PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B

Phil. Trans. R. Soc. B (2008) **363**, 495–515
doi:10.1098/rstb.2007.2166
Published online 26 July 2007

Drivers of change in global agriculture

Peter Hazell[1,*] and Stanley Wood[2]

[1]*Centre for Environmental Policy, Imperial College, Wye Campus, Kent TN25 5AH, UK*
[2]*International Food Policy Research Institute, Washington, DC 20006-1002, USA*

As a result of agricultural intensification, more food is produced today than needed to feed the entire world population and at prices that have never been so low. Yet despite this success and the impact of globalization and increasing world trade in agriculture, there remain large, persistent and, in some cases, worsening spatial differences in the ability of societies to both feed themselves and protect the long-term productive capacity of their natural resources. This paper explores these differences and develops a country×farming systems typology for exploring the linkages between human needs, agriculture and the environment, and for assessing options for addressing future food security, land use and ecosystem service challenges facing different societies around the world.

Keywords: sustainable development; agricultural development; world food situation; natural resource management

1. INTRODUCTION

Food problems have haunted mankind since time immemorial. Along with a few technological breakthroughs to increase yields, the food needs of growing populations were historically met by expanding the cultivated area. As the most fertile and irrigable lands became scarce, further expansion meant bringing poorer and lower yielding land into cultivation and placing greater reliance on fallow-based cultivation (Smith 1998). By the nineteenth century, there was growing pessimism about the possibilities of feeding ever-growing populations, as exemplified in the writings of Malthus. The task seemed even more overwhelming as advances in medicine and public health led to longer life expectancies and higher fertility rates.

Agricultural expansion through colonization of new continents provided an important safety valve for Europe, but by the late nineteenth century even this was not enough (Richards 1990). Public investments in modern scientific research for agriculture led to dramatic yield breakthroughs by the twentieth century. The story of English wheat is typical. It took nearly 1000 years for wheat yields to increase from 0.5 to 2 t ha^{-1}, but only 40 years to climb from 2 to 6 t ha^{-1}. These advances were fuelled by modern plant breeding, improved agronomy and development of inorganic fertilizers and modern pesticides (Evans 1998). Most industrial countries had achieved sustained food surpluses by the middle of the twentieth century, and many developing countries did the same in the closing decades. Asia, for example, which was threatened by hunger and mass starvation as late as the mid-1960s, became self-sufficient in staple foods within 20 years even though its population more than doubled (Evenson & Gollin 2003). Africa is the only continent that has yet to achieve food surpluses.

In aggregate, the global food situation is very favourable today. Already more food is produced than needed to feed the entire world population and at prices that have never been so low. The fundamental hunger problem today is one of income distribution rather than food shortages. The hungry are simply too poor to buy the food that abounds, while, at the same time, obesity and chronic illnesses associated with excessive food intake are becoming a serious problem among richer people (WHO 2002, 2003). Simply increasing global supplies will not solve this distribution problem. The prognosis for global food supplies is also good (Millennium Ecosystem Assessment (MEA) 2005; von Braun 2005; FAO 2006). While world food demand will continue to grow, there is already the capacity to grow more food, and continuing advances in the biological sciences should add to that capacity in the future.

Yet the global situation masks many serious concerns at regional and local levels. First, hunger and malnutrition persist in many countries. Today, there are still approximately 1.2 billion people who live in abject poverty, and many more who do not get enough to eat (including approximately 160 million malnourished children less than 5 years old; World Bank 2005). Approximately 90% of the poor live in South Asia and Africa and 75% of them live in rural areas where they depend primarily on agriculture and related activities for their livelihoods. Second, expected increases in agricultural demand associated with population growth, urbanization and rising *per capita* incomes will require continuing increases in agricultural production in many countries. Yet there is increasing evidence that yield growth is slowing in many important bread-basket regions, while the prospects for further expanding cropped and irrigated areas are limited. Third, growing environmental problems associated with agriculture could, if not checked, threaten future levels of agricultural productivity at regional and local levels, as well as impose serious health risks and loss of ecosystem services (Cassman & Wood 2005).

The real agricultural challenges of the future will, as today, differ according to their geopolitical and socio-

* Author for correspondence (p.hazell@imperial.ac.uk).

One contribution of 16 to a Theme Issue 'Sustainable agriculture I'.

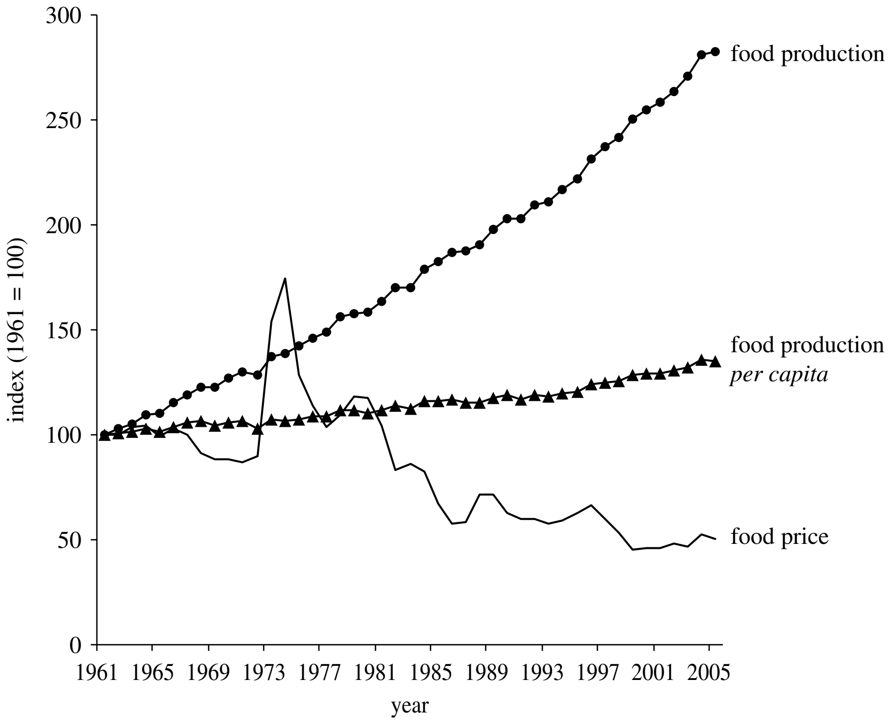

Figure 1. Global trends in food production and prices (index 1961–2005). Data from FAOSTAT (2006), IMF Yearbooks and World Bank (2005).

economic contexts. The current divide between those who eat well and those who go hungry will continue, defined largely by differences in *per capita* incomes within and between countries. Factors that distinguish the various trajectories of agricultural development also exhibit significant spatial variability, such as differences in farming systems and productive capacity, population densities and growth, evolving food demands, infrastructure and market access, as well as the capacity of countries to import food or to invest in agriculture and environmental improvement. Environmental problems associated with agriculture too vary according to their spatial context, ranging from problems associated with the management of modern inputs in intensively farmed areas to problems of deforestation and land degradation in many poor and heavily populated regions with low agricultural potential. In short, despite globalization and increasing world trade in agriculture, there remain large, persistent and, in some cases, worsening spatial differences in the ability of societies both to feed themselves and to protect the long-term productive capacity of their natural resources.

In this paper, we first summarize key issues and describe the major drivers of change in world agriculture. We then develop a country×farming systems typology as a framework for exploring linkages between human needs, agriculture and the environment, and for assessing options for addressing future food security, land use and ecosystem service challenges facing different societies around the world.

2. PAST ACHIEVEMENTS AND FUTURE CHALLENGES

At the global level, agricultural production has grown much faster than the population in recent decades, leading to a steady increase in *per capita* agricultural output (including food) and a steady decline in world prices for most agricultural commodities, particularly since the late 1970s (figure 1). This has been achieved primarily with a technological revolution that has increased yields through increases in modern inputs—irrigation, improved seeds, fertilizer, tractors and pesticides (figure 2). In a dramatic break with historical patterns, expansion of the total cropped area in most parts of the world has played a remarkably small role in increasing agricultural production in recent decades, to the point that growth in the global extent of cropland has virtually stagnated (table 1). The switch from area expansion to intensification of input use as the primary production growth strategy has reduced the demand for land conversion by over 1 billion hectares globally since the early 1960s (Cassman & Wood 2005).

As a result of this unprecedented growth in agricultural productivity, the world now produces more than enough food to feed the entire population to minimum UN standards if it were distributed more equitably. Even more remarkably, this surplus has been achieved despite the diversion of considerable land, labour and other rural resources to the production of higher-value foods (meat, milk, fruits, vegetables, etc.) to meet the changing food demands of growing, more urbanized and more affluent populations. This includes the additional cereals needed as feed grains in intensive livestock systems and oil crops for inland aquaculture (table 1). Despite these accomplishments, serious hunger, health and environmental concerns remain.

(a) *Hunger concerns*

Not all countries have shared in the global success of agriculture, and hunger and malnutrition persist in many parts of the world. Africa as a continent has not been able to increase its agricultural production to keep pace with population growth, leading to periods

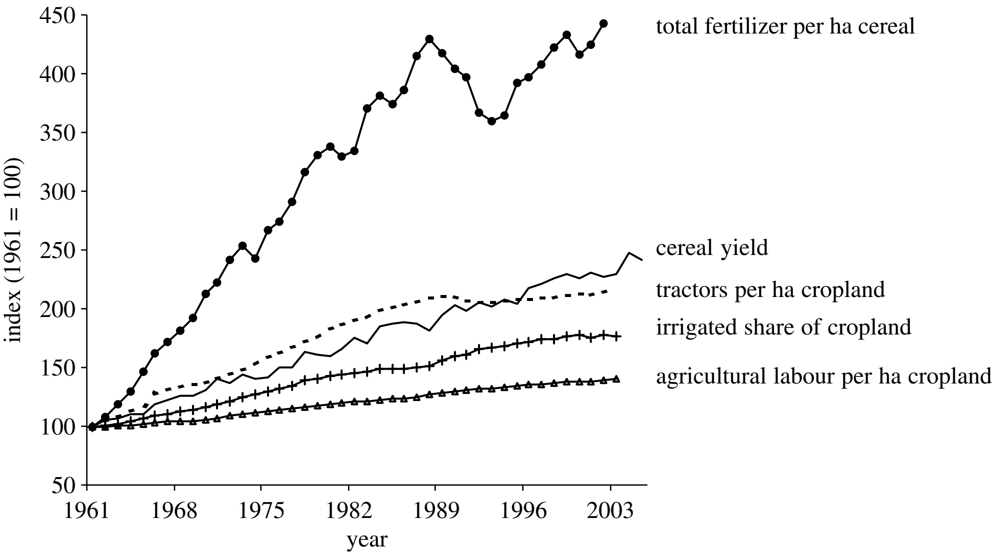

Figure 2. Global trends in the intensification of crop production (index 1961–2002/2005). Adapted from Cassman & Wood (2005), updated from FAOSTAT (2006; tractor and fertilizer data to 2002, land use to 2003, production to 2005).

Table 1. Trends in population, cropland and major commodity production (1963–2002). (Source: authors from FAOSTAT (2006). Perm, permanent.)

			growth(%)	annual growth rates (% per yr)		
	1963	2002	1963–2002	1963–1976	1976–1989	1989–2002
population (thousands)						
total	3 203 500	6 224 978	94.3	2.01	1.73	1.42
urban	1 092 165	2 979 757	172.8	2.75	2.74	2.30
rural	2 111 338	3 245 232	53.7	1.60	1.06	0.70
cropland (1000 ha)						
arable and perm cropland	1 368 097	1 534 466	12.2	0.33	0.45	0.16
arable land	1 288 097	1 404 052	9.0	0.28	0.39	0.07
perm crops	76 624	130 257	63.6	1.14	1.32	1.26
irrigated cropland	144 501	276 719	91.5	2.28	1.52	1.11
perm pasture	3 160 724	3 485 339	10.3	0.27	0.34	0.18
production (1000 Mt)						
cereals	1 898 917	4 057 886	113.7	3.14	1.85	0.84
oil crops	55 917	228 180	308.1	3.06	4.28	3.90
fruits and vegetables	820 825	2 557 890	214.1	2.45	2.88	3.98
poultry meat	19 507	149 225	665.0	5.84	5.02	5.27
milk	688 591	1 203 481	74.8	1.64	1.67	0.90
pig meat	56 035	190 789	240.5	3.27	3.80	2.59
bovine meat	63 961	121 842	90.5	2.86	1.12	0.81

of decline or stagnation in its food and total agricultural outputs *per capita* (figure 3). Africa has yet to experience the kind of technological revolution enjoyed elsewhere and still uses few modern inputs in agricultural production. For example its use of inorganic fertilizer (12 kg ha^{-1}), share of irrigated cropland (less than 4%) and use of tractors (1 tractor per 620 ha) rank the lowest of any region by a considerable margin (Wood *et al.* 2000). As a result, yields of all major crops in Africa have grown little over the past 40 years and cereal yields have stagnated for the past 20 years (figure 4).

