Climate-Smart Agriculture: A Synthesis of Empirical Evidence of Food Security and Mitigation Benefits from Improved Cropland Management

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Climate-Smart Agriculture: A Synthesis of Empirical Evidence of Food Security and Mitigation Benefits from Improved Cropland Management

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Contents

Abstract

Meeting the food demand of a global population expected to reach 9.1 billion in 2050 and over 10 billion by the end of the century will require major changes in agricultural production systems. Improving cropland management is key to increasing crop productivity without further degrading soil and water resources. At the same time, sustainable agriculture has the potential to deliver co-benefits in the form of reduced GHG emissions and increased carbon sequestration, therefore contributing to climate change mitigation. This paper synthesizes the results of a literature review reporting the evidence base of different sustainable land management practices aimed at increasing and stabilizing crop productivity in developing countries. It is shown that soil and climate characteristics are key to interpreting the impact on crop yields and mitigation of different agricultural practices and that technology options most promising for enhancing food security at smallholder level are also effective for increasing system resilience in dry areas and mitigating climate change in humid areas.

1. Introduction

Agriculture is the most important economic sector of many developing countries. Agricultural production systems are expected to produce food for a global population that will amount to 9.1 billion people in 2050 and over 10 billion by the end of the century (UNFPA 2011). To secure and maintain food security, agricultural systems need to be transformed to increase the productive capacity and stability of smallholder agricultural production. However, there is a question of which technologies and practices are most appropriate to reach this objective, and considerable discussion about the inadequacy of the dominant model used for intensification so far—relying on increased use of capital inputs such a fertilizer and pesticides. Generation of unacceptable levels of environmental damage and problems of economic feasibility are cited as key problems with this model (Tillman et al. 2002; IAASTD 2009; FAO 2010a). Greater attention is thus being given to alternative means of intensification, particularly the adoption of sustainable land management (SLM) technologies.[1] Key benefits of these technologies are increasing food production without further depleting soil and water resources (World Bank 2006), restoring soil fertility (IFAD 2011; Lal 1997), increasing the resilience of farming systems to climatic risk, and improving their capacity to sequester carbon and mitigate climate change (CC) (FAO 2009; FAO 2010c).

SLM technologies can generate both private and public benefits and thus constitute a potentially important means of generating “win-win” solutions to addressing poverty and food insecurity as well as environmental issues. In terms of private benefits to farmers, by increasing and conserving natural capital – including soil organic matter, various forms of biodiversity, water resources – SLM can generate productivity increases, cost decreases and higher stability of production (Pretty 2008; 2011). SLM practices contribute to improving soil fertility and structure, adding high amounts of biomass to the soil, causing minimal soil disturbance, conserving soil and water, enhancing activity and diversity of soil fauna, and strengthening mechanisms of elemental cycling (Woodfine 2008). This in turn translates into better plant nutrient content, increased water retention capacity and better soil structure, potentially leading to higher yields and greater resilience, thus contributing to enhancing food security and rural livelihoods (FAO 2009).

At the same time, widespread adoption of SLM has the potential to generate significant public environmental goods in the form of improved watershed functioning, biodiversity conservation and CC mitigation. The technical potential for mitigation from agriculture by 2030 is estimated to be between 4,500 $MtCO_2e$/year (Caldeira et al. 2004) and 6,000 $MtCO_2e$/year (Smith et al. 2008), which can be reached by reducing GHG emissions – of which agriculture is an important source representing 14% of the global total – and increasing soil carbon sequestration – which constitutes 89% of agriculture technical mitigation potential (IPCC 2007).[2] Many SLM technologies can increase the levels of soil organic matter, of which carbon is the main component, therefore delivering significant CC mitigation co-benefits in the form of reduced GHG emissions and increased carbon (C) sequestration.[3] Improving productivity would also reduce the need for additional land conversion to

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[1] According to the UN Earth Summit of 1992, SLM is “the use of land resources, including soils, water, animals and plants, for the production of goods to meet changing human needs, while simultaneously ensuring the long-term productive potential of these resources and the maintenance of their environmental functions”. SLM comprises four main categories of land management technologies: improved cropland management, improved pasture and grazing management, restoration of degraded land, and management of organic soils.

