages.[213] It has great potential for replication, but principally in the hard-rock aquifers that empty and refill quickly and that do not have vast lower layers common in other geological formations.[214]

These initiatives to encourage users to reduce overexploitation of natural resources can reduce dependence on overstretched government agencies and overcome broader governance issues. They can also be tools for governments, working with communities, to change user behavior. The Hai basin, the most water-scarce in China, is extremely important for agriculture. Together with two neighboring basins, it produces half of China's wheat. Water resources in the Hai basin are polluted, wetland ecosystems threatened, and groundwater severely overexploited. Every year the basin uses 25 percent more groundwater than it receives as precipitation.[215]

In this same basin, the Chinese government worked with 300,000 farmers to innovate in water management. This initiative focused on reducing overall water consumption rather than simply increasing water productivity. It combined investments in irrigation infrastructure with advisory services to help optimize soil water. It limited the use of aquifer water. It introduced new institutional arrangements, such as transferring responsibility for managing irrigation services to groups of farmers and improving cost-recovery for surface water irrigation. And it used the latest monitoring techniques, by measuring water productivity and groundwater consumption at the plot level with satellite data, combined with more traditional agronomic services. The monitoring provides real-time

Figure 3.10 In Andhra Pradesh, India, farmers generate their own hydrological data, using very simple devices and tools, to regulate withdrawals from aquifers

Source: Bank staff.

Note: Armed with information, each farmer sets his or her own limit for how much water to safely extract each growing season. Technical assistance helps them get higher returns for the water they use by managing soil water better, switching crops, and adopting different crop varieties.

information to policy makers and farmers so that they can adjust their practices, and detect noncompliance.[216]

The results have been impressive. Farmers increased their incomes while reducing water consumption by switching to higher-value crops. Cash crop production tripled, farm incomes increased up to fivefold in many areas, and agricultural production per unit of water consumed increased 60–80 percent. Total water use in the area fell by 17 percent, with the rate of groundwater depletion at 0.02 meters a year, compared with 0.41 meters a year outside the project areas.

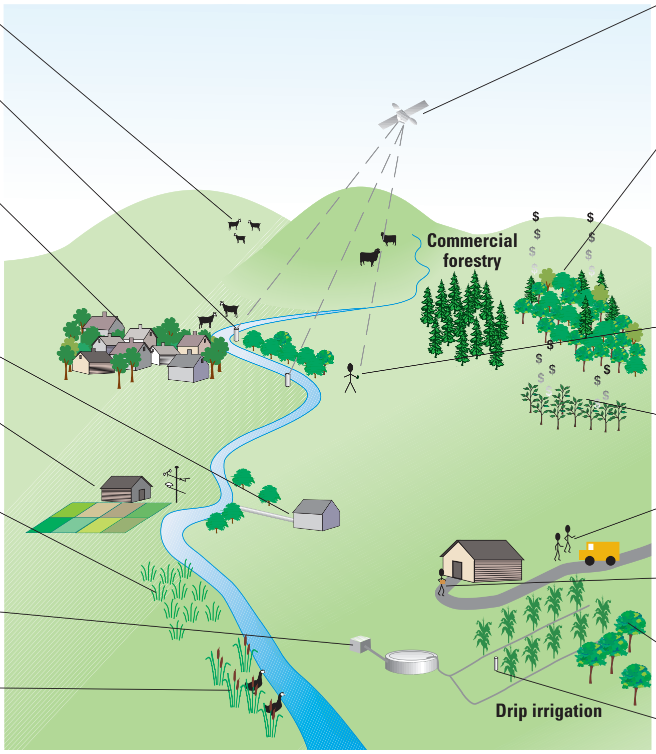
In summary, technologies and tools exist or are being developed to help farmers and other resource managers manage water, land, farms, and fisheries. In an ideal world the right people would have access to these technologies and tools. But they will be effective only with the right policies and infrastructure. This ideal world is represented pictorially in figures 3.11 and 3.12. Many of the steps toward this ideal world have frustrated societies for decades in the past. But circumstances are changing in ways that might accelerate progress.

Pricing carbon, food, and energy could be the springboard

This chapter suggests many new approaches to help developing countries cope with the additional stress that climate change will put on efforts to manage land and water resources well. It emphasizes repeatedly that new technologies and new investments will bear fruit only in a context of strong institutions and sensible policies—when the "fundamentals" are right. Yet the fundamentals are not right in many of the world's poorest countries. And getting them right—building strong institutions, changing subsidy regimes, changing the way valuable commodities are allocated—is a long-term process even in the best of circumstances.

To compound the problems, many of the responses this chapter proposes to help countries improve land and water

Figure 3.11 An ideal climate-smart agricultural landscape of the future would enable farmers to use new technologies and techniques to maximize yields and allow land managers to protect natural systems, with natural habitats integrated into agriculturally productive landscapes



Rangeland
with hardy varieties of livestock

Physical monitoring systems
- measure available water
- provide flood and other natural disaster warnings

Traditional communities
self regulate groundwater and grazing in response to carbon credit incentives: farmers use soil and water conservation techniques; plant natural windbreaks; establish buffer zones and fallow land to provide habitats for biodiversity

Conveyance
to direct stormwater to recharge aquifers

Research station
finds new ways to adapt crops and management techniques to new climatic conditions

Conservation tillage and intercropping
used to grow rain-fed crops
Biochar made from crop residue sequesters carbon and fertilizes the soil

Pump accesses groundwater for dry years and automatically shuts off when safe extraction is exceeded

Planned reserves
to allow species movement in response to climate change

Remote sensing systems
- measure species movement
- monitor safe extraction of water
- provide early warning for floods, droughts and landslides
- detect deforestation

Original forest ecosystem
- investors receive income based on carbon stored in soil and biomass
- indigenous communities receive income for verifying that deforestation is avoided and biodiversity preserved
- planned reserves to allow species movement in response to changing climate

Farmer receives SMS messages from remote sensing system with alerts about excess water consumption, crop water stress, etc.

