ARTICLE IN PRESS

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B

Phil. Trans. R. Soc. B
doi:10.1098/rstb.2007.2163

Agricultural sustainability: concepts, principles and evidence

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Concerns about sustainability in agricultural systems centre on the need to develop technologies and practices that do not have adverse effects on environmental goods and services, accessible to and effective for farmers and lead to improvements in food productivity. Despite great progress in agricultural productivity in the past half-century, with crop and livestock productivity strongly driven by increased use of fertilizers, irrigation water, agricultural machinery, pesticides and land, it would be over-optimistic to assume that these relationships will remain linear in the future. New approaches are needed that will integrate biological and ecological processes into food production, minimize the use of those non-renewable inputs that cause harm to the environment or to the health of farmers and consumers, make productive use of the knowledge and skills of farmers, so substituting human capital for costly external inputs and make productive use of people's collective capacities to work together to solve common agricultural and natural resource problems, such as for pest, watershed, irrigation, forest and credit management.

These principles help to build important capital assets for agricultural systems: natural; social; human; physical; and financial capital. Improving natural capital is a central aim, and dividends can come from making the best use of the genotypes (G) of crops and animals and the ecological (Ec) conditions under which they are grown or raised. Agricultural sustainability suggests a focus on both genotype improvements through the full range of modern biological approaches and improved understanding of the benefits of ecological and agronomic management, manipulation and redesign. The ecological management of agroecosystems that addresses energy flows, nutrient cycling, population-regulating mechanisms and system resilience can lead to the redesign of agriculture at a landscape scale. Sustainable agriculture outcomes can be positive for food productivity, reduced pesticide use and carbon balances. Significant challenges, however, remain to develop national and international policies to support the wider emergence of more sustainable forms of agricultural production across both industrialized and developing countries.

Keywords: environmental goods and services; natural capital; social capital; agroecology; carbon sequestration; pesticides

1. THE CONTEXT FOR AGRICULTURAL SUSTAINABILITY

The interest in the sustainability of agricultural and food systems can be traced to environmental concerns that began to appear in the 1950s–1960s. However, ideas about sustainability date back at least to the oldest surviving writings from China, Greece and Rome (Cato 1979; Hesiod 1988; Conway 1997; Li Wenhua Q2 2001; Pretty 2002; 2005*a*). Today, concerns about sustainability centre on the need to develop agricultural technologies and practices that: (i) do not have adverse effects on the environment (partly because the environment is an important asset for farming), (ii) are accessible to and effective for farmers, and (iii) lead to both improvements in food productivity and have positive side effects on environmental goods and services. Sustainability in agricultural systems incorporates concepts of both resilience (the capacity of systems to buffer shocks and stresses) and persistence (the capacity of systems to continue over long periods) and addresses many wider economic, social and environmental outcomes.

In recent decades, there has been remarkable growth in agricultural production, with increases in food production across the world since the beginning of the 1960s. Since then, aggregate world food production has grown by 145%. In Africa, it rose by 140%, in Latin America by almost 200% and in Asia by 280%. The greatest increases have been in China, where a fivefold increase occurred, mostly during the 1980s–1990s. In industrialized countries, production started from a higher base; yet it still doubled in the USA over 40 years and grew by 68% in Western Europe (FAO 2005).

Over the same period, world population has grown from three to more than six billion imposing an increasing impact on the human footprint on the Earth as consumption patterns change (Kitzes *et al.* 2007; Pretty 2007). Again, though, *per capita* agricultural production has outpaced population growth (Hazell & Wood 2007), for each person today, there is an additional 25% more food compared with 1960. These aggregate figures, though, hide important regional differences. In Asia and Latin America, *per capita* food production increased by 76 and 28%,

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

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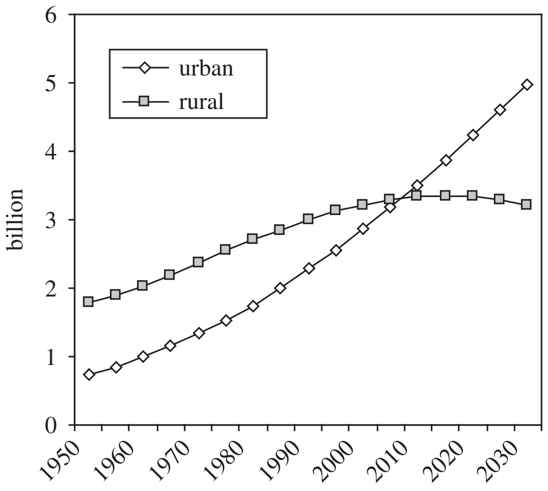

Figure 1. Rural and urban world population (1950–2030; from UN (2005)).

respectively. Africa, though, has fared badly with food production per person 10% lower today than in 1960. China, again, performs best, with a trebling of *per capita* food production over the same period. These agricultural production gains have lifted millions out of poverty and provided a platform for rural and urban economic growth in many parts of the world.

However, these advances in aggregate productivity have not brought reductions in the incidence of hunger for all. In the early twenty-first century, there are still more than 800 million people hungry and lacking adequate access to food. A third are in East and Southeast Asia, another third in South Asia, a quarter in sub-Saharan Africa and 5% each in Latin America/Caribbean and in North Africa/Near East. Nonetheless, there has been progress, as incidence of undernourishment was 960 million in 1970, comprising a third of all people in developing countries at the time.

Despite this progress in food output, it is probable that food-related ill health will remain widespread for many people. As world population continues to increase, until at least the mid-twenty-first century (UNPD 2005), the absolute demand for food will also increase. Increasing incomes will also mean that people will have more purchasing power and this will increase the demand for food. But as diets change, demand for the types of food will also shift radically, with large numbers of people going through the nutrition transition. In particular, increasing urbanization (figure 1) means people are more likely to adopt new diets, particularly consuming more meat, fats and refined cereals, and fewer traditional cereals, vegetables and fruits (Popkin 1998).

As a result of these transitions towards calorie-rich diets, obesity, hypertension and type II diabetes have emerged as serious threats to health in most industrialized countries (Popkin 1998; WHO 1998; Nestle 2003; Lang & Heasman 2004). A total of 20–25% of adults across Europe and North America are now classed as clinically obese (body mass index greater than $30\ \text{kg m}^{-2}$). In some developing countries, including Brazil, Colombia, Costa Rica, Cuba, Chile, Ghana, Mexico, Peru and Tunisia, overweight people now outnumber the hungry (WHO 1998). Diet-related illness now has severe and costly public health consequences (Kenkel & Manning 1999; Ferro Luzzi and James 2000). According to the comprehensive Eurodiet (2001) study, 'disabilities associated with high intakes of saturated fat and inadequate intakes of vegetable and fruit, together with a sedentary lifestyle, exceed the cost of tobacco use'. Some problems arise from nutritional deficiencies of iron, iodide, folic acid, vitamin D and omega-3 polyunsaturated fatty acids, but most are due to excess consumption of energy and fat (causing obesity), sodium as salt (high blood pressure), saturated and trans fats (heart disease) and refined sugars (diabetes and dental caries; Key *et al.* 2002; Frumkin 2005).

An important change in the world food system will come from the increased consumption of livestock products (Fitzhugh 1998; Delgado *et al.* 1999; Smil 2000). Meat demand is expected to rise rapidly with economic growth and this will change many farming systems. Livestock are important in mixed production systems, using foods and by-products that would not have been consumed by humans. But increasingly animals are raised intensively and fed with cheap though energetically inefficient cereals and oils. In industrialized countries, 73% of cereals are fed to animals; in developing countries, some 37% are used in this way. Currently, *per capita* annual demand in industrialized countries is 550 kg of cereal and 78 kg of meat. By contrast, in developing countries, it is only 260 kg of cereal and 30 kg of meat.

At the same time as these recent changes in agricultural productivity, consumer behaviour over food (Smith in press) and the political economy of farming and food (Goodman & Watts 1997), agricultural systems are now recognized to be a significant source of environmental harm (Tilman 1999; Pretty *et al.* 2000; MEA 2005). Since the early 1960s, the total agricultural area has expanded by 11% from 4.5 to 5 billion ha and arable area from 1.27 to 1.4 billion ha. In industrialized countries, agricultural area has fallen by 3%, but has risen by 21% in developing countries (figure 2*a*). Livestock production has also increased with a worldwide fourfold increase in numbers of chickens, twofold increase in pigs and 40–50% increase in numbers of cattle, sheep and goats (figure 2*b*).

