Annals of Botany **114**: 1571–1596, 2014
doi:10.1093/aob/mcu205, available online at www.aob.oxfordjournals.org

ANNALS OF BOTANY
Founded 1887

INVITED REVIEW

Sustainable intensification in agricultural systems

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Received: 18 June 2014 Returned for revision: 18 August 2014 Accepted: 2 September 2014 Published electronically: 28 October 2014

• **Background** Agricultural systems are amended ecosystems with a variety of properties. Modern agroecosystems have 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). In the coming decades, resource constraints over water, soil, biodiversity and land will affect agricultural systems. Sustainable agroecosystems are those tending to have a positive impact on natural, social and human capital, while unsustainable systems feed back to deplete these assets, leaving fewer for the future. Sustainable intensification (SI) is defined as a process or system where agricultural yields are increased without adverse environmental impact and without the conversion of additional non-agricultural land. The concept does not articulate or privilege any particular vision or method of agricultural production. Rather, it emphasizes ends rather than means, and does not pre-determine technologies, species mix or particular design components. The combination of the terms 'sustainable' and 'intensification' is an attempt to indicate that desirable outcomes around both more food and improved environmental goods and services could be achieved by a variety of means. Nonetheless, it remains controversial to some.

• **Scope and Conclusions** This review analyses recent evidence of the impacts of SI in both developing and industrialized countries, and demonstrates that both yield and natural capital dividends can occur. The review begins with analysis of the emergence of combined agricultural–environmental systems, the environmental and social outcomes of recent agricultural revolutions, and analyses the challenges for food production this century as populations grow and consumption patterns change. Emergent criticisms are highlighted, and the positive impacts of SI on food outputs and renewable capital assets detailed. It concludes with observations on policies and incentives necessary for the wider adoption of SI, and indicates how SI could both promote transitions towards greener economies as well as benefit from progress in other sectors.

Key words: Sustainable intensification, agricultural systems, natural capital, social capital, crop yields, resilience, hunger, green economies, food security.

AGRICULTURE, NATURE AND THE ENVIRONMENT

Interest in agricultural sustainability can be traced to environmental concerns that began to appear in the 1950s and 1960s (Carson, 1962; Ward and Dubos, 1972). However, concepts and practices regarding sustainability date back at least to the oldest surviving texts from China, India, Greece and Rome (King, 1911; Cato, 1979; Li Wenhua, 2001; Pretty 2003; Conway, 2012). Prominent Roman agricultural writers, including Cato, Varro and Columella, spoke of agriculture as having two components: *agri* and *cultura* (the fields and the culture). Cato, in the opening of *De Agri Cultura*, written 2200 years ago, celebrated the high regard in which farmers were held: 'when our ancestors… would praise a worthy man their praise took this form: "good husbandman", "good farmer"; one so praised was thought to have received the greatest commendation.' He also wrote about longevity: 'a good piece of land will please you more at each visit.'

It is in China, though, that there exists the greatest and most continuous record of agriculture's ties to communities and culture (King, 1911). Li Wenhua (2001) dates the earliest records of integrated crop, tree, livestock and fish farming to the Shang-West Zhou Dynasties of 1600–800 BC. Later, Mensius in 400 BC drew attention to the importance of tenure arrangements if individuals are to invest in improving systems that reap later rewards: 'If a family owns a certain piece of land with mulberry trees around it, a house for breeding silkworms, domesticated animals raised in its yard for meat, and crop fields cultivated and managed properly for cereals, it will be prosperous and will not suffer starvation.'

In an early recognition of the need for the sustainable use of natural resources, Mensius observed: 'If the forests are timely felled, then an abundant supply of timber and firewood is ensured; if the fishing net with relatively big holes is timely cast into the pond, then there will be no shortage of fish and turtle for use.' Still later, other treatises such as the collectively written Li Shi Chun Qiu (239 BC) and the Qi Min Yao Shu by Jia Sixia (AD 600) celebrated the value of agriculture to communities and economies, and documented approaches for sustaining food production without damage to the environment. These included rotation methods and green manures for soil fertility, rules and norms for collective management of resources, raising of fish in rice fields, and use of manures. Li Wenhua (2001) wrote: 'these present a picture of a prosperous, diversified rural economy and a vivid sketch of pastoral peace'. F. H. King's seminal study of Chinese and Japanese systems, *Farmers of Forty Centuries* (1911), documented a wide range of both productive and sustainable practices that has persisted for many centuries.

Over time, with the building of surpluses and the development of diversified economies, agriculture came increasingly to be framed as an economic sector separate from nature or the environment. The philosophical dominance of a Cartesian view of 'nature as machine' had built on long-standing monotheistic separations between humans and nature, and led to a gradual erosion of explicit connections to nature and the emergence of two entities – people with their constructed systems of production, and 'wild' nature or the environment. During recent years, with growing concerns for sustainability, different typologies have been developed to categorize shades of shallow- to deep-green thinking (e.g. Naess, 1973; Worster, 1994). For some, there is a more fundamental schism: whether nature exists independently of humans or whether it is part of a post-modern condition. However, there are dangers in dualisms that entirely separate humans from nature. These suggest that nature has boundaries, and can exist only in enclaves such as national parks, wildernesses, reserves, protected areas and zoos. Yet, untouched wilderness is a myth (Gomez-Pompa and Kaus, 1992); equally there are no dividing lines keeping out the 'wild' from agricultural systems (Bharucha and Pretty, 2010).

Tied in with a conceptual separation between the farmed and the wild is a common view that non-agricultural societies represent an early stage of cultural evolution, or even the outcome of devolution (Barnard, 1999). Cultural evolutionary views supposed that societies progressed from hunter–gatherer to agricultural to industrial (e.g. Meggers, 1954; Lathrap, 1968). Evidence has revealed the limitations of these perspectives (Kent, 1989; Kelly, 1995). The landmark *Man the Hunter* conference and book (Lee and DeVore, 1968) showed hunter–gatherers to be rich, knowledgeable, sophisticated and, above all, different from one another. There is no single stage of human development, just different adaptations to specific ecological and social circumstances. It is now better accepted that cultures are adapted to localities, and thus are configured with a wide variety of land uses and livelihoods. Thus, foraging and farming systems across the world are 'overlapping, interdependent, contemporaneous, coequal and complementary' (Sponsel, 1989). This suggests that many rural societies might be better known as variants of cultivator–hunters or farmer–foragers (Szuter and Bayham, 1989): some horticulturalists move that some hunter–gatherers are sedentary (Vickers, 1989; Kelly, 1995). Some groups maintain gardens for cultivated food as well as to attract antelopes, monkeys and birds for hunting (Posey, 1985). Many apparently hunter–gatherer and forager cultures farm; many agricultural communities use non-domesticated species and resources.

As culture and nature are bound together (Berkes, 1999; Pilgrim and Pretty, 2010; Boehm *et al*., 2014), and as the various forms of land use are potentially complementary to one another, this suggests scope for consideration of agriculture as a food-producing system with a significant role in influencing and being influenced by nature and environmental services (NRC, 2010; Foresight, 2011; NEA, 2011). Going beyond older divisions between 'land-sharing' and 'land-sparing', there is an emerging recognition of multiple interdependencies between agricultural and non-agricultural landscapes and the contribution of both to global social–ecological well-being (Tscharntke *et al*., 2012).

The challenge, though, is great. In order to provide sufficient food for growing populations and their changing consumption patterns, some indicate that agriculture will have to expand into non-agricultural lands. However, the competition for land from other human activities makes this an increasingly costly solution, particularly if protecting biodiversity and the public goods provided by natural ecosystems (e.g. carbon storage in forests) is given priority (MEA, 2005). Others suggest that yield increases must be achieved through redoubled efforts to repeat the approaches of the Green Revolution; or that agricultural systems should embrace only biotechnology or become solely organic. What is clear despite these differences is that more will need to be made of existing agricultural land (Tilman *et al*., 2011; Smith, 2013). Agriculture will, in short, have to be intensified. Traditionally agricultural intensification has been defined in three ways: (1) increasing yields per hectare; (2) increasing cropping intensity (i.e. two or more crops) per unit of land or other inputs (water), or livestock intensity (e.g. faster maturing breeds); and (3) changing land use from low value crops or commodities to those that receive higher market prices or have better nutritional content. The notion of 'intensification' remains controversial to some, as recent successes in increasing food production per unit of resource have often also caused environmental harm and disruption to social systems. However, sustainable intensification could both promote transitions towards greener economies and benefit from progress in other sectors

AGRICULTURAL REVOLUTIONS

Early agricultural revolutions in industrialized countries primarily involved expansion of an agricultural area to increase aggregate food production. Such extensification was later followed by intensified use of resources on the same land. In both Europe and North America, wild lands often used as commons came to be enclosed and privatized. The result was dramatic transformations of landscapes. In Britain during the 18th and early 19th centuries, some 2·75 Mha of common land were enclosed, comprising 1·82 Mha of open-field arable and 0·93 Mha of what were called 'wastes' (areas of wild biodiversity). Today, there are 18 Mha of agricultural land in the UK, of which 4 million are currently under arable farming and 0·5 million remain as commons.

These enclosures and expansions were accompanied by rapid innovation in agriculture in Europe and North America. Over a period of about 150 years, crop and livestock production in Britain increased 3- to 4-fold, as innovative technologies, such as the seed drill, novel crops, such as turnips and legumes, fertilization methods, rotation patterns, selective livestock breeding, drainage and irrigation were developed by farmers and spread to others through tours, open-days, farmer groups and publications, and then adapted to local conditions by rigorous experimentation (Pretty, 1991).

In affluent economies, changing numbers of farmers and average farm size show how first extensification occurred, followed by intensification combined with changes in farm size. In the USA, farm numbers increased steadily from 1·5 million to >6 million from 1860 to the 1920s, stabilized for 30 years, but then fell rapidly since the 1950s to today's 2 million. Over the same period, average farm size remained stable for 100 years, around 60–80 ha; but climbed from the 1950s to today's average of approx. 180 ha (Fig. 1). During the past 50 years, 4 million farms have disappeared in the USA. In France, 9 million farms in 1880 became just 1·5 million by the

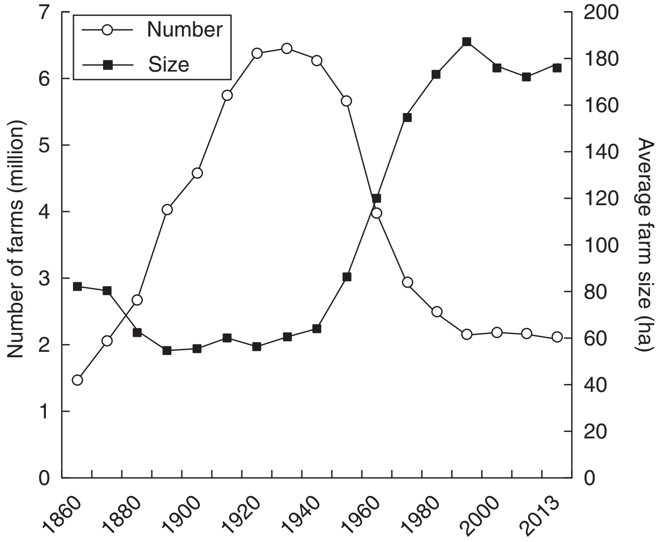

FIG. 1. Number of farms and farm size in the USA, 1860–2013 (USDA, 2014).

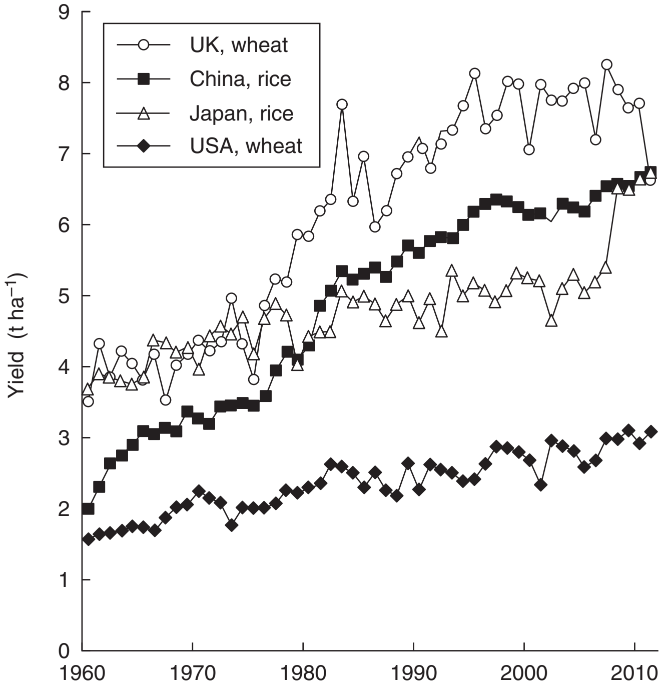

FIG. 2. Profiles of yield changes for rice and wheat in four countries (1961–2012) (FAO, 2014).

1990s. In Japan, 6 million farmers in 1950 became 4 million by 2000. To advocates of economic progress and narrow measures of efficiency, these were predictable losses, but inevitable if there was to be progress in increasing aggregate food production. Farmers increased their productivity, the inefficient were consolidated, and the remaining farms were better able to compete on world markets.

