Food security, climate change, and sustainable land management. A review

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REVIEW ARTICLE

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Abstract Agriculture production in developing countries must be increased to meet food demand for a growing population. Earlier literature suggests that sustainable land management could increase food production without degrading soil and water resources. Improved agronomic practices include organic fertilization, minimum soil disturbance, and incorporation of residues, terraces, water harvesting and conservation, and agroforestry. These practices can also deliver co-benefits in the form of reduced greenhouse gas emissions and enhanced carbon storage in soils and biomass. Here, we review 160 studies reporting original field data on the yield effects of sustainable land management practices sequestering soil carbon. The major points are: (1) sustainable land management generally leads to increased yields, although the magnitude and variability of results varies by specific practice and agro-climatic conditions. For instance, yield effects are in some cases negative for improved fallows, terraces, minimum tillage, and live fences. Whereas, positive yield effects are observed consistently for cover crops, organic fertilizer, mulching, and water harvesting. Yields are also generally higher in areas of low and variable rainfall. (2) Isolating the yield effects of individual practices is complicated by the adoption of combinations or "packages" of sustainable land management options. (3) Sustainable land management generally increases soil carbon sequestration. Agroforestry increases aboveground C sequestration and organic fertilization reduces CO_2 emissions. (4) Rainfall distribution is a key determinant of the mitigation effects of adopting specific sustainable land management practices. Mitigation effects of adopting sustainable land management are higher in higher rainfall areas, with the exception of water management.

Keywords Food security · Climate change mitigation · Crop yields · Sustainable land management

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1 Introduction

Agricultural production systems are expected to produce food for a global population that will reach nine billion people in 2050 (UNFPA 2012). Transformations to increase the productive capacity and stability of smallholder agricultural production are thus urgently needed. Identifying the most appropriate technologies and practices to achieve this objective is critical. This requires the building of a knowledge base to support this task.

There is considerable discussion about the inadequacy of the dominant model of agricultural intensification and growth, which relies on increased use of capital inputs, such as fertilizer and pesticides (IAASTD 2009). The generation of unacceptable levels of environmental damage and problems of economic feasibility are cited as key problems with this model (Tilman et al. 2002; IAASTD 2009).

Greater attention is thus being given to alternative models of intensification, and in particular, the potential of sustainable land management technologies. Such practices can generate private benefits for farmers, by improving soil fertility and structure, conserving soil and water, enhancing the activity and diversity of soil fauna, and strengthening the mechanisms of elemental cycling. The literature suggests that these benefits can lead to increased productivity and stability of agricultural production systems (Lal 1997a; World Bank 2006; Woodfine 2009; Pretty 2008, 2011). They thus offer a potentially important means of enhancing agricultural returns and food security, as well as reducing the vulnerability of farming systems to climatic risk.

At the same time, widespread adoption of sustainable land management has the potential to generate significant public environmental goods in the form of climate change mitigation (FAO 2009, 2010). The agriculture sector can contribute to mitigation by reducing greenhouse gas emissions, of which agriculture is an important source, representing 14 % of the global total. Agriculture can also increase the removal of greenhouse gas emissions through sequestration. Soil carbon sequestration was estimated to constitute 89 % of the technical mitigation potential from agriculture (IPCC 2007). Improving productivity would also reduce the need for additional land conversion to agriculture, which on its own represents almost as many greenhouse gas emissions as those directly generated from agricultural activities (Lal 2004a).

The goal of this review is to synthesize existing literature on the yield impacts of a range of sustainable land management options which are also known to have high potential for sequestering soil carbon (Fig. 1). By assessing the impact of adopting such practices on the level of food production, this paper also seeks to identify our current state of knowledge on the potential for capturing synergies between food security and mitigation in agricultural transformations.

2 Structure of the literature review

The present study is based on a review of the existing literature showing the impact of selected sustainable land management options on the productivity (average yield) of crops. We compiled data from the literature published in English, French, Spanish, and Portuguese, considering the set of technologies reported in Table 1.

To be included in the analysis, studies had to report: the specific sustainable land management practice adopted; the crop for which the practices have been implemented; and the corresponding change in crop yield. Reporting of variability data (min–max or range, variance, or standard deviation) was preferred but not essential.

Only studies reporting empirical results from implementation at farm level of the selected technologies in developing countries were taken into account. Thus, in general, publications reporting model estimations or results of plot experiments in research stations or on-farm field trials were not considered. Studies reporting only an overall indication of the sustainable land management practices on the yields (i.e., if positive or negative) were also excluded. Reports of projects implementing a technology package were excluded

Fig. 1 A view of terraced hills in Rwanda. The adoption of sustainable land management practices will increase the productivity of agricultural ecosystems and mitigate the effects of climate change through enhanced carbon sequestration (©FAO/Giulio Napolitano)

Table 1 Detailed list of sustainable land management practices considered in the analysis

Sustainable land management practices	Details of the practices
Agronomy	Cover crops
	Crop rotations and intercropping with nitrogen fixing crops
	Improved fallow rotations
Organic fertilization	Compost
	Animal and green manure
Minimum soil disturbance	Minimum tillage
	Mulching
Water management	Terraces, contour farming
	Water harvesting and conservation
Agroforestry	Trees on cropland (contours, intercropping)
	Bush and tree fallows
	Live barriers/buffer strips with woody species

as well, since it was not possible to isolate the impact of the specific practice on crop productivity.

The main data sources were published peer-reviewed studies. Literature searches were conducted through the Food and Agriculture Organization of the United Nations and the University of Illinois libraries, as well as through search engines such as Google Scholar. The following electronic databases have been consulted: Centre for Agricultural Bioscience, Science Direct, Science Magazine Online, ProQuest, Economist Intelligence Unit, and the library of the Centre de Coopération Internationale en Recherche Agronomique pour le Développement. The World Overview of Conservation Approaches and Technologies database has been also consulted. This database contains a full range of different case studies documented from all over the world, comprising datasets on 380 technologies from over 40 countries and reporting original field data as well as grey literature (thesis, manuscripts, and other unpublished work). Additional information was collected consulting the Global Farmer Field School Network and Resource Centre, and two databases from the Food and Agriculture Organization of the United Nations (the database on proven agricultural technologies for smallholders and the Investment Centre electronic library of project documents). Publications from the World Bank and the Organization for Economic Co-operation and Development have also been examined.