During this period, the intensity of production on agricultural lands has also risen substantially (Hazell & Wood 2007). The area under irrigation and number of agricultural machines has grown by approximately twofold and the consumption of all fertilizers by fourfold (nitrogen fertilizers by sevenfold; figure 2*c*,*d*). The use of pesticides in agriculture has also increased dramatically and now amounts to some 2.56 billion kg yr^{-1}. In the early twenty-first century, the annual value of the global market was US $25 billion, of which some $3 billion of sales was in developing countries (Pretty 2005*b*). Herbicides account for 49% of use, insecticides 25%, fungicides 22% and others approximately 3% (table 1). A third of the world market by value is in the USA, which represents 22% of active ingredient use. In the USA, though, large amounts of pesticide are used in the

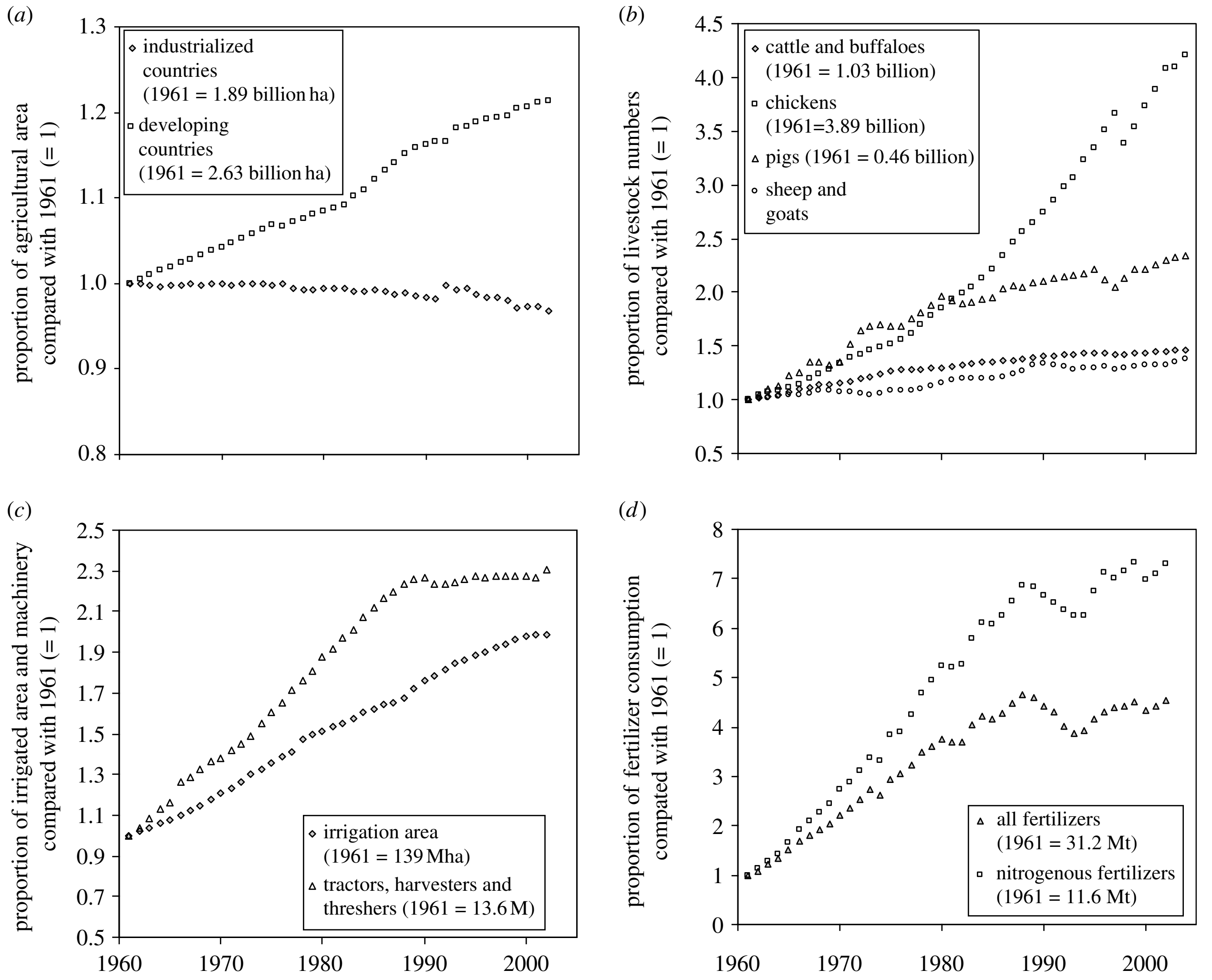

Figure 2. (*a*) Agricultural area (1961–2002; from FAO (2005)). (*b*) Head of livestock, world (1961–2004; from FAO (2005)). (*c*) Irrigated area and agricultural machinery, world (1961—2002; from FAO (2005)). (*d*) World fertilizer consumption (1961–2002; from FAO (2005)).

home/garden (17% by value) and in industrial, commercial and government settings (13% by value).

These factors of production have had a direct impact on world food production (figure 3*a–e*). There are clear and significant relationships between fertilizer consumption, number of agricultural machines, irrigated area, agricultural land area and arable area with total world food production (comprising all cereals, coarse grains, pulses, roots and tubers, and oil crops). The inefficient use of some of these inputs has, however, led to considerable environmental harm. Increased agricultural area contributes substantially to the loss of habitats, associated biodiversity and their valuable environmental services (MEA 2005; Scherr & McNeely 2007). Approximately 30–80% of nitrogen applied to farmland escapes to contaminate water systems and the atmosphere as well as increasing the incidence of some disease vectors (Smil 2001; Victor & Reuben 2002; Pretty *et al.* 2003*a*; Townsend *et al.* 2003; Giles 2005; Goulding *et al.* 2007). Irrigation water is often used inefficiently and causes waterlogging and salinization, as well as diverts water from other domestic and industrial users; and agricultural machinery has increased the consumption of fossil fuels in food production (Leach 1976; Stout 1998).

Table 1. World and US use of pesticide active ingredients (mean for 1998–1999). (Adapted from Pretty & Hine (2005); using EPA (2001) and OECD (2001).)

pesticide use	world pesticide use (million kg a.i.)	%	US pesticide use (million kg a.i.)	%
herbicides	948	37	246	44
insecticides	643	25	52	9
fungicides	251	10	37	7
other[a]	721	28	219[b]	40
total	2563	100	554	100

[a] Other includes nematicides, fumigants, rodenticides, molluscicides, aquatic and fish/bird pesticides, and other chemicals used as pesticides (e.g. sulphur, petroleum products).
[b] Other in the US includes 150 million kg of sulphur, petroleum used as pesticides.

These graphs clearly show the past effectiveness of these factors of production in increasing agricultural productivity. One argument is to suggest that the persistent world food crisis indicates a need for substantially greater use of these inputs (Avery 1995; Cassman *et al.* 2002; Trewevas 2002; Green *et al.* 2005; Tripp in press). But it would be both simplistic and optimistic to assume that all these relationships will remain linear in the future and that gains will continue