However, such farm consolidation brings side effects. Small farms continue to produce most of the world's food (Grain, 2014) and are the primary source of livelihood for most of the world's agricultural labour. Communities also benefit from hosting a diversity of small farms. Seminal research by Goldschmidt (1946, 1978) on the two communities of Arvin and Dinuba in California's San Joaquin Valley, similar in all respects except for farm size, illustrates important social outcomes. Dinuba was characterized by small family farms, and Arvin by large corporate enterprises. In Dinuba, Goldschmidt found a better quality of life, superior public services and facilities, more parks, shops and retail trade, twice the number of organizations for civic and social improvement, and better participation by the public. The small farm community was seen as a better place to live because, as Perelman (1976) later put it: 'The small farm offered the opportunity for 'attachment' to local culture and care for the surrounding land.' A still later study (Lobao, 1990) confirmed these findings: social connectedness, trust and participation in community life were greater where farm scale was smaller.

The mid 20th century then brought a new agricultural revolution, first in industrialized countries, and then in the tropics, where it came to be known as the Green Revolution. New crop varieties and livestock breeds, combined with increased use of inorganic fertilizers, pesticides and machinery, together with better water control, led to sharp increases in food production from agricultural systems. Many staple crops and livestock show productivity changes over time over this period (Fig. 2; Table 1).

The result has been remarkable growth in food production, with increases across the world since the beginning of the 1960s (Fig. 3). During the second half of the 20th century, intensification, rather than the spread of agricultural land, has been the prime driver of increased per capita food production globally. Though 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, aggregate world food production has grown 145 % (rising to 280 % in Asia and 200 % in Latin America). The greatest increases have been in China, where a 5-fold 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. Over the same period, the world population has grown from 3 billion to >7 billion, imposing an increasing impact on the human footprint on the Earth as consumption patterns also change (Pretty, 2013). Again, though, per capita agricultural production has outpaced population growth. Thus, for each person today, there is 25 % more food compared with 1960 (Fig. 4).

An important new challenge though, comes with shifting consumption patterns. Rising affluence is associated with nutrient transitions (Popkin, 1993), whereby populations consume more saturated fats, sugar and refined foods. A key feature of the global dietary transition has been increased demand for animal protein. Livestock production has increased, with a worldwide 4-fold increase in numbers of chickens, 2-fold increase in pigs and 40–50 % increase in numbers of cattle, sheep and goats (Pretty, 2008). In developing countries, consumption of meat and dairy has grown by 5·1 % and 3·6 % respectively since 1970 (Alexandratos and Bruinsma, 2012). Over the 20th century, the intensity of production on agricultural lands has also risen substantially: the area under irrigation and number of agricultural machines has grown by approx. 2-fold, fertilizer consumption by 4-fold and nitrogen fertilizers by 7-fold. The use of synthetic pesticides amounts to some 2·56

TABLE 1. *Changing livestock productivity in the USA, 1955–2012 (USDA, 1955, 2012)*

	1955	2012	Ratio
Beef cattle (average live weight, kg per animal)	433	577	1·33
Pigs (average live weight, kg animal)	108	124	1·15
Sheep (average live weight, kg animal)	43	62	1·44
Milk (kg milk per dairy cow per year)	2510	9569	3·88
Broiler chickens (kg per bird)	1·39	2·61	1·88
Layers (eggs/layer/year)	192	271	1·41

USDA (1955 and 2012). Agricultural Statistics. National Agricultural Statistics Service (NASS). At www.NASS.usda.gov/publications.

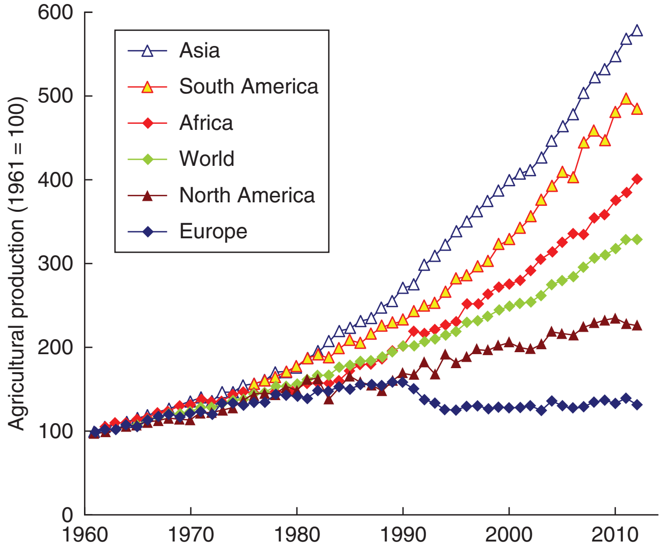

FIG. 3. Relative changes in net agricultural production (tonnes of food produced, 1961–2012).

billion kg year^{-1}, and by the early 21st century the annual value of the global market was US$25 billion, of which some US$3 billion of sales were in developing countries (Pretty, 2005). Herbicides accounted for 49 % of use, insecticides 25 %, fungicides 22 % and others approx. 4 %.

This phase of agricultural intensification has been accomplished at great expense to the environment. This in turn has made agricultural systems less efficient, by removing or degrading the environmental goods and services (such as groundwater for irrigation, pollinators and beneficial insects) they require. These negative externalities (Pingali and Roger, 1995; Dobbs and Pretty, 2004) shift conclusions about which agricultural systems are the most effective and suggest that alternative practices and systems that reduce negative externalities should be sought.

THE SCALE OF THE FOOD PRODUCTION CHALLENGE

By a narrow definition of calories per capita, global agriculture currently produces enough for all the world population to thrive (FAO, WFP and IFAD, 2012). Yet, the world continues to face a continued ‘triple burden’ of (1) undernutrition (inadequate consumption of calories and protein); (2) malnutrition (inadequate consumption of other important nutrients); and (3) overnutrition (excessive consumption of calories). This challenge is tightly enmeshed with other equally recalcitrant challenges of poverty, energy insecurity and breached planetary boundaries (Rockström *et al.*, 2009).

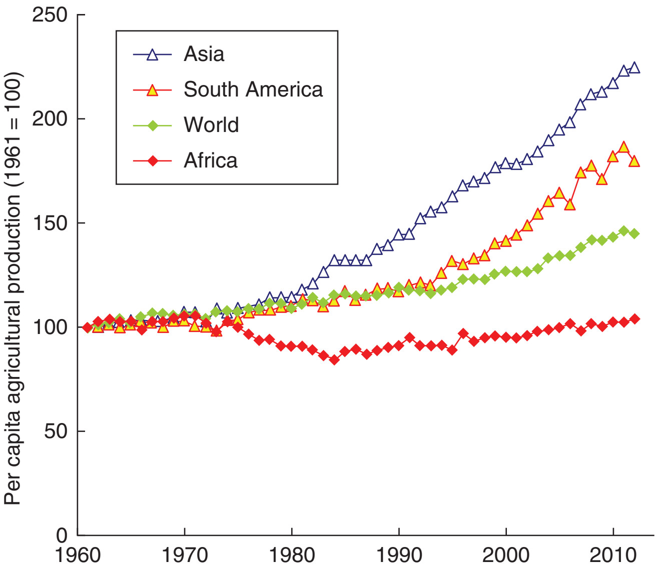

FIG. 4. Relative changes in per capita net agricultural production (tonnes of food produced, 1961–2012.

The agricultural revolutions of the 20th century chiefly focused on reducing undernutrition, seeking to boost the availability of calories through increased production of cereals and other staples. Yet, at the global level, some 870 million people remain undernourished, equivalent to one in eight of the global population (FAO, 2013*a*), and many countries will fail to meet the Millennium Development Goal target of halving the number of hungry people by 2015 (Gómez *et al.*, 2013). The situation across the African continent remains particularly urgent. Of 34 countries requiring external food assistance in 2013, 27 were in Africa (FAO, 2013*a*). Without significant effort, >500 million will still be food insecure in the region by 2020 (Shapouri *et al.*, 2010; Smith, 2013).

In addition to chronic hunger, protracted food crises have become a norm (Maxwell, 2012; Maxwell *et al.*, 2012). In the most vulnerable contexts, these crises may involve more than just crop failure or rising prices. The 2011 famine in Somalia touched on all four pillars of food security: there was a production shock, an access shock, a malnutrition crisis and increased instability of food sources (Maxwell, 2012). These shocks, like other disasters, stem from an increasingly complex combination of natural and human-made drivers. The 2007–2008 food price spike, for instance, was caused by a combination of rising oil prices, market regulation and speculative activity. In addition, there is predicted to be a spread of protracted crises, which may have many causes, no clear ending and limited potential for recovery (Foresight, 2011).

Secondly, 2 billion people suffer from various types of micronutrient malnutrition, deficiencies that particularly affect the health and human potential of women and children (FAO, WFP and IFAD, 2012). Vitamin A deficiency is a public health concern in 80 countries, affecting >7 million pregnant women and 127 million pre-school children worldwide (West, 2002; West and Darton-Hill, 2008). Micronutrient deficiencies during critical life stages have a lasting impact on both individuals and their societies.

Thirdly, overnutrition now negatively affects the health of over a billion people worldwide. At a point just under two generations after a world war that brought a legacy of food rationing persisting to 1954, the average incidence of obesity in the UK in the mid-1980s was 3 % and in the USA 6 %; it has since risen to 24 % of adults in the UK and to 35 % in the USA (CDC, 1996; CMO, 2013). Now many wealthier groups in fast developing countries are following a similar transition to overweight and obese populations (Popkin, 1998; Samson and Pretty, 2006; Foresight, 2011; Lang and Rayner, 2012; Pretty, 2013). Mexico is now the highest consumer of sugar-rich soft drinks, and has seen a rapid growth in incidence of obesity (Carolan, 2013). In developing countries, undernutrition persists despite economic growth (Frayne *et al.*, 2014), and simultaneously overnutrition and associated public health concerns are increasingly evident (Peer *et al.*, 2014). In India, diabetes and hypertension have emerged as major public health concerns (Shetty, 2012). Across Africa, despite the continued prevalence of undernutrition (Frayne *et al.*, 2014), the incidences of obesity (Muthuri *et al.*, 2014) and diabetes (Peer *et al.*, 2014) are increasing.

Thus what is important is not just increasing yields or producing more calories per capita. Globally, despite pockets of high dietary diversity amongst some land-based communities (Bharucha and Pretty, 2010), just 12 species contribute 80 % of dietary intake, and global agriculture has come to focus on just 150 commercialized species. Over 80 % of global croplands are currently devoted to annual crops (Monfreda *et al.*, 2008), which contribute about 70 % of human calories. This narrow focus on calories and commercial staples has resulted in some unintended nutritional outcomes. Across south Asia for example, cereal production increased by 4-fold from 1970, yet this was achieved alongside a decline of 20 % in the production of pulses (Welch and Graham, 2000). Thus, future efforts to intensify agriculture will have to be nutrition sensitive, explicitly incorporating attention to nutrition objectives, concerns and outcomes. This implies focused attention on a wider range of nutritionally dense crops, including fruit, vegetables, legumes, animal products (Gómez *et al.*, 2013) and non-cultivated species (Bharucha and Pretty, 2010).

Improving agricultural growth is also imperative for reducing poverty, in itself a cause of some forms of environmental degradation and hunger. Agricultural growth is more effective at reducing poverty than general economic growth, which is especially important in countries with largely agrarian populations and suffering from high levels of poverty (Irz *et al.*, 2001; de Janvry and Sadoulet, 2010; Christiansen *et al.*, 2011). It is clear, however, that agricultural systems alone cannot solve world problems: conflicts have reduced agricultural production (Allouche, 2011). Food production in 13 war-affected countries of sub-Saharan Africa during 1970–1994 was 12 % lower in war years compared with peace-adjusted values. Over the period 1970–1997, the FAO (2000) has estimated that conflict-related losses of agricultural outputs amounted to US$121 billion (US$4 billion per year).

USING AND SUSTAINING CAPITAL ASSETS FOR AGRICULTURAL SYSTEMS

Agricultural systems are amended ecosystems with a variety of properties (Table 2). Recent agricultural systems have amended some of these properties to increase productivity. Sustainable agroecosystems, in contrast, seek to shift some of these properties towards natural systems without significantly trading off productivity. In affluent economies, modern agroecosystems have 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 towards internal tropic interactions (e.g. to soil organic matter or to non-agricultural biodiversity for arable birds) so as to maintain other ecosystem functions. These properties suggest a role for agroecological design of systems so as to produce both food and environmental assets (Conway, 1997; Gliessman, 2005; Pretty, 2008; Smith, 2013).

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 recognized as being important (Pretty, 2008).

There are important 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

TABLE 2. *Properties of natural ecosystems compared with recent agroecosystems typical of affluent economies and sustainable agroecosystems*

Property	Natural ecosystem	Recent agroecosystem typical of affluent economies	Sustainable agroecosystem
Productivity	Medium	High	Medium (possibly high)
Species diversity	High	Low	Medium
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

Source: Gliessman (2005).

measurability, substitutability and transferability. If the value of something can be assigned a monetary figure, then it can appear not to matter if it is lost, if a replacement can simply be purchased or sourced from elsewhere. However, these capitals are not necessarily interchangeable (Ostrom, 1990; Costanza *et al.*, 1997; Pretty, 2008).

As agricultural systems shape the very assets on which they rely for inputs, a vital feedback loop occurs from outcomes to inputs. Sustainable agroecosystems are those tending to have a positive impact on natural, social and human capital, while unsustainable systems feed back to deplete these assets, leaving fewer for the future. The concept of sustainability does not require that all assets are improved at the same time. One agricultural system that contributes more to these assets than the other can be said to be more sustainable, but there are still likely to be trade-offs, with one asset increasing as another falls.