When a relevant study was found, papers which were cited by the study, as well as papers which cited the study itself, were checked, to obtain as complete a set of papers as possible. However, many articles cite evidence from others. Although a large number of studies are available on the topic, the actual number of original field studies is considerably more limited. Only original field studies have been taken into consideration here. Overall, 217 observations from about 160 publications were included in the database for the current study (Table 2).

Publications in the database therefore make reference to original field data from projects promoting the adoption of sustainable land management practices in a specific area and implemented by local institutions (e.g., Pretty 1999; Edwards 2000; Jagger and Pender 2000; Sharma 2000; Altieri 2001; Garrity 2002; Scialabba and Hattam 2002; Place et al. 2005; Erenstein et al. 2007, 2008; Pender 2007; Shetto and Owenya 2007; Sorrenson 1997; Verchot et al. 2007; Hine and Pretty 2008; Kassie et al. 2008; Kaumbutho and Kienzle 2008).

Most of these studies report results of observations over a limited number of years. However, some report results of long-term observations: for example, Sorrenson (1997) analyzed the profitability of conservation agriculture on farms in two regions of Paraguay over 10 years, 1987–1997.

Some publications report empirical results measured in other studies when building a model (e.g., Dutilly-Diane et al. 2003), while some others are a literature review. Lal (1987) basically reviews all advances in management technologies that have proven to be successful within the ecological constraints of Africa by looking at past studies and literature. Parrot and Marsden (2002) and Rist (2000) generated information through a desk-based literature review, supplemented by a semi-structured survey and a select number of face-to-face and telephone interviews. Pender (2007) reviews the literature on agricultural technology options in South and East Asia, drawing conclusions concerning technology strategies to reduce poverty among poor farmers in less-favored areas of this region.

Table 2 Dataset description: number of observations by management practice and geographical area

	Cereals *n*	Other crops	Total
Sustainable land management practices			
Agronomy	28	10	38
Organic fertilization	24	7	31
Minimum soil disturbance	55	15	70
Water management	44	8	52
Agroforestry	20	6	26
Total	171	46	217
Region			
Asia and Pacific	49	10	59
Latin America	32	15	47
Sub-Saharan Africa	90	21	111
Total	171	46	217

Only in a limited number of cases the results of research experiments have been included, specifically in the case of long-term or worldwide experiments or when a relatively high number of farmers have been involved. For example, Govaerts et al. (2007) report the results of a long-term experiment started in 1991 (to 2007) under rainfed conditions in the volcanic highlands of central Mexico, where maize–wheat crop rotations, zero tillage, and residue management practices have been successfully tested.

Unfortunately, in most cases the publications reviewed do not clearly explain how the information on the effect of the sustainable land management practices on yields was collected. Only a limited number of studies documented the effect of the introduction of the new technologies using proper impact analysis through farm surveys. For example, Erenstein et al. (2007) used community-level surveys conducted in 2004 to compare yields from smallholders under conventional tillage (high-intensity agriculture) and zero tillage in Zimbabwe. Franzel et al. (2004) provide evidence of agroforestry impact (improved tree fallows in Zambia, fodder shrubs in Kenya, and natural vegetative strips in the Philippines) through questionnaires documenting the results of farm-led trials conducted after researcher-led trials from 1990 through 1999.

Most studies report results from single cases in a specific area of a country, and with reference to a particular climate. However, some studies are a global review of results from various countries. For example, Derpsch and Friedrich (2009) compare conservation agriculture systems with conventional tillage systems in Latin America, Africa, and Asia; Hine and Pretty (2008)—which is by far the largest study examining sustainable agriculture initiatives in developing countries—compile the analyses of 286 projects covering 37 million hectares in 57 countries starting from 1970; Pretty (1999) examines a typology of eight technology improvements currently in use in 45 sustainable agriculture projects in 17 countries. Also, some studies report results under different climatic conditions. For example, Kassie et al. (2008) use two sets of plot-level data collected in 1999 and 2000 for their empirical analysis in Ethiopia, one from a low rainfall region and another from a high rainfall region.

To isolate the effects of sustainable land management technologies on crop production, the results have been often compared with control areas where the practices have not been implemented (e.g., Hellin and Haigh 2002; Franzel et al. 2004; Erenstein et al. 2008; Li et al. 2008). In other cases, the long-term trends in crop yields have been modeled for several alternative technology options and compared with crops produced under conventional management practices, on the basis of extensive farm experiments (e.g., Nelson et al. 1998; Garrity 2002).

In almost all cases included in the literature database, publications have analyzed the results of peasant farming projects which deal with small-sized farms (ranging from less than 1 ha to about 1-2 ha). Only a few cases report results of projects involving medium/large-scale farms: e.g., Alvarez and Flores (1998) in Honduras, Fileccia (2008) in Kazakhstan, and Sorrenson (1997) in Paraguay.

We have analyzed the effect of adopting sustainable land management technologies on crop productivity through a traditional literature review as well as a complementary meta-analysis of empirical evidence, using the results from the individual studies contained in the database. The basic assumption underlying the empirical analysis is that each study result is one observation that can be thought of as one data point in a larger dataset containing all available observations (Arnqvist and Wooster 1995; Gurevitch and Hedges 1999). A single publication might contribute more than once to the empirical analysis if a separate study was done for different countries or if more than one crop type was studied.

Most of the studies did not report any measure of variance for the crop yields resulting from the implementation of the improved practices. Thus, we have only been able to consider the percent change of average yields with respect to the corresponding yield obtained under conventional agriculture in the same geographical area and under the same climatic conditions. In most cases, the baseline conventional agricultural system that the sustainable land management practice was being compared with was a low input system, relying mostly on labor. In a few other cases, they were higher input intensity systems with the use of improved varieties and, in some cases, irrigation. The definition of the conventional system is correlated with geographic location, with higher input systems generally located in Asia.