[2] To a lesser extent, improvements in rice management and livestock can reduce CH_4 emissions, providing an additional 9% of mitigation potential. Adopting measures in crop management could reduce N_2O emissions from soils, representing the remaining 2% of agriculture’s mitigation potential.

[3] The SOC content is likely to reach its maximum 5 to 20 years after adoption of SLM practices and remain similar, under continuous use of SLM practices and similar environmental conditions. The actual rate of SOC sequestration in an agricultural system depends on soil texture, profile characteristics and climate, ranging from 0 to 0.15 t C/ha/year in dry and warm regions and 0.10 to 1 t C/ha/year in humid and cool climates.

agriculture, which on its own represents almost as much GHG emissions as those directly generated from agricultural activities (Cerri et al. 2007; Houghton 1999; Lal 2004).

Despite the capacity to generate both public and private benefits, the adoption of SLM practices has been relatively low globally (FAO 2010a). Thus, there is considerable interest in understanding better the benefits, costs and barriers to adoption of these practices. The goal of this present work is to synthesize the evidence base on the yield impacts (e.g. private benefits) of a range of improved cropland management options, known to have high potential for sequestering soil carbon and thus contributing to CC mitigation (e.g. public benefits). By assessing the impact of adopting such practices on the level of food production, this paper also highlights the state of knowledge on where synergies between food security and CC mitigation in croplands are most likely to be found.

To fully realize these synergies, we also need a better understanding of the costs and barriers faced by households when deciding to adopt SLM practices. In a separate companion piece, we consider in more detail household-level studies of adoption of SLM practices, focusing on the costs and barriers to adoption by farmers and the institutional changes and policy frameworks needed to reduce transactions costs and barriers to adoption (McCarthy 2011).

The Paper is structured as follows: Section 2 describes data and analytical methods used in this study (literature review and empirical analysis), Section 3 reports main results, which are then discussed in Section 4.

2. Materials and methods

2.1 Dataset

The present study is based on a review of the existing literature showing the impact of selected sustainable cropland management mitigation options on the productivity (average yield) of crops.[4] We compiled data from the literature published in English, Spanish and Portuguese, considering the following set of technologies as reported in IPCC 2007: (i) improved agronomic practices, (ii) integrated nutrient management, (iii) tillage and residue management, (iv) water management, and (v) agroforestry (see Table 1).

Table 1. Sustainable cropland management practices considered in the analysis

Management Practices	Details of the Practices
Agronomy	Use of cover crops
	Improved crop or fallow rotations
	Improved crop varieties
	Use of legumes in crop rotations
Integrated nutrient management	Increased efficiency of Nitrogen fertilizer
	Organic fertilization (use of compost, animal and green manure)
Tillage and residue management	Incorporation of crop residues
	Reduced/minimum/zero tillage
Water management	Irrigation
	Bunds/zai, tied ridge system
	Terraces, contour farming
	Water harvesting
Agroforestry	Live barriers, fences
	Crops on tree-land
	Trees on cropland

Source: IPCC 2007

To be included in the analysis, studies had to report: the specific improved cropland management practice (or group of practices) adopted; the crop on 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 wider implementation at farm level of the selected technologies in developing countries were taken into account. Thus, publications reporting model estimations or results of plot experiments in research stations or on-farm field trials and studies related to documented cases in developed countries were not considered. Studies which do not report any quantitative impact of the SLM practice on the yields, but only an overall indication of such impact (i.e. if positive or negative) were also excluded. Reports of projects implementing a set of different practices (technology package) were excluded as well since it was not possible to isolate the impact of the specific practice on crop productivity.

[4] Grasslands are also a potentially important resource for carbon sequestration. However, the evidence on benefits to grasslands management in terms of both carbon sequestration and livestock productivity is scarcer than for croplands (though see Abberton et al. 2010 and Lipper et al. 2007 for a review of empirical evidence on productivity, and Conant et al. 2001 for a review on carbon sequestration effects). This paper will focus only on cropland, while acknowledging the potential role of grasslands.