As agroecosystems are considerably more simplified than natural ecosystems, some natural properties need to be designed back into systems to decrease losses and improve efficiency. For example, loss of biological diversity (to improve crop and livestock productivity) results in the loss of some ecosystem services, such as pest and disease control. For sustainability, biological diversity needs to be increased to re-create natural control and regulation functions, and to manage pests and diseases rather than seeking to eliminate them. Modern agricultural systems have come to rely on synthetic nutrient inputs obtained from natural sources but requiring high inputs of energy, usually from fossil fuels. These nutrients are often used inefficiently, and result in losses in water and air as nitrate, nitrous oxide or ammonia (Thomson *et al.*, 2012). To meet principles of sustainability, such nutrient losses need to be reduced to a minimum, recycling and feedback mechanisms introduced and strengthened, and nutrients diverted for capital accumulation (e.g. Thomson *et al.*, 2012). Mature ecosystems are now known not to be stable and unchanging, but rather are in a state of dynamic equilibrium that buffers against large shocks and stresses. Modern agroecosystems have weak resilience, and transitions towards sustainability will need to focus on structures and functions that improve resilience as well as meeting the primary goal of food production.

BIOPHYSICAL RESOURCE CONSTRAINTS AND ENVIRONMENTAL SERVICES

Ecosystem health is a prerequisite for productive agriculture (MEA, 2005; NRC, 2010; Foresight, 2011; NEA, 2011). Agriculture is both driver and recipient of the impacts of global environmental change. Meeting projected demands for food, fodder and fibre will require finding ways to navigate the legacy of past environmental degradation while building natural capital. In the future, it is likely that crops will have to be produced under less favourable climatic and economic conditions than those which enabled yield increases during the past century (Glover and Reganold, 2010). There are four broad constraints to agricultural productivity and sustainability: water, soil, biodiversity and land. Together these form the context within which decisions on agricultural sustainability will need to be made, and call for a fundamental revision of the ways in which agricultural systems are designed.

Water

Agriculture accounts for 70 % of global freshwater use, even though 80 % of global agriculture is primarily rainfed (FAO, 2011*a*). In coming decades the share of global freshwater available for agriculture is likely to decline as a result of increasing demands from industry, power generation and domestic use. In addition, competition between different agricultural uses, changing dietary patterns (e.g. the increased consumption of meat and sugar) and the changing structure of the global energy mix (Gerbens-Leenes *et al.*, 2012) will also have a direct bearing on the availability of water for food production. The annual rate of efficiency improvement in agricultural water use between 1990 and 2004 was approx. 1 % across both rainfed and irrigated areas. At this rate, the sector will be able to close only 20 % of the projected demand–supply gap by 2030. Improvements in supply will address only a further 20 % of the gap (WRG, 2009). Gaps between supply and demand are likely to be most pronounced, and have the most negative impacts, in countries with high rates of economic growth coupled with high levels of poverty – India, China, Brazil and South Africa (WRG, 2009). Agricultural runoff from both crop and livestock systems is also a key source of pollution (Loehr, 1977; Conway and Pretty, 1991; Moss, 2008; O'Bannon *et al.*, 2014), thus further reducing the availability of uncontaminated water.

Soil

Deteriorating soil health poses a global challenge in the context of food insecurity, climate change and environmental degradation (McBratney *et al.*, 2014). Soil is an asset for agricultural systems; it is also a global sink for carbon. Soil health is diminished through loss of soil itself by erosion, and by loss of soil carbon, organic matter and nutrients. Agriculture is a key driver of global soil erosion (Montgomery, 2007), with an estimated reduction of some 0·3 % of production per year globally (den Biggelaar *et al.*, 2003).

Globally, the soil carbon pool is over five times the atmospheric pool and 6·5 times the biotic pool (Lal, 2014). A third of global land area (just under 44 Mkm^2) is classed as marginal land at high risk of degradation, yet this supports some 50 % of the world population (Glover and Reganold, 2010). Globally, cultivated soils have lost between 25 and 75 % of their organic carbon pool (Lal, 2014); yet some agricultural systems are able to capture and sequester carbon. Agricultural intensification has greatly increased soil nutrient demand from crop production; meeting this demand through synthetic fertilizers is associated with a high energetic, environmental and public health cost (Jones *et al.*, 2013). While nitrogen (N), phosphorus (P) and potassium (K) fertilization replenishes some of the nutrients removed by intensive production, many mineral nutrients are inadequately replenished, with negative implications for soil health and nutritional security (Jones *et al.*, 2013).

The industrial production of fertilizer moves some 120 Mt of atmospheric N to terrestrial and aquatic systems. A further 20 Mt of P are mined annually, and 8–9·5 Mt are released into the world's oceans, some eight times greater than the natural background rate of flux. In certain regions, lack of nutrients in soils remains a key constraint. Many African soils, for example, are nutrient poor, and fertilizer use is low across the continent compared with other regions. The average use of mineral fertilizers does not surpass 6–7 kg of NPK ha^{-1}, against a middle and low income country average of nearly 100 kg ha^{-1}, on land of generally low and declining inherent fertility (Reij and Smaling, 2008). As yields increase, so the net export of nutrients also increases (unless nutrient cycles are closed). Thus, farms in most contexts need to import or fix nutrients to replenish low stocks.

Biodiversity

Biodiversity is critical to global nutritional security, contributing to the availability of both farmed and wild foods, the provision of pollination services, predator–prey regulation and the provision of income through ecosystem-based livelihoods (IUCN, 2013). The majority of the global supply of vitamin C, vitamin A, folic acid, calcium, fluoride and iron comes from animal- and insect-pollinated crops (Eilers *et al*., 2011). Wild foods are critically important sources of protein, energy and micronutrients for those most vulnerable to hunger globally (Bharucha and Pretty 2010; IUCN, 2013).

Agricultural lands are multifunctional, providing a range of regulating, supporting and cultural ecosystem services in addition to food, fodder, fuel and fibre. This 'underscores the need to manage agricultural areas as multi-functional systems . . . not as ecological sacrifice zones' (Milder *et al*., 2012). Milder *et al*. define a nature gap as 'the deficit in the provision of ecosystem services and other conservation values between any given farming system and a system in the same environment and with the same level of agricultural output that is optimally managed for ecosystem co-benefits' (p. 2). While nature gaps are not necessarily related to the intensity of cultivation, agricultural intensification has in the past been associated with the creation of significant nature gaps. A challenge will be to create biodiverse farming systems that are productive, resilient and enablers of 'intensification without simplification' (Frison *et al*., 2011, p. 247).

Land availability and land-use change

Competition for land, between agricultural and non-agricultural uses and even for different agricultural uses, is increasing (Tilman *et al*., 2011). In the last decade, a key trend has been the diversion of agricultural land from food to fuel crops. In 2013, some 30 % of US maize output was diverted into ethanol production (NCGA, 2014), and thus burned in vehicles. In south-east Asia, palm oil production has displaced both food production and natural forest systems (Wicke, 2011; Obidzinski *et al*., 2012; Lee, 2014). Many local drivers of conflict relate to control over land and other resources required for livelihoods (Alinovi *et al*., 2008). These factors drive the conversion of some non-agricultural land to cultivation, and negative impacts include increased greenhouse gas (GHG) emissions from soils and the removal of carbon sinks (vegetation biomass) and increased fossil fuel use; and increased use of N fertilizer and the loss of provisioning services to land-based communities who depend on non-agricultural landscapes for food, medicine, fodder, fuel, fibre, cultural identity and spiritual value. Non-agricultural landscapes also support agriculture. Thus, the expansion of agricultural activity into previously uncultivated landscapes could have substantial detrimental outcomes. Instead, what is needed is to design and manage whole agricultural landscapes better (for both food and environmental services).

THE TERM 'SUSTAINABLE INTENSIFICATION'

The desire for agriculture to produce more food without environmental harm, or even positive contributions to natural and social capital, has been reflected in calls for a wide range of different types of more sustainable agriculture: for a 'doubly green revolution' (Conway, 1997), for 'alternative agriculture' (NRC, 1989), for an 'evergreen revolution' (Swaminathan, 2000), for 'agroecological intensification' (Milder *et al*., 2012), for 'green food systems' (DEFRA, 2012), for 'greener revolutions' (Snapp *et al*., 2010) and for 'evergreen agriculture' (Garrity *et al*., 2010). All centre on the proposition that agricultural and uncultivated systems should no longer be conceived of as separate from each other. In light of the need for the sector also to contribute directly to the resolution of global social–ecological challenges, there have also been calls for nutrition-sensitive (Thompson and Amoroso, 2011), climate-smart (FAO, 2013*b*) and low-carbon (Norse, 2012) agriculture.

Sustainable production systems should exhibit a number of key attributes at the production end of food systems (Pretty, 2008; Royal Society, 2009). They should:

(1) utilize crop varieties and livestock breeds with a high ratio of productivity to use of externally and internally derived inputs;
(2) avoid the unnecessary use of external inputs;
(3) harness agroecological processes such as nutrient cycling, biological nitrogen fixation, allelopathy, predation and parasitism;
(4) minimize use of technologies or practices that have adverse impacts on the environment and human health;
(5) make productive use of human capital in the form of knowledge and capacity to adapt and innovate and of social capital to resolve common landscape-scale or system-wide problems (such as water, pest or soil management); and
(6) minimize the impacts of system management on externalities such as GHG emissions, clean water, carbon sequestration, biodiversity, and dispersal of pests, pathogens and weeds.

Agricultural systems emphasizing these principles tend to display a number of broad features that distinguish them from the process and outcomes of conventional systems. First, these systems tend to be multifunctional within landscapes and economies (Dobbs and Pretty, 2004; MEA, 2005; IAASTD, 2009). They jointly produce food and other goods for farmers and markets, while contributing 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 and tourism opportunities. In their configuration, they capitalize on the synergies and efficiencies that arise from complex ecosystems, social and economic forces (NRC, 2010).

Secondly, these systems are diverse, synergistic and tailored to their particular social–ecological contexts. There are many pathways towards agricultural sustainability, and no single configuration of technologies, inputs and ecological management is more likely to be widely applicable than another. Agricultural sustainability implies the need to fit these factors to the specific circumstances of different agricultural systems (Horlings and Marsden, 2011). Challenges, processes and outcomes will also vary across agricultural sectors: in the UK, for example, Elliot *et al*. (2013) found that livestock and dairy operations transitioning towards sustainability had particular difficulties in reducing pollution while attempting to increase yields.

Thirdly, these systems often involve more complex mixes of domesticated plant and animal species and associated management techniques, requiring greater skills and knowledge by farmers. To increase production efficiently and sustainably, farmers need to understand under what conditions agricultural inputs (seeds, fertilizers and pesticides) can either complement or contradict biological processes and ecosystem services that inherently support agriculture (Settle and Hama Garba, 2011; Royal Society, 2009). In all cases, farmers need to see for themselves that added complexity and increased knowledge inputs can result in substantial net benefits to productivity.

Fourthly, these systems depend on new configurations of social capital, comprising relations of trust embodied in social organizations, 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 able to innovate in the face of uncertainty (Pretty and Ward, 2001; Wennink and Heemskerk, 2004; Hall and Pretty, 2008; Friis-Hansen, 2012), and farmer-to-farmer learning has been shown to be particularly important in implementing the context-specific, knowledge-intensive and regenerative practices of sustainable intensification (Pretty *et al.*, 2011; Settle and Hama Garba, 2011; Rosset and Martínez-Torres, 2012).

Conventional thinking about agricultural sustainability has often assumed that it implies a net reduction in input use, thus making such systems essentially extensive (requiring more land to produce the same amount of food). Organic systems often accept lower yields per area of land in order to reduce input use and increase the positive impact on natural capital. However, such organic systems may still be efficient if management, knowledge and information are substituted for purchased external inputs. Recent 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 is one that centres on intensification of resources, making better use of existing resources (e.g. land, water and biodiversity) and technologies (IAASTD, 2009; Royal Society, 2009; NRC, 2010; Foresight, 2011; FAO, 2011*b*; Tilman *et al.*, 2011).

Compatibility of the terms ‘sustainable’ and ‘intensification’ was hinted at in the 1980s (e.g. Raintree and Warner, 1986; Swaminathan, 1989), and then first used in conjunction in a paper examining the status and potential of African agriculture (Pretty, 1997). Until this point, ‘intensification’ had become synonymous for a type of agriculture that inevitably caused harm whilst producing food (e.g. Collier *et al.*, 1973; Poffenberger and Zurbuchen, 1980; Conway and Barbier, 1990). Equally, ‘sustainable’ was seen as a term to be applied to all that could be good about agriculture. The combination of the terms was an attempt to indicate that desirable ends (more food, better environment) could be achieved by a variety of means. The term was further popularized by its use in a number of key reports: *Reaping the Benefits* (Royal Society, 2009), *The Future of Food and Farming* (Foresight, 2011) and *Save and Grow* (FAO, 2011*b*).

Sustainable intensification (SI) is defined as a process or system where yields are increased without adverse environmental impact and without the cultivation of more land (Royal Society, 2009). The concept is thus relatively open, in that it does not articulate or privilege any particular vision of agricultural production (Garnett and Godfray, 2012; Smith, 2013). It emphasizes ends rather than means, and does not pre-determine technologies, species mix or particular design components. Sustainable intensification can be distinguished from former conceptions of ‘agricultural intensification’ as a result of its explicit emphasis on a wider set of drivers, priorities and goals than solely productivity enhancement (Table 3).