However, even in countries and regions that have performed better and now have food surpluses (e.g. much of South Asia), hunger and malnutrition are still widespread. Although many increasingly affluent Asians are rapidly diversifying and enriching their diets, leading to a sustained surge in demand for livestock products, fruits, vegetables and vegetable oils and some feed grains, over 500 million other Asians go hungry, and in South Asia (as in Central America, Near East and North Africa, sub-Saharan Africa and across the Commonwealth of Independent States countries), the actual number of hungry people continues to grow (FAO/SOFI 2005). These people do not have the means to buy sufficient food to meet basic food needs, and desperately need better livelihood opportunities. Past patterns of growth have been insufficient or have failed to adequately benefit the poor. However, while hunger is now largely a distributional problem in most parts of the world, Africa still faces the additional burden of a classic food shortage problem. Sub-Saharan Africa still relies on food aid, and the food

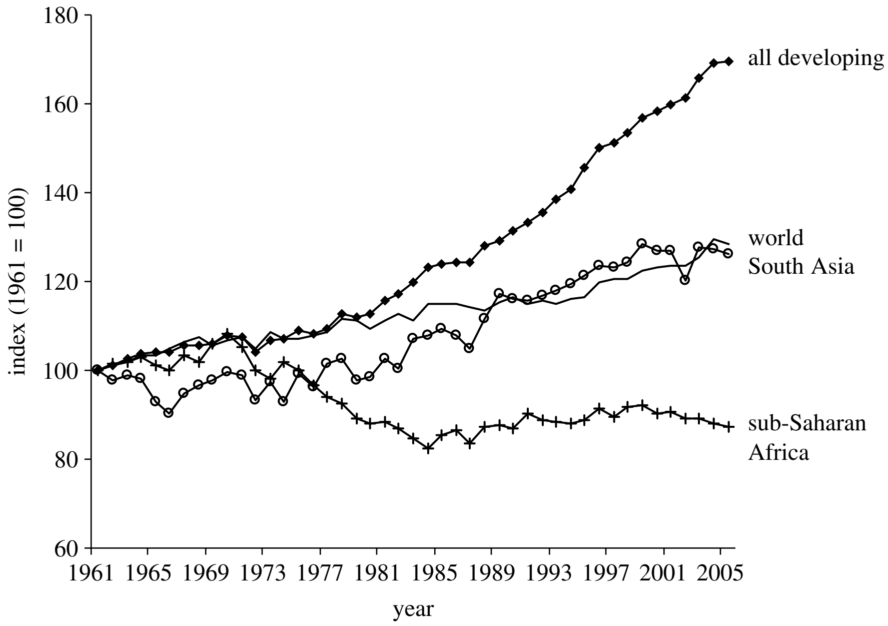

Figure 3. Index of total agricultural output *per capita* by region (index 1961–2005). Adapted from FAOSTAT (2006).

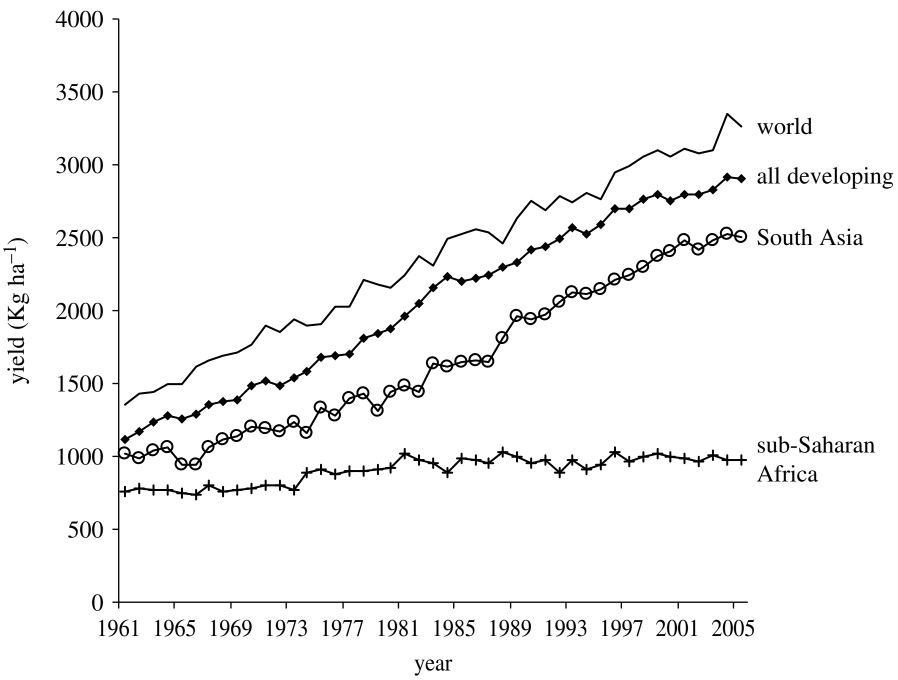

Figure 4. Global trends in cereal yield by region (1961–2005). Adapted from FAOSTAT (2006).

gap is projected to increase significantly in the future (Runge *et al.* 2003).

Looking ahead, future increases in population and staple food needs will largely occur in regions that are currently doing less well (low-income, high-poverty countries). These countries have limited capacity to pay for imported foods, and developing domestic agriculture will have to play a key role in solving local income and poverty problems. However, as we shall discuss later, the opportunities for agricultural growth will differ among countries.

(b) *Health concerns*

While the key health effects of agriculture are overwhelmingly positive through the nutrition benefits of food consumption, there are other aspects of agriculture that impinge on health. The two broadest categories of impact are those mediated through health hazards of food contamination (such as pesticide residues) and those associated with the conduct of agriculture through crop cultivation and animal rearing activities. Health effects of contaminated foods arise from shortcomings in production, processing, storage and preparation that are more prevalent in poorer countries. It is estimated that 70% of the 1.5 billion episodes per year of diarrhoea are due to biologically contaminated food (WHO 2002). However while considerable progress has been made in reducing food-related mortality and morbidity through improved education and advice on such things as food handling, of more recent concern is growth in the incidence and severity of zoonoses (illnesses and diseases communicated from animals to humans, e.g. salmonellosis, CJD, brucellosis, rabies and, of major contemporary concern, avian flu). The rapid growth in intensive livestock production in Asia, including in peri-urban areas, is adding to the risk of more serious disease outbreaks.

Agriculture is also a hazardous occupation. Globally, it is estimated that farm workers run at least twice the risk of dying on the job than workers in other sectors and that approximately 170 000 people die per year owing to these work hazards (Forastieri 1999). Not only mortality rates but also rates of accidents and injuries are high. Injudicious use of pesticides and a lack of safe spray equipment and protective clothing suitable for tropical conditions are causing significant short-term as well as long-term health problems. On a global scale, it is estimated that 20 000 people die of adverse effects of pesticide exposure each year, 3 million are poisoned and there are nearly 750 000 new cases of chronic pesticide exposure (WHO & UNEP 1990). Pingali & Roger (1995) documented long-term health effects to farmers, farm workers and their families through pesticide exposure during spraying as well as unsafe storage, handling and disposal of pesticides.

Beyond the health effects to humans, excess of agriculture-related contaminants in soil, water and the atmosphere all contribute to broader damage to the health of flora and fauna that could severely impact the biological functioning of terrestrial, freshwater and coastal ecosystems and the delivery of a range of vital ecosystem services (Millennium Ecosystem Assessment (MEA) 2005). Excess nitrates from farming that enter water systems is a prominent example.

(c) *Environmental concerns*

Environmental problems associated with agricultural growth could, if not checked, threaten future levels of agricultural productivity at country and regional levels as well as impose future health and ecosystem service costs. The full extent of environmental damage from agriculture is difficult to assess with available data and has only been attempted in a limited number of studies (see Pretty *et al.* (2000) for a UK case study). Here, we simply attempt to summarize indicative estimates from available sources.

(i) *Deforestation and forest degradation*

Every year approximately 13 Mha of forest are lost or degraded in developing countries, equivalent to just over 1% of the current tropical forest reserves (FAO 2005). More than 60% of deforestation has been attributed to subsistence farming in hillside areas, where declining yields force poor people to rely on shifting cultivation (FAO 2005). FAO attributes the major cause in Africa and parts of Asia to the expansion of subsistence farming, whereas government-backed logging and conversion of forest to other land uses, such as large-scale ranching or oil palm estates, are more common in Latin America and other parts of Asia. Developing countries have now lost about one-fifth of their total forest since 1960, with Asia losing 30%, and Africa and Latin America 18% (Bryant *et al.* 1997). In addition to outright deforestation, much of the remaining forest and woodland areas have been badly degraded through encroachment by farmers and livestock and selective logging (Geist & Lambin 2001; FAO 2005). Conversion or degradation of forests leads to loss of forest products, many of which (especially fuel wood, poles and non-timber forest products) are particularly important to the poor. Deforestation also gives rise to loss of important environmental services, especially watershed protection, maintenance of biodiversity and carbon sequestration (FAO 2005; Millennium Ecosystem Assessment (MEA) 2005).

(ii) *Water depletion and degradation of irrigated land*

Irrigated agriculture is associated with wasteful water use in many countries, usually accounting for more than 50% of total water use, as well as unsustainable mining of ground water and aquifers (Postel 1997, 1999; Wood *et al.* 2000). As demand for water has grown, especially in the non-agricultural sectors, countries have increasingly faced water scarcities, and farmers are having to learn to produce more with less water. Increasing water scarcity has the potential to seriously worsen food balances in hot spot areas, perhaps even globally if timely and judicious action is not taken (Rosegrant *et al.* 2002).

Salinization and waterlogging are two significant consequences of poor irrigation management and inadequate drainage and bring about decreased productivity and shifting ecological conditions (Ghassemi *et al.* 1995). Ghassemi *et al.* (1995) estimated that approximately 45 Mha, representing 20% of the world's total irrigated land, suffers from salinization or waterlogging. In Pakistan, which has the world's largest contiguous surface distribution system, an estimated 3.5 Mha (some 25% of the irrigated area) is affected by waterlogging and salinity, and 8% of these lands are seriously degraded (Pinstrup-Andersen & Pandya- Lorch 1994). Globally, some 1.5 Mha of irrigated land per year are lost to production (Ghassemi *et al.* (1995) quoting Dregne *et al.* (1991)) and approximately US$11 billion is lost annually from reduced productivity (Postel 1999), representing approximately 1% of the global totals of irrigated area and annual value of production, respectively (Wood *et al.* 2000).

(iii) *Soil degradation*

There are many and complex linkages between agriculture and land degradation. Farming in areas of fragile soils, poor management of crop, soil and water interaction, and unsustainable exploitation of soil nutrients are some of the major causes of land degradation (Lal 1997). Only some 16% of croplands globally are inherently free of soil constraints (Wood *et al.* 2000), and that figure is as low as 6–7% in Southeast Asia and sub-Saharan Africa. Assessing the biophysical and economic impacts of soil degradation is highly problematic, and while most studies point to broad extents and significant severity of degradation within the world's croplands, the implications for agricultural productivity and ecosystem services remain poorly understood at national and regional scales. Land degradation is particularly troublesome in hillside and mountain areas owing to its impact on downstream watersheds. Loss of tree cover leads to poorer water retention and storage and seasonal flooding, and soil erosion silts up reservoirs and irrigation and drainage structures downstream. In dry land areas, cropland encroachment into pastoral areas aggravates soil erosion problems and overstocking of the remaining grazing areas. Soil nutrient mining is endemic in low-input farming systems, especially in areas with poor infrastructure and marketing institutions, where use of inorganic fertilizers is uneconomic. In much of Africa, for example, with its average 12 kg ha^{-1} of inorganic fertilizer use (compared with over 100 kg ha^{-1} in all developing countries) and inadequate levels of other forms of nutrient replenishment, soil nutrient stocks continue to deplete in unsustainable ways (Smaling *et al.* 1993), often with harsh implications for rural lives and livelihoods (Scoones 2001; Sanchez 2002).