The main data source was publicly available published peer-reviewed studies. Literature searches (mainly in English, but also in Spanish, Portuguese and, some French) were conducted through the Food and Agriculture Organization of the United Nations (FAO) and the University of Illinois libraries as well as through search engines such as Google Scholar. The following electronic databases have been consulted: CAB Abstracts, Science Direct, Science Magazine Online, ProQuest, Economist Intelligence Unit, World Bank Publications, OECD Publications, CIRAD (*Centre de coopération internationale en recherche agronomique pour le développement*) library and the World Overview of Conservation Approaches and Technologies technology database (WOCAT 2011). Using the WOCAT database, case studies from the questionnaire of technologies were extratced, and those which report the effects of the practices on average yields (quantitative data) were selected. Also, the following journals were systematically checked: *Agriculture, Ecosystems & Environment; Agroforestry Systems; Soil & Tillage Research; Soil Science; Agricultural Systems.* Additional information was collected consulting the Global Farmer Field School Network and Resource Centre (FFSnet),[5] the FAO database on proven agricultural technologies for smallholders[6] (TECA) and the FAO Investment Centre (TCI) electronic library of project documents.[7]

Keywords used in the search include, among others: sustainable farming/SLM/improved agronomic practices/tillage management/water management/agroforestry/pasture management & crop yields. Key words for the search in Portuguese include: *rotacão de culturas/cobertura do solo/pousio/variedades melhoradas/cultivo minimo/plantio direto/incorporação de resíduos/cordão vegetado/cordão de pedra/patamar de pera/reflorestamento conservacionista/estercos/adubacao organica/adubacao verde & productividade*. Key words for the search in Spanish include: *cultivos de cobertura/rotación de cultivo/variedades mejoradas/labranza cero/sebes vivas/cercas vivas/agroforesteria o agrosilvicultura/estiércol/suministros o abonos organicos & cosechas o rendimientos*. Key words for the search in French include: *stratégie amélioration de la fertilité/rotations, successions et associations cultural/gestión de l'eau/plantes fourrageres et de couverture/paillage/haie vive antiérosive/productivité.*

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 set of papers as possible. For each case study, the following information is reported in the database: detailed description of the practice(s) adopted, crop(s), location (geography, climate), information about land-use history, and yield variation with respect to previous conventional agricultural practices.

[5] Unfortunately, we could not find useful quantitative data from this source of information. In fact, as shown in a recent study which reviewed 25 impact evaluations, largely from unpublished sources (van den Ban and Hawkins 1996), in assessing the results of Farmer Field School (FFS) activities, no agreement has yet to be reached as to what to measure and how to measure it. Nevertheless, almost unanimously, studies have demonstrated notable increases in rice, cotton and vegetable yields (Braun et al. 2006) consequent to the implementation of FFSs.

[6] Such as a technology for which there is evidence that the technology has been used or adopted by target beneficiaries (farmers), especially in rural areas, and that it can be easily reproduced, shows maturity by successful application in projects, the information that is available is a public good and has been developed with a participatory approach, and contributes to the increase in yields by making sustainable use of natural resources (FAO 2011).

[7] We examined reports such as: Staff Appraisal Report (SAR), Project Appraisal Document (PAD) and Completion Report (ICR). Unfortunately, due to a complicated and long consultation procedure, it was possible to extract only a limited amount of information. Also, in many cases, project documents provided only qualitative information or reported the impact of the whole technology package, without providing the productivity effect of the single management practices adopted.

Overall, 217 observations from about 160 publications were included in the database for the current study.[8] The database covers five main management practices – agronomy, integrated nutrient management, tillage and residue management, water management and agro forestry – applied in three regions – Asia and Pacific, Latin America and sub-Saharan Africa – 41 countries – Bangladesh, Benin, Bolivia, Botswana, Brazil, Burkina, Cameroon, China, Colombia, Dominican Republic, DR Congo, El Salvador, Ethiopia, Ghana, Ghana, Guatemala, Honduras, India, Indonesia, Kazakhstan, Kenya, Malawi, Mexico, Morocco, Mozambique, Nepal, Niger, Nigeria, Pakistan, Paraguay, Peru, Philippines, Rwanda, Senegal, South Africa, Sri Lanka, Tanzania, Togo, Uganda, Vietnam, Zambia and Zimbabwe – and mainly over cereals—maize, wheat, sorghum, millet and teff (see Tables 2 and 3).