SUSTAINABLE INTENSIFICATION: EMERGENT CRITICISMS

A number of debates currently shape the evolving conceptual and theoretical field of SI. Garnett and Godfray (2012) reviewed key contentions and debates surrounding SI, classifying these into three groups. The first relates to the vision and mode of SI, wherein the term is assumed to prescribe particular forms of agriculture deemed unsuitable for various reasons. The second questions the rationale for SI, and a third set of questions relates to the conceptual basis of SI: which is more important, ‘sustainable’ or ‘intensification’, and how do they relate to each other?

One contention relates to the potential for SI to be interpreted simply as a ‘productivist’ project. Much criticism of conventional agriculture centres on concerns over large-scale industrial monocultures concerned only with increasing yields and the gross productivity of systems. However, a good agriculture would also be efficient in its use of resources, and equitable in providing access to its food produced (Foresight, 2011; Freibauer *et al.*, 2011). In associating SI with a narrative that suggests production is the only key principle for agriculture, some critics have asked whether the concept represents a sufficiently radical departure from ‘business-as-usual’. Some have highlighted distinct and competing ‘strong’ and ‘weak’ interpretations of SI. ‘Weak’ interpretations may be open to the charge of promoting ‘an apparent oxymoron’ (Lang and Barling, 2012) that may simply be used as a ‘greenwash’. Such a view is exemplified by the recent testimony of a UK MP who expressed concern that ‘. . . is there not a danger that it [SI] will be used as a Trojan horse for those who want us to have lots more biotech and GM and so forth? . . . is there a potential conflict between how this idea might be used and the future of small-scale farming?’ (Lucas, 2011). Implicit in the ‘Trojan horse’ argument is the notion of an association between ‘large-scale’ and particular technologies, and a distinction between the values of ‘large’ and ‘small’, with an implicit preference for only the latter. This points to a tension between different conceptions of what is good in agriculture, and reveals some of the complexity that SI must navigate.

Garnett and Godfray (2012) highlight the core principles of the term, which has an openness that ‘denotes an aspiration of what is to be achieved rather than a description of existing

Table 3. *Differences between sustainable intensification and historically conventional forms of agricultural intensification*

	Conventional forms of agricultural intensification	Sustainable intensification
Primary goals of farmers	Increase crop and livestock yields	Improve yields and incomes, improve natural capital in on- and off-farm landscapes, build knowledge and social capital.
Knowledge development	Tends to be solely ‘expert’ driven	Collaborations between ‘experts’ and other stakeholders as key to emergence of agroecological design; participatory research and development leads to new technologies and practices.
Knowledge dissemination	Conventional extension chain from public or private research to farmers	Conventional extension combined with participatory dissemination via peer-to-peer learning.
Stewardship of ecosystem services	Emphasis on provisioning services derived from agricultural landscapes; use of external inputs to substitute for regulating and supporting services; interactions with surrounding non-agricultural landscapes treated as externalities	Greater appreciation of the contribution of multiple ecosystem services provided by agricultural landscapes and awareness of the two-way relationship between agricultural and non-agricultural components of landscapes.

production systems, whether this be conventional high-input farming, or smallholder agriculture, or approaches based on organic methods’ (p. 8). In practice, it may not be easy to distinguish between approaches. For example, conservation agriculture (CA) and integrated pest management (IPM) can both be thought of variously as SI, as agroecology, as ‘climate-smart agriculture’, as ‘ecological intensification’ or simply as a ‘greener agriculture’ (Kassam *et al*., 2009). These terms reflect differing priorities on agricultural inputs and outputs but ‘all will have to engage with the reality that there are hard trade-offs between different desirable outcomes and uncomfortable choices for all stakeholders’ (Garnett and Godfray, 2012, p. 18). Going beyond privileging any particular agricultural technology, focusing only on desirable social–ecological outcomes, there is a need to evaluate any technology, approach or practice pragmatically and empirically, and judge it on its merits: does it produce more food per unit of resource; and does it do so without harm to the environment? It remains clear, though, that better agricultural and food systems could be imagined by reducing food waste, increasing community engagement and reducing inequity, regardless of the forms of production in fields and farms (Foresight, 2011; Stock *et al*., 2015). As important in agricultural systems to farmers and workers are returns to labour, and the distribution of benefits between women and men.

However, even the openness of SI throws some difficult questions into relief. Defining ‘sustainability’ has always been hard. As with different versions of sustainability, it is possible to argue that SI has ‘light’ and ‘dark’ green interpretations. Defining boundaries – between agriculture and other economic sectors or around units of landscape (farms, watersheds, landscapes) or around time spans (5-year plans, decades, across generations) – is also difficult because of incomplete knowledge, continually evolving conditions and diverse human values (Garnett and Godfray, 2012). Again, outcomes are important: social and political transformations may be needed to ensure that yield increases delivered through SI actually reduce hunger and poverty (Holt-Giménez and Altieri, 2013).

Terminology can hide variations in practice, and often sustainability outcomes. For example, IPM constitutes a wide range of methods, practices and technologies available to reduce pest, weed and disease threats. Some approaches centre on agroecological management and habitat design, using the services of biodiversity on and off farm. Others centre on scheduling of pesticides. The NRC (2010, p. 138) noted that for some farmers in the USA, ‘IPM means simply scheduling pesticide applications based on monitoring and established economic thresholds; others use more integrated IPM . . . with pesticide use as a last resort.’

There may also be ambiguity about what is being intensified. As Jacobsen *et al*. (2013) argue, ‘Many arguments about feeding the world assume that we need more of our current, western diet, but it should be obvious that the world’s population can better be fed, both agriculturally, environmentally and with respect to human health, with a diet different from what is most common in the developed world today.’ It is not always accepted that yields need to be increased (Tomlinson, 2013). Elliot *et al*. (2013, p. 30) point out that in certain cases, SI ‘may not be an appropriate strategy [because] other ecosystem functions may be valued more highly than increases in food production (e.g. water quality, carbon storage, landscape quality)’.

A common objection made about many agroecological approaches for SI is their perceived need for increased labour (Tripp, 2005). However, sustainability concerns are highly site specific: in some cases more labour is not needed; in others the extra labour required is seen as a valuable contribution to local economies (De Schutter and Vanloqueren, 2011). In some contexts, labour is highly limiting, especially where HIV-AIDS has removed a large proportion of the active population; in other contexts, there is plentiful labour available as there are few other employment opportunities in the economy. Successful systems of sustainable intensification by definition fit solutions to local needs and contexts, and so thus take account of labour availability. In Kenya and Tanzania, for example, female owners of raised beds for vegetable production employ local people to work on vegetable cultivation and marketing (Muhanji *et al*., 2011). Labour for crop and livestock management is thus not necessarily a constraint on new technologies.

In Burkina Faso, work groups of young men have emerged for soil conservation. *Tassas* and *zai* planting pits are best suited to landholdings where family labour is available, or where farm hands can be hired (Reij and Smaling, 2008; Sawadogo, 2011). The technique has led to a network of young day labourers who have mastered this technique. Owing to the success of land rehabilitation, farmers are increasingly buying degraded land for improvement, and paying labourers to dig *zai* pits and construct the rock walls and half-moon structures, which have transformed productivity. This is one of the reasons why >3 Mha of land are now rehabilitated and productive. In other contexts, though, shifts to sustainable systems, such as incorporating agroforestry into maize systems in Africa, has led to both reduced and increased labour requirements, depending on the local social and ecological context.

SUSTAINABLE INTENSIFICATION: EVIDENCE OF IMPACTS

Can the sustainable intensification of agricultural systems work? Can it, at the first and production stage of food chains, produce more food, fibre and other valued products whilst improving natural capital? Is it possible to produce more whilst not trading off harm to key renewable capital assets?

Documenting and evaluating evidence from SI is complicated and sometimes contentious. First, conceptual diversity and the inclusivity of the approach mean that it is difficult to 'bound' evaluations. Agroecological approaches involve multiple practices, adapted from place to place depending on farmer and community needs. There may be no clear conceptual, methodological or practical dividing line between 'alternative' and 'conventional' practice. Depending on need and ability, farmers may apply agroecological principles to industrial farms, or introduce the mechanization and inorganic inputs into otherwise agroecologically managed farms (Milder *et al.*, 2012). Where studies seek to demonstrate simultaneous improvements to yields and environmental outcomes, results are highly sensitive to the variables and parameters selected to capture environmental improvements, the time scales involved and any weightings used (Elliot *et al.*, 2013).

Some assessments have been found to suffer from methodological flaws (Milder *et al.*, 2012). First, despite the heterogeneity of practices involved in any intensification strategy, assessments often focus on yields from specific, labelled approaches – such as CA, agroforestry or IPM. Analysis of distinct approaches is also difficult. For example, evidence on outcomes from CA and the system of rice intensification (SRI) is mixed, and debate on the general applicability and scalability of these approaches has been 'high profile, sustained and at times acrimonious and emotive' (Sumberg *et al.*, 2013, p. 71). Secondly, syntheses, meta-analyses and overviews have so far focused primarily on yield increases rather than on multiple outcomes and benefits (but see Pretty *et al.*, 2006, 2011; Milder *et al.*, 2012). Finally, there are not yet sufficient data on how different intensification strategies (e.g. agroecological methods) might meet aggregate regional and global goals.

Partly because SI is an umbrella term that includes many different agricultural practices and technologies, and because it is more an approach than a distinct set of technologies and processes, the precise extent of existing SI practice is also unknown. Milder *et al.* (2012) estimate that globally some 200 Mha of agricultural land are cultivated under some form of agroecological regime. Smallholder production is particularly dependent on healthy ecosystems on and around farms, and it has been estimated that half the world's smallholders practise some form of resource-conserving agriculture (Altieri and Toledo, 2011; IFAD and UNEP, 2013).

A number of syntheses have highlighted increased yields (amongst other positive social–ecological outcomes) as a result of the application of agroecological methods and redesign. These again have emphasized the beneficial outcomes of both–and approaches rather than either–or. Outcomes are key; pathways differ. Yields, though, can be a crude measure of the successful outputs or impacts of agricultural systems, particularly where more sustainable systems are expected to have positive impacts on the natural components of both agricultural and wild systems and habitats.

It is in developing countries that some of the most significant progress towards sustainable intensification has been made in the past two decades. The largest study comprised the analysis of 286 projects in 57 countries (Pretty *et al.*, 2006). In all, some 12·6 million farmers on 37 Mha were engaged in transitions towards agricultural sustainability in these 286 projects. This comprised just over 3 % of the total cultivated area (1·14 Mha) in developing countries. In 68 randomly re-sampled projects from the original study, there was a 54 % increase over the 4 years in the number of farmers, and a 45 % increase in the number of hectares (Pretty, 2008). These resurveyed projects comprised 60 % of the farmers and 44 % of the hectares in the original sample of projects. For the 360 reliable yield comparisons from 198 of the projects, the mean relative yield increase was 79 % across the very wide variety of systems and crop types. However, there was a wide spread in results. While 25 % of projects reported relative yields of $>2{\cdot}0$ (i.e. 100 % increase), half of all the projects had yield increases of between 18 and 100 %. Though geometric mean is a better indicator of the average for data with a positive skew, this still shows a 64 % increase in yield (Fig. 5; Table 4).

The UK Government Office of Science Foresight programme commissioned reviews and analyses from 40 projects in 20 countries of Africa where SI had been developed or practised in the 2000s (Pretty *et al.*, 2011, 2014). The cases comprised crop improvements, agroforestry and soil conservation, CA, IPM, horticultural intensification, livestock and fodder crop integration, aquaculture, and novel policies and partnerships. By early 2010, these projects had documented benefits for 10·4 million farmers and their families and improvements on approx. 12·75 Mha. Across the projects, yields of crops rose on average by a factor of 2·13 (i.e. slightly more than doubled) (Table 5). The time scale for these improvements varied from 3 to 10 years. It was estimated that this resulted in an increase in aggregate food production of 5·79 Mt year^{-1}, equivalent to 557 kg per farming household (in all the projects).

Milder *et al.* (2012) undertook a broad review of five sets of agroecological systems, examining their contribution to yields, as well as nine distinct ecosystem services which were relevant to both on- and off-farm beneficiaries (Table 6).

In the UK, Elliot *et al.* (2013) explored outcomes across 20 farms, of which four appeared to have achieved yield increases alongside environmental improvements (denoted by reduced pollution and increased biodiversity). The study shows some of the first evidence of SI in the UK, achieved through a mixture of new technologies (improved genetics and precision farming), new practices (zero-tillage and improved water management), diversification (the installation of small-scale energy generation) and the application of available agri-environmental schemes.