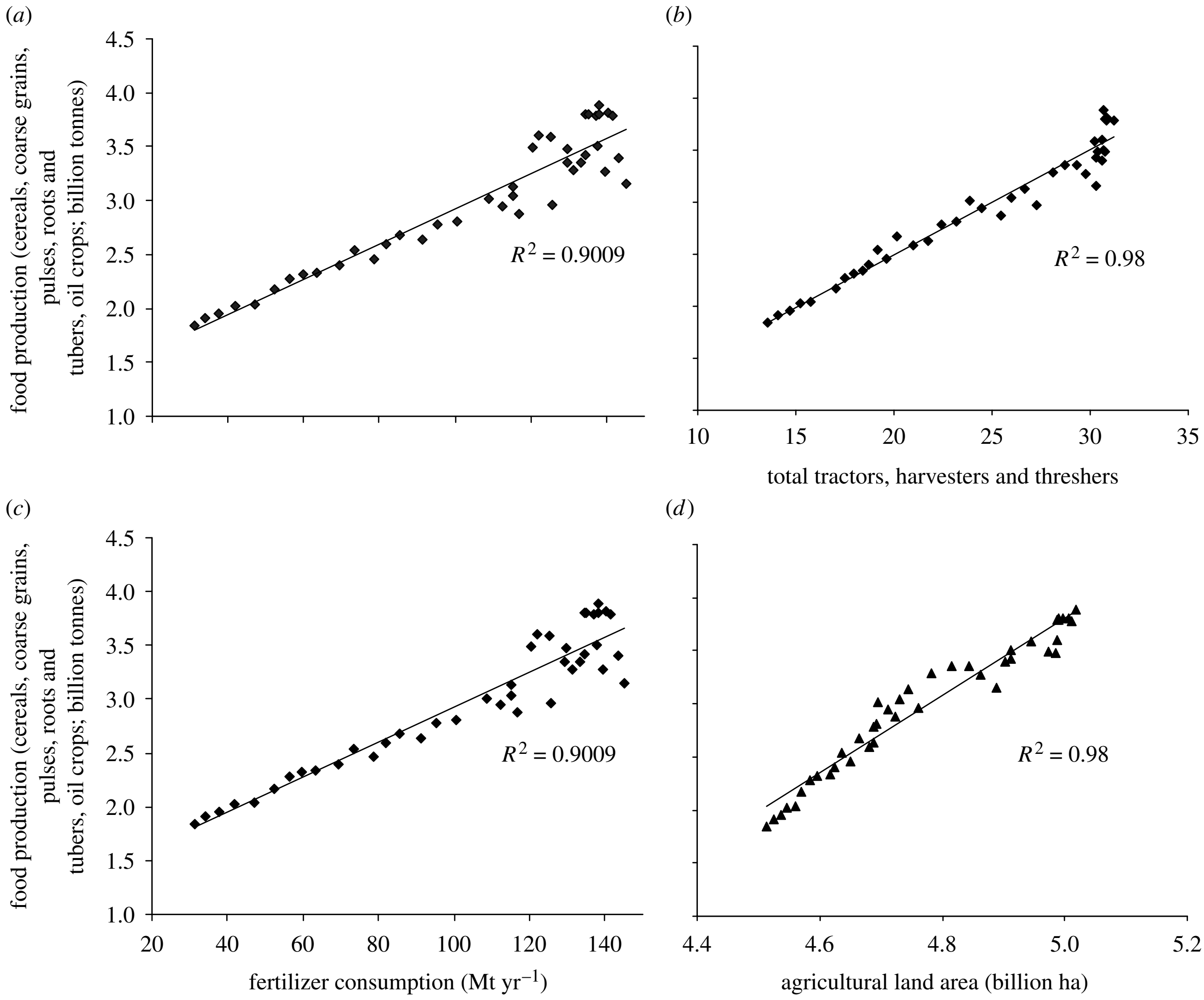

Figure 3. (*a*) Relationship between all fertilizers applied and world plant food production (1961–2002; from FAO (2005)). (*b*) Relationship between world agricultural machinery and world plant food production (1961–2002; from FAO (2005)). (*c*) Relationship between world irrigation area and world plant food production (1961–2002; from FAO (2005)). (*d*) Relationship between world agricultural land area and world plant food production (1961–2002; from FAO (2005)).

at the previous rates (Tilman 1999). This would assume a continuing supply of these factors and inputs, and that the environmental costs of their use will be small. There is also growing evidence to suggest that this approach to agricultural growth has reached critical environmental limits, and that the aggregate costs in terms of lost or foregone benefits from environmental services are too great for the world to bear (Ruttan 1999; MEA 2005; Kitzes *et al.* 2007). The costs of these environmental problems are often called externalities as they do not appear in any formal accounting systems. Yet many agricultural systems themselves are now suffering because key natural assets that they require to be plentiful are being undermined or diminished.

Agricultural systems in all parts of the world will have to make improvements. In many, the challenge is to increase the food production to solve immediate problems of hunger. In others, the focus will be more on adjustments that maintain food production while increasing the flow of environmental goods and services. World population is set to continue to increase for approximately another 40 years to approximately 2040–2050, and then is likely to stabilize or fall owing to changes in fertility patterns (figure 4). The high-fertility projection by the UN (2005) is unlikely to arise, as shifts towards lower fertility are already occurring in many countries worldwide and so there are very real prospects of world population eventually falling over one to two centuries after the maximum is reached. This suggests that the agricultural and food

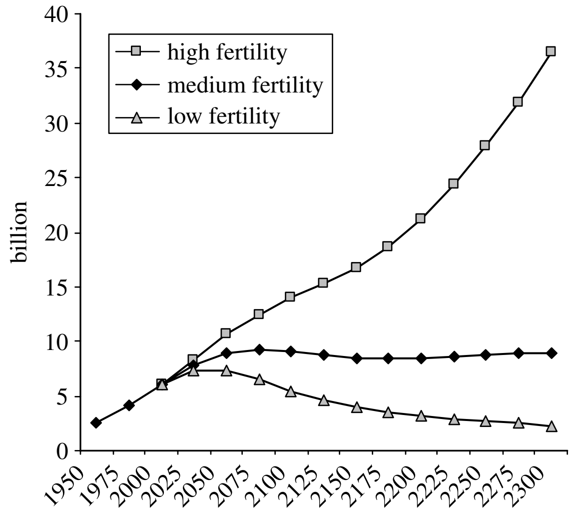

Figure 4. World population 1950–2300 (from UN, 2005).

challenge is likely to be more acute in the next half-century, and thereafter qualitatively change according people's aggregate consumption patterns.

2. WHAT IS SUSTAINABLE AGRICULTURE?

What, then, do we now understand by agricultural sustainability? Many different expressions have come to be used to imply greater sustainability in some agricultural systems over prevailing ones (both pre-industrial and industrialized). These include biodynamic, community based, ecoagriculture, ecological, environmentally sensitive, extensive, farm fresh, free range, low input, organic, permaculture, sustainable and wise use (Pretty 1995; Conway 1997; NRC 2000; McNeely & Scherr 2003; Clements & Shrestha 2004; Cox *et al.* 2004; Gliessman 2005). There is continuing and intense debate about whether agricultural systems using some of these terms can qualify as sustainable (Balfour 1943; Lampkin & Padel 1994; Altieri 1995; Trewevas 2002).

Systems high in sustainability can be taken as those that aim to make the best use of environmental goods and services while not damaging these assets (Altieri 1995; Pretty 1995, 1998, 2005*a*,*b*; Conway 1997; Hinchcliffe *et al.* 1999; NRC 2000; Li Wenhua 2001; Jackson & Jackson 2002; Tilman *et al.* 2002; Uphoff 2002; McNeely & Scherr 2003; Gliessman 2004, 2005; Swift *et al.* 2004; Tomich *et al.* 2004; MEA 2005; Scherr & McNeely 2007; Kesevan & Swaminathan in press). The key principles for sustainability are to:

(i) integrate biological and ecological processes such as nutrient cycling, nitrogen fixation, soil regeneration, allelopathy, competition, predation and parasitism into food production processes,
(ii) minimize the use of those non-renewable inputs that cause harm to the environment or to the health of farmers and consumers,
(iii) make productive use of the knowledge and skills of farmers, thus improving their self-reliance and substituting human capital for costly external inputs, and
(iv) make productive use of people's collective capacities to work together to solve common agricultural and natural resource problems, such as for pest, watershed, irrigation, forest and credit management.

The idea of agricultural sustainability, though, does not mean ruling out any technologies or practices on ideological grounds. If a technology works to improve productivity for farmers and does not cause undue harm to the environment, then it is likely to have some sustainability benefits. Agricultural systems emphasizing these principles also tend to be multifunctional within landscapes and economies (Dobbs & Pretty 2004; MEA 2005). They jointly produce food and other goods for farmers and markets, but also contribute to a range of valued public goods, such as clean water, wildlife and habitats, carbon sequestration, flood protection, groundwater recharge, landscape amenity value and leisure/tourism. In this way, sustainability can be seen as both relative and case dependent and implies a balance between a range of agricultural and environmental goods and services.

As a more sustainable agriculture seeks to make the best use of nature's goods and services, technologies and practices must be locally adapted and fitted to place. These are most likely to emerge from new configurations of social capital, comprising relations of trust embodied in new social organizations, new horizontal and vertical partnerships between institutions, and human capital comprising leadership, ingenuity, management skills and capacity to innovate. Agricultural systems with high levels of social and human assets are more able to innovate in the face of uncertainty (Chambers *et al.* 1989; Uphoff 1998; Bunch & Lopez 1999; Olsson & Folke 2001; Pretty & Ward 2001). This suggests that there likely to be many pathways towards agricultural sustainability, and further implies that no single configuration of technologies, inputs and ecological management is more likely to be widely applicable than the other. Agricultural sustainability implies the need to fit these factors to the specific circumstances of different agricultural systems.

A common, though erroneous, assumption about agricultural sustainability is that it implies a net reduction in input use, thus making such systems essentially extensive (they require more land to produce the same amount of food). Recent empirical evidence shows that successful agricultural sustainability initiatives and projects arise from shifts in the factors of agricultural production (e.g. from use of fertilizers to nitrogen-fixing legumes; from pesticides to emphasis on natural enemies; from ploughing to zero-tillage). A better concept than extensive is one that centres on intensification of resources, making better use of existing resources (e.g. land, water, biodiversity) and technologies (Conway & Pretty 1991; Pretty *et al.* 2000; Buttel 2003; Tegtmeier & Duffy 2004). The critical question centres on the 'type of intensification'. Intensification using natural, social and human capital assets, combined with the use of best available technologies and inputs (best genotypes and best ecological management) that minimize or eliminate harm to the environment, can be termed 'sustainable intensification'.

3. CAPITAL ASSETS FOR AGRICULTURAL SYSTEMS

What makes agriculture unique as an economic sector is that it directly affects many of the very assets on which it relies for success. Agricultural systems at all levels rely on the value of services flowing from the total stock of assets that they influence and control, and five types of asset, natural, social, human, physical and financial capital, are now recognized as being important. There are, though, some advantages and misgivings with the use of the term capital. On the one hand, capital implies an asset, and assets should be cared for, protected and accumulated over long periods. On the other hand, capital can imply easy measurability and transferability. Since the value of something can be assigned a monetary value, then it can appear not to matter if it is lost, as the required money could simply be allocated to purchase another asset or to transfer it from elsewhere. But nature and its wider values is not so easily replaceable as a commodity (Coleman 1988; Q5 Ostrom 1990; Putnam *et al.* 1993; Flora & Flora 1996; Q6 Benton 1998; Scoones 1998; Uphoff 1998, 2002; Q7 Costanza *et al.* 1999; Pretty 2003). Nonetheless, terms such as natural, social and human capital are useful in helping to shape concepts around basic questions such as what is agriculture for and what system works best. The five capitals are defined in the following ways:

(i) *Natural capital* produces environmental goods and services and is the source of food (both farmed and harvested or caught from the wild), wood and fibre; water supply and regulation; treatment, assimilation and decomposition of wastes; nutrient cycling and fixation; soil formation; biological control of pests; climate regulation; wildlife habitats; storm protection and flood control; carbon sequestration; pollination; and recreation and leisure (Costanza *et al.* 1999; MEA 2005).