Land degradation is most severe in 'hot spot' areas such as the foothills of the Himalayas, sloping areas in southern China, Southeast Asia and the Andes, the forest margins of East Asia and the Amazon, rangelands in Africa and West and Central Asia, and the Sahel (Scherr & Yadav 1995).

The economic costs of land degradation are difficult to assess and few of the available estimates are based on reliable data (Crosson & Anderson 1992). Studies have placed the total cost as high as 3% of agricultural gross domestic product (GDP) per year for Java, Indonesia (Magrath & Arens 1989); at between 4 and 16% of agricultural GDP per year for Mali (Bishop & Allen 1989); and at 10% of annual agricultural production in Costa Rica (World Resources Institute (WRI) 1991). However, improved understanding of the role of processes such as silt deposition within catchments (Trimble 1999) and meta-analyses of empirical observations (e.g. Lindert 2000; Biggelaar *et al.* 2001) have recently provided more conservative assessments of long-term soil degradation. Nonetheless, costs to poor farmers in terms of lower yields are often very real and have important implications for their food security and income earning opportunities (Scherr 1999).

(iv) *Biodiversity losses*

Agriculture has had large and well-documented adverse impacts on biodiversity in a number of ways. The first and most apparent impact has been a locally extensive, if globally declining, conversion of natural ecosystems for agricultural purposes. Second is the management of agricultural landscapes in ways that can limit the existence of natural biodiversity within them. Third is the use of production practices such as the application of pesticides and use of other agrochemicals that further constrain the viability of natural biodiversity, e.g. bees, bird populations and soil biodiversity. Since these animals and organisms can often perform beneficial economic services from a production perspective, these losses impact human well-being both directly and indirectly (e.g. the economic contribution of pollinators to coffee revenues in Costa Rica, Ricketts *et al.* 2004).

From an agrobiodiversity perspective, there has been serious loss of traditional food crop species and, even for the crop species that are grown, large areas are planted to a few modern varieties (for example, the IR36 variety of rice has been planted on more than 10 Mha in Asia). This varietal specialization has occasionally led to widespread crop losses due to outbreaks of diseases and pests (e.g. brown plant hopper in rice) to which widely planted varieties had no resistance. And the constant evolution of pest and diseases so as to overcome inbred resistance has required that larger shares of agricultural research expenditures be allocated to 'maintenance' research and germplasm conservation programmes (Anderson *et al.* 1987).

(v) *Global and regional climate change*

There is significant evidence that agriculture has both contributed to and been impacted by climate change. Agriculture contributes to greenhouse gas emissions (both carbon and nitrogen based) primarily through land conversion, particularly: deforestation, tillage and burning practices, volatization of organic and inorganic fertilizers and methane emission from ruminant livestock and paddy rice cultivation. Globally, carbon dioxide emissions from land use change (approx. 1600 Mt C yr^{-1}), largely driven by agricultural expansion, grew most rapidly in the period 1950–1970. Current growth has been assessed at approximately 0.5% yr^{-1}, predominantly driven by land use change in developing countries. While much smaller in quantity (approx. 170 Mt C yr^{-1}), methane emissions from agriculture are more significant. Agriculture is the major anthropogenic source of methane, a gas with very high 'global warming potential', and probably driven by recent rapid growth in meat consumption, methane emissions continue to grow at approximately 1% yr^{-1} (IPCC 2000; Wood *et al.* 2000).

Assessing the impacts of climate change on agriculture is more complex. While there is extensive scientific debate about the nature of the underlying driving forces, there is clear evidence of changing temporal and spatial patterns of climate phenomena that impact agriculture. Of most significance to farmers has been the increased instability and variability of rainfall events. For example, the unusually frequent El Niño Southern Oscillation (ENSO) events of the late 1980s and the 1990s caused widespread losses in agriculture due to heavy rainfall and floods in some areas (mainly in the Americas) and more intensive droughts in others (mainly in Asia). One study of the effects of past El Niño and La Niña events estimated losses to US agriculture of between US$1.5 and US$6.5 billion per event (Adams *et al.* 1999). Impacts of longer-term climatic trends have also been reported: such as a 10 day increase in the average length of annual growing season and a 12% increase in greenness across Europe over the period 1962–1995 (Voigt *et al.* 2004).

Climate change will affect different localities in different ways, with potential benefits to some important food growing areas (e.g. the Canadian Prairies) but making agriculture more difficult in some other regions (e.g. many drought prone areas in Africa). Agricultural systems do have considerable capacity to adapt to climate change, but this poses many new challenges that are not yet fully understood. More research is needed to identify the best ways to adapt.

The various concerns discussed above are highly interactive, making it difficult to predict or evaluate their combined impact. However, so far, the combined effects of most of these environmental problems have not threatened the overall capacity of the world to feed itself, though they have had important local impacts on human well-being.

3. DRIVERS OF CHANGE IN AGRICULTURE

To properly understand the forces driving change in global agriculture and land use, we propose consideration of three scales of drivers. We define a driver as 'any natural- or human-induced factor that directly or indirectly brings about change in an agricultural production systems'.

- *Global-scale drivers*. They affect all agriculture around the world, but to varying degrees. These include trade expansion, value chain integration and climate change, as well as international processes established to facilitate or mitigate them, such as agricultural support in the Organisation for Economic Co-Operation Development (OECD) and the World Trade Organization (WTO). Other drivers include the rapid globalization of science and knowledge access, facilitated by expanding global communications options that can serve to accelerate the flow of information, technology and products relevant to agricultural development.
- *Country-scale drivers*. They affect all agriculture within a country, although factors such as poor infrastructure and market access may lead to spatially differentiated impacts.
- *Local-scale drivers*. They are specific to each local geographical area and different types of agricultural production system.

At any given location, the relative importance of the impacts attributable to each scale of driver or to the interactions among them is difficult to determine. However, it is, we argue, important to keep focus on the underlying scales of those drivers' most shaping local challenges and opportunities. Doing so can greatly facilitate evaluation of appropriate response strategies. For example, strategies for responding to unwelcome change are largely conditioned by the ability of local actors to influence the drivers of that change. A local response to climate change must focus on adaptation or coping, while local resource degradation might involve effective mitigation of the drivers through household or community decisions and actions.

We summarize some of the key global-, national- and local-scale drivers in table 2 and provide some indicative assessment of their overall relevance and rate of change. In the following section, we provide further assessment of many of these drivers.

(a) *Global-scale drivers*

(i) *International trade and globalization of markets*

International agricultural trade has increased 10-fold since the 1960s owing to more open trade policies, market liberalization in many developing countries and advances in communications and transport systems. Some important consequences have been

- more intense competition in export and domestic markets for nearly all major agricultural commodities,
- more integrated global and regional markets that are dominated by a few large international trading companies,
- increasing demand for higher quality and safer foods, and
- increasing amounts of food travel longer distances with growing concerns about the energy used in 'food miles' and the transmission of pests and diseases to humans, plants and animals.

These changes have induced significant changes in the crop mix in countries that have opened their borders. Some developing countries have taken advantage of new trade opportunities to increase exports of non-traditional products such as flowers, fruits, wine and fish. Good examples are Chile, South Africa, Thailand, Costa Rica and Kenya. In Africa, many small countries have lost significant market shares for their traditional exports (e.g. coffee and tea) owing to high costs, poor quality and an inability to raise productivity. Such countries also face more intense competition in their own domestic food markets, including those for food staples. Farmers in OECD countries have been much less affected in their domestic markets because these are still protected, but some have seen increased export opportunities (such as cereals and oilseeds to Africa and Asia). There has also been an expansion in agricultural trade between developing countries (e.g. soybeans from Brazil to China).

(ii) *Low world prices*

The remarkable increase in the productivity of global agriculture achieved in recent decades has also led to lower production costs that, where markets are competitive, have been passed on to consumers through lower prices. Low-cost producers have also expanded their market reach through greater opportunities for international trade. As a result, there has been a continuing decline in world prices (see for example the food price index in figure 1). By artificially increasing the competitiveness of their farmers, OECD countries have also contributed to lower world prices through their agricultural support programs. However, world trade modelling studies suggest that world cereal prices would only be 10–15% higher if all OECD agricultural support policies are dismantled, so this is not the primary source of the decline in world prices.

Low prices are good for consumers, especially poor urban consumers in developing countries. On the contrary, they are a disincentive for farmers. They particularly discourage investment and production in countries and regions that are not sharing technological advances and whose costs are not declining as fast as others. The technology divide is widening between many rich and poor countries as a result of differences in research and development expenditures (Pardey *et al.* 2006). Low commodity prices are also a chronic

Table 2. Summary of global, country and local scale drivers of agricultural change. Source: authors (Importance: 0, very low; +, low–medium; ++, high. Trend: −−, strongly declining/negative; −, declining/negative; 0, stable; +, increasing/positive; ++, strongly increasing/positive; '/' indicates a range (reflecting both an observed range but also uncertainty). S&T, science and technology; LDC, less-developed country; R&D, research and development.)

drivers	importance	trend	remarks
global-scale drivers			
international trade and globalization of markets	+	+/++	greater role of trade; vertical integration and market power; higher quality foods
world prices for agricultural products	++	−−/0	long-term decline in prices; benefits consumers; squeezes small farmers
OECD agricultural support	++	0/−	over supply, further reduces prices; limits markets for LDC farmers
climate change: variability/extremes and trends	+/++	−/+	increasing variability/unpredictability; greater negative impacts in tropics
high energy prices	+	+/++	increase food costs, promote bio-fuel crops (perhaps increasing food price further)
globalization and privatization of agricultural science	+/++	+/++	increasing private sector role and IP for new science (e.g. biotechnology)
country-scale drivers			
per capita income growth	++	−/++	driver of expansion of food demand, investment assets (including human capital)
urbanization	+	+/++	alters food demand (more processed, fast food, oils, sugars and less home cooking)
commercializing/shortening market chains	+	+/++	greater consolidation; supermarkets; stricter price, volume, quality and timing norms
shifts in public policy: (i) agricultural support	+/++	+	LDC removal of state support (liberalization); hurt marginal/remote farmers
(ii) investments in agricultural S&T, extension, credit	++	−/+	public retreat from funding R&D, extension and other service provision
security: financial/business and conflict/crisis	+/++	−/+	climate for business and household investment; migration/re-settlement pressures
increasing water scarcities	++	++	water shortages within river basins and depleted ground-water and aquifers will curtail irrigated agriculture in many countries if not addressed soon
local-scale drivers			
poverty	++	−/+	aggregate declining; but growing in some LDC's; forces short-term perspectives
population pressure and demographic structure	+/++	−/++	growth negative/declining in many rich countries; positive/declining many LDCs
health (food production and consumption related)	++	−/+	malnourishment, obesity, HIV/AIDS, malaria; zoonoses; pesticide exposure, etc.
technology design	+/++	−/+	fitness for purpose (productivity, sustainability, profit-ability) often poor
property rights	+/++	−/+	absent/adverse property rights promote resource exploi-tation and underinvestment
condition and capacity of natural resources (on-site)	++	−−/+	on-site/off-site impact of residues greater in high-input systems
(externalities)	++	−−/0	externalities from resource degradation and agricultural expansion in low-input systems
infrastructure and market access	+	+/++	improves access to services, inputs, technologies as well as to output markets
non-farm opportunities	++	0/+	investment source; enable part-time farming and exit from agriculture

problem for many less-favoured agricultural areas owing to their uncompetitive yield levels and high transport costs.

(iii) *High energy prices*

High energy prices can have mixed environmental impacts. In mechanized farming systems, they may encourage lower tillage practices that reduce soil erosion. However, in many poor countries, they may contribute to additional deforestation and land degradation through greater use of wood, manures and crop by-products as sources of household energy in rural areas. Biomass energy already accounts for about one-third of total energy use in developing countries, with most being used for household purposes such as cooking and water and space heating (FAO 2000). On the other hand, if more land is planted to dedicated energy crops, agriculture might also make important contributions to reducing national energy costs and green house gas emissions. Current oil prices are already sufficiently high that investment (public and private) in bioenergy is increasing, but the real impetus for expansion in biomass is likely to come from growth in carbon payments and mandated requirements for mixing biofuels with existing transport fuels. Already several countries are moving in this direction. A significant expansion in bioenergy production could be immensely helpful to farmers around the world, but its impact on food prices and poverty and hunger needs to be carefully managed.