Tea plantation
pays forest conservation fund for pollination and soil preservation services provided by the forest

Private and public advisory services
help farmers adopt new agronomic developments

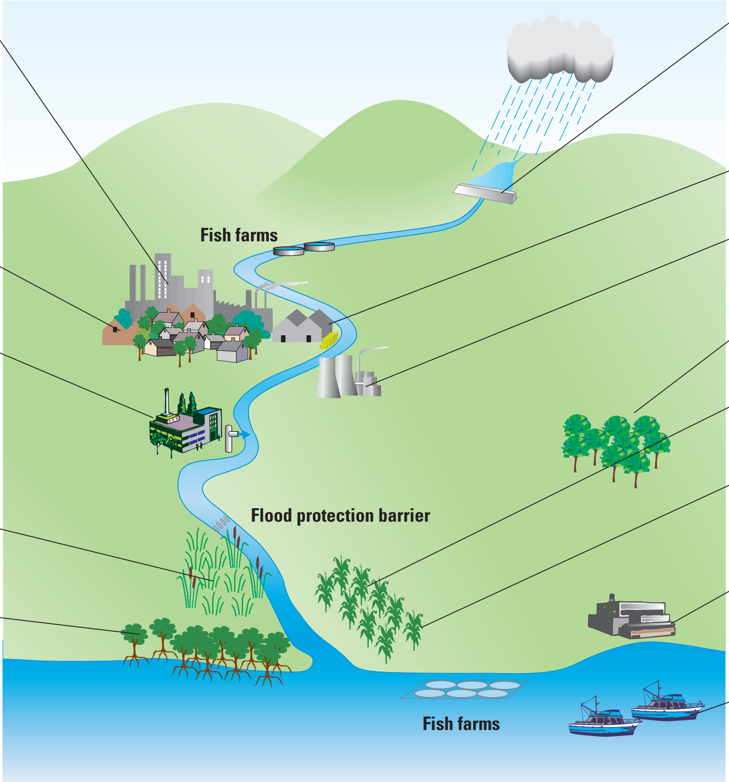
Skilled employees
store, process and pack products for direct contracts with markets

Carbon credits encourage farmers to intersperse crops with trees that provide habitat biodiversity

Water monitors
measure soil moisture

Source: WDR team.

Figure 3.12 An ideal climate-smart landscape of the future would use flexible technology to buffer against climate shocks through natural infrastructure, built infrastructure, and market mechanisms



City
built away from the flood plain
- distributed energy system including renewables
- planned for low-carbon transport
- buildings use low environmental-impact materials
- road materials and drainage designed for increased temperatures and severe storms

Bonded warehouse
for grain stocks to buffer price shocks in international grain market

Wastewater treatment plant
treated water
- injected into aquifer to protect against saline intrusion
- piped to coastal wetlands to counteract excess abstraction
- used for irrigation upstream

Wetlands
preserved to sequester carbon, provide habitat, and purify water

Mangroves protected:
- in response to incentives from carbon credits
- to provide ecosystem services, including fish nursery and storm protection

Dam
- provides energy, irrigation, and drought and flood protection
- re-engineered to cope with extreme rainfall and minimize environmental damage

Upgraded port and customs facility
to facilitate international trade

Power station
carbon captured and stored underground

Bio-engineered trees
sequester carbon in former wasteland

Modern crop varieties
adapted to climate change stress

Coastal agriculture
with irrigation from coastal aquifers protected from saline intrusion

Desalination plant
- uses renewable energy
- provides water to city and coastal agriculture

Regulated fishery
ensures catch is at sustainable levels

Source: WDR team.

management in the face of climate change require farmers, many of them among the world's poorest, to change their practices. It also requires people operating beyond the law (illegal loggers, illegal miners) and wealthy, influential people (including property developers) to stop practices that have brought them extreme profits. This chapter is proposing accelerating actions that have at best seen slow progress in the past few decades. Is it realistic to expect change on a sufficient scale to really tackle the challenge climate change confronts us with?

Three new factors might provide the stimulus for change and overcome some of the barriers that have hampered these improvements in the past. First, climate change is expected to increase the price of energy, water, and land and thus of food and other agricultural commodities. That will increase the pace of innovation and accelerate the adoption of practices that increase productivity. Of course higher prices will also make it more profitable to overexploit resources or encroach on natural habitats. Second, a carbon price applied to carbon in the landscape, may encourage landowners to conserve natural resources. If implementation difficulties could be overcome, this would buy down the risk to farmers of adopting new practices. It might also give landowners the right incentives to protect natural systems. Third, if the world's $258 billion a year in agricultural subsidies were even partially redirected to carbon sequestration and biodiversity conservation, it would demonstrate the techniques and approaches outlined in this chapter on the necessary scale.

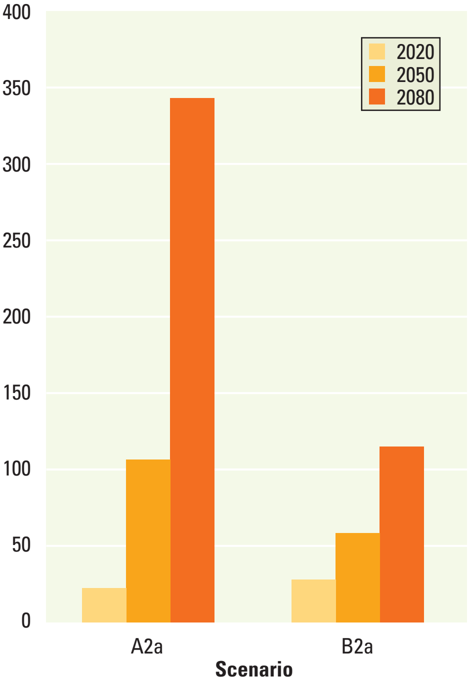
Rising energy, water, and agricultural prices could spur innovation and investment in increasing productivity

A combination of factors will drive up food prices in the next few decades. They include increased demand for food from growing and increasingly rich populations. They also include increased production of biofuels, which could result in competition for agricultural land and water. Furthermore, it will become more difficult to grow food because of climate change. And as chapter 4 shows, climate change policies are likely to drive up energy prices.[217]

Higher electricity prices mean higher water prices when water is pumped. In those cases, efficient water allocation mechanisms will become more important, as will efforts to reduce leaks from any poorly maintained water transfer and distribution networks. Higher energy prices also increase the cost to the government of subsidizing water services. This could increase incentives for long-needed reform of water management policies and investments.[218] And because fertilizers are a petroleum-based product, higher oil prices will encourage more judicious use.