In 1989, the US National Research Council (NRC) published the seminal *Alternative Agriculture*. Partly driven by increased costs of fertilizer and pesticide inputs, plus growing scarcity of natural resources (such as groundwater for irrigation), and

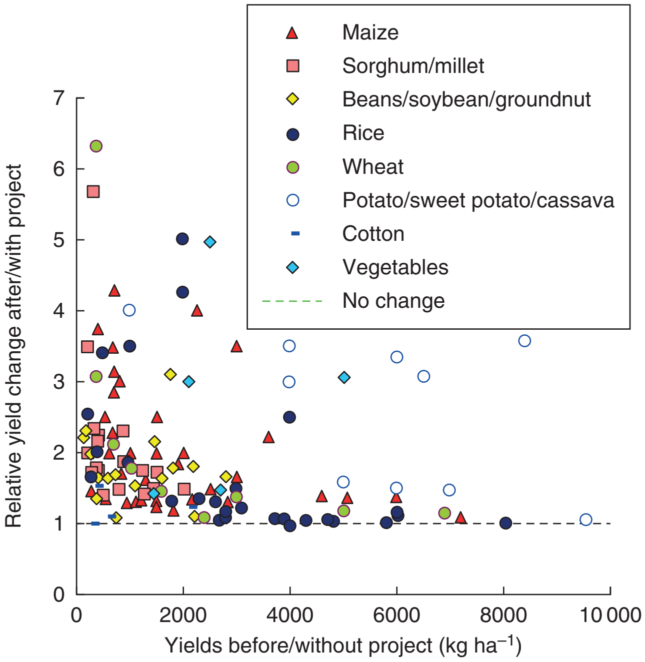

FIG. 5. Relative changes in crop yields under sustainable intensification (Pretty *et al.*, 2006).

TABLE 4. *Summary of adoption and impact of agricultural sustainability technologies and practices on 286 projects in 57 countries*

FAO farm system category*	Number of farmers adopting	Number of hectares under sustainable intensification	Average % increase in crop yields[‡]
1. Smallholder irrigated	177 287	357 940	129·8 (±21·5)
2. Wetland rice	8 711 236	7 007 564	22·3 (±2·8)
3. Smallholder rainfed humid	1 704 958	1 081 071	102·2 (±9·0)
4. Smallholder rainfed highland	401 699	725 535	107·3 (±14·7)
5. Smallholder rainfed dry/cold	604 804	737 896	99·2 (±12·5)
6. Dualistic mixed	537 311	26 846 750	76·5 (±12·6)
7. Coastal artisanal	220 000	160 000	62·0 (±20·0)
8. 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)

*Farm categories from Dixon *et al.* (2001).

[†] Yield data from 360 crop–project combinations; reported as % increase (thus a 100 % increase is a doubling of yields). Standard errors are given in parentheses.

TABLE 5. *Summary of productivity outcomes from Africa case studies for the Foresight project (Foresight, 2011; Pretty* et al., *2014)*

Thematic focus	Area improved (ha)	Mean yield increased (ratio)	Net multiplicative increase in food production (1000 t year^{-1})
Crop variety and system improvements	391 060	2·18	292
Agroforestry and soil conservation	3 385 000	1·96	747
Conservation agriculture	26 057	2·20	11
Integrated pest management	3 327 000	2·24	1418
Horticulture and small-scale agriculture	510	ND	ND
Livestock and fodder crops	303 025	ND	ND
Novel regional and national partnerships and policies	5 319 840	2·05	3,318
Aquaculture	523	ND	ND
Total	12 753 000	2·13	5786

ND, no data, largely because horticulture, livestock and aquaculture are additive components to systems, increasing total food production but not necessarily yields.

TABLE 6. *Global extent of five agroecological systems (Milder* et al., *2012)*

System	Extent (Mha)	Total land under analogous production (Mha)	Proportion of land under agroecological intensification
Conservation agriculture	116	2098	6 %
Holistic grazing management	40	3200	1·25 %
Organic agriculture	37	2459	1·5 %
Precision agriculture	ND	2098	ND
System of rice intensification	>1·5	153	>1 %

ND, no data.

continued soil erosion, farmers had been adopting novel approaches in a wide variety of farm systems. The NRC noted that ‘alternative agriculture’ was ‘not a single system of farming practices’, that they were compatible with large and small farms and that they were often diversified. Such alternative agricultural systems used crop rotations, IPM, soil and water conserving tillage, animal production systems that emphasized disease prevention without antibiotics, and genetic improvement of crops to resist pests and disease and use nutrients more efficiently. Well-measured alternative farming systems ‘nearly always used less synthetic chemical pesticides, fertilizers and antibiotics per unit of production than comparable conventional farms’ (NRC, 1989). They also required ’more information, trained labour, time and management skills per unit of production (p. 9).

The NRC (1989) commissioned 11 detailed case studies of 14 farms as exemplars of effective and different approaches to achieving similar aims: economically successful farms with a positive impact on natural capital. The NRC (2010) conducted follow-up studies in 2008 on ten of the original farms. These included integrated crop–livestock enterprises, fruit and vegetable farms, one beef cattle ranch and one rice farm. After 22 years, common features of farms included:

(1) all farms emphasizing the importance of maintaining and building up their natural resource base and maximizing the use of internal resources;
(2) all farmers emphasizing the values of environmental sustainability and the importance of closed nutrient cycles;
(3) the crop farms emphasizing careful soil management, the use of crop rotations and cover crops; the livestock farms continuing with management practices that did not use hormones or antibiotics;
(4) more farmers participating in non-traditional commodity and direct sales markets (via farmers markets and/or the internet); some selling at a premium with labelled traits (e.g. organic, naturally raised livestock);
(5) farms relying heavily on family members for labour and management; and
(6) the challenges and risks centred on rising land and rental values associated with urban development pressure, the availability of water and the spread of new weed species.

In France, the IAD (2011) has called for a new European agriculture based around maintaining healthy soil, biodiversity, appropriate fertilization and appropriate plant protection techniques. Deploying these 'helps protect the environment whilst producing more, better and in another way' (p. 8). Testing 26 indicators classed into seven themes (economic viability, social viability, input efficiency, soil quality, water quality, GHG emissions and biodiversity) across 160 different types of farm, the authors found that positive ecological externalities can be both achieved and measured. Together, these indicators comprise a comprehensive scorecard that can be applied to test progress towards the production of positive ecological externalities as well as maintenance of productivity.

Farmers adopting SI approaches have been able to increase food outputs by sustainable intensification in two ways. The first is multiplicative – by which yields per hectare have increased by combining use of new and improved varieties with changes to agronomic–agroecological management. The second is improved food outputs by additive means – by which diversification of farms resulted in the emergence of a range of new crops, livestock or fish that added to the existing staples or vegetables already being cultivated. These additive system enterprises included the following.

(1) Aquaculture for fish raising (in fish ponds or concrete tanks) (e.g. Miller and Atanda, 2011; Brummett and Jamu, 2011).
(2) Small patches of land used for raised beds and vegetable cultivation (e.g. Muhanji *et al.*, 2011).
(3) Rehabilitation of formerly degraded land (e.g. Sawadogo, 2011).
(4) Fodder grasses and shrubs that provide food for livestock (and increase milk productivity) (e.g. Wambugu *et al.*, 2011).
(5) Raising of chickens, and zero-grazed sheep and goats (e.g. Peacock and Hastings 2011; Roothaert *et al.*, 2011).
(6) New crops or trees brought into rotations with staple (e.g. maize, sorghum) yields not affected, such as pigeonpea, soyabean, indigenous trees (e.g. Asaah *et al.*, 2011; Ajayi *et al.*, 2011).
(7) Adoption of short-maturing varieties (e.g. sweet potato, cassava) that permit the cultivation of two crops per year instead of one (e.g. Mwanga and Ssemakula, 2011; Roothaert and Magado, 2011).

Environmental externalities have been shown to be positive. Carbon content of soils is improved where legumes and shrubs are used, and where conservation agriculture increases the return of organic residues to the soil. Legumes also fix nitrogen in soils, thereby reducing the need for inorganic fertilizer on subsequent crops. In IPM-based projects, most have seen reductions in synthetic pesticide use (e.g. in cotton and vegetables in Mali, pesticide use fell to an average of 0·25 L ha^{-1} from 4·5 L ha^{-1}: Settle and Hama Garba, 2011). In some cases, biological control agents have been introduced where pesticides were not being used at all, or habitat design has led to effective pest and disease management (Royal Society, 2009; Khan *et al.*, 2011). The greater diversity of trees, crops (e.g. beans, fodder shrubs and grasses) and non-cropped habitats has generally helped to reduce runoff and soil erosion, and thus increased groundwater reserves. Projects across sub-Saharan Africa, where nutrient supply is a key constraint, have used a mix of inorganic fertilizers, organics, composts, legumes, and fertilizer trees and shrubs to improve nutrient availability, in conjunction with conservation tillage to improve soil health. Policy and institutional support has also been important. The Malawi fertilizer subsidy programme is a rare example of a national policy that has led to substantial changes in farm use of fertilizers and the rapid shift of the country from food deficit to food exporter (Dorward and Chirwa, 2011). In this case, the importance of both bonding social capital between farmers in groups and linking social capital between national institutions and farmers was critical to rapid adoption.

SEVEN INTERVENTIONS AND IMPROVEMENTS FOR SUSTAINABLE AGROECOSYSTEMS

The earlier sections of this review have drawn attention to a central need for agricultural systems successfully to produce valued outputs (e.g. food and fibre) whilst having a positive impact on natural, social and human capital. We selected here seven interventions and improvements to illustrate how practices can have such combined impacts, but also how these may differ according to type of intervention. We address: (1) crop variety improvements; (2) integrated pest management; (3) management-intensive rotational grazing (MIRG) systems; (4) conservation agriculture; (5) agroforestry systems; (6) patch intensification; and (7) system of rice intensification.

Crop variety improvements

Varietal improvements, particularly focused on increased yield and pest resistance, have long been at the forefront of agricultural intensification. Yield improvements in key agricultural staples – wheat (208 %), paddy rice (109 %), maize (157 %), potato (78 %) and cassava (36 %) – between 1960 and 2000 (Pingali and

Raney 2005) were key to reducing protein-energy malnutrition (undernourishment) in the developing world (Gómez *et al.*, 2013) by increasing output and reducing food prices. The key technological development came from conventional plant breeding – crossing plants with different genetic backgrounds and selecting individuals with desirable characteristics. An international network of public sector bodies, the CGIAR, played a central role. This provided the dominant source of improved germplasm, particularly for rice, wheat and maize. Even in the 1990s, some 36 % of all varietal releases were based on CGIAR crosses and 26 % of all modern varieties had some CGIAR content (Evenson and Gollin, 2003). Crucially, global benefits from conventional plant breeding in the mid to late 20th century were realized as a result of the international spread of germplasm. This enabled countries to make strategic decisions about how much they needed to invest in their own plant breeding capacity and enabled developing countries to capture the spillover effects of international investment in crop improvement (Pingali and Raney, 2005).

From the 1990s onwards, varietal improvement has also focused on the methods of biotechnology and genetic modification (GM). Since they were first commercialized in 1996, there has been a 100-fold increase in global hectarage of GM crops. As of 2013, some 18 million farmers sowed approx. 175 Mha in 27 countries (ISAAA, 2013). Just over half of the global hectarage under GM crops was in Latin America, Asia and Africa, the primary crops being soybean, cotton, maize and canola (oil seed rape). To date, commercialized varieties mainly express two traits – herbicide tolerance and resistance to specific insect pests. Some other traits have been developed to deliver nutritional benefits (e.g. golden rice with high levels of vitamin A), but have not yet been cultivated commercially.

This ‘gene revolution’ has catalysed a substantial break between private and public sector involvement in varietal improvement (Pingali and Raney, 2005). Overall, private investment in agricultural research has significantly overtaken public investment. In 2005, Pingali and Raney reported that ten multinational bioscience corporations had an annual expenditure on agricultural research and development of US$3 billion. The CGIAR, in contrast, spent under U$300 million a year on plant improvement. Public investment in agricultural biotechnology in the developing world has been led by China, followed by Brazil and India (Pray and Naseem, 2003). Bangladesh is soon to follow. Many other developing countries have increasing capacity to adopt and adapt innovations developed elsewhere (Pingali and Raney, 2005).

Adoption has been relatively scale-neutral, with both large and small farmers using GM crops. Some 90 % (15 million) of farmers cultivating GM crops were small and resource-poor farmers in developing countries (ISAAA, 2012). In a 2006 review, Raney concludes that ‘the economic evidence available to date does not support the widely held perception that transgenic crops benefit only large farms; on the contrary the technology may be pro-poor. Nor does the available evidence support the fear that multinational biotechnology firms are capturing all the economic value created by transgenic crops’ (Raney, 2006, p. 1).

Alongside these developments, there have also been calls for increased attention to ‘orphan crops’ in developing countries (Varshney *et al.*, 2012*a*). These are varieties which are ‘valued culturally, often adapted to harsh environments, nutritious, and diverse in terms of their genetic, agroclimatic, and economic niches’ (Naylor *et al.*, 2004). They are important for nutritional security in the world’s most disadvantaged regions. Many orphan varieties and legumes are also coming to attention as a result of international research collaborations and advances in sequencing and genotyping technologies (Varshney *et al.*, 2012*b*; Bohra *et al.*, 2014).