(iv) *OECD agricultural policies*
Although many developing countries have liberalized and opened up their agricultural markets to international trade in recent years (often as part of International Monetary Fund (IMF)/World Bank-supported structural adjustment programmes), the protectionist agricultural polices of most OECD countries are increasingly recognized as discriminating against the well-being of farmers in developing countries. Developing country farmers not only have limited access to rich country agricultural markets but also face domestic markets distorted by subsidized imports. The size of these distortions is immense. In 2000, the producer subsidy equivalent of these policies in the OECD countries was US$330 billion (World Bank 2002); equal to Africa's entire annual GDP that year. These policies are particularly damaging to small farmers in poor countries because they limit their opportunities to produce more of the products in which they have comparative advantage. This is not just a matter of developing country farmers being squeezed out of export markets for tropical 'cash' crops like cotton, sugar and tobacco, but they are even pressured in their own domestic and regional markets for staple foods like cereals and livestock products. The recent collapse of the Doha round of the WTO negotiations does not bode well for any immediate correction of these distortions.

(b) *Country-scale drivers*
(i) Per capita *income and urbanization*
Growth in national *per capita* income leads to major transformations within the agricultural sector.

— Agriculture's share in national income and employment falls as countries grow richer and diversify into manufacturing and service sector activities, even though agricultural output and employment typically keep growing until quite late in the development process. This means that agriculture becomes progressively less important for national economic growth. However, the decline in agriculture's importance is often overstated in the sense that the locus of value-added activities derived from agriculture shifts to the processing of food and non-food products, packing, distribution, retail and so on whose benefits are attributed to other sectors, e.g. services. However, the fundamental reliance on agriculture still remains.
— As *per capita* incomes rise, labour becomes more expensive relative to land and capital and small farms begin to get squeezed out by larger and more capitalized farms that become better placed to compete. This also leads to an exodus of agricultural workers and the adoption of more capital intensive technologies.
— As *per capita* incomes rise, consumers diversify their diets and demand higher-value livestock products, fruits and vegetables and relatively less food staples. They also demand higher-quality and safer products, and more processed and pre-cooked foods. Urbanization accentuates these patterns and also places a high premium on market access, especially for perishable products.

As a result of these changes, farms become larger, more commercial and more specialized in higher-value products. Many small farms disappear, while others adapt either by specializing in high-value niches in which they can compete or by becoming part-time farmers (Lipton 2005). Fortunately, opportunities for small farms and agricultural workers to leave agriculture or diversify their incomes also increase with economic growth.

This transformation has historically taken many generations to unfold (e.g. in Europe and the USA where the agricultural work force is now less than 2% of the total) but is happening at a much faster rate today in some parts of the developing world. For example, the rapid growth of *per capita* incomes and urbanization in Asian countries like China and India (where about half the work force is still in agriculture) is leading to enormous pressure for many millions of small farms to adapt and/or find exit strategies. Europe is still struggling to solve the remnants of its own small-farm problem after several decades of highly expensive interventions. Yet the scale of the problem Europe faced after World War II was tiny compared with that faced by Asia today. A key question is whether Asia will be able to handle its small farm transition without resorting to the kinds of expensive and market-distorting agricultural support programmes that ensnared most OECD countries.

Growth in *per capita* income also affects a country's ability to cope with environmental problems. Historically, there is an inverted U-curve relationship between economic development and many types of environmental degradation (Yandle *et al.* 2004). Countries initially degrade resources and pollute their environment as they begin to grow, and degradation typically continues to worsen until levels of *per capita* income are attained at which growing aspirations for improved quality of life, together with sufficient economic means and institutional capabilities, enable many environmental problems to be addressed and even reversed. Evidence for this broad relationship can be found in cross-country and historical country studies of air pollution and water contamination (e.g. World Bank 1992; Lomborg 2001), and community and regional studies of resource degradation (Tiffen *et al.* 1994).

(ii) *Changing market chains*
Marketing chains are changing in countries of all types with trade liberalization and globalization. Supermarkets, for example, are expanding rapidly to become the dominant player in controlling access to retail markets in Asia and Latin America (Reardon *et al.* 2003), and direct links to international trading companies are often essential for accessing high-value

export markets. As a result, developing country farmers are increasingly being challenged to compete in markets that are much more consumer driven and demanding in terms of the type, quality and safety of agricultural products, more concentrated and integrated, and much more open to international competition. As farmers struggle to diversify into higher-value products, they must increasingly meet the requirements of these demanding and fickle markets, at both home and overseas. These changes offer new opportunities to farmers who can successfully access and compete in such transformed markets, but they are also a serious threat to those who cannot. Many small farmers are particularly under threat from these developments and cannot easily compete with large farms on the basis of cost, quality or volume. Solutions sometimes lie in the formation of producer marketing groups or in contract arrangements with large farms or buyers (Narayanan & Gulati 2003).

(iii) *Shifts in public policy*

In developing countries, fundamental shifts in the internationally accepted development paradigm have transformed public sector policies towards the agricultural sector. As part of the IMF/World Bank-led structural adjustment programmes of the 1980s and early 1990s, state agencies in many countries have been removed from providing direct marketing and service functions to farmers, supposedly creating opportunities for the private sector to take over as a more efficient supplier. This change in paradigm may be working for the larger national good in countries with reasonable infrastructure and effective legal and regulatory frameworks, especially for high-value markets. Evidence on the net impact of the policy reforms on agricultural growth remains mixed (Fan & Rao 2003). While the reforms led to some improvements in farm gate prices and costs that should have induced more on-farm investment and productivity increases, they also led to a decline in public investment in agriculture in many poor countries, which will have weakened the competitiveness of the sector. The mixed response of the private sector in assuming the mantle for providing key services adds to the ambiguities of the net impact of the reforms. However, the private sector has not stepped in to fill the vacuum left by the withdrawal of state agencies in many low-income countries (LICs; Dorward *et al.* 1998; Kherallah *et al.* 2002). The removal of subsidies has also made some key inputs (e.g. fertilizer) prohibitively expensive for many farms, and the removal of price stabilization programmes has exposed farmers to more volatile farmgate prices. These problems are especially difficult for small farms located in more remote regions with poor infrastructure and market access.

These policy-related driving forces are particularly challenging for Africa and South Asia, where small farms account for over 80% of total farms and 40% or more of total agricultural output. Left to market forces alone, the major beneficiaries of the new high-value and liberalized agriculture will mostly be the larger and commercially oriented farms, and farms that are well connected to roads and markets. Many more small farmers and agricultural workers will need to leave the industry if these polices continue unabated (Lipton 2005).

Some OECD countries have also reformed their domestic agricultural policies in recent years, moving away from price support polices that encourage high-input use and excess production to more direct payments that are less tied to production. These include income support payments and environmental conservation payments in the US and Europe. These policy changes have helped reduce domestic agricultural surpluses and public food stocks, but they have been insufficient to level the playing field for most developing countries. Farmers in developing countries must still compete with subsidized exports from OECD countries, and they face many non-price barriers on agricultural exports to OECD countries.

(c) *Local-scale drivers*

(i) *Poverty*

Poor people have been widely implicated as a primary cause of much of the observed environmental degradation in rural areas. A prevalent view in the literature is that poor people are less able to contain or reverse resource degradation because they are more desperate and more likely to trade-off tomorrow's production in order to eat today (Mink 1993). They are also more likely than richer people to have large families, lack investment capital, face insecure property rights, have limited access to suitable technologies and be less informed about the consequences of their actions. Worsening degradation contributes to lower incomes and deepening poverty. Since this aggravates many of the factors thought to prevent poor people from stabilizing or improving the condition of their natural resources, the degradation of these resources continues to worsen. Over time, poor people are trapped in a downward spiral, with ever-worsening poverty and resource degradation (Cleaver & Schrieber 1994). The spiral is further aggravated by population growth that increases the number of poor people who are dependent on the deteriorating resource base.

Although there are clear cases where poverty is an important driving force behind resource degradation, empirical research shows this is more likely to occur in poor-quality and fragile agricultural lands, especially those with high and increasing population densities. More generally, degradation results from the behaviour of all kinds of farmers, including larger-scale and richer farmers. Environmental degradation in highly productive irrigated areas is a case in point, since most of the farmers in those areas are not poor. Even in many less-productive rainfed lands, richer households actually own most of the land and livestock and are major contributors to resource degradation (e.g. large-scale cattle ranchers in the Amazon Basin, large-scale sheep herders and mechanized crop farmers in the low-rainfall areas of North Africa and the Near East). Even among the poor themselves, there is considerable diversity in how they manage natural resources. This reflects complex socioeconomic factors that may relate to broader issues concerning rights of access to, and control of, natural resources, political empowerment, alternative livelihood options and ability to marshal investment capital than simply to levels of poverty and

Table 3. Development indicators by country income group.

indicator	units	average 2000–2002	growth 1961–2002 (% per yr)	growth 1992–2002 (% per yr)
high-income countries (HICs)				
GDP *per capita*	US$(2000)	26 086	2.84	1.47
agricultural GDP in total GDP	%	1.7	−4.08	−0.95
total population	1000	943 571	0.77	0.65
rural population	1000	211 445	−0.41	−0.44
urban population	1000	732 127	1.24	0.98
agricultural population	1000	34 191	−3.28	−3.74
agricultural labour force	1000	16 939	−2.83	−3.43
arable and permanent cropland	1000 ha	371 738	0.02	−0.25
irrigated land	1000 ha	43 366	1.23	0.50
N fertilizer per ha cropland	kg ha^{-1}	64	2.30	0.51
average cereal yield	kg ha^{-1}	4802	1.79	1.31
middle-income countries (MICs)				
GDP *per capita*	US$(2000)	1763	3.09	2.71
agricultural GDP in total GDP	%	9.4	−1.82	−1.24
total population	1000	2 978 142	2.17	1.11
rural population	1000	1 442 105	1.08	−0.18
urban population	1000	1 536 038	3.98	2.46
agricultural population	1000	1 274 616	0.88	−0.17
agricultural labour force	1000	710 147	1.40	0.19
arable and permanent cropland	1000 ha	741 755	1.76	0.23
irrigated land	1000 ha	130 393	2.00	0.79
N fertilizer per ha cropland	kg ha^{-1}	56	5.31	1.70
average cereal yield	kg ha^{-1}	3162	2.21	1.68
low-income countries (LICs)				
GDP *per capita*	US$(2000)	412	1.70	2.62
agricultural GDP in total GDP	%	24.2	−1.45	−1.78
total population	1000	2 234 481	2.49	2.25
rural population	1000	1 575 585	2.49	2.25
urban population	1000	658 896	4.04	3.42
agricultural population	1000	1 271 802	1.75	1.43
agricultural labour force	1000	598 323	1.67	1.67
arable and permanent cropland	1000 ha	417 953	0.59	0.64
irrigated land	1000 ha	102 145	2.30	1.36
N fertilizer per ha cropland	kg ha^{-1}	41	7.95	2.15
average cereal yield	kg ha^{-1}	2029	1.96	1.52

resource availability (Barraclough & Ghimire 1995; Reardon & Vosti 1995; Forsyth *et al.* 1998; Scherr 1999).

The fact that poverty is not a clear driver of resource degradation also helps explain why recent gains in reducing poverty in some countries have not always led to noticeable improvements in sustainable resource management. However, unless chronic hunger and food insecurity are reduced, the poor will continue to exploit natural resources in the short run, thereby undermining the sustainability of natural ecosystems and consequent food security in the long run (Webb 2002).

(ii) *Population pressure*

Rural population growth is still high in many, particularly poorer, countries despite migration and rapid urbanization (table 3). However, how this impacts on agricultural productivity and environmental management is still a matter of some debate. There are two competing theories about the impact of population growth on natural resource degradation and agricultural productivity. The traditional Malthusian argument assumes limited technological advance in agriculture, hence growth in population leads to expansion of the cropped area into ever more marginal lands, with a resulting decline in labour productivity and *per capita* output. This process of impoverishment continues until *per capita* output declines to subsistence levels, below which population growth is unsustainable (Malthus 1993). Extensions of this model to include resource degradation lead to 'downward spirals' that accelerate the process of impoverishment (Cleaver & Schrieber 1994).