Figure 3.13 Global cereal prices are expected to increase 50 to 100 percent by 2050

Cereal price increase without CO_2 fertilization (percentage change)



Source: Parry and others 2004.

Note: The IPCC SRES A2 family of emission scenarios describes a world where population continues to grow, and the trends of per capita income growth and technological change vary between regions and are slower than in other story lines. The B2 scenario family describes a world where global population grows at a rate lower than in A2, economic development is intermediate, and technological change is moderate.

Food prices are expected to be higher and more volatile in the long run. Modeling for the IAASTD projected that maize, rice, soybean, and wheat prices will increase by 60–97 percent between 2000 and 2050 under business as usual, and prices for beef, pork, and poultry, by 31–39 percent.[219] Other simulations of the world food system also show that climate-induced shortfalls of cereals increase food prices.[220] In most estimates, cereal prices are projected to increase, even if farmers adapt.[221] By 2080 different scenarios project that world food prices will have increased by around 7–20 percent with CO_2 fertilization and by around 40–350 percent without (figure 3.13).[222]

Poor people, who spend up to 80 percent of their money on food, probably will be hardest hit by the higher food prices. The higher prices associated with climate change risk reversing progress in food security in several low-income countries. Although scenario results differ, nearly all agree that climate change will put more people at risk of hunger in poorer nations, with the largest increases in South Asia and Africa.[223]

Like energy prices, high food prices have profound effects on the potential adjustments in land and water use stemming from climate change. Investments in agriculture, land, and water become more profitable for farmers as well as the public and private sectors. Private agricultural companies, international aid donors, international development banks, and national governments can see and act on the higher international prices fairly quickly. But the transmission of increases in international food prices to farmers is imperfect, as shown in the 2007–08 food price crisis. For example, farmers in most of Sub-Saharan Africa saw higher food prices only after some lag, and the transmission of higher prices was slower and less complete than in most of Asia and Latin America.[224]

The better the quality of rural infrastructure, the more farmers benefit from higher international prices. High food prices can spur land conversion to crops and livestock, with negative impacts on ecosystems. But they can also induce significant new investments in agricultural research, irrigation development, and rural infrastructure to intensify production. The simultaneous rise in energy and food prices will also make some big investments profitable again, including large multipurpose dams for power and irrigation. It will be important to channel the incentives from high food prices into innovative investments and policy reforms to boost agricultural productivity while making land and water use sustainable.

An international price that paid for avoiding emissions and sequestering carbon in agriculture could encourage better protection of natural systems

Under the Clean Development Mechanism of the Kyoto Protocol, agricultural soil carbon sequestration projects in the developing world are not eligible for selling carbon credits to investors in the developed world. If they were, incentives for farmers and other land users would change fundamentally. Carbon markets that cover greenhouse gases from agricultural and other land-management practices could be one of the most important mechanisms to drive sustainable development in a world affected by climate change. The potential is huge: one source estimates 4.6 gigatons of CO_2 or more a year by 2030, which is more than half of the potential from forestry (7.8 gigatons of CO_2 a year).[225] At $100 a ton of CO_2e, potential emission reductions from agriculture are on par with those from energy (see overview, box 8). Models show that pricing carbon in agriculture and land-use change would help prevent the conversion of intact ecosystems ("unmanaged land" in figure 3.14) to meet rising demand for biofuel.

Although the mechanisms for conserving soil carbon through a carbon price are not yet developed, the potential to reduce emissions from agriculture is large. Even in Africa, where relatively carbon-poor drylands make up 44 percent of the continent, the possibility for agricultural carbon sequestration is great.[226] The projected mean agricultural mitigation potential across the continent is 100 million to 400 million metric tons of CO_2e a year by 2030.[227] With a relatively low price of $10 a metric ton in 2030, this financial flow would be comparable to the annual official development assistance to Africa.[228] A study of African pastoralists shows that even modest improvements in natural resource management could produce additional carbon sequestration of 0.50 metric ton of carbon a year per hectare. A price of $10 per metric ton of CO_2 would increase their incomes by 14 percent.[229]