(ii) *Social capital* yields a flow of mutually beneficial collective action, contributing to the cohesiveness of people in their societies. The social assets comprising social capital include norms, values and attitudes that predispose people to co-operate; relations of trust, reciprocity and obligations; and common rules and sanctions mutually agreed or handed down. These are connected and structured in networks and groups (Flora & Flora 1996; Cramb & Culasero 2003; Pretty 2003).

(iii) *Human capital* is the total capability residing in individuals, based on their stock of knowledge skills, health and nutrition (Orr 1992; Byerlee Q8 1998; Leeuwis 2004; Lieblin *et al.* 2004). It is enhanced by access to services that provide, such as schools, medical services and adult training. People's productivity is increased by their capacity to interact with productive technologies and other people. Leadership and organizational skills are particularly important in making other resources more valuable.

(iv) *Physical capital* is the store of human-made material resources and comprises buildings such as housing and factories, market infrastructure, irrigation works, roads and bridges, tools and tractors, communications and energy and transportation systems, that make labour more productive.

(v) *Financial capital* is more of an accounting concept, as it serves as a facilitating role rather than as a source of productivity in and of itself. It represents accumulated claims on goods and services, built up through financial systems that gather savings and issue credit such as pensions, remittances, welfare payments, grants and subsidies.

As agricultural systems shape the very assets on which they rely for inputs, a vital feedback loop occurs from outcomes to inputs (Worster 1993). Thus, sustainable agricultural systems tend to have a positive effect on natural, social and human capital, while unsustainable ones feedback to deplete these assets, leaving fewer for future generations. For example, an agricultural system that erodes soil while producing food externalizes costs that others must bear. But one that sequesters carbon in soils through organic matter accumulation helps to mediate climate change. Similarly, a diverse agricultural system that enhances on-farm wildlife for pest control contributes to wider stocks of biodiversity, while simplified modernized systems that eliminate wildlife do not. Agricultural systems that offer labour-absorption opportunities, through resource improvements or value-added activities, can boost local economies and help to reverse rural-to-urban migration patterns (Carney 1998; Dasgupta 1998; Ellis 2000; Morison *et al.* 2005; Pretty *et al.* 2006).

Any activities that lead to improvements in these renewable capital assets thus make a contribution towards sustainability. However, agricultural sustainability does not require that all assets are improved at the same time. One agricultural system that contributes more to these capital assets than the other can be said to be more sustainable, but there may still be trade-offs with one asset increasing as the other falls. In practice, though, there are usually strong links between changes in natural, social and human capital (Pretty 2003), with agricultural systems having many potential effects on all three.

Agriculture is, therefore, fundamentally multifunctional. It jointly produces many unique non-food functions that cannot be produced by other economic sectors so efficiently. Clearly, a key policy challenge, for both industrialized and developing countries, is to find ways to maintain and enhance food production. But a key question is: can this be done while seeking to both improve the positive side effects and eliminate the negative ones? It will not be easy, as past agricultural development has tended to ignore both the multifunctionality of agriculture and the considerable external costs.

4. SIDE EFFECTS AND EXTERNALITIES

There are surprisingly few data on the environmental and health costs imposed by agriculture on other sectors and interests. Agriculture can negatively affect the environment through overuse of natural resources as inputs or their use as a sink for pollution. Such effects are called negative externalities because they are usually non-market effects and therefore their costs are not part of market prices. Negative externalities are one of the classic causes of market failure whereby the polluter does not pay the full costs of their actions, and therefore these costs are called external costs (Baumol & Oates 1988; Pretty *et al.* 2000, 2003*a*; Dobbs & Pretty 2004; Moss 2007).

Externalities in the agricultural sector have at least four features: (i) their costs are often neglected, (ii) they often occur with a time lag, (iii) they often damage groups whose interests are not well represented in political or decision-making processes, and (iv) the identity of the source of the externality is not always known. For example, farmers generally have few incentives to prevent some pesticides escaping to water bodies, to the atmosphere and to nearby natural systems as they transfer the full cost of cleaning up the environmental consequences to society at large. In the same way, pesticide manufacturers do not pay the full cost of all their products, as they do not have to pay for any adverse side effects that may occur.

Partly as a result of lack of information, there is little agreement on the economic costs of externalities in agriculture. Some authors suggest that the current system of economic calculations grossly underestimates the current and future value of natural capital (Abramovitz 1997; Costanza *et al.* 1997; Daily 1997; MEA 2005). However, such valuation of ecosystem services remains controversial owing to methodological and measurement problems (Georgiou *et al.* 1998; Hanley *et al.* 1998; Carson 2000; Farrow *et al.* 2000; Pretty *et al.* 2003*a*) and the role monetary values have in influencing public opinions and policy decisions.

What has become clear in recent years is that the success of modern agriculture has masked some significant negative externalities, with environmental and health problems documented and recently costed for Ecuador, China, Germany, the Philippines, the UK and the USA (Pingali & Roger 1995; Crissman *et al.* 1998; Waibel *et al.* 1999; Pretty *et al.* 2000, 2001, 2003*a*, 2005; Cuyno *et al.* 2001; Norse *et al.* 2001; Buttel 2003; Tegtmeier & Duffy 2004; Sherwood *et al.* 2005; Zhao *et al.* in press). These environmental costs begin to change conclusions about which agricultural systems are the most efficient and suggest that alternatives which reduce externalities should be sought.

Examples of costs in developing countries include that in the Philippines, where agricultural systems that do not use pesticides result in greater net social benefits owing to the reduction in illnesses among farmers and their families, and the associated treatment costs (Rola & Pingali 1993; Pingali & Roger 1995). In China, the externalities of pesticides used in rice systems cause $1.4 billion of costs per year through health costs to people, and adverse effects on both on- and off-farm biodiversity (Norse *et al.* 2001). In Ecuador, annual mortality in the remote highlands due to pesticides is among the highest reported anywhere in the world at 21 people per 100 000 people, and so the economic benefits of integrated pest management (IPM)-based systems that eliminate these effects are increasingly beneficial (Sherwood *et al.* 2005). In the UK, agricultural externalities have been calculated to be some £1.5 billion per year in the late 1990s, a cost that is greater than net farm income (Pretty *et al.* 2000, 2001). These, though, are exceeded by the environmental costs of transporting food from farm to retail outlet to place of consumption—these ‘food miles’ in the UK result in a further £3.8 billion of environmental costs per year (Pretty *et al.* 2005).

These data suggest that all types of agricultural systems impose some kinds of costs on the environment. It is, therefore, impossible to draw a boundary between what is sustainable and what is not. If the external costs are high and can be reduced by the adoption of new practices and technologies, then this is a move towards sustainability. Agricultural sustainability is thus partly a matter of judgement, which in turn depends on the comparators and baselines chosen. One system may be said to be more sustainable relative to another if its negative externalities are lower. Monetary criteria do, though, only capture some of the values of agricultural systems and the resources upon which they impinge (Carson 2000), and so choices may depend on wider questions about the sustainability of farm practices (on farm, in field) and the sustainability of whole landscapes (interactions between agricultural and wild habitats; Green *et al.* 2005; Shennan in press; Waage & Mumford in press; Wade *et al.* in press).

5. IMPROVING NATURAL CAPITAL FOR AGROECOSYSTEMS

Agricultural sustainability emphasizes the potential benefits that arise from making the best use of both genotypes of crops and animals and their agroecological management. Agricultural sustainability does not, therefore, mean ruling out any technologies or practices on ideological grounds (e.g. genetically modified or organic crops)—provided they improve biological and/or economic productivity for farmers and do not harm the environment (NRC 2000; Pretty 2001; Uphoff 2003; Nuffield Council on Bioethics 2004). Agricultural sustainability, therefore, emphasizes the potential dividends that can come from making the best use of the genotypes (G) of crops and animals (Dennis *et al.* 2007; Shennan in press; Witcombe *et al.* in press) and the ecological (Ec) conditions under which they are grown or raised. The outcome is a result of this G×Ec interaction (Khush *et al.* 1998). Agricultural sustainability suggests a focus on both genotype improvements through the full range of modern biological approaches, as well as improved understanding of the benefits of ecological and agronomic management, manipulation and redesign (Collard & Mackill 2007; Flint & Wooliams 2007; Thomson in press).