In contrast, Boserup (1965) has offered the much more optimistic view that as population pressure grows and labour becomes cheaper relative to land, then a process of 'induced innovation' occurs whereby communities invest in agricultural intensification and in improving their natural resources. For example, in many Asian societies, growing population pressure led eventually to investment in the terracing and levelling of cropland, to the construction of elaborate irrigation systems and to the use of composting and manures. The induced innovation model predicts increases in agricultural output per unit of land, but it does not necessarily predict that output per worker (or average labour productivity) will also increase, or that investments will be made in technologies that improve the long-term sustainability of resources. This will depend on the speed and type of the induced technological change. If average output per worker continues to decline, then the induced innovation model can also lead to the same state of impoverishment as the Malthusian model, but over a longer-time horizon. Geertz (1968) documented such a process in Java and coined the term 'agricultural involution'. However, if technological change can raise labour productivity then, even as more workers are absorbed into the system, *per capita* incomes will rise on average, and a sustained process of economic development may be launched. A growing body of empirical studies lends support to the induced innovation model (see Pender (1999) for a review), though often without showing any sustained increases in labour productivity.

Migration out of rural areas, whether permanent or seasonal, has increased dramatically in many developing countries in recent years and has helped contain, though not reverse, rural population growth. Migration has mixed impacts on agriculture. It affects labour supplies (negatively in the home areas, but perhaps positively in other rural areas in the case of rural–rural migration) and remittances can be an important source of income for the home areas, reducing poverty and providing available funds for investment in farm inputs and investments that enhance productivity (Reardon *et al.* 1994).

(iii) *Health*

Worsening health problems such as malaria and HIV/AIDS are taking a severe and increasing toll among rural people in many locales. Some of these problems are specific to particular ecosystems (e.g. malaria in tropical lowlands), while others are more pervasive and can have strong links to urban areas (e.g. HIV/AIDS) and impact agricultural areas with better links to transport routes and urban areas. HIV/AIDS is particularly pernicious in that it first strikes adults, reducing the number of able adult workers and leaving many children as orphans with limited knowledge about how to farm. Many small farms will eventually disappear as a result of HIV/AIDS, but only after a difficult transition period during which local communities must find ways to cope with the human tragedies involved. Health problems correlate strongly with income and poverty, since poor countries and poor regions have the least resources to prevent and control health problems. Health problems may also be aggravated by global and regional climate change.

(iv) *Technology design*

New and improved technology has proven to be the most important driver of agricultural productivity growth. How new technologies are designed and managed therefore have an important bearing on the environmental impact of agricultural growth. When poorly designed, or inappropriately used, technologies can lead farmers to increase production in ways that degrade natural resources. New technologies have often been developed with a narrow focus on short-term profitability to farmers and without due consideration of their longer-term sustainability. For example, the development of powerful pesticides and herbicides reduced costs and improved yields but often had negative effects on the environment, human health and long-term yields. The construction of modern irrigation systems without adequate provision for water drainage has also been implicated in a lot of waterlogging and salinization problems. A related problem is the spread of new technologies from the agroclimatic zones or farming systems for which they were developed to other, less-suitable areas where they may degrade resources. A good example is the encroachment of barley cultivation into low-rainfall grazing areas in the Middle East, leading to widespread land degradation, a development that became profitable partly in response to new varieties and growing techniques developed for higher rainfall areas. The widespread transfer of technologies between countries can pose similar risks.

On the other hand, well-designed technologies can make important contributions to productivity growth while also improving environmental outcomes. Integrated pest management is a good example, as is low tillage farming and growing of fertilizer crops and trees (legumes that provide nitrogen to the soil). Another example is the use of pest-resistant crop varieties that reduce or eliminate the need for use of pesticides.

Many publicly funded international and national agricultural research systems have taken important steps in recent years to better address sustainability issues in technology design and to address some important natural resource management (NRM) issues at farm, landscape and watershed levels. The private sector has less incentive to undertake this kind of research and the rapid expansion of privately funded research in some countries implies that the public sector may have to increase its own share of NRM research.

(v) *Property rights*

The property rights that farmers have over natural resources can be important in determining whether they take a short- or long-term perspective in managing resources. For example, farmers who feel that their tenure is insecure, with or without formal rights, are less likely to be interested in conserving resources or in making investments that improve the long-term productivity of resources. Secure property rights can also be important for obtaining credit in order to make resource-improving investments (Feder *et al.* 1988). Property rights are often problematic during the transition from extensive to intensive agricultural systems, when they typically must evolve from indigenous, community-based tenure systems to registered and legally recognized, private property arrangements. Although there is evidence that property rights do evolve in response to changing needs (Bruce & Mighot-Adholla 1993; Place & Hazell 1993), this cannot always be taken for granted, especially if states have intervened in traditional property rights systems (e.g. nationalized land), or if government investments (e.g. in irrigation or roads) have abruptly increased the value of land. Property rights systems are usually codified and registered as countries develop, and as a result they are not an issue in most high-income countries (HICs). Many of the transitional economies (i.e. former communist countries) are an exception, and their property rights systems are typically in a state of flux. In the former Soviet Union, for example, many of the collective farms have yet to be sub-divided and privatized, whereas in China land has been subdivided but farmers have only been given tenancy rather than ownership rights.

Property rights over common property resources, such as open rangeland or forest, can be a problem in countries of all kinds because the local institutions that traditionally control and regulate the use of such resources are becoming less effective. They are particularly challenged by increasing numbers of resource users, and encroachment by outsiders. Privatization to individuals is sometimes the most efficient solution to the management of these resources. However, in many cases, there are good economic or social reasons for maintaining them as common properties (Knox *et al.* 2002).

(vi) *Infrastructure and market access*

Adequate levels of rural infrastructure are essential for agricultural growth, and poor infrastructure is one of the most binding constraints for many poor countries (Fan & Hazell 2001; Fan & Chan-Kang 2005). Spencer (1994) compared the density of Africa's road network in early 1990s with that of India in the 1950s prior to the green revolution and found that India had nearly six times the density on average. If one takes the Indian density as broadly indicative of what is needed for rapid agricultural growth, then it is clear that much of Africa will need massive investments in rural infrastructure before it can hope to launch a successful agricultural revolution (see also Platteau (1996)). This gap continues to widen as Asian countries are investing in rural infrastructure at higher rates than most African countries (Fan & Rao 2003).

Access to rural infrastructure has an important bearing on the types of land uses and livelihood strategies that communities and households are able to pursue. Better road access to markets, for example, enhances opportunities for high-value agriculture, including production of more perishable products. It can also enhance opportunities for off-farm employment and for engaging in own non-farm businesses (Pender 2004). On the other hand, construction of new roads in environmentally fragile areas can be destructive since they may attract new settlement and increase the profitability of less sustainable land uses.

(vii) *Non-farm opportunities*

Rural non-farm income, such as non-farm wage or self-employment earnings, is already an important component of the livelihood strategies of rural people around the world, sometimes accounting for more than half their income. Its importance is also growing with urbanization and greater spatial integration of markets (Ellis & Harris 2004). However, in many developing countries and other less-developed regions, opportunities for farmers and agricultural workers to reduce their dependence on agriculture are constrained by the paucity of their human, financial and physical assets and by the poor economic performance of the region and country in which they live. History shows that countries invariably diversify as they develop, and that involves a decline of agriculture relative to the rest of the economy and the movement of workers out of agriculture and into other occupations. However, diversification is demand driven and follows rising *per capita* incomes; it is not a primary engine of growth in its own right.

In richer and growing economies, rural–urban migration and rural income diversification are indicators of economic growth and structural transformation and a sign that workers are typically being 'pulled' out of agriculture into higher-paying occupations. However, when economic growth has stalled, as in much of Africa, migration and income diversification are more typically distress phenomena, with workers seeking to augment already low and declining *per capita* incomes from farming by increasing production of low-paying services and household manufactures for sale into already saturated local markets.

4. STRATEGIES FOR A MORE SUSTAINABLE AGRICULTURE

While a global review of drivers can point to broad challenges and opportunities, it is of limited value in designing sustainable strategies in a world in which food surpluses coexist with widespread hunger and where numerous forms of environmental degradation stem from agricultural growth. To better appreciate the relevance of specific drivers and to gain clearer insights into potential response options, we must recognize and deal with the heterogeneity of agricultural development conditions around the world.

The links between agricultural growth and environmental outcomes depend very much on the type of farming system and their country's economic context. For example, the environmental consequences of intensive farming in irrigated areas are quite different from those of extensive farming in low-potential rainfed areas, and richer countries have far more options than poor countries for correcting environmental problems. A useful way to capture these differences is through construction of a relatively simple global typology of agricultural domains (ADs) based on a country× farming systems approach.

(a) *A typology of agricultural domains*

To capture important differences in country situations, we examined the literature on the determinants of national food security and hunger. This literature points to a wide range of factors including national level of income, income distribution, *per capita* food production, trade openness, risk exposure, conflict and insecurity and so on. However, of all these variables, *per capita* income and agricultural productivity appear to be the two strongest correlates of food security at the country level (e.g. Zhang *et al.* 2004), and we adopt them for our AD characterization.

The standard measure of national income is gross national income (GNI) *per capita*, and the World Bank categorizes countries into one of three broad income

Table 4. Agricultural domain rural populations (millions of people). Source: authors calculations based on rural populations from the Global Rural/Urban Mapping Project (GRUMP: CIESIN 2006). (*Other includes extensive grazing lands that fall outside of the global extent of agriculture as defined based on satellite and climate data and areas where satellite and climate data are not available (e.g. islands, some coastal areas).)

	income group						
agricultural productivity group	OECD/high		middle		low		total
irrigated agriculture	24.7	17.1%	534.1	38.8%	649.1	46.2%	1208.4
	0.8%		18.2%		22.2%		41.3%
High-potential rainfed agriculture	68.4	47.4%	373.0	27.1%	351.4	25.0%	793.6
	2.3%		12.7%		12.0%		27.1%
low-potential rainfed agriculture	51.0	35.4%	470.7	34.2%	404.4	28.8%	926.8
	1.7%		16.1%		13.8%		31.6%
total (agriculture)	144.1	100.0%	1377.8	100.0%	1404.9	100.0%	2928.8
	4.9%		47.0%		48.0%		100.0%
other*							333.0
total							3261.8

bands: HICs, middle-income countries (MICs) and LICs (World Bank 2005). GNI measures the total domestic and foreign values added as claimed by residents. GNI comprises GDP plus net receipts of primary income from foreign sources. GNI is computed in U.S. dollars from GNI reported in national currencies, using a 3-year average of exchange rates. LICs are those whose GNI/capita is less than US$825, middle income US$826–US$10 065, and high income more than US$10 065 (World Bank 2005). Table 3 summarizes key development indicators for the three country groupings.

In keeping with the changing role of agriculture during the economic transformation of a country (see earlier), agriculture accounts for diminishing shares of national GDP and population as one moves from the LIC to the HIC group. Agriculture accounts for only 1.7% of total GDP and 3.6% of total population in the HICs, compared with 24% of GDP and 57% of the total population in LICs (table 3). Although agriculture is a relatively modest component of GDP in MICs (9.4%), it still provides an important source of livelihood for nearly half the population (46%). With GDP shares that are smaller than population shares, there is an implied income gap between the agricultural and non-agricultural populations. This gap is growing fastest in LICs and is exacerbated by a still growing agricultural population (1.43% yr^{-1}) despite negative growth (−1.78% yr^{-1}) in agriculture's share of total GDP. The agricultural population is declining in MICs (−0.17% yr^{-1}) and HICs (−3.74% yr^{-1}).

Calculations undertaken by the authors with World Bank data (World Bank 2005) show that the incidence of poverty (measured as the per cent of the population living on less than $1/day) is much higher (34.9%) in LICs than MICs (12.4%) and both are much higher than in HICs (1.9%). The shares of undernourished people follow a similar pattern—25% of the population in LICs, 10.1% in MICs, and 5% in HICs.

Crop productivity is highest in HICs as reflected in higher nitrogen application rates and average cereal yields (table 3), but yield growth rates during 1992–2002 were marginally higher in both LICs and MICs than in HICs. At these rates of growth, it will take several hundred years for yields to converge between the three groups of countries.