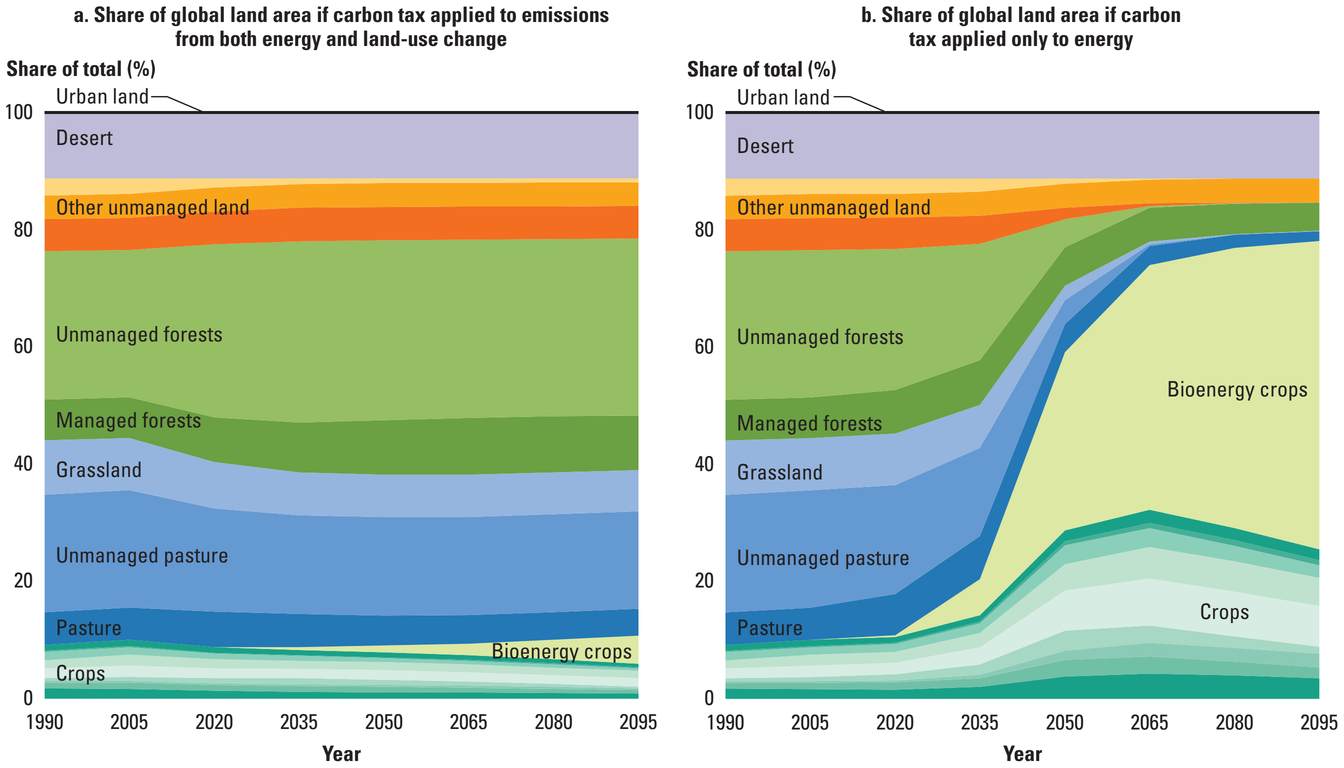
Carbon sequestration in agriculture would be a relatively inexpensive and efficient response to climate change. The abatement cost in agriculture in 2030 is estimated to be almost an order of magnitude lower than that in the forestry sector ($1.8 per metric ton of CO_2 equivalent compared with $13.5 per metric ton of CO_2 equivalent).[230] One reason for this is that many agricultural techniques that improve carbon sequestration also increase agricultural yields and revenues.

So, the techniques for storing more carbon in soil already exist, but they are not being adopted. The list of causes is long—inadequate knowledge of management techniques appropriate to tropical and subtropical soils, weak extension infrastructure to deliver the available innovations, lack of property rights to encourage investments with long-term payoffs but short-term costs, inappropriate fertilizer taxation policies, and poor transport infrastructure.

The world community could take four practical steps to expand the carbon market. First, rather than attempt to monitor detailed emissions and uptakes in each field, the people involved in the carbon markets (local and international) need to agree on a simplified actuarial-based accounting system that monitors the activities of farmers and conservatively estimates the associated carbon sequestration.[231] It would not be cost-effective or feasible to measure carbon sequestration across multiple, dispersed smallholder parcels in the developing world. Moreover, the approach is transparent and would allow the farmer to know up front what the payments and penalties would be for various activities.

The processes by which soils take up or emit carbon are complex. They vary from place to place (even within a field) and depend on soil properties, climate, farming system, and land-use history. Further,

Figure 3.14 A carbon tax applied to emissions from agriculture and land-use change would encourage protection of natural resources.



a. Share of global land area if carbon tax applied to emissions from both energy and land-use change

b. Share of global land area if carbon tax applied only to energy

Source: Wise and others 2009.

Note: Projections based on the MiniCAM Global Integrated Assessment Model. Both scenarios represent a path to achieve a CO_2 concentration of 450 ppm by 2095. In figure 3.14a, a price is put on carbon emissions from fossil fuels, industry, and land-use change. In figure 3.14b, the same price is applied but only to fossil-fuel and industry emissions. When a price is not applied to terrestrial emissions, growers are likely to encroach into natural habitats, mainly in response to the demand for biofuels.

annual changes are usually small relative to existing stocks. And the sequestration plateaus quickly. Carbon accumulation in soil saturates after about 15–30 years, depending on the type of agriculture, and few emission reductions would occur after that time.[232] Furthermore, no-till agriculture in heavy clay soils can result in releases of nitrous oxide—a powerful greenhouse gas. These emissions would more than outweigh the carbon storage benefits of adopting the new techniques over the first five years. No-till may therefore not be a good greenhouse gas emission reduction technique in some soils.[233] But it is possible, based on existing data and modeling, to broadly estimate carbon sequestration per agricultural practice for agroecological and climatic zones. Moreover, cost-effective techniques for measuring soil carbon in the field (using lasers, ground-penetrating radar, and gamma ray spectroscopy) now allow for faster measurement of carbon sequestration and the updating of model estimates at smaller spatial scales.[234] In the meantime, programs could use conservative estimates of sequestration across soil types and focus on regions where there is more certainty about soil carbon stocks and flows (such as the more productive agricultural areas). Moreover, no carbon sequestration technique (such as conservation tillage) is a panacea in every cropping system and across every soil type.

A model for such a system may be the Conservation Reserve Program administered by the U.S. Department of Agriculture on nearly 14 million hectares of land since 1986.[235] This voluntary program was initially established to reduce soil erosion, with landowners and agricultural producers entering contracts to retire highly erodible and environmentally sensitive cropland and pasture from production for 10–15 years in return for payments. Over time the program expanded its objective to include the conservation of wildlife habitat and water quality, and the payments are based on an aggregate Environmental

Benefits Index of the parcel and of the specific activity (such as riparian buffers and shelterbelts). The actual environmental benefits of each parcel are not directly measured but rather estimated based on activities, and a similar activity-based system could apply to agricultural carbon sequestration.[236]

The second practical step involves developing "aggregators"—typically private or nongovernmental organizations that reduce transaction costs of the activities by integrating them over multiple smallholder farmers, forest dwellers, and pastoralists. Without them the market will tend to favor large reforestation projects, because the land of the average individual smallholder farmer in the developing world cannot sequester very large amounts. Scaling up spatially will also reduce concerns related to the uncertainty and impermanence of the carbon stock. Adopting an actuarial approach, pooling across a portfolio of projects, and applying conservative estimates could make soil carbon sequestration fully equivalent to CO_2 reductions in other sectors.[237]

Third, the up-front costs for carbon-sequestering management practices must be addressed. Adopting new practices is risky, especially for poor farmers.[238] Carbon finance is typically delivered only after the farmers have actually reduced emissions (as in pilot projects in Kenya described in box 3.9). But the promise of future carbon finance can be used to make up-front payments to buy down farmers' risks either as collateral for loans, or by having investors make some of the payments up front.