3 Crop yield effects of the adoption of sustainable land management practices

The main benefit of implementing sustainable land management practices is expected to be higher and more stable crop yields, increased system resilience and, therefore, enhanced livelihoods and food security, and reduced production risk (Vallis et al. 1996; Pan et al. 2006; Thomas 2008; Conant 2009; Woodfine 2009). In this section, we summarize findings from a global literature review of the yield effects of the adoption of specific sustainable land management practices. As far as possible, we distinguish between agro-ecological and farming system types, as well as long- vs. short-run effects. However, the analysis of these factors is highly constrained by the availability of information in the literature cited.

3.1 Agronomy

Cover crops are defined either as additional crops planted on the field postharvest, or crops intercropped with the main crop (usually the case where there is a single, relatively short rainy season, e.g., in the semi-arid regions of the Sahel). Continuous cover crops can reduce on-farm erosion nutrient leaching and grain losses due to pest attacks and build soil organic matter and improve the water balance, leading to higher yields (Blanco and Lal 2008; Olson et al. 2010). For example, Kaumbutho and Kienzle (2008) showed that maize yield increased from 1.2 to 1.8–2.0 t/ha in Kenya with the use of a mucuna (*Velvet Bean*) cover crop using case studies conducted from 2004 to 2007; Pretty and Hine (2001) found that farmers who adopted mucuna cover cropping benefited from higher yields of maize with less labor input for weeding (maize following mucuna yields 3–4 t/ha without application of nitrogen fertilizer, similar to yields normally obtained with recommended levels of fertilization at 130 kg N/ha) based on 208 projects conducted between 1998 to 2001; Altieri (2001) reported that maize yields in Brazil increased by 198–246 % with the use of cover crops in 1999.

Crop rotations and intercropping with nitrogen-fixing crops, such as groundnuts, beans, and cowpeas will enhance soil fertility and enrich nutrient supply to subsequent crops, leading to increased crop yields (Woodfine 2009). For example, Hine and Pretty (2008) showed that in the North Rift and western regions of Kenya maize yields increased by 71 % and bean yields by 158 % in 2005; Parrot and Marsden (2002) report that, in Brazil, intercropping maize with legumes (*Vigna unguiculata* and *Canavalis ensiformis*), and ploughing these back in as green manures, led to significant grain yield increase (Fig. 2).

Fallow is the practice of allowing crop land to lie idle during a growing season to build up the soil moisture and fertility content. *Improved fallows* generally mean the deliberate planting of fast-growing species—usually legumes—that produce easily decomposable biomass and replenish soil fertility (Sanchez 1999; Matata et al. 2010). Increased crop yields after fallow and improved fallow periods have been widely reported (Agboola 1980; Hamid et al. 1984; Saleen and Otsyina 1986; Prinz 1987; Palm et al. 1988; Conant 2009), although the magnitude of the yield increment after each successive fallow is variable.

Fig. 2 Hedgerow intercropping of *Laucaena leucocephala* (Leguminosae) and maize as a companion crop in a field in Ghana. Intercropping with nitrogen-fixing crops will enhance soil fertility and enrich nutrient supply to subsequent crops, leading to increased crop yields (©FAO/Pietro Cenini)

3.2 Organic fertilization

Adopting *organic fertilization* (compost, animal, and green manure) is widely found to have positive effects on the yields. For example, Hine and Pretty (2008) showed that maize yields increased by 100 % (from 2 to 4 t/ha) in Kenya in 2005; Parrot and Marsden (2002) showed that millet yields increased by 75-195 % (from 0.3 to 0.6–1 t/ha) and groundnut by 100–200 % (from 0.3 to 0.6–0.9 t/ha) in Senegal in 2001; and Scialabba and Hattam (2002) showed that potato yields increased by 250–375 % (from 4 to 10-15 t/ha) in Bolivia between the early 1980s and 2000s.

Altieri (2001) notes several examples from Latin America where adoption of green manure and composting led to increases in maize/wheat yields between 198 and 250 % (Brazil, Guatemala, and Honduras) and in coffee yield by 140 % (in Mexico) between 1999 and 2001; Edwards (2000) showed that in the Tigray province of Ethiopia, composting led to yield increases compared with chemically fertilized plots: barley (+9 %), wheat (+20 %), maize (+7 %), teff (+107 %), and finger millet (+3 %) based on projects conducted between 1996 and 2000; Rist (2000), as cited in Parrott and Marsden (2002), reports that farmers in Bolivia increased potato yields by 20 % using organic fertilizers in 2000. Sakala et al. (2003) report that in Malawi, in 1997–1999, maize yields following green manures without inorganic fertilizer additions were much higher than yields from continuous maize with no fertilizer added.

3.3 Minimum soil disturbance

There is an extensive literature on practices aimed at reducing soil disturbance and different terminologies are often adopted. Among the important aspects of these practices is the decreased disturbance to the structure of the uppermost soil layers (Stavi and Lal 2012). This is achieved through the simultaneous adoption of two essential farm practices: a reduced tillage method of seedbed preparation and permanent soil cover through crop residue management (mulching). Therefore we report here the effects on crop yields of minimum tillage coupled with mulching practices (Fig. 3).

Following Blanco and Lal (2008), there are a wide range of minimum tillage practices that reduce soil disturbance in

Fig. 3 Maize grown adopting minimum tillage and mulching in Zambia. Positive effects of these practices on crop yields are widely reported, especially in semi-arid and dry sub-humid areas of sub-Saharan Africa (©FAO)

seedbed preparation vis-à-vis conventional tillage. Conventional tillage is usually defined as animal or mechanical mouldboard ploughing. Minimum tillage practices include zero tillage, strip or zonal tillage, and ridge tillage. Zero tillage is as the name suggests; no mechanical preparation of the seedbed, except for the use of narrow holes for seed placement. In strip or zonal tillage systems, the seedbed is divided between seeding zones that are prepared mechanically or by hand-hoe only where seeds will be planted, and zones that are not ploughed. The undisturbed portion is often also mulched. Finally "planting pits", where small holes are dug and seeds deposited, are often used in semi-arid areas prone to crusting, in order to retain moisture and build soil fertility (Roose et al. 1993; Imbraimo and Munguambe 2007). In summary, minimum tillage may take on different meanings in different contexts, which has led to some difficulty in comparing across a range of empirical assessments.