While a country grouping is useful for capturing many important contextual issues that impinge on the constraints and opportunities for agriculture in general, it is insufficient for addressing many important agriculture–environment linkages. Although there are many farming systems classifications (e.g. Dixon *et al.* 2001), our primary interest lies in capturing differences in agricultural productivity that are also linked to environmental issues. To this end, we have drawn upon spatially referenced information about the location and extent of rainfed and irrigated croplands and pasture/rangelands, and further split the rainfed areas into those that are more or less favoured according to rainfall and terrain conditions. This process yielded three categories of location in terms of agricultural productivity classes, as follows.

— *Irrigated agriculture (IA)*. Cropland and pasture areas with more than 15% of their surface area serviced by irrigation infrastructure.
— *High-potential rainfed agriculture (HPRA)*. Rainfed cropland and pasture/rangeland areas in which the length of growing period (LGP) is 180 d yr^{-1} or more and the average slope is less than 15%.
— *Low-potential rainfed agriculture (LPRA)*. Rainfed cropland and pasture/rangeland areas with LGP of less than 180 d yr^{-1} or where average slopes are 15% or greater.

Our typology intersects the three classes of *per capita* GNI with the three agricultural productivity classes to define nine AD categories. The area, population and production attributes of each AD are summarized in tables 4–7.[1]

Only 4.9% of the world's rural population of 3.3 billion live in HICs, while the remaining 95% are equally split between MICs and LICs (table 4). The largest share of rural people live in IA areas (41.3%), while 27.1% live in areas of HPRA and 31.6% live in areas of LPRA.

Of the world's total agricultural area, more than half (55%) are LPRA areas, while 10% are IA areas and 35% are HPRA areas (table 5). Interestingly, the split

Table 5. Agricultural domain areas (1000 km^2). Source: authors.

	income group						
agricultural productivity group	OECD/high		middle		low		total
irrigated agriculture	1307		3284		2193		6783
	2.0%	10.2%	5.0%	9.6%	3.3%	11.7%	10.3%
high-potential rainfed agriculture	4236		11 884		6788		22 908
	6.4%	33.1%	18.1%	34.7%	10.3%	36.2%	34.8%
low-potential rainfed agriculture	7254		19 068		9786		36 107
	11.0%	56.7%	29.0%	55.7%	14.9%	52.1%	54.9%
total	12 796		34 235		18 767		65 798
	19.4%	100.0%	52.0%	100.0%	28.5%	100.0%	100.0%

Table 6. Estimated value of crop and livestock production by agricultural domain (US$ million), 2003–2005. Source: authors. (Value of production is computed from the average annual production of FAO crop and livestock commodities/products for the period 2003–2005 and international prices for the period 1989/91—the most recent time for which a full set of compatible prices for all commodities was available. *Other includes extensive grazing lands that fall outside of the global extent of agriculture as defined using satellite and climate data as well as areas where satellite and climate data are not available (e.g. islands, some coastal areas). Afghanistan, Iraq and Somalia are not included due to lack of data for 2003–2005.)

	income group						
agricultural productivity group	OECD/high		middle		low		total
irrigated agriculture (IA)	83 834	21.9%	270 429	36.1%	142 895	53.9%	497 158
	6.0%		19.4%		10.2%		35.6%
high-potential rainfed agriculture (HPRA)	179 050	46.7%	243 446	32.5%	55 489	20.9%	477 986
	12.8%		17.4%		4.0%		34.2%
low-potential rainfed agriculture (LPRA)	120 221	31.4%	235 078	31.4%	66 895	25.2%	422 195
	8.6%		16.8%		4.8%		30.2%
total (agriculture)	383 104	100.0%	748 954	100.0%	265 279	100.0%	1397 339
	27.4%		53.6%		19.0%		100.0%
other*							127 711
total							1525 050

between IA areas, HPRA areas and LPRA areas is about the same in all three country groups (i.e. 10, 35 and 55%, respectively). The majority of the world's agricultural land falls in the MICs (52%), followed by LICs (29%) and HICs (19%).

The global value of crop and livestock production is about equally split at one-third each between IA areas, HPRA areas and LPRA areas (table 6). Production is concentrated in MICs (54%), followed by HICs (27.4%) and LICs (19.0%). The high MIC share is in keeping with their large area share, but the LIC and HIC shares of production are the inverse of their shares of the land area, implying significant differences in land productivity. This is confirmed in table 7, where it can be seen that on average land productivity in LICs is about half that in HICs and 64% of that in MICs. There are even wider disparities in labour productivity (measured as agricultural production *per capita* of agricultural population).

The disparities in land productivities across major farming systems are huge. On average, LPRA areas generate less than 15% of the total value of output of IA areas, and in LICs even HPRA areas do not perform much better than LPRA areas. Fortunately, population densities are also much lower in LPRA areas (table 8), so disparities in *per capita* agricultural output are much smaller (table 7). In LICs, for example, LPRA areas are only 10% as productive as IA areas, but because the population density in these areas is only 13% of that in

Table 7. Estimated value of agricultural production *per capita* of rural population and per unit of agricultural land, by agricultural domain (US$ per person and US$ per 1000 km^2), early 2000s. Source: derived from tables 4–6.

	income group			
agricultural productivity class	OECD/high	middle	low	average
labour productivity				
irrigated agriculture	3393	506	220	411
high-potential rainfed agriculture	2618	653	158	602
low-potential rainfed agriculture	2356	499	165	456
all systems	2658	544	189	477
land productivity				
irrigated agriculture	64.1	82.3	65.2	73.3
high-potential rainfed agriculture	42.3	20.5	8.2	20.8
low-potential rainfed agriculture	16.6	12.3	6.8	11.7
all systems	29.9	21.9	14.1	21.2

Table 8. Population density by agricultural domain (rural persons per 1000 km^2 of agricultural land). Source: authors.

agricultural productivity group	income group		
	OECD/high	middle	low
irrigated agriculture	18 910	162 639	296 020
high-potential rainfed agriculture	16 146	31 389	51 771
low-potential rainfed agriculture	7036	24 684	41 326

Table 9. Percent of agricultural extent area free of soil constraints. Source: authors.

agricultural productivity group	income group			
	OECD/ high	upper-middle	low	total
irrigated	40.6	17.2	18.2	22.1
good rainfed	16.7	15.9	6.6	13.3
less-favoured rainfed	31.7	15.4	13.4	18.2
agricultural extent total	27.7	15.8	11.5	16.9
non-agricultural				14.5
total				15.7

IA areas, their *per capita* production is only 25% smaller.

From the perspective of economic development, the most important ADs are the IA areas and HPRA areas. Together, these account for 70% of the total value of crop and livestock production in the developing world (MICs+LICs) and for 51% of the global value of crop and livestock production. These ADs feed the developing world, and strategies for sustaining and increasing their productivity will be essential for feeding growing developing country populations. They are also home to 68% of the developing world's rural population.

However, from a poverty perspective, the LPRA areas cannot be neglected. These are home to about one-third of the developing world's rural population, and to a larger share of the rural poor. We do not have matching poverty data for our ADs, but studies of India and China (which together account for the majority of the developing world's total and rural populations) show that two-thirds or more of their rural poor live in less-favoured rainfed areas (Fan & Hazell 2001).

From an environmental perspective, the spatial distribution of IA and HPRA systems reflect the global distribution of many of the environmental problems associated with intensive farming systems (e.g. surface water and aquifer depletion, water logging and salinization of soils, chemical pollution, biodiversity loss). The distribution of LPRA systems reflects the global distribution of environmental problems associated with an expansion in extensive agriculture (e.g. deforestation, habitat and biodiversity loss, decreasing carbon sequestration capacity, soil erosion and soil fertility depletion), the problems being more severe the greater the population density, and the slower the growth in yields. These are typically poorer and more remote regions that are very likely food-deficit regions. Table 9, for example, shows that the prevalence of intrinsic soil quality constraints is lowest in HICs and irrigated areas and highest in rainfed lands in LICs.

(b) *Strategies for sustainable agricultural development*

(i) *Country perspectives*

The prospects for agricultural development differ considerably between our three country groups. In many MICs, past successes in meeting national food needs and transforming the economy have created a fundamental shift in the opportunities for farming. The prices of food staples are at historic lows, and remaining hunger and malnutrition is largely a problem of income distribution rather than food supplies. Rising incomes for many are leading to an unprecedented growth in demand for livestock, oilseed and horticultural and processed food products. In this situation, future agricultural strategies will need to focus on the very favourable opportunities that now exist for farmers to diversify away from food grains and into higher-value products. Farmers are prospering most in regions best able to compete in the market—those with good infrastructure and with marketing and distribution systems for higher-value, perishable foods. The private sector is taking the lead in making many of these investments and in organizing the markets.

High-value agriculture is already making substantial contributions to income growth in many MICs. However, left to market forces alone, many small farmers and poorer regions are likely to be left further behind. While growth in the service and manufacturing sectors is creating attractive income diversification and exit opportunities for many rural workers, such opportunities are still too limited in relation to need. Already there are signs of worsening spatial and inter-household inequalities in countries like China (Zhang & Fan 2004). Public interventions are needed to help distribute the benefits of the new agricultural growth more widely. These should include policies and investments to help integrate small farmers into modern market chains and to promote the long-term development of more remote and less-favoured regions.

The rapid growth of high-value agriculture often requires more flexible water management practices and this can be a challenge in areas with outmoded irrigation infrastructure and water management institutions. On the other hand, diversification does open up new opportunities for reducing water use and increasing the value of output per unit of water used. High-value agriculture also presents its own environmental challenges. These include use of pesticides on horticultural crops, problems in disposing of effluent and other animal waste products from intensive livestock systems (especially in peri-urban areas) and greater health risks. The ability to monitor and manage these kinds of problems has become important in most MICs.

While some LICs (e.g. India) are now growing very fast and are beginning to experience many of the opportunities and transition problems challenging MICs, many others (especially in sub-Saharan Africa) face a very different situation. Reminiscent of Asia in the early 1960s, these LICs are struggling with widespread poverty and malnutrition, national food deficits and increasing dependence on food imports and concessionary aid. Food staples still account for the majority share of their total value of agricultural output, and demand is projected to grow rapidly (e.g. doubling by 2020 across much of Africa). Moreover, with low and stagnant *per capita* incomes and widespread poverty, demand for higher-value foods remains low. The main growth in these markets lies in exports, but their current value is typically small and they are difficult markets for most LIC farmers to penetrate. Unlike MICs, the manufacturing sector remains small and lacklustre in most LICs, and the only real off-farm opportunities for small farmers are low-paying jobs in the service sector. In this context, the most viable prospects for most rural people in stagnant LICs still lie in agriculture, and in food staples rather than high-value agriculture.

Increasing production of food staples is challenging for many LICs owing to poor rural infrastructure and weak institutions to support agricultural development. Market access and transport costs are daunting obstacles to development. Modern technologies are simply not economic when farmers have to pay multiples of the world price of fertilizer and receive only a small share of the final market value of their products. In many cases, the problem has been exacerbated by structural adjustment programmes that removed the public institutions and subsidies providing farmers with affordable access to key inputs and markets. It will take significant investment in infrastructure and new technology to make the food staples sector competitive in today's markets. Moreover, since the privatization of markets for food staples and basic agricultural services has largely failed, there is urgent need for public sector innovation in models of public–private partnership that might fill the main marketing gaps; provide farmers with access to essential inputs like fertilizers, seeds and credit; and provide effective instruments for managing risk (Dorward *et al.* 2004).

The prospects for many agriculturally dependent LICs that fail to develop their food staples sectors are not favourable. Failure will emerge in the form of more dualistic patterns of agricultural growth, with a relatively small commercial farm sector producing high-value products for export and urban elites, and a large mass of subsistence-oriented farmers. In the absence of rapid growth in productive non-farm job opportunities, subsistence agriculture will inevitably lead to further degradation of the natural resource base and worsening poverty and hunger. Massive relief programmes funded by rich countries through grants or loans cannot provide a sustainable solution to this problem, and anyway may well be cut once the 2015 time frame for the millennium development goals has passed.

In most OECD countries, agriculture is at a cross roads, and future opportunities will hinge on the final outcome of the Doha Round of the world trade negotiations. If successful, and that seems far from certain, there would be an accelerated transition to modes of farm income support that are de-linked from production, and export subsidies would be removed. Greater exposure to world prices would encourage many farmers in these countries to diversify away from cereals and industrial crops like sugar beet and cotton into higher-value products and niche markets like organics. This would have mixed environmental impacts, with an overall reduction in nitrogen use and an increase in crop biodiversity, but perhaps greater use of pesticides and water. There would also be a sizeable expansion in the land area set aside for forest and other environmental purposes, and perhaps even bio-energy crops.