Agricultural systems, or agroecosystems, are amended ecosystems (Conway 1985; Gliessman 1998, 2005; Olsson & Folke 2001; Dalgaard *et al.* 2003; Odum & Barrett 2004; Swift *et al.* 2004) that have a variety of different properties (table 2). Modern agricultural systems have amended some of these properties to increase productivity. Sustainable agroecosystems, by contrast, have to seek to shift some of these properties towards natural systems without significantly trading off productivity. Modern agroecosystems have, for example, tended towards high through-flow systems, with energy supplied by fossil fuels directed out of the system (either deliberately for harvests or accidentally through side effects). For a transition towards sustainability, renewable sources of energy need to be maximized and some energy flows directed to fuel essential internal tropic interactions (e.g. to soil organic matter or to weeds for arable birds) so as to maintain other ecosystem functions (Rydberg & Jansén 2002; Champion *et al.* 2003; Haberl *et al.* 2004; Firbank *et al.* 2005, in press). All annual

Table 2. Properties of natural ecosystems compared with modern and sustainable agroecosystems. (Adapted from Gliessman (2005).)

property	natural ecosystem	modern agroecosystem	sustainable agroecosystem
productivity	medium	high	medium (possibly high)
species diversity	high	low	medium
functional diversity	high	low	medium–high
output stability	medium	low–medium	high
biomass accumulation	high	low	medium–high
nutrient recycling	closed	open	semi-closed
trophic relationships	complex	simple	intermediate
natural population regulation	high	low	medium–high
resilience	high	low	medium
dependence on external inputs	low	high	medium
human displacement of ecological processes	low	high	low–medium
sustainability	high	low	high

crops, though, are derived from opportunists and so their resource use is inherently different to perennials.

Modern agriculture has also come to rely heavily of nutrient inputs obtained from or driven by fossil fuel-based sources. Nutrients are also used inefficiently and together with certain products (e.g. ammonia, nitrate, methane, carbon dioxide) are lost to the environment. For sustainability, nutrient leaks need to be reduced to a minimum, recycling and feedback mechanisms introduced and strengthened, and nutrients and materials diverted to capital accumulation. Agroecosystems are considerably more simplified than natural ecosystems, and loss of biological diversity (to improve crop and livestock productivity) results in the loss of some ecosystem services, such as pest and disease control (Gallagher *et al.* 2005). For sustainability, biological diversity needs to be increased to recreate natural control and regulation functions and to manage pests and diseases rather than seeking to eliminate them. Mature ecosystems are now known to be not stable and unchanging, but in a state of dynamic equilibrium that buffers against large shocks and stresses. Modern agroecosystems have weak resilience, and for transitions towards sustainability need to focus on structures and functions that improve resilience (Holling *et al.* 1998; Folke *et al.* 2005; Shennan in press). **Q10**

But converting an agroecosystem to a more sustainable design is complex, and generally requires a landscape or bioregional approach to restoration or management (Kloppenburg *et al.* 1996; Higgs 2003; Jordan 2003; Odum & Barrett 2004; Swift *et al.* 2004; Terwan *et al.* 2004). An agroecosystem is a bounded system designed to produce food and fibre, yet it is also part of a wider landscape at which scale a number of ecosystem functions are important (Gliessman 2005). For sustainability, interactions need to be developed between agroecosystems and whole landscapes of other farms and non-farmed or wild habitats (e.g. wetlands, woods, riverine habitats), as well as social systems of food procurement. Mosaic landscapes with a variety of farmed and non-farmed habitats are known to be good for birds as well as farms (Bignall & McCracken 1996; Shennan *et al.* 2005; Woodhouse *et al.* 2005; Wade *et al.* in press).

There are several types of resource-conserving technologies and practices that can be used to improve the stocks and use of natural capital in and around agroecosystems. These are:

(i) *IPM*, which uses ecosystem resilience and diversity for pest, disease and weed control, and seeks only to use pesticides when other options are ineffective (e.g. Lewis *et al.* 1997; Gallagher *et al.* 2005; Herren *et al.* 2005; Hassanali *et al.* 2007; Bale *et al.* in press).
(ii) *Integrated nutrient management*, which seeks both to balance the need to fix nitrogen within farm systems with the need to import inorganic and organic sources of nutrients and to reduce nutrient losses through erosion control (Crews & Peoples 2004; Leach *et al.* 2004; Goulding *et al.* 2007; Moss 2007).
(iii) *Conservation tillage*, which reduces the amount of tillage, sometime to zero, so that soil can be conserved and available moisture used more efficiently (Petersen *et al.* 2000; Holland 2004; Hobbs *et al.* 2007).
(iv) *Agroforestry*, which incorporates multifunctional trees into agricultural systems and collective management of nearby forest resources (Leakey *et al.* 2005).
(v) *Aquaculture*, which incorporates fish, shrimps and other aquatic resources into farm systems, such as into irrigated rice fields and fish ponds, and so leads to increases in protein production (Bunting in press).
(vi) *Water harvesting* in dryland areas, which means formerly abandoned and degraded lands can be cultivated, and additional crops can be grown on small patches of irrigated land owing to better rain water retention (Pretty 1995; Reij 1996), and improving water productivity of crops (Morison *et al.* 2007).
(vii) *Livestock integration* into farming systems, such as dairy cattle, pigs and poultry, including using zero-grazing cut and carry systems (Altieri 1995; Wilkins 2007).

Many of these individual technologies are also multifunctional (Pretty 1995; Lewis *et al.* 1997). This implies that their adoption should mean favourable changes in several components of the farming system at the same time. For example, hedgerows and alley crops encourage predators and act as windbreaks, thus reducing soil erosion. Legumes introduced into rotations fix nitrogen, and also act as a break crop to prevent carry-over of pests and diseases. Grass contour strips slow surface-water run-off, encourage percolation to groundwater and can be a source of fodder for livestock. Catch crops prevent soil erosion and leaching during critical periods, and can also be ploughed in as a green manure. The incorporation of green manures not only provides a readily available source of nutrients for the growing crop but also increases soil organic matter and hence water-retentive capacity, further reducing susceptibility to erosion.

Although many resource-conserving technologies and practices are currently being used, the total number of farmers using them worldwide is still relatively small. This is because their adoption is not a costless process for farmers. They cannot simply cut their existing use of fertilizer or pesticides and hope to maintain outputs, thus making operations more profitable. They also cannot simply introduce a new productive element into their farming systems and hope it would succeed. These transition costs arise for several reasons. Farmers must first invest in learning (Orr 1992; Röling & Q11 Wagermakers 1997; Bentley *et al.* 2003; Lieblin *et al.* 2004; Bawden 2005; Chambers 2005). As recent and current policies have tended to promote specialized, non-adaptive systems with a lower innovation capacity, farmers have to spend time learning about a greater diversity of practices and measures (Gallagher *et al.* 2005; Kesevan & Swaminathan in press). Lack of information and management skills is, therefore, a major barrier to the adoption of sustainable agriculture. During the transition period, farmers must experiment more and thus incur the costs of making mistakes as well as of acquiring new knowledge and information.

The on-farm biological processes that make sustainable agroecosystems productive also take time to become established (Firbank *et al.* in press; Kibblewhite *et al.* in press; Wade *et al.* in press). These include the rebuilding of depleted natural buffers of predator stocks and wild host plants; increasing the levels of nutrients; developing and exploiting microenvironments and positive interactions between them; and the establishment and growth of trees. These higher variable and capital investment costs must be incurred before returns increase. Examples include for labour in construction of soil and water conservation measures; planting of trees and hedgerows; pest and predator monitoring and management; fencing of paddocks; the establishment of zero-grazing units; and purchase of new technologies, such as manure storage equipment or global positioning systems for tractors.

It has also been argued that farmers adopting more sustainable agroecosystems are internalizing many of the agricultural externalities associated with intensive farming and hence could be compensated for effectively providing environmental goods and services. Providing such compensation or incentives would be likely to increase the adoption of resource conserving technologies (Dobbs & Pretty 2004). Nonetheless, periods of lower yields seem to be more apparent during conversions of industrialized agroecosystems. There is growing evidence to suggest that most pre-industrial and modernized farming systems in developing countries can make rapid transitions to both sustainable and productive farming.

6. EFFECTS OF SUSTAINABLE AGRICULTURE ON YIELDS

One persistent question regarding the potential benefits of more sustainable agroecosystems centres on productivity trade-offs. If environmental goods and services are to be protected or improved, what then happens to productivity? If it falls, then more land will be required to produce the same amount of food, thus resulting in further losses of natural capital (Green *et al.* 2005). As indicated earlier, the challenge is to seek sustainable intensification of all resources in order to improve food production. In industrialized farming systems, this has proven impossible to do with organic production systems, as food productivity is lower for both crop and livestock systems (Lampkin & Padel 1994; Caporali *et al.* 2003). Nonetheless, there are now some 3 Mha of agricultural land in Europe managed with certified organic practices. Some have led to lower energy use (though lower yields too), others to better nutrient retention and some greater nutrient losses (Dalgaard *et al.* 1998, 2002; Løes & Øgaard 2003; Q12 Gosling & Shepherd 2004), and some to greater labour absorption (Morison *et al.* 2005; Pretty *et al.* 2006).