The decreased disturbance of the soil profile contributes to maintaining its structure, encouraging activity of soil fauna (Stavi and Lal 2012), which supports agro-ecosystem health (Huggins and Reganold 2008). The retention of crop residues on the soil surface can limit nutrient leaching, decrease raindrop impact, protect the soil from water and wind erosion, increase water retention, and improve soil structure and aeration (Unger et al. 1991; Barros and Hanks 1993; Arshad and Gill 1997; Scopel et al. 2004; Govaerts et al. 2007; Blanco and Lal 2008; Stavi and Lal 2012), with the expected positive effects on crop yields (Smolikowski et al. 1997; Silvertown et al. 2006; Conant 2009) especially where water availability limits production (Stavi and Lal 2012).

The studies reviewed here compare minimum soil disturbance with conventional tillage management. Substantial increases in rain-use efficiency with implementation of minimum tillage practices and mulching in sub-Saharan Africa are reported by Rockström et al. (2009), based on farm trials conducted between 1999 and 2003. Positive effects on crop yields are widely reported, especially in semi-arid and dry sub-humid areas (Bhatt et al. 2004; Scopel et al. 2005), on severely degraded soils (Acharya et al. 1998) and with reference to sub-Saharan Africa. For example, maize yields (monoculture) increased by 4–32 % in Nigeria in the 1976–1980 period (Agboola 1981; Osuji 1984) and by 9 % in Zimbabwe in 2004–2010 (Thierfelder and Wall 2012). Rice yields (monoculture) increased by 4 % in Nigeria in 1979–1983 (Lal 1986).

However, negative effects are often recorded in south Asia. For example, Acharya and Sharma (1994) report an average 19 % decrease in maize yields (maize–wheat systems) in India in the 1980–1985 period; Sharma et al. (1988) report a 30 % drop in rice yields (monoculture) in the Philippines in 1984–1985.

3.4 Water management

Terraces and contour farming practices can increase yields due to reduced erosion and soil loss, and mitigated flooding and runoff velocity (Fig. 4).

Altieri (2001) showed that restoration of Incan terraces has led to a 150 % increase in a range of upland crops in 1999; Shively (1999) finds that contour hedgerows can improve maize yields up to 15 % compared with conventional practices on hillside farms in the Philippines, based on data collected on farmers' fields between November 1994 and March 1995; based on surveys conducted in 2000, Dutilly-Diane et al. (2003) reported an increase in millet yields from 150 to 300 to 400 kg/ha (poor rainfall) and 700 to 1,000 kg/ha (good rainfall) in Burkina Faso, and from 130 to 480 kg/ha in Niger. However, they also note that bunds

Fig. 4 Rice terraces in Madagascar. Terraces can increase crop yields by reducing erosion, soil loss, flooding, and runoff (©FAO/Jeanette Van Acker)

lead to increased yields in the low and medium-rainfall areas, but to lower yields in the high rainfall areas.

Branca et al. (2011) report that building excavated terraces (bench/fanya juu) in the Ulugurus mountains in Tanzania has improved soil composition: for example, soil testing results have shown that the average soil compaction in areas with terraces/fanya juu is lower than in areas with no terraces (1.05 vs. 3.05 km/cm^2), based on case studies conducted in two phases, 2005–2007 and 2008–2012. Consequently, maize and beans yields harvested on excavated structures have improved (Branca et al. 2011).

Water harvesting and *conservation* techniques (e.g., run-off collection techniques, microcatchment water conservation with film mulching, bunds and planting pits, and tied ridge systems) can help capture rainfall (Vohland and Barry 2009), making more water available to crops (Rockstrom and Barron 2007), which is crucially important for increased agricultural production (Conant 2009; Rockstrom et al. 2010). These techniques also increase yields (Critchley at al. 1992; Ngigi 2003; Hatibu et al. 2005), particularly where increased soil moisture is a key constraint (Lal 1987). Parrott and Marsden (2002) showed that water harvesting in Senegal changes the yields of millet and peanuts by 75–195 and 75–165 %, respectively, and that water conservation techniques resulted in a 50 % increase in productivity in eastern and central Kenya in 2001; Pretty and Hine (2001) report that cereal yields went up more than 100 % in Zimbabwe between 1999 and 2001 thanks to the implementation of water harvesting technologies.

3.5 Agroforestry

Agroforestry encompasses a wide range of land use practices (e.g., farming with trees on contours, bush and tree fallows, establishing shelter belts, and riparian zones/buffer strips with woody species) in which woody perennials are deliberately integrated with agricultural crops, varying from very simple and sparse to very complex and dense systems. This improves land productivity by providing a favorable microclimate, permanent cover, improved soil structure and organic carbon content, increased infiltration, reduced erosion, and enhanced soil fertility (Schroth and Sinclair 2003; Garrity 2004).

For example, Sharma (2000), as cited by Parrott and Marsden (2002), reports yield increases of 175 % on farms in Nepal between 1999 and 2000; Soto-Pinto et al. (2000) studied outputs from shade-grown coffee production in Mexico and found that shaded groves had yields 23–38 % higher than conventional production, based on surveys conducted between 1996 and 1999.

Use of live fences (e.g., use of trees or shrubs to delimit fields) is also expected to increase yields. For example, Ellis-Jones and Mason (1999) report increased yields from 13.5 to 31.7 t/ha of cassava between 1996 and 1999. However, results are controversial. For example, Hellin and Haigh (2002) report no difference in yields from the adoption of live barriers/fences, based on experimental trials over the period 1996–1998.

3.6 Main findings

The literature reviewed in this section indicates that the adoption of sustainable land management generally leads to increased yields, although the magnitude and variability of results varies by specific practice. Yield effects are variable, and in some cases negative for improved fallows, terraces, minimum tillage, and live fences. Cover crops, organic fertilizer, mulching, and water harvesting were found to have consistently positive yield effects. Rainfall distribution is a key determinant of the yield effects of sustainable land management adoption, and the yield results are generally found to be higher in areas of low and variable rainfall. Isolating the yield effects of individual practices is complicated by the adoption of combinations or “packages” of sustainable land management practices. Further research identifying optimal combinations for specific agro-ecological and farming systems is needed.