(ii) *Farming system perspectives*

The management of intensive farming in irrigated and high-potential rainfed areas requires better management of modem inputs. Deficient management of such inputs is commonplace in many developing countries where millions of poorly educated farmers now use them, and the problem has been exacerbated by inadequate extension and training, ineffective regulation of water quality, and input pricing and subsidy policies that made modern inputs too cheap and encouraged excessive use. Rich countries have not escaped these problems either, in part owing to government support policies that made highly intensive farming more profitable than it should have been, and owing to water resource and water quality regulation weaknesses similar to those of developing countries. Policy and institutional reforms that correct inappropriate incentives can make an important difference. Improved technologies, such as precision farming (using geographical information system (GIS)), ecological approaches to pest management, pest resistant varieties and improved water management practices can even increase yields while reducing chemical use (Pingali *et al.* 1997), implying that intensification does not have to be inconsistent with good management of the environment.

Farmers have been slow to switch to these kinds of improved practices. One reason is the continuing subsidies on water and agrochemicals that many governments provide. By making these inputs less costly, subsidies encourage farmers to be more wasteful in their use. However, another reason is that many of these improved practices are more labour and knowledge intensive (Pingali *et al.* 1997), and they can be difficult and costly for farmers to adopt. Rising labour costs in many South East Asian countries reduce the likelihood of adoption there, but the prospects seem more promising in the labour abundant regions of South Asia where they could also generate useful employment for the poor.

As demand for water has grown, especially in the non-agricultural sectors, many countries are increasingly facing water scarcities that will impact on water supplies available for irrigation. A priority for irrigated farming must be to obtain more crop value per unit of water while substantially reducing total water use, water pollution and the unsustainable mining of groundwater and aquifers. Although better technology and water pricing policies can make an important difference, the problems in many river basins will ultimately require a fundamental shift towards more market driven water allocation systems and more effective management and regulation of environmental externalities by governments and local communities. The prognosis for change is not good, given the politically contentious nature of changes in water ownership and allocation rights in many countries.

The prospects for reform of intensive farming systems are greatest in HICs and many MICs. Farmers in these countries face new market opportunities for diversifying away from monocrop farming, and even for expanding into niche markets for organic produce. The high quality, health and environmental standards imposed by governments and marketing organizations such as supermarkets are also compelling farmers to shift to better and more sustainable farming practices. Public institutions and civil society are also well organized in many of these countries and have the capacity to both regulate and assist farming communities in managing natural resources, including common property resources like groundwater, forests, rangelands and biodiversity. Improvements will be more challenging in many LICs where these institutional capacities and market pressures are much weaker and where most farmers remain poor.

The improved management of many low-potential rainfed areas in LICs and MICs lies partly in greater use of small-scale irrigation, water harvesting and modern inputs (including better synergies of new and indigenous knowledge systems) to achieve higher yields, restore soil fertility and reduce poverty and hunger. Continued reliance on low-productivity approaches, in the face of often rapidly mounting local food demands, has exacerbated soil nutrient depletion and soil erosion. Unfortunately, since many of such regions have limited infrastructure and market access, greater use of modern inputs is problematic and often unprofitable, access to information is limited and farmers must find alternative ways of increasing output. This brings additional pressure to shorten fallows unsustainably and to open up new land to agriculture, the latter often with high costs in terms of habitat and biodiversity loss.

Across all types of farming system, there has been a growing sense of urgency—notwithstanding the primacy of food security—that agriculture needs to do much more to reduce its environmental footprint. High external input systems are highly consumptive of energy and water for which demand is increasingly competitive with other sectors. We have also described how these systems tend to generate high external costs through emissions and residues (e.g. greenhouse gases, agrochemical residues in water and pesticide toxicity to humans and biodiversity) and through other land use and management strategies that often take a severe toll on wild biodiversity. Low-productivity systems are overly consumptive of land and, consequently, of wild biodiversity, increase carbon dioxide emissions through greater land conversion and management practices such as burning, and increased sediment transport and downstream siltation. However, more holistic approaches that simultaneously maintain the necessary focus on improved productivity as well as improved environmental outcomes, in ways that are profitable to farm households, are emerging (McNeely & Scherr 2003; Gliessman 2005; Pretty 2005, 2008; Pretty *et al.* 2006). However, the success of many of these approaches depends on improved assimilation of new scientific knowledge as well as more progressive policy and institutional environments (Pretty 2008).

Sustainable agriculture approaches focus attention on the integrated and more synergistic use of a range of pest, nutrient, soil and water management technologies. Reliance on purchased or external inputs such as chemical fertilizers, pesticides and improved seed is minimized, as is that of high energy-consuming mechanization. These methods are particularly appropriate for fragile and low-yield farming systems located in dry lands, wetlands, uplands, near-deserts, mountains and hillsides. Examples of specific technologies encompass: improved fallows, contour grass strips, rock bunds, rainwater harvesting, integrated pest management, zero tillage, and crop rotations and mixed farming, including integration of trees and livestock into the farming system. Such technologies generally result in increased land productivity, particularly in the case of technologies that produce consumable or saleable outputs. Technologies such as rock bunds do not produce food or produce for sale in the short run, but can contribute to long-term increases in land productivity by helping intercept and retain water, soil and nutrients. Some sustainable agriculture technologies are labour intensive, making them better suited to regions with surplus labour and small farms. On the other hand, some technologies contribute to greater water availability by acting as water conservation mechanisms. Technologies that improve soil water and nutrient management can also increase the profitability of using greater amounts of modern inputs.

Most improved NRM strategies for less-favoured areas require effective property rights and a high degree of collective action (Meinzen-Dick *et al.* 2002). For example, agroforestry and perennial tree crops are long-term investments, and individual farmers will only plant trees if they have secure (land or tree) property rights to ensure the capture of future returns from their investment. In the absence of formal legal property rights systems in many developing countries, secure access to resources can only be assured by local communities and hence customary property rights systems remain important. Some types of investments (e.g. watershed development and soil erosion control on hillsides) also require effective collection action between neighbouring farmers as well as long-term and secure property rights at household and community levels. Improvement of common property resources like woodlands, rangelands and groundwater, which play key roles in the livelihood strategies of many rural people in less-favoured areas, also requires effective local institutions for their management and regulation. Indigenous institutions that performed these roles quite successfully in the past have often been undercut by population growth, encroachment by outsiders and by state interventions (such as nationalization and public management of forests and rangelands in some countries). Recent attempts to re-empower local communities to manage their own resources have met with mixed success, but building upon and scaling up from recent successes probably offer the best hope for the future.

The management of less-favoured areas in HICs is much less of a problem. There is relatively little human pressure on the natural resource base and many such areas are managed under regulated systems of financial support that are linked to the provision of environmental services.

5. CONCLUDING REMARKS

We have reviewed a number of the key issues and drivers of significance to agriculture globally. We have seen that immense progress has been made from a humanitarian perspective in feeding a world population that has doubled in the past 40 years, become more wealthy, and increased its *per capita* demand for low-cost food in terms of quantity, quality and diversity. However, much still remains to be done both to further strengthen food security for the majority, and to attack the persistent, large and, in some places, still-growing pockets of hunger. Furthermore, all this needs to be done in ways that improve (or at least damage less) our long-term capacity to sustain food production. This means conserving biodiversity, soils, water and other resources that will provide the level and quality of ecosystem services necessary to support agriculture in the future.

However, while some drivers may be common, it is unlikely that appropriate responses to change either positive or negative impacts will likewise be similar. The geo-political and agroecological contexts under which agriculture is conducted globally—which we have broadly dubbed ADs—are very heterogeneous. We have proposed some broad categories of AD that might be helpful in thinking through the different ways in which drivers have impact and society might respond most appropriately. There are unlikely to be quick and easy adjustments to change in any domain, but working more diligently to organize our understanding of how and at what scale drivers operate and how they might interact, might help us find more quickly the commonalities of approach, and provide a structure for scaling these insights up and out.

The authors would like to thank Kate Sebastian (GIS) and Ulrike Wood-Sichra (database) for their excellent technical support in the preparation of this paper.

ENDNOTE

[1]A map showing the global graphical distribution of the nine ADs is available at http://www.ifpri.org/pubs/otherpubs/hw_agdomains.jpg.

REFERENCES

Adams, R. M., Chen, C., McCarl, B. A. & Weiher, R. F. 1999 The economic consequences of ENSO events for agriculture. *Clim. Res.* **13**, 165–172.

Anderson, J., Hazell, P. & Evans, L. 1987 Variability in cereal yields: sources of change and implications for agricultural research and policy. *Food Policy* **12**, 199–212. (doi:10.1016/0306-9192(77)90021-5)

Barraclough, S. & Ghimire, K. 1995 *Forests and livelihoods: the social dynamics of deforestation in developing countries*. New York, NY: St Martin's Press, Inc.

Biggelaar, D., Lal, R., Wiebe, K. & Breneman, V. 2001 Soil erosion impact on crop yields in North America. *Adv. Agron.* **72**, 1–52.

Bishop, J. & Allen, J. 1989 *The on-site costs of soil erosion in Mali. Environment working paper 21*. Washington, DC: Environment Department, World Bank.

Boserup, E. 1965 *The conditions of agricultural growth*. London, UK: Allen and Unwin.

Bruce, J. W. & Mighot-Adholla, S. E. 1993 *Searching for land tenure security in Africa*. Dubugue, MA: Kendall/Hung Publishing Company.

Bryant, D., Nielsen, D. & Tangley, L. 1997 *The last frontier forests: ecosystems and economies on the edge*. Washington, DC: World Resources Institute.

Cassman, K., & Wood, S. (coordinating lead authors) 2005 *Cultivated systems. Ecosystems and human well being, millennium ecosystem assessment (current state and trends)*, vol. 1, ch. 26. Washington, DC: Island Press.

CIESIN 2006 Global Rural-Urban Mapping Project (GRUMP). Dataset and documentation http://beta.sedac.ciesin.columbia.edu/gpw/documentation.jsp#.

Cleaver, K. & Schrieber, G. 1994 *Reversing the spiral: the population agriculture, and environment nexus in sub-Saharan Africa*. Washington, DC: World Bank.

Crosson, P. R. & Anderson, J. R. 1992 *Resources and global food prospects: supply and demand for cereals to 2030.* World Bank technical paper no. 184. Washington, DC: World Bank.

Dixon, J., Gulliver, A. & Gibbon, D. 2001 *Farming systems and poverty: improving farmers' livelihoods in a changing world.* Rome, Italy: Food and Agriculture Organization of the United Nations (FAO); Washington, DC: World Bank.

Dorward, A., Kydd, J. & Poulton, C. 1998 *Smallholder cash crop production under market liberalization: a new institutional economics perspective*. Wallingford, CT; New York, NY: CAB International.

Dorward, A. *et al.* 2004 *Institutions and economic policies for pro-poor agricultural growth.* Discussion paper no. 15. Washington, DC: Development Strategy and Governance Division, International Food Policy Research Institute.

Dregne, H., Kassas, M. & Razanov, B. 1991 A new assessment of the world status of desertification. Desertification Control Bulletin, United Nations Environment Programme no. 20.

Ellis, F. & Harris, N. 2004 New thinking about urban and rural development. Keynote paper prepared for the U.K. Department for International Development Sustainable Development Retreat.

Evans, L. T. 1998 *Feeding the ten billion: plants and population growth*. Cambridge, UK: Cambridge University Press.

Evenson, R. E. & Gollin, D. 2003 Assessing the impact of the Green Revolution, 1960 to 2000. *Science* **300**, 758–762. (doi:10.1126/science.1078710)

Fan, S. & Chan-Kang, C. 2005 *Road development, economic growth, and poverty reduction in China.* Research report no. 138. Washington, DC: International Food Policy Research Institute.

Fan, H. & Hazell, P. 2001 Returns to public investments in the less-favored areas of India and China. *Am. J. Agricult. Econ.* **83**, 1217–1222. (doi:10.1111/0002-9092.00270)

Fan, S. & Rao, N. 2003 *Public spending in developing countries: trends, determination, and impact.* Environment, production and technology division discussion paper no. 99. Washington, DC: International Food Policy Research Institute.