Many other farmers have adopted integrated farming practices, which represent a step or several steps towards sustainability. What has become increasingly clear is that many modern farming systems are wasteful, as integrated farmers have found they can cut down many purchased inputs without losing out on profitability (EA 2005). Some of these cuts in use are substantial, others are relatively small. By adopting better targeting and precision methods, there is less wastage and more benefit to the environment. They can then make greater cuts in input use once they substitute some regenerative technologies for external inputs, such as legumes for inorganic fertilizers or predators for pesticides. Finally, they can replace some or all external inputs entirely over time once they have learned their way into a new type of farming characterized by new goals and technologies (Pretty & Ward 2001).

However, it is in developing countries that some of the most significant progress towards sustainable agroecosystems has been made in the past decade (Uphoff 2002; McNeely & Scherr 2003; Pretty *et al.* 2003*b*). The largest study comprised the analysis of 286 projects in 57 countries (Pretty *et al.* 2006). This involved the use of both questionnaires and published reports by projects to assess changes over time. As in earlier research (Pretty *et al.* 2003*b*), data were triangulated from several sources and cross-checked by external reviewers and regional experts. The study involved analysis of projects sampled once in time ($n=218$) and those sampled twice over a 4-year period ($n=68$). Not all proposed cases were accepted for the dataset and rejections were based on a strict set of

Table 3. Summary of adoption and impact of agricultural sustainability technologies and practices on 286 projects in 57 countries.

FAO farm system category[a]	no. of farmers adopting	no. of hectares under sustainable agriculture	average % increase in crop yields[b]
smallholder irrigated	177 287	357 940	129.8 (±21.5)
wetland rice	8 711 236	7 007 564	22.3 (±2.8)
smallholder rainfed humid	1 704 958	1 081 071	102.2 (±9.0)
smallholder rainfed highland	401 699	725 535	107.3 (±14.7)
smallholder rainfed dry/cold	604 804	737 896	99.2 (±12.5)
dualistic mixed	537 311	26 846 750	76.5 (±12.6)
coastal artisanal	220 000	160 000	62.0 (±20.0)
urban-based and kitchen garden	207 479	36 147	146.0 (±32.9)
all projects	12 564 774	36 952 903	79.2 (±4.5)

[a] Farm categories from Dixon *et al.* (2001).

[b] Yield data from 360 crop-project combinations; reported as % increase (thus a 100% increase is a doubling of yields). Standard errors in brackets.

criteria. As this was a purposive sample of 'best practice' initiatives, the findings are not representative of all developing country farms.

Table 3 contains a summary of the location and extent of the 286 agricultural sustainability projects across the eight categories of FAO farming systems (Dixon *et al.* 2001) in the 57 countries. In all, some 12.6 million farmers on 37 Mha were engaged in transitions towards agricultural sustainability in these 286 projects. This is just over 3% of the total cultivated area (1.136 Mha) in developing countries. The largest number of farmers was in wetland rice-based systems, mainly in Asia (category 2), and the largest area was in dualistic mixed systems, mainly in southern Latin America (category 6). This study showed that agricultural sustainability was spreading to more farmers and hectares. In the 68 randomly re-sampled projects from the original study, there was a 54% increase over the 4 years in the number of farmers and 45% in the number of hectares. These resurveyed projects comprised 60% of the farmers and 44% of the hectares in the original sample of 208 projects.

For the 360 reliable yield comparisons from 198 projects, the mean relative yield increase was 79% across the very wide variety of systems and crop types. However, there was a widespread in results (figure 5). While 25% of projects reported relative yields greater than 2.0 (i.e. 100% increase), half of all the projects had yield increases between 18 and 100%. The geometric mean is a better indicator of the average for such data with a positive skew, but this still shows a 64% increase in yield. However, the average hides large and statistically significant differences between the main crops (figure 6*a*,*b*). In nearly all cases, there was an increase in yield with the project. Only in rice there were three reports where yields decreased, and the increase in rice was the lowest (mean = 1.35), although it constituted a third of all the crop data. Cotton showed a similarly small mean yield increase.

These sustainable agroecosystems also have positive side effects, helping to build natural capital, strengthen communities (social capital) and develop human capacities (Ostrom 1990; Pretty 2003). Examples of positive side effects recently recorded in various developing countries include:

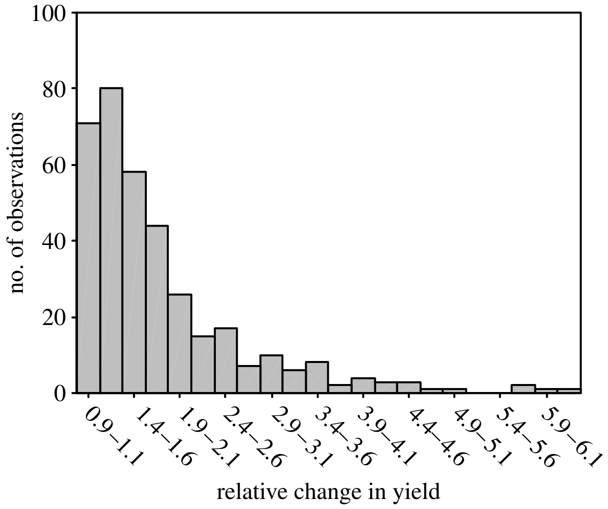

Figure 5. Histogram of change in crop yield after or with project, compared to before or without project ($n = 360$, mean $= 1.79$, s.d. $= 0.91$, median $= 1.50$, geometric mean $= 1.64$).

— *improvements to natural capital*, including increased water retention in soils, improvements in water table (with more drinking water in the dry season), reduced soil erosion combined with improved organic matter in soils, leading to better carbon sequestration and increased agrobiodiversity

— *improvements to social capital*, including more and stronger social organizations at local level, new rules and norms for managing collective natural resources and better connectedness to external policy institutions

— *improvements to human capital*, including more local capacity to experiment and solve own problems, reduced incidence of malaria in rice-fish zones, increased self-esteem in formerly marginalized groups, increased status of women, better child health and nutrition, especially in dry seasons, and reversed migration and more local employment.

What we do not know, however, is the full economic benefits of these spin-offs. In many industrialized countries, agriculture is now assumed to contribute very little to GDP, leading many commentators to

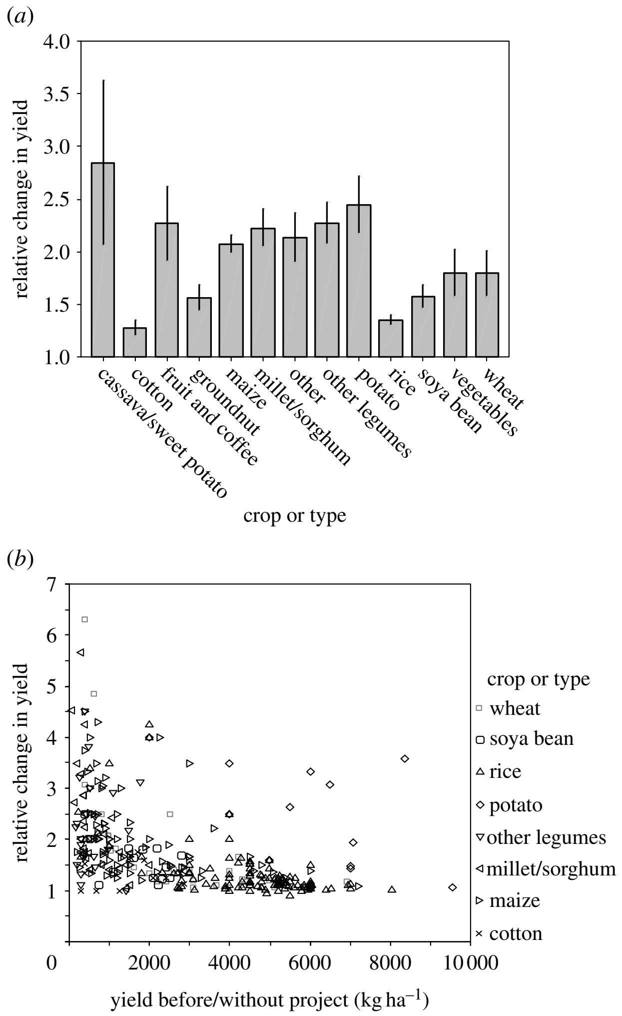

Figure 6. (*a*) Mean changes in crop yield after or with project, compared with before or without project. Vertical lines indicate ±s.e.m. 'Other' group consists of sugar cane ($n=2$), quinoa (1), oats (2). (*b*) Relationship between relative changes in crop yield after (or with project) to yield before or (without project). Only field crops with $n>9$ shown.

assume that agriculture is not important for modernized economies (NRC 2000). But such a conclusion is a function of the fact that very few measures are being made of the positive side effects of agriculture (MEA 2005). In poor countries, where financial support is limited and markets weak, then people rely even more on the value they can derive from the natural environment and from working together to achieve collective outcomes.