4 Potential mitigation effects of the adoption of sustainable land management practices

The review has indicated the state of the literature on the conditions under which sustainable land management practices can increase crop productivity, which is an important component of achieving food security. The same practices can also deliver significant mitigation co-benefits in the form of removal of atmospheric carbon dioxide by plants and storage of fixed carbon as soil organic matter. Sustainable land management increases and stabilizes soil organic carbon density in the soil, improving its depth distribution and encapsulating it within stable micro-aggregates so that carbon is protected from microbial processes (Lavelle 2000; Lal 2004b). Converting agricultural land to a more natural or restorative land use essentially reverses some of the effects responsible for soil organic carbon losses that occurred upon conversion of natural to managed ecosystems (Lal 2004b).

4.1 Agronomy

Improved agronomic practices enhance soil quality and biodiversity, reduce erosion, and increase biomass production. A healthy soil is teeming with life and comprises highly diverse soil biota. The activity of these animals has a strong influence on the soil’s physical and biological qualities especially with regards to its structure, porosity, aeration, water infiltration, drainage, nutrient cycling, organic matter pool and fluxes, and improving the soil organic carbon pool (Lavelle 1997; Lal 2004b).

Rotations and intercropping with nitrogen-fixing crops enhance biodiversity, the quality of residue input and the soil organic carbon pool (Uhlen and Tveitnes 1995). It is well established that, all other factors being equal, ecosystems with high biodiversity absorb and sequester more carbon in soil and biota than those with low or reduced biodiversity (Lal 2004b). Also, Drinkwater et al. (1998) observed that legume-based cropping systems reduce carbon and nitrogen losses from soil.

Improving land cover by limiting bare fallow and growing cover crops during the off-season avoids carbon dioxide release and increases soil carbon, particularly when combined with zero or minimum tillage (Govaerts et al. 2009).

4.2 Organic fertilization

Judicious nutrient management is crucial to humification of carbon in the residues and to soil organic carbon sequestration. Soils under low-input and subsistence agricultural practices have low soil organic content which can be improved using organic amendments and strengthening nutrient recycling mechanisms (Lal and Bruce 1999). This can also lead to decreased nitrous oxide emissions by reducing leaching and volatile losses and improve nitrogen use efficiency (Lal 2003). Manure management can improve soil fertility and enhance carbon storage by increasing biomass and improving soil equilibrium. In general, the use of organic manures and compost enhances the soil organic carbon pool more than application of the same amount of nutrients as inorganic fertilizers (Leiva et al. 1997; Gregorich et al. 2001). Use of residue mulching improves the soil structure, lowers bulk density and increases infiltration capacity and the soil organic carbon pool (Shaver et al. 2002).

4.3 Minimum soil disturbance

The reduced disturbance of the soil structure decreases emission rates of carbon dioxide, nitrous oxide and methane (Ussiri et al. 2009; Stavi and Lal 2012). Also, soil organic carbon can accumulate in soils because tillage-induced soil disturbances are eliminated, erosion losses are minimized, and large quantities of root and above-ground biomass (precursors of soil organic matter) are returned to the soil (Lal 1987, 1997b). The resultant increase in soil organic carbon concentration further stimulates the formation and stability of the soil structure (Govaerts et al. 2007; Stavi and Lal 2012). Recent literature reviews show that minimum soil disturbance (Bernoux et al. 2006; Lichtfouse et al. 2009) and conservation agriculture (Corsi et al. 2012) practices permit higher rates of soil organic carbon accumulation as compared with conventional tillage agriculture and generally improve ecosystem functioning and services.

4.4 Water management

Proper water management can enhance biomass production, increase the amount of aboveground and root biomass, therefore increasing the soil organic carbon concentration. It can also improve the soil organic carbon sequestration potential by increasing the available water in the root zone (Kimmelshue et al. 1995).

4.5 Agroforestry

In agroforestry systems, the standing stock of carbon above ground is usually higher than the equivalent land use without trees. Planting trees and bushes increases the carbon sequestered above ground. Agroforestry may also reduce soil carbon losses stemming from erosion, thus improving the soil's organic carbon pool (Paustian et al. 1997; Lal and Bruce 1999; Lal 2003, 2004b; Verchot et al. 2007).

4.6 Mitigation potential and climate zones

The mitigation potential of adopting any sustainable land management practice varies depending on specific soil and climate conditions. For example, Table 3 summarizes the annual mitigation potential in each climate region for the sustainable land management options discussed, expressed in units of carbon dioxide equivalent per hectare and per year. The table shows average net mitigation through increase in soil carbon stocks or nitrous oxide and reduction of methane emissions. Such estimates were derived from studies conducted in regions throughout the world, standardized using a linear mixed–effect modeling approach, and integrated by results of simulation models (IPCC 2007).

4.7 Main findings

The studies reviewed in this section indicate that the adoption of sustainable land management can generally be expected to increase soil carbon sequestration. Some practices also increase aboveground sequestration (e.g., agroforestry) or reduce emissions (e.g., nutrient management). The results indicate that, as in the case of yield effects, rainfall distribution is a key determinant of the mitigation effects of adopting specific sustainable land management practices. With the exception of water management, the mitigation effects of sustainable land management adoption are higher in areas of higher rainfall. In general, the evidence base on the mitigation effects of sustainable land management is

Table 3 Annual mitigation potential of sustainable land management practices in each climatic region

Climate zone	Sustainable land management practices	Mitigation potential tCO_2e ha^{-1} year^{-1}
Cool-dry	Agronomy	0.39
	Organic fertilization	0.33
	Minimum soil disturbance	0.17
	Water management	1.14
	Agroforestry	0.17
Cool-moist	Agronomy	0.98
	Organic fertilization	0.62
	Minimum soil disturbance	0.53
	Water management	1.14
	Agroforestry	0.53
Warm-dry	Agronomy	0.39
	Organic fertilization	0.33
	Minimum soil disturbance	0.35
	Water management	1.14
	Agroforestry	0.35
Warm-moist	Agronomy	0.98
	Organic fertilization	0.62
	Minimum soil disturbance	0.72
	Water management	1.14
	Agroforestry	0.72

Adapted from the contribution of working group III to the fourth assessment report of the IPCC (2007)

quite thin and dependent on few sources. Expanding research efforts to cover a wider range of agro-ecologies and sustainable land management practices, and involving a wider group of researchers, is needed.