Fourth, farmers need to know about their options. This will involve better agricultural advisory services in the developing world. Agricultural extension services are good investments: the average rate of return globally is 85 percent.[239] Companies or organizations that can measure or verify results will also be required.

The Chicago Climate Exchange, one subset of the voluntary market, shows the possible benefits of trading the carbon sequestration from landscape-related activities.[240] It allows emitters to receive carbon credits for continuous conservation tillage, grassland planting, and rangeland management. For agricultural carbon trading, the exchange requires that members place 20 percent of all earned offsets in a reserve to insure against possible future reversals. The Exchange shows that simplified rules and modern monitoring techniques can overcome technical barriers. However, some critics claim that "additionality" has not been fully assessed: the net emission reductions may not be greater than they would have been in the absence of a market.

In the near term the voluntary market incubates methods for agricultural and landscape-level sequestration. But for these measures to really expand in this direction, the market for them will need to be linked to the future global compliance market. The economies of scale that landscape-level sequestration promises will be more readily accessed if there are no divisions separating sequestration in agriculture and forestry.

Because carbon sequestration activities tend to have a positive impact on soil and water management as well as on yields,[241] the most important aspect of carbon finance applied to soil management may be to serve as a "lever" to execute the sustainable agricultural practices that also have many other benefits. From 1945 to 1990 soil degradation in Africa reduced agricultural productivity by an estimated 25 percent.[242] And about 86 percent of the land in Sub-Saharan Africa is moisture-stressed.[243] Effective carbon finance mechanisms would help reduce the rate of land degradation. A soil compliance carbon market holds great potential for helping to achieve the necessary balance between intensifying productivity, protecting natural resources, and simultaneously helping rural development in some of the world's poorest communities. Such a market is not yet ready. Technical issues regarding verification, scale, and time frame remain to be solved. The United Nations Framework Convention on Climate Change proposes a phased approach starting with capacity building and financial support. The first phase would demonstrate techniques, monitoring approaches, and financing mechanisms. In the second phase soil carbon techniques would be incorporated into the broader compliance carbon market.[244]

BOX 3.9 *Pilot projects for agricultural carbon finance in Kenya*

Preliminary results from two pilot projects in western Kenya indicate that smallholder agriculture can be integrated into carbon finance. One involves mixed cropping systems across 86,000 hectares, using a registered association of 80,000 farmers as the aggregator. Another smaller coffee project encompasses 7,200 hectares thus far, and a 9,000-member farmer cooperative serves as the aggregator. The average size of landholdings for both projects is small (about 0.3 hectare).

The amount of carbon sequestration is estimated to be 516,000 tons and 30,000 tons of CO_2e a year, respectively,

The sequestration activities include reduced tillage, cover crops, residue management, mulching, composting, green manure, more targeted application of fertilizers, reduced biomass burning, and agroforestry. The projects use activity-based monitoring. The estimates of carbon sequestration over 20 years are derived from a model known as RothC. The World Bank BioCarbon Fund is purchasing the carbon credits based on a price per ton mutually agreed on by the fund and the project developers, VI Agroforestry and Swedish Cooperative Centre and ECOM Agroindustrial Group. Of the total revenues that the communities receive, 80 percent will go to the community and 20 percent to monitoring and project development.

Two lessons are emerging. First, a good aggregator is essential, especially one that can also advise on agricultural practices. Second, the method for monitoring must be simple and accessible and transparent to the farmer. In these cases, the farmer can easily consult a table to determine the exact payment he or she will receive for each activity, a system that encourages participation.

Sources: Kaonga and Coleman 2008; Woelcke and Tennigkeit 2009.

Redirecting agricultural subsidies could be an important mechanism for achieving climate-smart land and water management

The member countries of the Organisation for Economic Co-operation and Development provide $258 billion every year in support to their farmers, which amounts to 23 percent of farm earnings.[245] Of this support 60 percent is based on the quantity of a specific commodity produced and on variable inputs with no constraints attached to their use—only 2 percent is for noncommodity services (such as creating buffer strips to protect waterways, preserving hedgerows, or protecting endangered species).

The political imperatives of climate change offer an opportunity to reform those subsidy schemes, to focus them more on climate change mitigation and adaptation measures that would also benefit domestic soil, water, and biodiversity resources as well as increase farm productivity. In addition to these direct benefits, allocating resources on that scale would also demonstrate whether these climate-smart techniques can be applied on a large scale in the developing world and attract entrepreneurial ingenuity and energy to find new ways of solving the technical and monitoring problems that will arise.

The European Union has already reformed its Common Agricultural Policy so that any income support to farmers is contingent on their meeting good environmental and agricultural standards, and any rural development support goes to measures that improve competitiveness, manage the environment and the land, improve the quality of life, and increase diversification. Through the rural development support category, farmers can be compensated if they provide environmental services that go beyond the mandatory standards.[246] This reform is a promising initiative to jump-start climate- and farmer-smart agricultural and natural resource policies, and the European Union could serve as a testbed for mechanisms that could be applied for sustainable land and water management in the developing world.

To cope with the effects of climate change on natural resources and simultaneously reduce emissions of greenhouse gases, societies need to produce more from land and water and protect their resources better. To produce more, they need to increase investment in agriculture and water management, particularly in developing countries. For agriculture that means investing in roads and research and development as well as adopting better policies and institutions. For water, it means using new decision-making tools and better data, strengthening policies and institutions, and investing in infrastructure. The expected increase in prices of agricultural production will give farmers and other resource users an incentive to innovate and invest. But the increased profitability will also increase incentives to overexploit resources. Protection needs the same increase in effort as production.