7. EFFECTS OF SUSTAINABLE AGRICULTURE ON PESTICIDE USE AND YIELDS

Recent IPM programmes, particularly in developing countries, are beginning to show how pesticide use can be reduced and pest management practices can be modified without yield penalties (Brethour & Weerskink 2001; Wilson & Tisdell 2001; Gallagher *et al.* 2005; Herren *et al.* 2005; Pretty & Waibel 2005; Hassanali *et al.* 2007). In principle, there are four possible trajectories of impact if IPM is introduced:

(i) pesticide use and yields increase (A),
(ii) pesticide use increases, but yields decline (B),

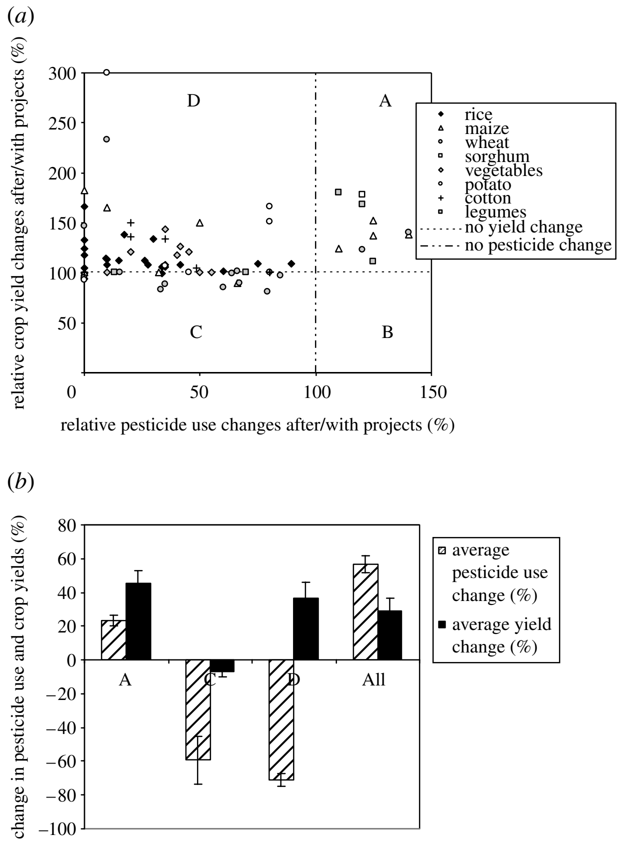

Figure 7. (*a*) Association between pesticide use and crop yields (data from 80 crop combinations, 62 projects, 26 countries). (*b*) Changes in pesticide use and yields in 62 projects (A: $n=10$; C: $n=5$; D: $n=47$).

(iii) both pesticide use and yields fall (C) and
(iv) pesticide use declines, but yields increase (D).

The assumption in modern agriculture is that pesticide use and yields are positively correlated. For IPM, the trajectory moving into sector A is therefore unlikely but not impossible, for example in low-input systems. What is expected is a move into sector C. While a change into sector B would be against economic rationale, farmers are unlikely to adopt IPM if their profits would be lowered. A shift into sector D would indicate that current pesticide use has negative yield effects or that the amount saved from pesticides is reallocated to other yield-increasing inputs. This could be possible with excessive use of herbicides or when pesticides cause outbreaks of secondary pests, such as observed with the brown plant hopper in rice (Kenmore *et al.* 1984).

Figure 7*a*,*b* shows data from 62 IPM initiatives in 26 developing and industrialized countries (Australia, Bangladesh, China, Cuba, Ecuador, Egypt, Germany, Honduras, India, Indonesia, Japan, Kenya, Laos, Nepal, Netherlands, Pakistan, Philippines, Senegal, Sri Lanka, Switzerland, Tanzania, Thailand, UK, USA, Vietnam and Zimbabwe; Pretty & Waibel 2005). The 62 IPM initiatives have some 5.4 million farm households on 25.3 Mha. The evidence on pesticide use is derived from data on both the number of sprays per hectare and the amount of active ingredient used per hectare. This analysis does not include recent evidence on the effect of some genetically modified crops, some of which result in reductions in the use of herbicides (Champion *et al.* 2003) and pesticides (Nuffield Council on Bioethics 2004), and some of which have led to increases (Benbrook 2003).

There is only one sector B case reported in recent literature (Feder *et al.* 2004). Such a case has recently been reported from Java for rice farmers. The cases in sector C, where yields fall slightly while pesticide use falls dramatically, are mainly cereal-farming systems in Europe, where yields typically fall to some 80% of current levels while pesticide use is reduced to 10–90% of current levels (Röling & Wagemakers 1997; Pretty 1998). Sector A contains 10 projects where total pesticide use has indeed increased in the course of IPM introduction. These are mainly in zero-tillage and conservation agriculture systems, where reduced tillage creates substantial benefits for soil health and reduced off-site pollution and flooding costs. These systems usually require increased use of herbicides for weed control (de Freitas 1999), though there are some examples of organic zero-tillage systems (Petersen *et al.* 2000). Over 60% of the projects are in category D where pesticide use declines and yields increase. While pesticide reduction is to be expected, as farmers substitute pesticides by information, yield increase induced by IPM is a more complex issue. It is probable, for example, that farmers who receive good quality field training will not only improve their pest management skills but also become more efficient in other agronomic practices such as water, soil and nutrient management. They can also invest some of the cash saved from pesticides in other inputs such as higher quality seeds and inorganic fertilizers.

8. EFFECTS ON CARBON BALANCES

The 1997 Kyoto Protocol to the UN Framework Convention on Climate Change established an international policy context for the reduction of carbon emissions and increases in carbon sinks in order to address the global challenge of anthropogenic interference with the climate system. It is clear that both emission reductions and sink growth will be necessary for mitigation of current climate change trends (Watson *et al.* 2000; IPCC 2001; Royal Society 2001; Swingland 2003; Oelbermann *et al.* 2004; Hobbs *et al.* 2007; Lal in press; Smith *et al.* in press). A source is any process or activity that releases a greenhouse gas, or aerosol or a precursor of a greenhouse gas into the atmosphere, whereas a sink is such mechanism that removes these from the atmosphere. Carbon sequestration is defined as the capture and secure storage of carbon that would otherwise be emitted to or remain in the atmosphere. Agricultural systems emit carbon through the direct use of fossil fuels in food production, the indirect use of embodied energy in inputs that are energy intensive to manufacture, and the cultivation of soils and/or soil erosion resulting in the loss of soil organic matter. Agriculture also contributes to climate change through the emissions of methane from irrigated rice systems and ruminant livestock. The direct effects of land use and land-use change (including forest loss) have led to a net emission of 1.7 Gt C yr^{-1} in the 1980s and 1.6 Gt C yr^{-1} in the 1990s (Watson *et al.* 2000; Bellamy *et al.* 2005).

Table 4. Mechanisms for increasing carbon sinks and reducing CO_2 and other greenhouse gas emissions in agricultural systems. (Adapted from Pretty *et al.* (2002) and Smith *et al.* (in press).)

Mechanism A. Increase carbon sinks in soil organic matter and above-ground biomass

- replace inversion ploughing with conservation- and zero-tillage systems
- adopt mixed rotations with cover crops and green manures to increase biomass additions to soil
- adopt agroforestry in cropping systems to increase above-ground standing biomass
- minimize summer fallows and periods with no ground cover to maintain soil organic matter stocks
- use soil conservation measures to avoid soil erosion and loss of soil organic matter
- apply composts and manures to increase soil organic matter stocks
- improve pasture/rangelands through grazing, vegetation and fire management both to reduce degradation and increase soil organic matter
- cultivate perennial grasses (60–80% of biomass below ground) rather than annuals (20% below ground)
- restore and protect agricultural wetlands
- convert marginal agricultural land to woodlands to increase standing biomass of carbon

Mechanism B. Reduce direct and indirect energy use to avoid greenhouse gas emissions (CO_2,CH_4 and N_2O)

- conserve fuel and reduce machinery use to avoid fossil fuel consumption
- use conservation- or zero-tillage to reduce CO_2 emissions from soils
- adopt grass-based grazing systems to reduce methane emissions from ruminant livestock
- use composting to reduce manure methane emissions
- substitute biofuel for fossil fuel consumption
- reduce the use of inorganic N fertilizers (as manufacturing is highly energy intensive), and adopt targeted- and slow-release fertilizers
- use IPM to reduce pesticide use (avoid indirect energy consumption)

Mechanism C. Increase biomass-based renewable energy production to avoid carbon emissions

- cultivate annual crops for biofuel production such as ethanol from maize and sugar cane
- cultivate annual and perennial crops, such as grasses and coppiced trees, for combustion and electricity generation, with crops replanted each cycle for continued energy production
- use biogas digesters to produce methane, so substituting for fossil fuel sources
- use improved cookstoves to increase efficiency of biomass fuels

On the other hand, agriculture is also an accumulator of carbon when organic matter is accumulated in the soil, and when above-ground biomass acts either as a permanent sink or is used as an energy source that substitutes for fossil fuels and thus avoids carbon emissions. There are 3 main mechanisms and 21 technical options (table 4) by which positive actions can be taken by farmers by:

(i) increasing carbon sinks in soil organic matter and above-ground biomass,

Table 5. Summary of potential carbon sequestered in soils and above-ground biomass in the 286 projects. (*Note.* ±s.e. in brackets.)