5 Synergies between food security and climate change mitigation: the case of cereal production

Combining the results of the literature review with the analysis of mitigation potential from the Intergovernmental Panel on Climate Change (IPCC 2007), it is possible to identify where capturing synergies between food security and climate change mitigation through the adoption of sustainable land management may be possible. As a first step, we present a meta-analysis of cereal crop yield impacts from the adoption of sustainable land management. The analysis uses the results from individual studies reported in the database. Figure 5 summarizes the results of this analysis, showings the average global increase in cereal productivity with respect to average yield under conventional agriculture (in percentages) in dry and humid areas.

The results show that all the sustainable land management practices considered in the review are found to increase the yield of cereals. However, agronomy, integrated nutrients, and water management practices are more effective at increasing crop yields in humid than in dry areas. In contrast, the average yield increases observed under tillage and agroforestry systems are higher in dry areas. These results highlight the key role of water as a determinant of crop productivity, and the value of sustainable land management practices in improving the productivity of water use in both humid and dry areas.

In more humid areas, effective water management through terracing and other soil and water conservation measures will have the effect of reducing soil erosion, therefore increasing soil organic matter and nutrient availability in the root zone. In drier environments, practices that allow plants to make better use of the limited amount of water available prove to be the most productive. Minimum tillage systems are found to increase water availability to plants by reducing direct evaporation and improving the hydraulic conductivity of the topsoil and soil surface porosity (Scopel et al. 2001). Agroforestry controls runoff and soil erosion—thereby reducing water loss—and increases water-use efficiency from crops and trees, which could be improved if used in combination with water harvesting techniques.

For the meta-analysis, differences in the impact of sustainable land management practices at regional level were also assessed. Interestingly, the impact was higher in sub-Saharan Africa than in Asia for most of the practices (Fig. 6).

These results may be partially due to the greater prevalence of low input systems as a baseline conventional practice in sub-Saharan Africa, as compared with Asia, where use of capital inputs in baseline systems is more common.

In Asia, agricultural production systems may be closer to productivity limits due to the wider use of improved crop varieties, synthetic fertilizers, pesticides, irrigation, and mechanization. Evidence from Southeast Asia suggests that there are serious and growing threats to the sustainability of the yields of the Green Revolution lands (Pingali and Rosegrant 1998). Even greater evidence of declines in the rates of yield growth have been found (Cassman 1999; Mann 1999; Pingali and Heisey 1999).

In contrast, in sub-Saharan Africa, crop yields have been stable in recent decades and food production increases are largely a result of agriculture area expansion (mostly onto marginal lands, which are generally more susceptible to degradation and with poor productivity) due to poor access to fertilizer and other inputs (Henao and Baanante 2006; Bruinsma 2009). However, at present, the scope for further expansion is highly limited. Thus productivity increases on existing lands, mostly under low input systems, is urgently needed.

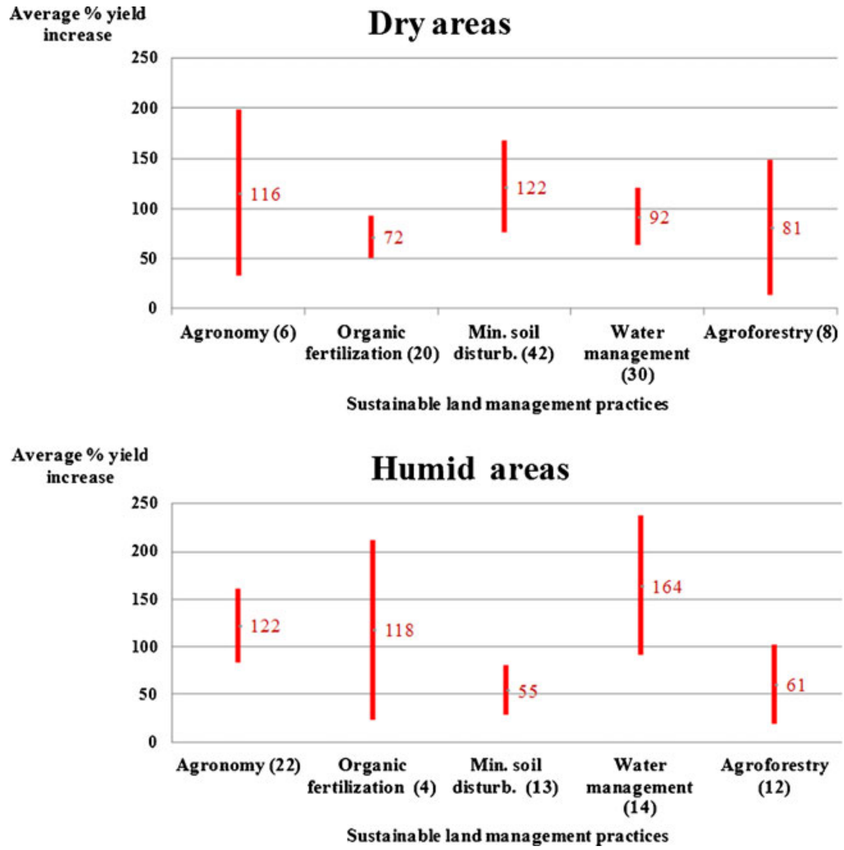

Fig. 5 Global average percentage increase of cereal yields with sustainable land management practices compared to conventional agriculture in dry and humid areas. All practices are effective in increasing yields, although differences exist between humid and dry areas (95 % confidence intervals are shown and numbers of observations are in *parenthesis*)

The review conducted here suggests that sustainable land management could have an important role to play in achieving such increases, although more complete information on their associated costs and their compatibility with specific farming systems and agro-ecologies is needed to effectively judge their merit.