Sweet potato is particularly important in Uganda, where it underpins farm-level food security as an important source of starch in addition to calcium and riboflavin. Ugandan yields for sweet potato are around 4 t ha^{-1} (compared with an average global yield of 14 t ha^{-1}) (Naylor *et al.*, 2004). Conventional breeding for sweet potato is relatively slow because it is a vegetatively propagated perennial; biotechnology-based approaches on the other hand could confer pest resistance to weevils and viruses and improved starch/dry matter ratios, and it has been estimated that effective resistance could raise yields to 7 t ha^{-1} (Naylor *et al.*, 2004). Transfer of the technology across half the sweet potato area in sub-Saharan Africa would result in a gross annual benefit of US$121 million (Naylor *et al.*, 2004). In Kenya, it has been estimated that effective resistance to viruses and weevils could result in income increases of 28–39 % (Qaim, 1999). Other approaches to sweet potato improvements have centred on conventional breeding to improve vitamin A content and to shorten time to harvest (Mwanga and Ssemakula, 2011). Emerging evidence demonstrates the value of participatory varietal development. Promising models of participatory varietal development have been demonstrated in Ethiopia for tef (Assefa *et al.*, 2011) and white pea bean (Assefa *et al.*, 2013), in Ghana for cassava (Manu-Aduening *et al.*, 2014) and in Uganda for sweet potato (2011).

Varietal improvements will increasingly need to focus on improved nutritional content, better resource-use efficiency and the reduction of GHG emissions (Tilman *et al.*, 2002). As annuals cover nearly 70 % of global cropland (Pimentel *et al.*, 1997), there is scope for increasing the share of perennials in the global crop mix. These offer several advantages for the preservation of ecosystem services and cost savings to farmers (Pimentel *et al.*, 1997; Dewar, 2007; Glover and Reganold, 2010; Kell, 2011; Crews and Brookes, 2014). Beneficial traits may include the ability to be grown on resource-poor and ‘marginal’ lands and the ability to sustain more production per unit of land than most annual crops grown on fertile lands. Varietal development is also needed in order to produce perennial alternatives that express desired traits – larger seed size, stronger stems, improved palatability and higher seed yield (Glover and Reganold, 2010). Breeding plants with deeper and bushy root systems may also offer improved soil structure, water and carbon sequestration, nutrient retention and higher yields (Kell, 2011). Estimates suggest that between 5 and 10 kg m^{-2} (50–100 t ha^{-1}) could be sequestered through increased root mass, resulting in globally significant sequestration of atmospheric carbon (Kell, 2011).

Integrated pest management

Pathogens, weeds and invertebrates result in up to 30 % losses in particular locations for particular crops (Oerke and Dehne, 2004; Flood, 2010). Viewed in terms of food security, crops lost to pests represent the equivalent of food required to feed >

1 billion people (Birch *et al.*, 2011). Over the coming decades, pest damage may worsen due to the response of pest species to global climate change (Birch *et al.*, 2011) and the distribution of pests and pathogens will change (Bebber *et al.*, 2013). Resistance to synthetic pesticides poses a continuing challenge. Since the discovery of triazine resistance in common groundsel in the late 1960s, herbicide resistance in weeds has grown rapidly. Globally, some 220 weed species have evolved herbicide resistance, posing a particular challenge to cereals and rice (Heap, 2014). Five species (*Avena* spp., *Lolium* spp., *Phalaris* spp., *Setaria* spp. and *Alopecurus myosuroides*) infest >25 Mha of cereal crops globally (Heap, 2014). For insect pests, >600 cases of insecticide resistance have become apparent since the 1950s (Pretty, 2005; Head and Savinelli, 2008).

Overall, the impact of synthetic pesticides has been mixed. While these prevent a significant amount of potential losses, especially in the short term, they pose threats to human and ecosystem health, and effectiveness declines as pest and weed resistance develops (Pretty, 2005). Thus, over-reliance on agrichemicals as a sole form of plant protection is not sustainable (Shaner, 2014). Moreover, with the development of poorly regulated generics, especially in developing countries, cheap alternatives which do not meet international quality standards 'lock-in' the use of obsolete pesticides (Popp *et al.*, 2012) and result in associated risks for ecosystems and human health (de Bon *et al.*, 2014).

Thus, complementary and alternative modes of pest control, relying on the manipulation of pest ecologies, have been gaining increasing attention as part of a suite of diversified strategies to control pest populations and increase crop resilience to infestation. The preservation and strategic use of on- and off-farm biodiversity is an overarching principle in new forms of pest management. A key principle is that biodiverse agroecosystems demonstrate less pest damage and more natural pest enemies than non-biodiverse systems (Letourneau *et al.*, 2011).

Integrated pest management consists of a toolbox of management decisions and interventions designed to combine the use of targeted compounds, and agronomic and biological techniques to control crop pests. SI with IPM has shown how pesticide use can be reduced and pest management practices modified without yield penalties. Contemporary IPM systems have had several traditional and modern precursors, as farmers and agricultural scientists have long struggled to contain pest populations where inorganic compounds were unavailable (Birch *et al.*, 2011). Contemporary systems began to be developed from the 1950s onwards and gained increasingly widespread recognition through the 1970s (Conway and Pretty, 1991).

Various IPM programmes were spurred onwards as a result of a number of pest outbreaks and, concomitantly, growing awareness of the potential health concerns associated with the use of conventional inorganic pesticides. IPM is now a globally dominant paradigm for crop protection, though there remains much scope for its development and spread, in both developing and developed countries. Over time, IPM strategies have transitioned from individual field-based practice to co-ordinated, community-scale decision-making covering wider landscapes (Brewer and Goodell, 2012). While this improves the effectiveness of pest control, it presents a significant obstacle to wider adoption (notably in developing country contexts) by presenting a collective action dilemma (Pretty, 2003). Farmer field schools play a central role in training farmers in IPM, and have been shown to result in improved outcomes (Van den Berg and Jiggins, 2007; Pretty *et al.*, 2011; Settle *et al.*, 2014).

In principle, there are four possible trajectories of IPM impact: (1) both pesticide use and yields increase (A); (2) pesticide use increases but yields decline (B); (3) both pesticide use and yields fall (C); or (4) pesticide use declines, but yields increase (D).

A widely held assumption 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.

Figure 6 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, The Netherlands, Pakistan, Philippines, Senegal, Sri Lanka, Switzerland, Tanzania, Thailand, the UK, the USA, Vietnam and Zimbabwe) (Pretty and Waibel, 2005). These 62 IPM initiatives at the time were being used by some 5·4 million farming 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 the effect of some GM crops, some of which result in reductions in the use of herbicides and pesticides, and some of which have led to increases.

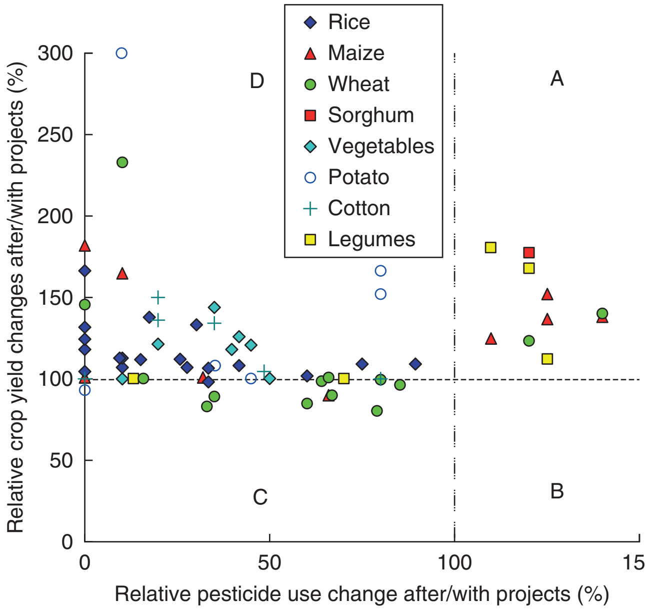

FIG. 6. Association between pesticide use and crop yields (from 62 IPM projects) (Pretty *et al.*, 2006). For discussion of sectors A–D on the graph, see the text.

There was only one sector B case reported in the recent literature (Feder *et al.*, 2004). 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 (Pretty, 1998; Röling and Wagemakers, 1998). Sector A contains ten projects where total pesticide use increased in the course of IPM introduction. These are mainly in zero-tillage and CA systems, where reduced tillage creates substantial benefits for soil health and reduced off-site pollution and flooding costs, but which require increased use of herbicides for weed control, though there are some examples of organic zero-tillage systems. Over 60 % of the projects were in category D where pesticide use declines and yields increase. While pesticide reduction is to be expected, as farmers substitute pesticides with information, yield increases induced by IPM is more complex. It is likely, for example, that farmers who receive good quality field training not only will improve their pest management skills but also will 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.

One of the most effective and rapidly adopted IPM systems is the 'push–pull' system, which is yielding notable successes from redesign of monocropped cereal systems (Cook *et al.*, 2007; Royal Society, 2009; ICIPE, 2013). Khan *et al.* (2014) estimate that across Kenya, Uganda, Tanzania and Ethiopia, push–pull systems are used across 69 000 small farms. These have been deployed with great effect against *Striga* weed and stem-borer infestations in maize, millet and sorghum (Khan *et al.*, 2014). Interplanting of the leguminous forage crop *Desmodium* suppresses *Striga* and repels stem-borer moths while attracting their natural enemies; planting *Napier* grass as a border crop attracts stem-borer moths. Positive externalities include nitrogen fixation by *Desmodium* and the provision by new plants of high quality animal fodder. This has enabled farmers to diversify into dairy and poultry production, which in turn has increased the availability of animal manure for application on fields. The adoption of push–pull systems has resulted in median yield increases of approx. 23 % and a 75 % decrease in pesticide use across West Africa (FAO, no date).

Management-intensive rotational grazing systems

Extensive low-intensity grazing systems are well adapted to many landscapes, such as the dry steppes of Asia, savannahs of Africa, tundra and boreal habitats of the sub-Arctic, rangelands of North America, and wet uplands of Britain. Cattle, sheep, goats and reindeer are important shapers of whole landscapes as well as a source of food. In these contexts, intensification is not desirable, mainly because the landscapes are generally at or close to carrying capacity. However, there has been a recent rapid expansion in intensive grazing management systems, particularly in the lowlands and on smaller farms (NRC, 2010). These MIRG systems use short-duration grazing episodes on small paddocks or temporarily fenced areas, with longer rest periods that allow grassland plants to regrow before grazing returns.

These systems substitute knowledge and active management for external inputs to maintain grassland productivity. As many have replaced zero-grazed confined livestock systems, the animals themselves are bred for different characteristics: large mouths, shorter legs, stronger feet and hooves, and larger rumens. MIRGs were first developed in New Zealand, and now have become common in part of the USA: on 20 % of dairy farms in Wisconsin, Pennsylvania, New York and Vermont (NRC, 2010). Some whole communities, such as the Amish of Holmes County, Ohio, have converted all dairy systems to rotational grazing (Pretty, 2014), where their response to family labour availability and reduced costs of MIRG systems has been to reduce animal milk productivity to save time at milking.

There is good evidence that MIRG systems result in improved soil quality, increased carbon sequestration, reduced soil erosion, improved wildlife habitat and decreased input use (Hensler *et al.*, 2007). Livestock in housing create waste disposal challenges and costs; livestock continually grazed manure the land. However, animals on the same grassland for too long cause overgrazing, sparse pastures with low persistence, and soils low in carbon. In typical MIRG systems, animals are moved twice a day. This requires high levels of monitoring and active management by farmers. Such short and intensive periods of grazing mean the animals consume all plants, rather than leave those they otherwise find unpalatable. Well-managed grazing systems have been associated with greater temporal and spatial diversity of species. There is also evidence that MIRG systems result in improved animal welfare (Fuhlendorf and Smeins, 1999). MIRG systems outperform traditional confinement (50–75 cows) and large modern confinement systems (250 cows) on economic measures (Table 7).

TABLE 7. *Economic indicators of performance of three systems of dairy production in Wisconsin (mean over 8 years) (NRC, 2010)*

	Management-intensive rotational grazing	Traditional confinement system	Large recently developed confinement system
Kg milk per cow per year	34 570	43 070	49 510
Costs (US$) per 1000 kg of milk	165	170	180
Net farm income (US$) per 1000 kg milk	69	47	51

Conservation agriculture

A variety of measures to mitigate soil erosion, improve water-holding capacity and increase soil organic matter help to improve soil health and boost crop yields. A key feature is the revision or reduction of soil disturbance through tilling. Zero tillage involves no ploughing prior to sowing. Conservation agriculture consists of a group of management strategies to minimize soil disturbance, maintain soil cover and rotate crops. This seeks to maintain an optimum environment in the root zone in terms of water availability, soil structure and biotic activity (Kassam *et al.*, 2009).

Conservation agriculture evolved in part as a response to the severe soil erosion that devastated the US Midwest in the 1930s. Currently, CA systems are practised successfully across a range of agroecological conditions, soil types and farm sizes (Derpsch *et al*., 2010). At present, CA practices cover just over 8 % of global arable cropland, but are estimated to be spreading globally by some 6 million ha year^{-1} to a total of 155 Mha in 2014 (Kassam *et al*., 2009, 2014). Adoption varies greatly by region. CA covers some 69 % of arable cropland in Australia and New Zealand, 57 % of arable cropland across South America and 15 % in North America (Jat *et al*., 2014). In contrast, adoption across Europe and Africa is low (covering only 1 % of arable cropland in each of the two continents) (Jat *et al*., 2014).