A number of tools, techniques, and approaches exist that can help users protect natural resources better. But users often do not have the right incentives to apply them. There are disparities in space and in time. What is best for a farmer is not best for the whole landscape or watershed. What is optimal over a short time period is not optimal over decades. Doing things differently also involves asking poor farmers and rural dwellers to take risks they may not be willing to take.

Governments and public organizations can take three types of actions to make the incentives for resource users more climate-smart. First, they can provide information so that people can make informed choices and can enforce cooperative agreements. This can be high-tech information. It can also be information that communities themselves gather. Second, they can set a price for retaining or storing carbon in the soil. Done right, this will reduce the risks to farmers of adopting new practices. It will also help resource users consider a longer time horizon in their decisions. Third, they can redirect agricultural subsidies, particularly in rich countries, so that they encourage climate-smart rural development practices. These subsidies can be transformed to show how the new techniques can be adopted on a large scale, and they can be used to make individual actions fit better with the needs of the landscape as a whole. Finally, they can attract the ingenuity and creativity needed to achieve the delicate balancing act of feeding the world of nine billion people, reducing greenhouse gas emissions, and protecting the natural resource base.

Notes

1. See for example Lotze-Campen and others 2009.
2. IPCC 2007b.
3. OECD 2008.
4. Burke and Brown 2008; Burke, Brown, and Christidis 2006.
5. Milly and others 2008; Barnett, Adam, and Lettenmaier 2005.
6. de la Torre, Fajnzylber, and Nash 2008.
7. World Water Assessment Programme 2009.
8. Perry and others, forthcoming.
9. World Water Assessment Programme 2009.
10. World Bank, forthcoming d.
11. World Bank, forthcoming d.
12. Molden 2007.
13. Milly and others 2008; Ritchie 2008; Young and McColl 2005.
14. As the public trustee of the nation's water resources, the national government, acting through the minister of water affairs, must ensure that water is protected, used, developed, conserved, managed, and controlled in a sustainable and equitable manner, for the benefit of all persons and in accordance with its constitutional mandate. Salman M. A. Salman, World Bank Staff, personal communication, July 2009.
15. Dye and Versfeld 2007.
16. Bates and others 2008.
17. Molle and Berkoff 2007.
18. Molle and Berkoff 2007; OECD 2009.

> *"Our globe is facing environmental problems due to human behavior—cutting down trees, air pollution, use of plastics cannot be reused or recycled, chemical hazards in agriculture. . . . Tree planting would reduce CO_2."*
>
> —Netpakaikarn Netwong, Thailand, age 14

19. Olmstead, Hanemann, and Stavins 2007.

20. Molle and Berkoff 2007.

21. Asad and others 1999.

22. Bosworth and others 2002.

23. See Murray Darling Basin Agreement Schedule E, http://www.mdbc.gov.au/about/the_mdbc_agreement.

24. Molle and Berkoff 2007.

25. Rosegrant and Binswanger 1994.

26. World Bank 2007b.

27. Bates and others 2008; Molden 2007.

28. Young and McColl 2005.

29. http://www.environment.gov.au/water/mdb/overallocation.html (accessed May 7, 2009).

30. Molden 2007.

31. World Bank, forthcoming b.

32. World Bank, forthcoming b.

33. World Bank, forthcoming b.

34. Bhatia and others 2008.

35. Strzepek and others 2004.

36. World Commission on Dams 2000. For discussion of the impacts of the High Dam at Aswan on soil fertility and coastlines in the Nile Delta, see Ritchie 2008.

37. World Water Assessment Programme 2009.

38. Danfoss Group Global. http://www.danfoss.com/Solutions/Reverse+Osmosis/Case+stories.htm (accessed May 9, 2009).

39. FAO 2004b.

40. Desalination is also viable for high-value agriculture in some parts of the world, such as Spain. Gobierno de España 2009.

41. World Water Assessment Programme 2009.

42. Molden 2007.

43. Molden 2007.

44. Molden 2007.

45. Rosegrant, Cai, and Cline 2002.

46. For example, see the reference to the *Indian Financial Express* on December 1 2008, cited in Perry and others, forthcoming.

47. De Fraiture and Perry 2007; Molden 2007; Ward and Pulido-Velazquez 2008.

48. Perry and others, forthcoming.

49. Moller and others 2004; Perry and others, forthcoming.

50. Perry and others, forthcoming.

51. www.fieldlook.com (accessed May 5, 2009).

52. Perry and others, forthcoming.

53. World Bank, forthcoming c.

54. Carbon dioxide (CO_2) is an input in photosynthesis, the process by which plants use sunlight to produce carbohydrates. Thus, higher CO_2 concentrations will have a positive effect on many crops, enhancing biomass accumulation and final yield. In addition, higher CO_2 concentrations reduce plant stomatal openings—the pores through which plants transpire, or release water—and thus reduce water loss. The so-called C3 crops, such as rice, wheat, soybeans, legumes, as well as trees, should benefit more than the C4 crops, such as maize, millet, and sorghum. However, recent field experiments indicate that past laboratory tests have overstated the positive effect. For example, one study indicates that at CO_2 concentrations of 550 parts per million, yield increases amounted to 13 percent for wheat, not 31 percent; 14 percent for soybeans, not 32 percent; and 0 percent, not 18 percent, for C4 crops. Cline 2007. For this reason, the graphics in this chapter show only yields without CO_2 fertilization.

55. Easterling and others 2007.

56. EBRD and FAO 2008.

57. Fay, Block, and Ebinger 2010.

58. A food production shortfall is a situation in which the weather makes annual potential production of the most important crops in an administrative region less than 50 percent of the region's average production level during 1961–1990. The greater likelihood of shortfalls occurring in more than one region in a given year may reduce the potential for exports from other regions to compensate for food production deficiencies, thus leading to food security concerns. Alcamo and others 2007.