Sustainable land management practices can generate significant mitigation co-benefits, as well as increases in crop productivity. Combining the results of the meta-analysis on cereal yield effects with the expected mitigation co-benefits of sustainable land practices from IPCC (2007) estimates, it is possible to highlight potential synergies between food security and climate change mitigation. Figure 7 shows a comparison of yield and mitigation effects by practice and major agro-ecological zone.

The figure indicates that all the sustainable management practices considered in the analysis can result in yield increases and, at the same time, sequester carbon and reduce

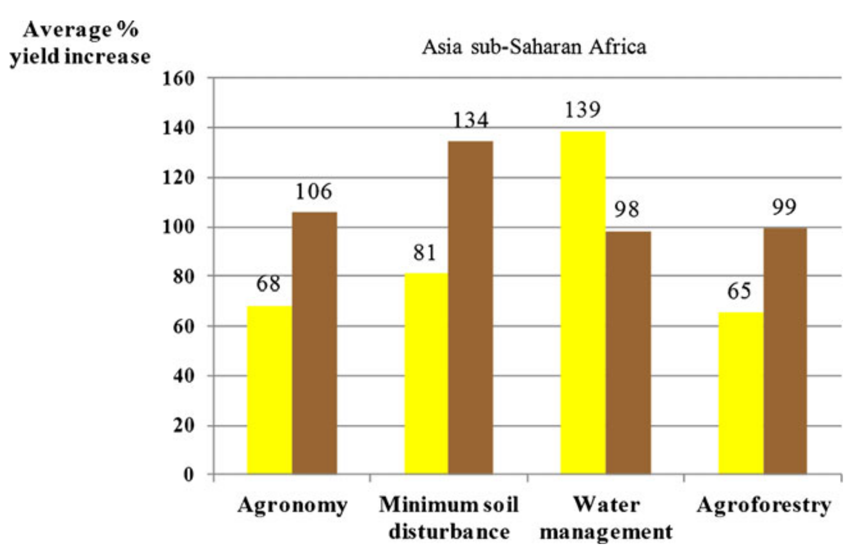

Fig. 6 Yield effects of sustainable land management compared with conventional agriculture in Asia and Pacific and sub-Saharan Africa. The yield impact is higher in sub-Saharan Africa (*dark color bars*) than in Asia (*light color bars*) for most of the practices

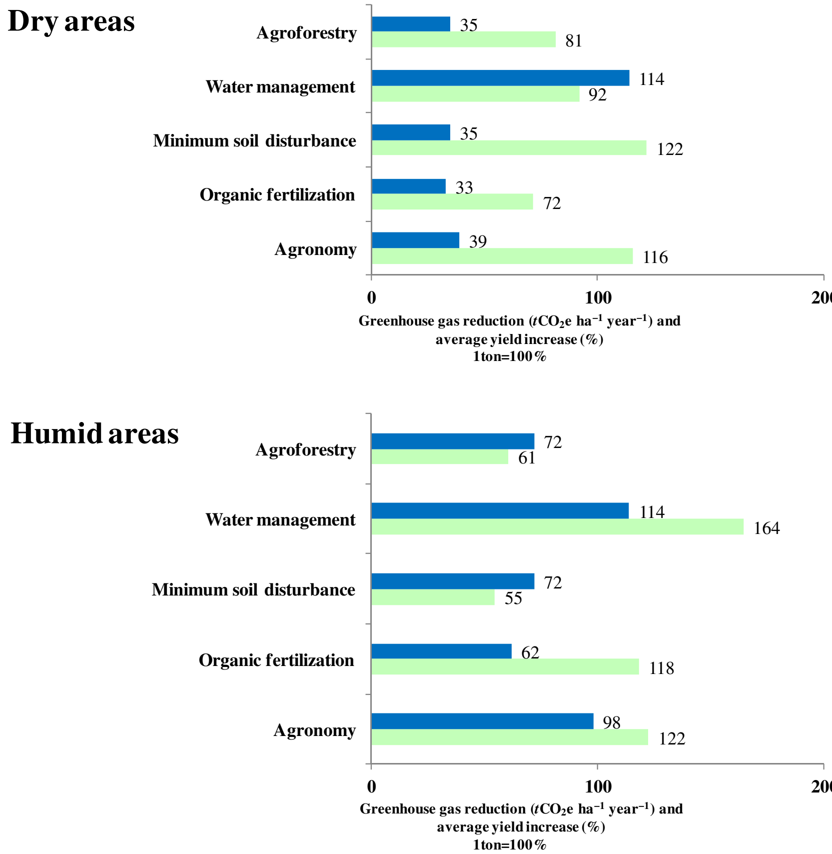

Fig. 7 Effects of sustainable land management practices on climate change mitigation (expressed as greenhouse gas reduction measured in $t\mathrm{CO_2e}$ ha^{-1} year^{-1}) and crop yields (measured in average percentage increase) by major agro-ecological zone. All practices result in mitigation (*dark color bars*) and yield increases (*light color bars*). However, in humid areas the magnitude of yield and mitigation effects are more evenly balanced than in dry areas where yield effects are greater than those of mitigation

green house gas emissions, although the relative effects vary considerably by practice and agro-ecological zone. In dry areas, the magnitude of yield effects is greater than those of mitigation. The only exception is water management, which can deliver high levels of food security and mitigation benefits in both dry and humid areas. In contrast, in humid areas, the magnitude of yield and the mitigation effects are more evenly balanced. This finding has important implications for the potential and means of capturing synergies between mitigation and food security (Branca et al. 2013). The higher potential "mitigation productivity" (e.g., tons of emissions reduction per hectare) found in humid areas provides an economic basis for supporting higher transaction costs in mitigation crediting programmes—which is key to accessing many forms of climate change mitigation finance.

However, dry lands offer another type of potential, since they are characterized by a large number of producers which crop their land in areas where small incremental improvements in management of water resources and soil fertility can lead to large productivity—and ultimately food security—gains. Sustainable land management implemented over a large enough scale, could generate significant mitigation benefits, although requiring mechanisms for efficient crediting and financing adapted to these circumstances.

6 Conclusions

We have synthesized the literature on the yield impacts of the adoption of sustainable land management amongst smallholder farmers. We have also assessed potential mitigation benefits from carbon sequestration for the same set of practices. The literature review of yield and mitigation effects indicates that sustainable land management has been found to have positive effects on both in a range of circumstances, although the depth and breadth of the results varies considerably, as do the results themselves.