FAO 2000 *The energy and agriculture nexus.* Environment and natural resources working paper no. 4. Rome, Italy: Food and Agriculture Organization of the United Nations.

FAO 2005 *Global forest resource assessment*. Rome, Italy: Food and Agriculture Organization of the United Nations.

FAO 2006 World agriculture towards 2030/2050: interim report. Rome, Italy: Global Perspectives Studies Unit, Food and Agriculture Organization of the United Nations.

FAO/SOFI 2005 *The state of food insecurity in the world (SOFI) 2005*. Rome, Italy: Food and Agriculture Organization of the United Nations.

FAOSTAT 2006 FAO Statistical databases. See http://faostat.fao.org.

Feder, G., Ohchan, T., Chalamwong, Y. & Hongladaron, C. 1988 *Land policies and farm productivity in Thailand*. Baltimore, MD: Johns Hopkins University Press.

Forastieri, V. 1999 Safework: the ILO program on occupational safety and health in agriculture, ILO. Geneva. See http://www-ilo-mirror.cornell.edu/public/english/protection/safework/agriculture/agrivf01.htm.

Forsyth, T., Leach, M. & Scoones, I. 1998 Poverty and environment: priorities for research and policy, an overview study, prepared for the UNDP and European Commission, Institute of Development Studies, Brighton.

Geertz, C. 1968 *Agricultural involution*. Berkeley/Los Angeles, CA: University of California Press.

Geist, H. J. & Lambin, E. F. 2001 *What drives tropical deforestation?* Land Use Cover Change (LUCC) report series no. 4. Louvain, Belgium: LUCC International Project Office.

Ghassemi, F., Jakeman, A. J. & Nix, H. A. 1995 *Salinisation of land and water resources: human causes, extent, management, and case studies*. Wallingford, UK: CAB International.

Gliessman, S. R. 2005 Agroecology and agroecosystems. In *The earthscan reader in sustainable agriculture* (ed. J. Pretty). London, UK: Earthscan.

IPCC (Intergovernmental Panel on Climate Change) 2000 *Land use, land use change, and forestry*. (eds R. T. Watson, L. R. Noble & B. Bolin). Cambridge, UK: Cambridge University Press. Summary available online at: http://www.ipcc.ch/pub/spm_srlulucf.pdf

Kherallah, M., Delgado, C., Gabre-Madhin, E., Minot, N. & Johnson, M. 2002 *Reforming agricultural markets in Africa*. Baltimore, MD: The Johns Hopkins University Press.

Knox, A., Meinzen-Dick, R. & Hazell, P. 2002 Property rights, collective action, and technologies for natural resource management: a conceptual famework. In *Innovation in natural resource management; the role of property rights and collective action in developing countries* (eds R. Meinzen-Dick, A. Knox, F. Place & B. Swallow). Washington, DC: Johns Hopkins University Press for IFPRI.

Lal, R. 1997 Degradation and resilience of soils. *Phil. Trans. R. Soc. B* **352**, 997–1010. (doi:10.1098/rstb.1997.0078)

Lindert, P. H. 2000 *Shifting ground: the changing agricultural soils of China and Indonesia*. Cambridge, MA: MIT Press.

Lipton, M. 2005 *The family farm in a globalizing world: the role of crop science in alleviating poverty*. Discussion paper no. 40. Washington, DC: International Food Policy Research Institute.

Lomborg, B. 2001 *The skeptical environmentalist: measuring the real state of the world*. Cambridge, UK: Cambridge University Press.

Magrath, W. & Arens, P. 1989 *The costs of soil erosion on Java: a natural resource accounting approach*. Environment department working paper no. 18. Washington, DC: The World Bank.

Malthus, T. 1993 *An essay on the principle of population*. Oxford, UK: Oxford World's Classics, Oxford University Press. (First published in 1798.)

McNeely, J. A. & Scherr, S. J. 2003 *Ecoagriculture*. Washington, DC: Island Press.

Meinzen-Dick, R., Knox, A., Place, F. & Swallow, B. 2002 *Innovation in natural resources management: the role of property rights and collective action*. Baltimore, MD: Johns Hopkins University Press.

Millennium Ecosystem Assessment (MEA) 2005 *Ecosystems and well-being*. Washington, DC: Island Press.

Mink, S. D. 1993 *Poverty, population and the environment*. World Bank discussion paper no. 189. Washington, DC: The World Bank.

Narayanan, S. & Gulati, A. 2003 *Globalization and the smallholders: a review of issues, approaches and implications*. MTID discussion paper no. 50. Washington, DC: International Food Policy Research Institute.

Pardey, P. G., Beintema, N., Dehmer, S. & Wood, S. 2006 Agricultural research: a growing global divide? Food policy report. Agricultural science and technology indicators initiative. Washington, DC: International Food Policy Research Institute.

Pender, J. 1999 *Rural population growth, agricultural change and natural resource management in developing countries*. EPTD discussion paper no. 48. Washington, DC: International Food Policy Research Institute.

Pender, J. 2004 Development pathways for hillsides and highlands: some lessons from Central America and East Africa. *Food Policy* **29**, 339–367. (doi:10.1016/j.foodpol.2004.07.005)

Pingali, P. L. & Roger, P. A. (eds) 1995 *Impact of pesticides on farmer health and the rice environment*. Laguna, The Philippines: International Rice Research Institute.

Pingali, P. L., Hossain, M. & Gerpacio, R. V. 1997 *Asian rice bowls: the returning crisis*. Wallingford, UK: CAB International.

Pinstrup-Andersen, P. & Pandya-Lorch, R. 1994 *Alleviating poverty, intensifying agriculture, and effectively managing natural resources*. 2020 discussion paper no. 1. Washington, DC: International Food Policy Research Institute.

Place, F. & Hazell, P. B. R. 1993 Productivity effects of indigenous land tenure systems in sub-Saharan Africa. *Am. J. Agricult. Econ.* **75**, 10–19. (doi:10.2307/1242949)

Platteau, J. P. 1996 Physical infrastructure as a constraint on agricultural growth: the case of sub-Saharan Africa. *Oxford Dev. Studies* **24**, 189–222.

Postel, S. 1997 *Last oasis: facing water scarcity*. New York, NY: W. W. Norton.

Postel, S. 1999 *Pillar of sand: can the irrigation miracle last?* New York, NY: W. W. Norton.

Pretty, J. (ed.) 2005 *The pesticide detox*, p. 291. London, UK: Earthscan.

Pretty, J. 2008 Agricultural sustainability: concepts, principles and evidence. *Phil. Trans. R. Soc. B* **363**, 447–465. (doi:10.1098/rstb.2007.2163)

Pretty, J. N., Brett, C., Gee, D., Hine, R. E. & Mason, C. F. 2000 An assessment of the total external costs of UK agriculture. *Agricult. Syst.* **62**, 113–136. (doi:10.1016/S0308-521X(00)00031-7)

Pretty, J., Noble, A., Bossio, D., Dixon, J., Hine, R. E., Penning de Vries, P. & Morison, J. I. L. 2006 Resource conserving agriculture increases yields in developing countries. *Environ. Sci. Technol.* **40**, 1114–1119. (doi:10.1021/es051670d)

Reardon, T. A. & Vosti, S. A. 1995 Links between rural poverty and environment in developing countries: asset categories and 'investment poverty'. *World Dev.* **23**, 1495–1506. (doi:10.1016/0305-750X(95)00061-G)

Reardon, T., Eric, C. & Valerie, K. 1994 Links between non-farm income and farm investment in African households: adding the capital market perspective. *Am. J. Agricult. Econ.* **76**, 1172–1176. (doi:10.2307/1243412)

Reardon, T., Timmer, C. P., Barrett, C. & Berdegué, J. 2003 The rise of supermarkets in Africa, Asia, and Latin America. *Am. J. Agricult. Econ.* **85**, 1140–1146. (doi:10.1111/j.0092-5853.2003.00520.x)

Richards, J. F. 1990 Land transformation. In *The earth as transformed by human action* (ed. B. L. Turner). New York, NY: Cambridge University Press.

Ricketts, T. H., Daily, G. C., Ehrlich, P. R. & Michener, C. D. 2004 Economic value of tropical forest to coffee production. *Proc. Natl Aacd. Sci. USA* **101**, 12 579–12 582. (doi:10.1073/pnas.0405147101)

Rosegrant, M. W., Cai, X. & Cline, S. 2002 *World water and food to 2025: dealing with scarcity*. Colombo, Sri Lanka: International Food Policy Research Institute; Washington, DC: International Water Management Institute.

Runge, C. F., Senaur, B., Pardey, P. & Rosegrant, M. W. 2003 *Ending hunger in our lifetime: food security and globalization*. Baltimore, MD: Johns Hopkins University Press.

Sanchez, P. 2002 Soil fertility and hunger in Africa. *Science* **295**, 2020. (doi:10.1126/science.1065256)

Scherr, S. J. 1999 *Soil degradation. 2020 vision briefs 58*. Washington, DC: International Food Policy Research Institute.

Scherr, S. J. & Yadav, S. 1995 *Land degradation in the developing world: implications for food, agriculture, and the environment to 2020*. Food agriculture and the environment discussion paper 14. Washington, DC: International Food Policy Research Institute.

Scoones, I. (ed.) 2001 *Dynamics and diversity: soil fertility and farming livelihoods in Africa*. London, UK: International Institute for Environment and Development, Earthscan.

Smaling, E. M. A., Stoorvogel, J. J. & Windmeijer, P. N. 1993 Calculating soil nutrient balances in Africa at different scales: district scale. *Fertilizer Res.* **35**, 250. (doi:10.1007/BF00750642)

Smith, B. D. 1998 *The emergence of agriculture*. New York, NY: Scientific American Library.

Spencer, D. 1994 *Infrastructure and technology constraints to agricultural development in the humid and sub-humid tropics of Africa*. Discussion paper no. 3. Washington, DC: Environment and Production Technology Division, International Food Policy Research Institute.

Tiffen, M., Mortimore, M. & Gichuki, F. 1994 *More people, less erosion: environmental recovery in Kenya*. New York, NY: John Wiley.

Trimble, S. W. 1999 Decreased rates of alluvial sediment storage in the Coon Creek basin, Wisconsin, 1975–93. *Science* **285**, 1244–1246. (doi:10.1126/science.285.5431.1244)

Voigt, T., van Minnen, J., Erhard, M., Zebisch, M. & Viner, D. 2004 Indicators of Europe's changing climate. In *Europe Topic Centre on Air and Climate Change*. SB-20 Meeting, Bonn.

von Braun, J. 2005 *The world food situation: an overview*. CGIAR Annual General Meeting. Marrakech, Morocco. December 2005.

Webb, P. 2002 *Cultivated capital: agriculture, ecosystems and sustainable development*. Discussion paper no. 15. Boston, MA: Tufts University.

WHO (World Health Organization) 2002 *Globalization, diets and non-communicable diseases*. Geneva, Switzerland: WHO.

WHO 2003 *Diet, nutrition and the prevention of chronic diseases*. WHO technical report series 916.

WHO and UNEP (World Health Organization and United Nations Environment Programme) 1990 *Public health impact of pesticides used in agriculture*. Geneva, Switzerland: World Health Organization.

Wood, S., Sebastian, K. & Scherr, S. J. 2000 Pilot analysis of global ecosystems: agroecosystems. A joint study by the International Food Policy Research Institute and the World Resources Institute, Washington, DC.

World Bank 1992 *World development report 1992: development and the environment*. Oxford, UK: Oxford University Press.

World Bank 2002 *World Bank development report*. Washington, DC: World Bank.

World Bank 2005 CD-ROM World development indicators. Washington, DC: World Bank.

World Resources Institute (WRI) 1991 *Accounts overdue: natural resources depreciation in Costa Rica*. Washington, DC: World Resources Institute.

Yandle, B., Bhattarai, M. & Vijayaraghavan, M. 2004 Environmental Kuznets curves: a review of findings, methods, and policy implications, Research Study 02-1 (update April 2004), Property and Environment Research Center, Boseman.

Zhang, X. & Fan, S. 2004 Public investment and regional inequality in rural China. *Agricult. Econ.* **30**, 89–100. (doi:10.1111/j.1574-0862.2004.tb00179.x)

Zhang, X., Johnson, M., Resnick, D. & Robinson, S. 2004 *Cross country typologies and development strategies to end hunger in Africa*. DSGD discussion paper 8. Washington, DC: International Food Policy Research Institute.