59. Easterling and others 2007.

60. Cline 2007. The high-emission scenario is the IPCC's SRES A2 scenario, which, over a range of models, leads to a mean temperature increase of 3.13°C from 2080 to 2099 relative to 1980–99. Meehl and others 2007.

61. Lobell and others 2008.

62. Schmidhuber and Tubiello 2007.

63. Based on five climate models and the high-emission SRES A2 scenario. Fischer and others 2005.

64. Calculation based on FAO 2009c.

65. IPCC 2007a.

66. Emissions come from converting unmanaged land to agriculture, and from soil erosion.

67. van der Werf and others 2008.

68. Steinfeld and others 2006.

69. This 18 percent sums the estimated contribution of livestock production to emissions across several categories, such as land use, land-use change, and forestry, to get the total contribution of livestock. It comprises livestock greenhouse gas emissions from land-use change (36 percent); manure management (31 percent); direct emission by animals (25 percent); feed production (7 percent); and processing and transport (1 percent). Steinfeld and others 2006.

70. IEA 2006. This estimate assumes that current trade restrictions are maintained. If those restrictions change, particularly those that restrict imports of biofuels into the United States, there could be a large regional shift in production.

71. Gurgel, Reilly, and Paltsev 2008.

72. NRC 2007; Tilman, Hill, and Lehman 2006.

73. Beckett and Oltjen 1993.

74. Hoekstra and Chapagain 2007. Pimentel and others (2004) give an estimate of 43,000 liters per kilogram of beef.

75. Peden, Tadesse, and Mammo 2004. In this system one head of cattle consumes 25 liters of water a day over a two-year period to produce 125 kilograms of dressed weight and consumes crop residues for which no additional water input is required.

76. Williams, Audsley, and Sandars 2006. Moreover, some sources give higher emission estimates for meat production—up to 30 kilogram of CO_2e per kilogram of beef produced, for example (Carlsson-Kanyama and Gonzales 2009).

77. Randolph and others 2007; Rivera and others 2003.

78. Delgado and others 1999; Rosegrant and others 2001; Rosegrant, Fernandez, and Sinha 2009; Thornton 2009; World Bank 2008e.

79. One study projects that total "good" and "prime" agricultural land available will remain virtually unchanged at 2.6 billion and 2 billion hectares, respectively, in 2080 compared with the average during 1961–1990 (based on the Hadley Centre HadCM3 climate model and assuming the very high emission scenario, SRES A1F1). Fischer, Shah, and van Velthuizen 2002; Parry and others 2004.

80. Lotze-Campen and others 2009.

81. Cassman 1999; Cassman and others 2003.

82. Calculated from FAO 2009c.

83. Diaz and Rosenberg 2008.

84. Schoups and others 2005.

85. Delgado and others 1999.

86. Hazell 2003.

87. Hazell 2003; Rosegrant and Hazell 2000.

88. Pingali and Rosegrant 2001.

89. Reardon and others 1998.

90. Rosegrant and Hazell 2000.

91. Rosegrant and Hazell 2000.

92. One form of specialized agricultural products is known as functional foods. These are products in food or drink form that influence functions in the body and thereby offer benefits for health, well-being, or performance beyond their regular nutritional value. Examples include antioxidant foods, such as guarana and açaí berry, vitamin A-rich golden rice and orange-fleshed sweet potato, margarine fortified with plant sterols to improve cholesterol levels, and eggs with increased omega-3 fatty acids for heart health. Kotilainen and others 2006.

93. Ziska 2008.

94. T. Christopher, "Can Weeds Help Solve the Climate Crisis?" *New York Times*, June 29, 2008.

95. Ziska and McClung 2008.

96. UNEP-WCMC 2008. In the oceans the share of total area under protection is even more paltry. Approximately 2.58 million square kilometers, or 0.65 percent of the world's oceans and 1.6 percent of the total marine area within Exclusive Economic Zones, are marine protected areas. Laffoley 2008.

97. Gaston and others 2008.

98. Hannah and others 2007.

99. Dudley and Stolton 1999.

100. Struhsaker, Struhsaker, and Siex 2005.

101. Scherr and McNeely 2008; McNeely and Scherr 2003.

102. van Buskirk and Willi 2004.

103. McNeely and Scherr 2008.

104. Chan and Daily 2008.

105. Leguminous trees contain symbiotic bacterial nodules that fix atmospheric nitrogen thereby enhancing the nutrients load in the plants and in the soil.

106. McNeely and Scherr 2003.

107. Ricketts and others 2008.

108. Klein and others 2007.

119. Lin, Perfecto, and Vandermeer 2008.

110. World Bank 2008a.

111. World Bank 2008a.

112. Of the $6 billion spent annually on land trusts and conservation easements, a third is in the developing world. Scherr and McNeely 2008.

113. A typical system of zoning for conservation allows development in some areas and limits it in conservation areas. Tradable development rights are an alternative to pure zoning that allows for substitutability between areas in meeting conservation goals and provides incentives for compliance. Some landowners agree to limits on development—that is, restrictions on their property rights—in return for payments. For instance, a government law may prescribe that 20 percent of each private property be maintained as natural forest. Landowners would be permitted to deforest beyond the 20 percent threshold only if they purchase from other landowners who keep more than 20 percent of their property forested and sell the development rights of this "surplus" forest, which is irreversibly placed under forest reserve status. Chomitz 2004.

114. World Bank 2008c.

115. Alston and others 2000; World Bank 2007c.

116. Beintema and Stads 2008.

117. IAASTD 2009.

118. Blaise, Majumdar, and Tekale 2005; Govaerts, Sayre, and Deckers 2005; Kosgei and others 2007; Su and others 2007.

119. Thierfelder, Amezquita, and Stahr 2005; Zhang and others 2007.

120. Franzluebbers 2002.

121. Govaerts and others 2009.

122. Derpsch and Friedrich 2009.

123. Derpsch 2007; Hobbs, Sayre, and Gupta 2008.

124. World Bank 2005.

125. Derpsch and Friedrich 2009; Erenstein and Laxmi 2008.

126. Erenstein 2009.

127. Erenstein and others 2008.

128. de la Torre, Fajnzylber, and Nash 2008.