FAO farm system category	carbon sequestered per hectare (t C ha^{-1} yr^{-1})	total carbon sequestered (Mt C yr^{-1})	carbon sequestered per household (t C yr^{-1})
smallholder irrigated	0.15 (±0.012)	0.011	0.06
wetland rice	0.34 (±0.035)	2.53	0.29
smallholder rainfed humid	0.46 (±0.034)	0.34	0.20
smallholder rainfed highland	0.36 (±0.022)	0.23	0.56
smallholder rainfed dry/cold	0.26 (±0.035)	0.20	0.32
dualistic mixed	0.32 (±0.023)	8.03	14.95
coastal artisanal	0.20 (±0.001)	0.032	0.15
urban-based and kitchen garden	0.24 (±0.061)	0.015	0.07
total	0.35 (±0.016)	11.38	0.91

(ii) avoiding carbon dioxide or other greenhouse gas emissions from farms by reducing direct and indirect energy use, and
(iii) increasing renewable energy production from biomass that either substitutes for consumption of fossil fuels or replacing inefficient burning of fuelwood or crop residues, and so avoids carbon emissions.

The potential annual contributions being made in the 286 projects (Pretty *et al.* 2006) to carbon sink increases in soils and trees were calculated, using an established methodology (Pretty *et al.* 2002; table 5). As the focus is on what sustainable methods can do to increase quantities of soil and above-ground carbon, no account was taken of existing stocks of carbon. Soil carbon sequestration is corrected for climate, as rates are higher in humid when compared with dry zones and generally higher in temperate than tropical areas.

These projects were potentially sequestering 11.4 Mt C yr^{-1} on 37 Mha. The average gain was 0.35 t C ha^{-1} yr^{-1}, with an average per household gain of 0.91 t C yr^{-1}. The per hectare gains vary from 0.15 t C ha^{-1} yr^{-1} for smallholder irrigated systems (category 1) to 0.46 t C ha^{-1} yr^{-1} for category three systems. For most systems, per households gains were in the range 0.05–0.5 t C yr^{-1}, with the much larger farms of southern Latin America using zero-tillage and conservation agriculture achieving the most at 14.9 t C yr^{-1} (Hobbs *et al.* 2007). Such gains in carbon may offer new opportunities for income generation under carbon trading schemes (Swingland 2003).

9. THE WIDER POLICY CONTEXT

Three things are now clear from evidence on the recent spread of agricultural sustainability:

(i) Many technologies and social processes for local scale adoption of more sustainable agricultural systems are increasingly well tested and established,
(ii) The social and institutional conditions for spread are less well understood, but have been established in several contexts, leading to more rapid spread during the 1990s–early 2000s, and
(iii) The political conditions for the emergence of supportive policies are the least well established, with only a few examples of positive progress.

As indicated above, agricultural sustainability can contribute to increased food production, as well as makes a positive impact on environmental goods and services. Clearly, much can be done with existing resources, but a wider transition towards a more sustainable agriculture will not occur without some external support and money. There are always transition costs in developing new or adapting old technologies, in learning to work together and in breaking free from existing patterns of thought and practice. It also costs time and money to rebuild depleted natural and social capital.

Most agricultural sustainability improvements occurring in the 1990s and early 2000s appear to have arisen despite existing national and institutional policies, rather than owing to them (Dasgupta 1998). Although almost every country would now say it supports the idea of agricultural sustainability, the evidence points towards only patchy reforms. Only three countries have given explicit national support for sustainable agriculture: Cuba has a national policy for alternative agriculture; Switzerland has three tiers of support to encourage environmental services from agriculture and rural development; and Bhutan has a national environmental policy coordinated across all sectors (Funes *et al.* 2002; Pretty 2002; Herzog *et al.* 2005; Zhao *et al.* in press).

Several countries have given subregional support to agricultural sustainability, such as the states of Santa Caterina, Paraná and Rio Grande do Sul in southern Brazil supporting zero-tillage, catchment management and rural agribusiness development and some states in India supporting participatory watershed and irrigation management. A larger number of countries have reformed parts of agricultural policies, such as China's support for integrated ecological demonstration villages, Kenya's catchment approach to soil conservation, Indonesia's ban on pesticides and programme for farmer field schools, Bolivia's regional integration of agricultural and rural policies, Sweden's support for organic agriculture, Burkina Faso's land policy and Sri Lanka and the Philippines' stipulation that water users' groups be formed to manage irrigation systems. In Europe and North America, a number of agri-environmental schemes have been implemented in the past decade (Dobbs & Pretty 2004), though their success has been patchy (Kleijn *et al.* 2001; Marggraf 2003; Carey *et al.* 2005; Feehan *et al.* 2005; Herzog *et al.* 2005; Meyer-Aurich 2005).

A good example of a carefully designed and integrated programme comes from China (Li Wenhua Q14 2001). In March 1994, the government published a White Paper to set out its plan for implementation of Agenda 21 and put forward ecological farming, known as *Shengtai Nongye* or agroecological engineering, as the approach to achieve sustainability in agriculture. Pilot projects have been established in 2000 townships and villages spread across 150 counties. Policy for these 'eco-counties' is organized through a cross-ministry partnership, which uses a variety of incentives to encourage adoption of diverse production systems to replace monocultures. These include subsidies and loans, technical assistance, tax exemptions and deductions, security of land tenure, marketing services and linkages to research organizations. These eco-counties contain some 12 Mha of land, approximately half of which is cropland, and though only covering a relatively small part of China's total agricultural land, do illustrate what is possible when policy is appropriately coordinated.

Many countries now have national policies that now advocate export-led agricultural development. Access to international markets is clearly important for poorer countries, and successful competition for market share can be a very significant source of foreign exchange. However, this approach has some drawbacks: (i) poor countries are in competition with one another for market share, and so there is likely to be a downward pressure on prices, which reduces returns over time unless productivity continues to increase, (ii) markets for agri-food products are fickle, and can be rapidly undermined by alternative products or threats (e.g. avian bird flu and the collapse of the Thai poultry sector), (iii) distant markets are less sensitive to the potential negative externalities of agricultural production and are rarely pro-poor (with the exception of fair-trade products and efforts by some food companies; Smith in press), and (iv) smallholders have many difficulties in accessing international markets and market information.

More importantly, an export-led approach can seem to ignore the in-country opportunities for agricultural development focused on local and regional markets. Agricultural policies with both sustainability and poverty reduction aims should adopt a multi-track approach that emphasizes five components: (i) small farmer development linked to local markets, (ii) agri-business development—both small businesses and export-led, (iii) agro-processing and value-added activities to ensure that returns are maximized in-country, (iv) urban agriculture, as many urban people rely on small-scale urban food production that rarely appears in national statistics, and (v) livestock development to meet local increases in demand for meat (predicted to increase as economies Q15 become richer). In industrialized countries, however, it is perverse subsidies that still promote harm to the environment (Myers & Kent 2003), though agricultural reforms are now putting into place systems that pay for the provision of environmental services and the development of multifunctional agriculture (Kenkel & Manning 1999; Terwan *et al.* 2004; Shennan *et al.* 2005; Scherr & McNeely 2007; Kesevan & Swaminathan in press; Shennan in press).

Like all major changes, transitions towards sustainability can also provoke secondary problems. For example, building a road near a forest can not only help farmers reach food markets, but also aid illegal timber extraction. If land has to be closed off to grazing for rehabilitation, then people with no other source of feed may have to sell their livestock; and if cropping intensity increases or new lands are taken into cultivation, then the burden of increased workloads may fall particularly on women. Producers of current agrochemical products are likely to suffer market losses from a more limited role for their products. The increase in assets that could come from sustainable livelihoods based on sustainable agriculture may simply increase the incentives for more powerful interests to take over. In addition, with benefits weighted towards the future while requiring current costs, this may leave poor farmers unable to adopt novel technologies, while richer farmers in industrialized countries are being paid to make the changes (Lee 2005; Tripp in press).

New winners and losers will emerge with the widespread adoption of sustainable agriculture. A differentiated approach for agricultural policies will thus become increasingly necessary if agroecosystems are to become more productive while reducing negative impacts on the environment, thus improving efficiency (Dobbs & Pretty 2004; Lee 2005; Wilkins 2007). This will require wider attention to exchange rate policies, trade reforms, domestic agricultural prices, input subsidies, labour market reforms, education and investment in schools, rural infrastructure, secure property rights to water and land, development of institutions for resource management and substantial investments in agricultural research and extension. At the same time, the environmental costs of transporting food are increasing, and in some countries are greater than the costs arising from food production on farms, suggesting that sustainability priorities need to be set for whole food chains (Pretty *et al.* 2005; Smith in press).

In this context, it is unclear whether progress towards more sustainable agricultural systems will result in enough food to meet the current food needs in developing countries, let alone the future needs after continued population growth (and changed consumption patterns) and adoption of more urban and meat-rich diets (Popkin 1998). But what is occurring should be cause for cautious optimism, particularly as evidence indicates that productivity can grow over time if natural, social and human assets are accumulated.

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