Increased productive potential has resulted in yield differences ranging from 20 to 120 % for CA compared with conventional tillage systems (Kassam *et al*., 2009). Beneficial impacts in terms of resource efficiency include reduced need for fertilizer application over time, lower runoff and increased resilience to pest and disease. All these result in significant savings, which, combined with yield increases, may translate to significant financial benefits for farmers relative to conventional ploughing practice (Sorrenson *et al*., 1997). A recent European Conference on Green Carbon highlighted the importance of soil carbon content as a marker and enabler of sustainability in agroecosystems, and concluded that CA presents a good strategy to maintain and improve soil carbon levels. Comparisons between conventional tillage and reduced or no-till systems have found higher soil organic carbon, lower emissions and improved soil quality under the former (Brenna *et al*., 2013 in Italy; Franzluebbers, 2005, 2010 for the south-eastern USA; Spargo *et al*., 2008 in Virginia), especially on certain types of soils and with the addition of cover cropping.

While CA offers much potential for sustainable intensification, scientific debate highlights a number of difficulties and contentions. Each component in the CA ‘package’ requires interpretation (Stevenson *et al*., 2014), and the applicability and scalability of CA to smallholder systems has been questioned, especially for developing country contexts (Giller *et al*., 2009, 2011; Stevenson *et al*., 2014). While the applicability of CA to sub-Saharan contexts has been called into question, some case studies nevertheless show remarkable social–ecological outcomes. Comparisons between CA and conventional plots demonstrate yield increases in the former, as well as reduced soil loss, increased soil carbon content, and improved soil structure and water productivity (Marongwe *et al*., 2011). Collectively, recent evidence from the African Union (Pretty *et al*., 2011) shows that the adoption of CA principles has led to improvements on 26 000 ha, with a mean yield increase ratio of 2·20 and annual net multiplicative yield increases in food production of some 11 000 t year^{-1}. In addition, a number of positive externalities, with cost-saving or income-boosting effects, were also reported, including reduced soil erosion, increased resilience to climate-related shocks, increased soil carbon, improved water productivity, reduced debt, livelihood diversification and improved household-level food security (Marongwe *et al*., 2011; Owenya *et al*., 2011; Silici *et al*., 2011).

Nevertheless, there have been calls for improvements to the evidence-base on CA (Brouder and Gomez-MacPherson, 2014). Meta-analyses and reviews across cases also show that the evidence on yield impacts and carbon sequestration potential is mixed (Stevenson *et al*., 2014). This may, in part, reflect the context sensitivity of CA, where outcomes depend on the precise combination of practices used, and differ by crop type. There is some evidence that zero-tillage may result in yield penalties in the short term (Brouder and Gomez-MacPherson, 2014). This may hinder adoption amongst smallholders, who may ‘attribute more value to immediate costs and benefits than those incurred in the future’, as they must navigate precarious and pressing concerns over food and livelihood security (Giller *et al*., 2011, p. 3). Other studies find yield increases to be stable over time. For example, Derpsch (2008) compared conventional and CA systems over a decadal scale, and found yield decreases over the period in the former, and yield increases over the period under CA, in addition to lower use of inputs. There is also a need for more evidence on the precise implications of improved land management across agricultural sectors and agroecosystems (e.g. Morgan *et al*., 2010), using appropriate soil sampling strategies (Baker *et al*., 2007) and standardized methodologies (Derpsch, 2014).

Agroforestry systems

Agroforestry is a form of intercropping where perennial trees or shrubs are intercropped with annual herbaceous crops. In a first attempt at estimating the global extent of agroforestry initiatives, Zomer *et al*. (2009) find that just under half of all agricultural land now has > 10 % tree cover, 27 % of agricultural land has >20 % tree cover and just over 7 % of global agricultural land has >50 % tree cover. While not all tree cover necessarily represents agroforestry, and while agroforestry does not necessarily imply high tree densities, these results nonetheless denote that there is not necessarily a trade-off between cultivation and tree cover, as has often been assumed. Instead, it is apparent that ‘trees are an integral part of the agricultural landscape in *all* regions except North Africa/West Asia’ (Zomer *et al*., 2009, p. 15).

A wide variety of agroforestry systems are practised worldwide (Jamnadas *et al*., 2013). Lorenz and Lal (2014) estimate that worldwide tree intercropping covers some 700 Mha, multistrata systems 100 Mha, protective systems 300 Mha, silvopasture 450 M ha and tree woodlots 50 Mha. Over 100 distinct agroforestry systems have been recorded (Atangana *et al*., 2014), and modern agroforestry systems have a number of precursors, such as traditional systems across India (Murthy *et al*., 2013), the Sahel (Garrity *et al*., 2010) or the Javanese systems of *pekarangan* (combining agricultural and tree crops with livestock) and *kebums-talun* (rotational cultivation of agricultural and tree crops) (Christanty *et al*., 1986). In temperate Europe, fruit trees have traditionally been cultivated on cropland or managed grassland, a system that, while in relative decline, still occupies 1 Mha across 11 countries (Herzog, 1998).

The inclusion of trees within cultivated landscapes delivers a range of social–ecological benefits. It has been estimated that each additional tree planted in an agroforestry system results in an average value of US$1·40 year^{-1} through improved soil fertility, fodder, fruit, firewood and other produce. This would result in additional production value of at least US$56 ha year^{-1}, and a total production value of US$280 million (Larwanou and Adam, 2008). In India, Murthy *et al*. (2013) review carbon sequestration within agrisilvicultural and silvipastoral systems and estimate that these could hold a soil carbon stock of 390

Mt C (excluding soil organic carbon stocks). Ickowitz *et al.* (2013) found that in 21 African countries, dietary diversity amongst children increases with tree cover after controlling for relevant confounding variables. Under 'evergreen agriculture' systems, trees are planted within fields of annual crops, and replenish soil fertility, and provide food, fodder, timber and fuelwood. Overall, this portfolio of benefits provides 'an overall value greater than that of the annual crop within the area that they occupy per m^3' (Garrity *et al.*, 2010, p. 199).

Legume tree-based farming systems offer an important route to increase the availability of N_2 while avoiding synthetic fertilization. This has led to the use of the term 'fertilizer tree' (Garrity *et al.*, 2010). Nitrogen fixation depends on tree species and soil status, and can range from 5 to >300 kg N ha^{-1} year $^{-1}$ (Rosenstock *et al.*, 2014). The use of *Gliricidia sepium* in improved fallows resulted in a 55 % increase in sorghum yield over two cropping seasons (Hall *et al.*, 2006). Sileshi *et al.* (2012) compared yields across three systems: maize–*Gliricidia* (the agroforestry cohort), conventional monoculture (with fertilization) and regular practice (absence of any external input). Yields in the agroforestry system were comparable with those achieved via synthetic fertilization, but 42 % higher than non-fertilized fields. They were also more stable over time than yields achieved through synthetic fertilization.

Another promising fertilizer tree, *Faidherbia albida*, presents one of the few examples of intercropping being practised at scale (Montpellier Panel, 2013), resulting in what has been called the Green Wall of the Sahel (Reij and Smalling, 2008). *Faidherbia* is a nitrogen-fixing acacia indigenous to Africa. The tree is particularly suited to intercropping with maize, as it sheds its leaves during the monsoon season when maize is sown. This prevents it from competing with maize seedlings for light and nutrients, while falling leaves provide nutrients. Intercropping with *Faidherbia* can result in cereal yields of 3 t ha^{-1} without the application of additional fertilizer, while contributing to significant carbon sequestration, weed suppression, increased water filtration and increased adaptability to serious droughts (Garrity *et al.*, 2010). In Zambia, the planting of *F. albida* within maize fields is practised over some 300 000 ha (Garrity *et al.*, 2010). In Malawi, *F. albida*, *G. sepium*, *Sesbania sesban* and *Tephrosia* spp. are intercropped with maize. Niger has experienced the most remarkable 'regreening' as a result of farmer-managed regeneration of trees in fields. As a result of the relaxation of restrictive policies prohibiting farmers from managing the trees on their own lands, agricultural landscapes in Niger now harbour significant densities of *Faidherbia* (Garrity *et al.*, 2010). It has been estimated that 'regreening' has resulted in a per year increase of 500 000 additional tonnes of food (Reij *et al.*, 2009). Maize, sorghum, millet, groundnuts and cotton have all shown increased yields – even without additional fertilizer application – as a result of *Faidherbia* (Garrity *et al.*, 2010). In Burkina Faso, *Crombretum glutinosum* and *Piliostigma reticulatum* are included to generate additional biomass and yield fodder and increased yields (Garrity *et al.*, 2010).

Legume-based agroforestry systems could result in increased N_2O emissions (e.g. Hall *et al.*, 2006), depending on species, soil type, climatic conditions and management practices. Based on a review of evidence from agroforestry systems in tropical regions and improved fallows in sub-Saharan Africa, Rosenstock *et al.* (2014) conclude: 'legume-based agroforestry is unlikely to contribute an additional threat to increasing atmospheric N_2O concentrations, by comparison to the alternative (e.g. mineral fertilizers).' Legume-based tree systems also sequester and accumulate carbon, and may also affect methane exchanges. Overall, there is a need for further research on the precise impacts of changes to C and N cycling, and an exploration of other environmental trade-offs such as increased leaching of N into local water supplies. Given these potential negative externalities, further, context-appropriate research is needed to identify 'win–win–win' systems which deliver for yields, climate and water quality. This will require a 'fundamental departure' from conventional research on the subject, which has focused on single outcomes (e.g. yield) or single media (e.g. outcomes for water, or air, or C or N in isolation) (Rosenstock *et al.*, 2014).

Patch intensification

The use of small plots of land to cultivate crops or rear fish, poultry or small livestock, near places of human settlement, represents the oldest form of agriculture (Niñez, 1984), and these are amongst the most diverse and productive (per unit area) cultivation systems in the world (Conway, 1997). They provide several significant nutritional, financial and ecosystem benefits including pollination; gene flow between plants inside and outside the garden; control of soil erosion and improvements to soil fertility; improved urban air quality; carbon sequestration; and temperature control through the creation of microclimates. Patches contribute directly to household food and nutritional security, by increasing the availability, accessibility and utilization of nutrient-dense foods (Galhena *et al.*, 2013), including wild edible species and traditional varieties no longer cultivated on a commercial scale (Galluzzi *et al.*, 2010). Intensification on patches often comprises an additive change to productivity of agricultural and farm systems.

Tropical home gardens are typically multilayered environments with multiple trophic levels and management zones, and can include fruit trees, shaded coffee, residential, ornamentals with shade trees, multipurpose trees, herbaceous crops, ornamentals with vine-crop shade, grass, space for working and storage, and ornamentals. Such agroforestry home gardens can host >300 plant species (Méndez *et al.*, 2001). In Peru, four kinds of small food production systems have been documented: fenced gardens near homes; plots planted as gardens near fields; field margins cropped with vegetables; and intercropping of the outer rows of staple fields with climbing vegetables (Niñez, 1984). In Java, village agroforestry gardens (*pekarangan*) provide a safeguard against crop failure, and Tanzanian *chagga* gardens produce 125 kg of beans, 275 bunches of banana and 280 kg of parchment coffee annually on plots of just over half a hectare, insuring against crop failure and supporting poultry and small livestock (Niñez, 1984).

Patch cultivation at varying scales is also important for urban food security. An estimated 800 million people practise some form of urban food production around the world, most on relatively small patches of land cultivated for subsistence in the developing world (Lee-Smith, 2010).

While there is comparatively little research on home gardens and other forms of urban agriculture in the global North (Taylor and Lovell, 2014), there is a growing recognition of their complexity, productivity and potential at all scales. The

American Community Gardening Association (2014) estimates that there are >18 000 community gardens across the USA and Canada. In the UK, there are an estimated 330 000 allotment plots (Crouch and Ward, 1997; National Allotment Society, 2014) and interest in gardening for food is growing: some 90 000 people are on the waiting list for an allotment plot (Campbell and Campbell, 2011). Private gardens may also make a significant contribution to household food supply. In the late 1950s, it was estimated that 14 % of private garden area in London may have been allocated to fruit and vegetable cultivation (Wibberley, 1959). Though the current figure may be lower, in 2000 it was estimated that assuming productivity of 10·7 t ha^{-1} and consumption of 0·5 kg of fruit and vegetables per capita per day, London could produce enough to supply its residents with 18 % of intake (Garnett, 2000). In Chicago, the aggregate production of home gardens may even exceed that of community gardens and other forms of urban agriculture (Taylor and Lovell, 2012). In Florida, it was estimated that small gardens yielded 69 % of vegetables consumed by farm families (Gladwin and Butler, 1982). In Peru and Brazil, urban home gardens increased the availability of staple and non-staple foods to slum dwellers (Niñez, 1985; WinklerPrins, 2003; WinklerPrins and de Souza, 2005). Small patches are also important for household resilience during lean seasons, in conditions of political instability and turmoil, for marginalized households, in degraded or highly populated areas with few endowments of land and materials, and in disaster, conflict and post-crisis situations. Examples include the use of gardens for food during the Tajik civil war (Rowe, 2009); the conflicts in Sri Lanka (Niñez, 1984); the use of 'relief' and 'victory' gardens in the USA and UK during the world wars; and the use of gardens to tide over political and economic crises in Cuba (Pretty, 2002). Food growing on neglected patches of city land, along highways 'often represent the only green spots in abandoned and neglected city parks' (Niñez, 1984, p. 28).