129. Passioura 2006.

130. Yan and others 2009.

131. Thornton 2009.

132. Smith and others 2009.

133. Doraiswamy and others 2007; Perez and others 2007; Singh 2005.

134. Such as the deep placement of urea briquettes or supergranules.

135. Singh 2005.

136. Singh 2005.

137. Poulton, Kydd, and Dorward 2006; Dorward and others 2004; Pender and Mertz 2006.

138. Hofmann and Schellnhuber 2009; Sabine and others 2004.

139. Hansen and others 2005.

140. FAO 2009e.

141. FAO 2009e.

142. Delgado and others 2003.

143. FAO 2009e.

144. Arkema, Abramson, and Dewsbury 2006.

145. Smith, Gilmour, and Heyward 2008.

146. Gordon 2007.

147. Armada, White, and Christie 2009.

148. Pitcher and others 2009.

149. OECD 2008; World Bank 2008d.

150. FAO 2009e.

151. World Bank 2008d.

152. Costello, Gaines, and Lynham 2008; Hardin 1968; Hilborn 2007a; Hilborn 2007b.

153. FAO 2009c. Fish and seafood include both marine and freshwater fish and invertebrates. Total animal protein includes the former, plus all terrestrial meat, milk, and other animal products. The data are for 2003.

154. United Nations 2009.

155. FAO 2009c (2003 data).

156. FAO 2009e.

157. FAO 2009e.

158. World Bank 2006.

159. De Silva and Soto 2009.

160. De Silva and Soto 2009.

161. FAO 2004a.

162. Gyllenhammar and Hakanson 2005.

163. Deutsch and others 2007.

164. Gatlin and others 2007.

165. Tacon, Hasan, and Subasinghe 2006.

166. Tacon, Hasan, and Subasinghe 2006.

167. Naylor and others 2000.

168. Primavera 1997.

169. Tal and others 2009.

170. Naylor and others 2000.

171. FAO 2001; Lightfoot 1990.

172. Delgado and others 2003.

173. FAO 2009b.

174. For example, China and Nepal are not parties to an agreement between Bangladesh and India for the water of the Ganges basin and receive no allocation.

175. Salman 2007.

176. Qaddumi 2008.

177. Kurien 2005.

178. FAO 2009e.

179. Duda and Sherman 2002.

180. FAO 2009d; Sundby and Nakken 2008.

181. Lodge 2007.

182. BCLME Programme 2007.

183. GEF 2009.

184. World Bank 2009.

185. Fischer and others 2005.

186. Rosegrant, Fernandez, and Sinha 2009.

187. Easterling and others 2007.

188. FAO 2008.

189. Mitchell 2008. Climate shocks have led to restrictive domestic food trade policies and exacerbated price increases in the past as well; for examples, see Battisti and Naylor 2009.

190. World Bank 2009.

191. World Bank 2009.

192. von Braun and others 2008.

193. Bouet and Laborde 2008.

194. Other issues need a case-by-case assessment, such as exemptions from tariff cuts on special products, as sought by developing countries for products specified as important for food security, livelihood security, and rural development. World Bank 2007c.

195. WMO 2000.

196. Xiaofeng 2007.

197. United Nations 2004.

198. "Africa's Weather Stations Need 'Major Effort,'" Science and Development Network. www.SciDev.net, November 7, 2006.

199. WMO 2007.

200. Barnston and others 2005; Mason 2008.

201. Moron and others, forthcoming; Moron, Robertson, and Boer 2009; Moron, Robertson, and Ward 2006; Moron, Robertson, and Ward 2007.

202. Sivakumar and Hansen 2007.

203. Patt, Suarez, and Gwata 2005.

204. Bastiaanssen 1998; Menenti 2000.

205. WaterWatch, www.waterwatch.nl (accessed May 9, 2009).

206. Bastiaansen, W., WaterWatch, personal communication, May 2009.

207. http://www.globalsoilmap.net/ (accessed May 15, 2009).

208. Bindlish, Crow, and Jackson 2009; Frappart and others 2006; Turner and others 2003.

209. Bouma, van der Woerd, and Kulik 2009.

210. UNESCO 2007.

211. World Bank 2008d.

212. Kumar 2004.

213. World Bank 2007a.

214. World Bank, forthcoming b.

215. World Bank 2008b.

216. World Bank 2008b.

217. Mitchell 2008.

218. Zilberman and others 2008.

219. Rosegrant, Fernandez, and Sinha 2009.

220. Parry and others 1999; Parry, Rosenzweig, and Livermore 2005; Rosenzweig and others 2001.

221. Rosenzweig and others 2001.

222. Parry and others 2004.

223. Fischer and others 2005; Parry and others 1999; Parry and others 2004; Parry 2007; Parry, Rosenzweig, and Livermore 2005; Schmidhuber and Tubiello 2007.

224. Dawe 2008; Robles and Torero, forthcoming; Simler 2009.

225. McKinsey & Company 2009.

226. Perez and others 2007.

227. Smith and others 2009.

228. The official development assistance flow to Africa from 1996 to 2004 was about $1.30 billion a year: World Bank 2007c.

229. Perez and others 2007.

230. McKinsey & Company 2009.

231. The sequestration benefits of those activities would be regularly updated based on the state-of-the-art measurement and model-based approaches.

232. West and Post 2002.

233. Rochette and others 2008.

234. Johnston and others 2004.

235. Sullivan and others 2004.

236. In the Conservation Reserve Program, however, landowners bid on the payments and the government accepts or rejects the bids, which is quite different than a carbon emissions trading market.

237. McKinsey & Company 2009.

238. Tschakert 2004.

239. Alston and others 2000.

240. Chicago Climate Exchange, http://www.chicagoclimatex.com/index.jsf (accessed February 10, 2009).

241. Lal 2005.

242. UNEP 1990.

243. Swift and Shepherd 2007.

244. FAO 2009a.

245. OECD 2008.

246. http://ec.europa.eu/agriculture/capreform/infosheets/crocom_en.pdf (accessed May 12, 2009).

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