The robustness of our results differs across the technologies considered. Results on the yield effects of tillage and residue management, as well as water management practices, show less variability and more consistent results than those related to other technologies. For example, the adoption of agronomy practices and integrated nutrient management show relatively high variability in the results, as they constitute heterogeneous technology packages and include practices which are significantly varied in terms of their effects on soil fertility. Likewise, the effects of agronomic practices such as the use of cover crops, which is often associated with minimum tillage in conservation agriculture systems, vary considerably depending on the crops and varieties used in the rotation. The use of organic fertilization techniques and green manure differs from technologies aimed at increasing nitrogen efficiency. Also, the effect of agroforestry practices on the yields of crops is not well documented and sometimes contradictory.

The practices can be adopted in a wide range of different combinations. This matters very much for their impacts on yields as well as externalities across different locations. This issue of packaging and combining practices is key to obtaining the desired results from the adoption of sustainable land management and creates difficulties in generating comparisons across sites and combinations of technologies. As far as possible, we have tried to identify the set of practices being evaluated in any of the evaluated studies, but this is clearly an area where better information is needed.

Geographic differences influence the magnitude of crop productivity increases in response to the adoption of improved practices. Specifically, sustainable land management practices seem to be more effective at increasing crop yields in low fertility and drier areas of sub-Saharan Africa than in other regions of the world (especially in Asia). In contrast, differences in farm size are not found to be a factor determining the impact on yields. However, most publications cited here focused on smallholders (only a very small number of observations refer to medium and large-scale farming), thus it is not possible to derive conclusions of general validity on the relationship between farm size and yield effects.

Another major issue that arises is the timing of yield effects, i.e., short run vs. long run. In many of the studies analyzed in this review, yield benefits emerge only over time. For several options, short-term impacts may be negative depending on underlying agro-ecological conditions, previous land use patterns, and current land use and management practices. Yield variability can also increase in the short-term, where changes in activities require new knowledge and experience. Farmers unfamiliar with such systems may require a period to successfully adopt the practice (e.g., fertilizer application or the construction of water retention structures where the incidence and severity of both droughts and floods are expected to increase in the future) (FAO 2009).

Long-term impacts were generally found to be positive for increasing both the average and the stability of production levels. For instance, crop and grassland restoration projects often take land out of production for a significant period of time, reducing cultivated or grazing land available in the short run, but leading to overall increases in productivity and stability in the long run (FAO 2009). Giller et al. (2009) present data from several field studies of the adoption of conservation agriculture indicating a significant lag in yield effects. They also emphasize the importance of specific site characteristics in influencing yield effects and timing. In areas where soil moisture is a key constraint on yields, conservation agriculture can have very immediate yield benefits. However, in humid areas on water-logged soils the same practices could lead to yield decreases.

A final general finding from this analysis is that there are relatively few studies that report decreases or lack of yield effects. Giller et al. (2009) do report a few for the case of conservation agriculture but, in general, agronomic studies on the adoption of sustainable land management practices report yield benefits. This finding can lead to two different conclusions: one is that sustainable land management does indeed have yield benefits across a wide range of practices, agro-ecologies and farming systems when compared with low input conventional systems. The second is that studies where sustainable land management did not generate any yield benefit or actually reduced benefits are much less likely to be published and thus a bias exists in the literature in terms of our understanding of sustainable land management impacts on yield. This latter conclusion is only speculation and not based on any evidence. But it may be important to keep this in mind as a possibility when assessing the overall conclusions from the literature.

The results of the analysis may be biased by the limited number of crops and agro-environmental conditions considered in the studies reviewed. Most studies focus on cereals (especially maize and wheat) and there are only a few examples of positive effects on other food crops like roots and tubers (e.g., cassava and potato) and legumes (e.g., beans and soybeans). The studies are based mainly in warm dry and warm humid climate zones, with much thinner representation of others (e.g., only a few studies are conducted in mountain areas and refer to cool climates). The results of the analysis may also be biased by the small number of researchers involved in some aspects (particularly mitigation), and likewise by the absence of studies reporting negative yield responses in the literature reviewed. This may be explained by the fact that the analysis has considered only studies reporting empirical results from wider implementation at farm level of the selected technologies in developing countries. It is plausible to expect that only technologies that have been proven to be successful were implemented on a wide scale.

7 Recommendations

More research is needed. A coordinated effort to identify yield and mitigation effects from sustainable land management for several agro-ecological zones and farming systems is needed to fill the gaps in our understanding identified in this review.

Possible approaches to doing so include expanding the review (e.g., exploring grey literature and national surveys and project reports) in order to: (1) increase the number of observations and types of crops analyzed, thus improving the statistical significance of the empirical analysis; (2)

clearly establish the "baseline" production system in order to assess sustainable land management against low as well as high input conventional systems; (3) refine the analysis, reporting results at the level of single practices instead of combinations of practices (e.g., analyzing the use of cover crops and the adoption of crop rotations instead of focusing on the "agronomy" package, or better examining the yield effect of organic fertilization techniques); (4) identifying key cross-cutting practices (such as the use of leguminous crops in agronomy, nutrient management, and agroforestry) for analysis; and (4) improve evidence across different agro-ecological zones and land-use systems.

Second, it may be interesting to expand the analysis to also consider the results of plot experiments in research stations or on-farm field trials. This would give a more balanced picture, in particular as concerns the quantification of the short-term yield losses. Additionally, a quantitative analysis of experimental data would enable more analysis of the factors involved, especially if there is experimental data which combines research on crop productivity with climate research.

Third, it would be interesting to replicate the same analysis focusing on grassland productivity, sustainable grazing and pasture management, and livestock production.

Finally, it will be critical to link the results of this analysis and further reviews of yield and mitigation effects to economic analysis of the costs and barriers to adoption of sustainable land management practices. This will be essential to understanding the trade-offs of sustainable land management implementation and ultimately its viability in supporting sustainable intensification (e.g., see Antle et al. 2007; Ringius 2002; Tschakert 2004).

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