In recognition of these benefits, home gardening and the cultivation of small patches around fields has been promoted in development initiatives to improve food security and incomes. Across Africa, an important strategy has been the construction of raised beds to improve the retention of water and organic material (Pretty *et al*., 2011). In Kenya and Tanzania, the FarmAfrica project has encouraged the cultivation of African indigenous vegetables by 500 participating farmers who have used 50 % less fertilizer and 30 % less pesticide than for conventionally grown vegetables (Muhanji *et al*., 2011). In Bangladesh, the Homestead Food Production has involved 942 040 households (some 5 million beneficiaries) between 1988 and 2010 (Iannotti *et al*., 2009). Through home gardening and small animal husbandry, the project has achieved notable success in increasing the production of fruit, vegetables and eggs relative to controls, and increased income from the sale of produce.

Research on home gardens has focused more on tropical home gardens in the developing world rather than on temperate gardens in developing countries [Galhena *et al*., (2013); but see Vogl and Vogl-Lukasser (2003) and Calvet-Mir *et al*. (2012) for studies from Austria and Spain]. Agricultural extension and research have also largely ignored patches that fall outside regular field boundaries (Pretty *et al*., 2011), despite calls for more attention to be given to home gardens, kitchen gardens and other small-scale, subsistence-oriented enterprises in agricultural research, development and extension (Niñez, 1984). Research on urban agriculture and home gardening in industrialized countries is still lacking, and studies remain largely descriptive (Taylor and Lovell, 2014).

Three decades ago, Niñez (1984) concluded that they represented 'one of the last frontiers for increasing food production in the struggle against world hunger and malnutrition' (p. 35).

System of rice intensification

The system of rice intensification (SRI) emerged from on-farm experimentation in Madagascar whereby existing norms of paddy rice were radically amended: reduced planting density, improvement of soil with organic matter, reduced application of water and very early transplantation of young plants. The adoption of these four general principles has been shown to lead to considerable increases in yields with reduced inputs of water and other external inputs (Uphoff, 1999, 2003; Stoop *et al*., 2002). Since its inception in the 1980s, SRI principles have been adapted and applied to a variety of other crops, including wheat, sugarcane, tef, finger millet, various pulses and turmeric (Stoop, 2011; SRI-Rice, 2014*a*, *b*), all again emphasizing changes in resource use and application combined with crop planting design. Adaptation, to suit local contexts and farmers' preferences, is encouraged. Therefore, participatory models of development and dissemination have been important for the spread of SRI approaches, resulting in adaptations that enable farmers to increase yields, lower resource use and buffer against risk in ways that suit them (Krupnik *et al*., 2012).

The SRI remains, however, a subject of controversy, largely because yield increases remain only partially explained. Important questions remain related to the basic agronomy of SRI and to claims of large yields (Dobermann, 2004; Sheehy *et al*., 2004, 2005; Stoop, 2011). In India, experimental comparisons between SRI and conventional recommended practice showed 42 % higher yields under SRI as a result of changes in plants' physiological processes and characteristics including longer panicles, more grains per panicle, a higher proportion of grain filling, deeper and better distributed root systems, and more and larger leaves (Thakur *et al*., 2010). Another Indian study compared SRI and conventional cultivation across 13 rice-growing states and showed between 12 and 54 % higher yields in the former, combined with improved water-use efficiency (Palanisami *et al*., 2013).

As with other agroecologically based management approaches, SRI practices are fluid and flexible. In Mali, Styger *et al*. (2011) report increased yields without the addition of expensive inputs in the Timbuktu region, where traditional rice cultivation has depended on the annual flooding of the Niger River. Africare has worked with farmers to adapt SRI principles to local conditions and evaluate the potential of SRI to increase rice yields and thus food security in the region: SRI plots yielded 66 % more than control plots and 87 % more than surrounding rice fields. SRI plots used substantially fewer seeds per hectare (85–90 % less than conventional plots), 30 % less inorganic fertilizer and 10 % less irrigation water. However, a meta-analysis by Turmel *et al*. (2011) of data from 72 studies comparing SRI and conventional practice found that SRI outperformed conventional practice on weathered and infertile soils, but demonstrates no yield advantage on more favourable soils.

There has also been debate as to whether, on balance, yields under SRI compare favourably with best-recommended practice (McDonald *et al.*, 2006, 2008; Uphoff *et al.*, 2008).

Other systems of rice cultivation that save water and labour include direct seeding, whereby rice is sown and sprouted directly into the field rather than raising and transplanting seedlings. Direct seeding has long been practised traditionally, and is having a resurgence in response to water scarcity and labour shortages in Asia (Rao *et al.*, 2007). In Sri Lanka, some 95 % of all rice grown is direct seeded under either wet or dry seeding (Weerakoon *et al.*, 2011). Weed infestations and relatively low or variable yields (compared with those under traditional transplantation) pose problems in direct seeded systems. Reviews suggest the need for the development and dissemination of improved cultivars (including herbicide-resistant and early-maturing varieties), improved nutrient management and the provision of high quality herbicides (Farooq *et al.*, 2011).

POLICIES AND INCENTIVES TO ADOPT SUSTAINABLE INTENSIFICATION

Enabling policy environments are crucial for the adoption of agricultural systems that deliver public goods (natural capital) alongside private goods (increased food and fibre) over time. Policy intervention in agricultural systems has clearly worked to increase output, such as during the Asian Green Revolutions, but intensification may involve trade-offs between provisioning ecosystem services (food production) and regulating and supporting services (Firbank *et al.*, 2011). The key question is: can it also address challenges such as improving natural capital, nutritional security and social–ecological resilience. Global-scale policy leaders are increasingly focused on these wider goals. Recently, the FAO made the case that agricultural policies need to emphasize nutrition, and can improve nutritional outcomes by emphasizing R&D that is inclusive of smallholders, focusing on important non-staple, but nutritionally dense foods, and integrated production systems (FAO, 2013*a*). Similarly, there is an effort to spread awareness of climate-smart agriculture (FAO, 2013*b*) and 'save and grow' models (FAO, 2011*b*) that build natural capital while improving yields and nurturing resilience.

At regional and national scales, notable recent successes include the combined spread of nitrogen fertilizer use and agroforestry systems in Malawi, land reform in China in the 1980s, modest Common Agricultural Policy reforms in the European Union to emphasize payments for environmental services, and tree use regulations in the Sahel. Yet, challenges remain. Sustainable intensification represents a suite of approaches, methods and technologies that can deliver more food per area of land and improve natural capital. However, most national and international policy environments are still configured to favour food production; some still actively result in damage to natural capital.

One set of policy options centres on the principle of payments for ecosystem services, whereby farmers are paid for their contributions to defined services with monetary value. Few examples have yet to work, even where there is research to show how payment for ecosystem service could work, such as Kenya's Amboseli Park with regard to compensating farmers for not cropping lands that cross elephant migration routes (Bulte *et al.*, 2008). Other options include market chain development, though usually this means having a sub-set of consumers willing to pay price premiums for certain products.

In general, policy-makers and regulators have found it easier to seek to prevent practices or problems, such as the regulation of certain pesticide compounds and the establishment of safe drinking water limits for certain compounds. Some have called for a revision of the regulatory frameworks governing new crop varieties, with a view to realizing potential benefits for more food crops. Fedoroff (2010) call for an 'authoritative assessment' of GM safety, including protein safety, gene stability, toxicity, nutritional value, allergenicity, gene flow and impacts on other organisms. This, they conjecture, would reduce the complexity of the regulatory process.

It has been harder to encourage positive practices. This is where the concept and practices of SI offer opportunities to engage with the wider challenges of agricultural production in a sustainability context. Norse (2012) highlights the need for creating an evidence-base to support decision-making on low-carbon agriculture, and also mentions the need to create awareness of existing approaches which can entail 'a win–win–win change that can be justified in terms of short-term economic, social and environmental benefits' in addition to longer term social-ecological benefits (pp. 31–32).

The NRC (2010, p. 521) stated that 'sustainability is best evaluated not as a particular end state, but rather a process that moves farming systems along a trajectory towards greater sustainability.' This suggests that no single policy instrument, research output or institutional configuration will work to maximize sustainability and productivity over spatially variable conditions and over time. The NRC (2010) made a series of recommendations regarding public research for public goods, and integration of agencies to address multidisciplinary challenges in agriculture. It was recommended that the national (in this case, USDA) and state agricultural institutions should continue publicly funded research and development of key farming practices for improving sustainability and productivity, and that federal and state agricultural research and development programmes should deliberately pursue integrated research and extension on farming systems, with a focus on whole agroecosystems. It was further suggested that all agricultural and environmental agencies, universities and farmer-led organizations should develop a long-term research and extension initiative to understand and shape the aggregate effect of farming at landscape scale. Researchers were encouraged to adopt farmer-participatory research and farmer-managed trials as critical components of their research. At the national level, there should finally be investment in studies to understand how market structures, policies and knowledge institutions provide opportunities or barriers to expanding sustainable practices in farming. This is particularly important in enabling farmers to navigate the complex and evolving trade-offs between resource conservation and increasing farmers' incomes through participation in markets. Policies designed to conserve resources and stabilize resource availability and farmers' incomes may not work well over time given market imperatives to maximize resource use and incomes (see, for example, Bharucha *et al.*, 2014).

In the context of developing countries, the 30 African cases of SI (Pretty *et al.*, 2011, 2014) have illustrated key lessons regarding policy challenges. These projects contained many different technologies and practices, yet had similar approaches to working with farmers, involving agricultural research, building social infrastructure, working in novel partnerships and developing new private sectors options. Only in some of the cases were national policies directly influential. These projects indicated that there were seven key requirements for such scaling up of sustainable intensification to larger numbers of farmers.

(1) Scientific and farmer input into technologies and practices that combine crops and animals with appropriate agroecological and agronomic management.
(2) Creation of novel social infrastructure that both results in flows of information and builds trust amongst individuals and agencies.
(3) Improvement of farmer knowledge and capacity through the use of farmer field schools, videos and modern information communication technologies.
(4) Engagement with the private sector to supply goods and services (e.g. veterinary services, manufacturers of implements, seed multipliers, milk and tea collectors) and development of farmers' capacity to add value through their own business development.
(5) A focus particularly on women's educational, microfinance and agricultural technology needs, and building of their unique forms of social capital.
(6) Ensuring that microfinance and rural banking is available to farmers' groups.
(7) Ensuring public sector support to lever up the necessary public goods in the form of innovative and capable research systems, dense social infrastructure, appropriate economic incentives (subsidies, price signals), legal status for land ownership, and improved access to markets through transport infrastructure.

However, no single project or programme will be able to address all seven of these at once, and thus the generic need is for an integrated approach that seeks positive synergies over time. Despite great progress, and now the emergence of the term 'sustainable intensification' and its component parts, there is still much to be done to ensure thst agricultural systems worldwide increase productivity fast enough whilst ensuring impacts on natural and social capital are only positive.

CONCLUDING COMMENTS ON SUSTAINABLE INTENSIFICATION FOR GREENER ECONOMIES

It is difficult to say how much of the world's agricultural lands are already under forms of more sustainable agricultural production. There has been significant progress on both reducing negative impacts on natural capital and environmental services, and creating systems with the potential to improve all forms of renewable capital assets (natural, social and human). It is clear, though, that considerably more food will need to be produced as populations continue to grow and food consumption patterns converge on the diets typical of affluent countries and societies, regardless of how much progress is made on reducing waste in food systems (Foresight, 2011; Pretty, 2013).

The sustainable intensification of agricultural systems should thus be seen as part of a wide range of initiatives and efforts to create greener economies. Green growth and the greener economies have become important targets for national and international organizations, including the OECD (2011), UNEP (2011), World Bank (2012), the Rio+20 conference (UNCSD, 2012) and the Global Green Growth Initiative (2012). UNEP (2011) defines the green economy as 'resulting in human wellbeing and social equity, while significantly reducing environmental risks and ecological scarcities.' Deep political commitment is rare, even though Stern (2007) pointed to the economic value of early action with respect to climate change: the cost of stabilizing all GHGs was a 'significant but manageable' 1 % of global GDP, but a failure to reduce emissions would result in annual costs of 5–20 % of GDP.

Policies in some countries are actively promoting greener agendas, including China, Denmark, Ethiopia, South Africa and South Korea: such a pursuit of greener economies could lead to a new industrial revolution (Stern and Rydge, 2012) and promote further sustainable intensification of agriculture. China has invested US$100 billion since 2000 in eco-compensation schemes, mostly in forestry and watershed management. A total of 65 countries have implemented feed-in-tariffs to encourage renewable energy generation (Renewables, 2012), and, by 2010, renewable energy sources had grown to supply 16·7 % of global energy consumption, the fastest growing sector being solar panels. This alone could have a significant impact on remote rural communities, and thus lead to changes in agricultural and food systems.

The revenue of many poorer countries is absorbed by the costs of oil imports: for example, Kenya, Senegal and India spend 45–50 % of export earnings on energy imports. Investing in renewable energy benefits these three countries by saving export earnings, increasing self-reliance and improving domestic natural capital. Kenya has introduced feed-in-tariffs on energy generated from wind, biomass, hydro, biogas, solar and geothermal sources from 2008 (UNEP, 2011). In this way, a greener economy that dramatically changes aspirations and consumption patterns by increasing consumption of the currently poor and reducing that of the affluent, increases well-being and protects natural capital, is not likely to look much like the current economy. Relevant to all sectors of economies will be important questions about material consumption, and in particular how modes of consumption based on 'enough not more' can be created, so resulting in mass behaviours of 'enoughness' (O'Neill *et al.*, 2010). In this way, the sustainable intensification of agricultural systems could both promote transitions towards greener economies and benefit from progress driven in other sectors.

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