Table 2. Dataset description: number of observations by management practice

Management practice	Cereals	Other crops	Total
		n.	
Agronomy	28	10	38
Integrated nutrient management	24	7	31
Tillage and residue management	55	15	70
Water management	44	8	52
Agroforestry	20	6	26
Total	171	46	217

Table 3. Dataset description: number of observations by geographical area

Region	Cereals	Other crops	Total
		n.	
Asia and Pacific	49	10	59
Latin America	**32**	**15**	**47**
Sub-Saharan Africa	90	21	111
Total	**171**	**46**	**217**

2.2 Study designs

The studies used in the current review are essentially journal articles and reports of academic research, edited books and book sections, and project reports. Although seemingly a large number of studies are available on the topic – since many articles cite evidence from others – the number of original field studies is considerably more limited. However, the search was expanded using the World Overview of Conservation Approaches and Technologies (WOCAT 2011) database which 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).

Most publications in the database make reference to original project data and report findings from projects aimed at promoting the adoption of improved cropland practices in a specific area and implemented by local institutions, often in cooperation with scientists (e.g. Altieri 2001; Edwards

[8] The number of observations (data points) does not coincide with the number of publications for two reasons: if the publication reports a separate analysis for different countries or for more than one crop type, then the corresponding results were considered as separate cases in the database; in some cases one observation results from more than one publication (e.g. data reported in WOCAT database of technologies).

2000; Erenstein et al. 2007; Garrity 2002; Hine and Pretty 2008; Jagger and Pender 2000; Kassie et al. 2008; Kaumbutho and Kienzle 2008; Pender 2007; Place et al. 2005; Pretty 1999; Scialabba and Hattam 2002; Sharma 2000; Shetto et al. 2007; Sorrenson 1997; Verchot et al. 2007). Most of these studies report results of observations over a limited number of years. However, some also report results of long-term observations: e.g. Sorrenson (1997) analyzed the profitability of Conservation Agriculture on farms in two regions of Paraguay over ten years.

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 of organic organisations, NGOs and academics, 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-favoured areas of this region; Derpsh et al. (2010) report and comment on results from previous studies on tillage management.

Only in a limited number of cases have results of research experiments been included, specifically in the case of long-term or worldwide experiments or when a relatively high number of farmers have been involved: e.g. 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 crop rotations maize/wheat, zero tillage and residue management practices have been successfully tested; Hossain et al. (2003) assessed the contributions of international research centres to rice productivity gains in the developing countries of Asia and Latin America over the period 1965-99, through a questionnaire and in-depth interviews; Rockstrom et al. (2009) conducted on-farm trials over 1999-2003 in eight different locations at 11 experimental sites, engaging varying numbers of farmers at each site.

Unfortunately, in most cases the publications reviewed do not explain clearly how the information on the effect of the SLM practices on the yields were collected. Only a limited number of studies used proper impact analysis to document the effect of the introduction of the new technologies. For example, in the study by CIAT (2008) – aimed at estimating the impacts of new bean varieties released in eastern, central and southern Africa – the Pan-Africa Bean Research Alliance (PABRA) coordinated a set of impact studies: field research was conducted between 2004 and 2006 in Kivu province of DR Congo, Ethiopia, western Kenya, Malawi, northern Tanzania, Rwanda and Uganda, and data for the country studies was obtained through sample surveys covering 2,476 farm households. Place et al. (2005) combined qualitative and quantitative analysis: quantitative measures from surveys, enumerator ratings and farmer self-assessments and qualitative research methods. Stoll (undated) reported impacts of programmes and projects promoting SLM technologies. Some studies report the results of surveys conducted among farmers: e.g. Ekboir et al. (2002) asked an open-ended question about the three most important changes that no-till brought to farming activities and a majority of the farmers (62%) mentioned higher yields; Erenstein et al. (2007) used community-level surveys to compare yields from smallholders under conventional tillage (high-intensity agriculture) and zero tillage in Zimbabwe; Franzel et al. (2004) used questionnaires to document the results of other report results of farm-led trials conducted after researcher-led trials.

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: e.g. 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; Pretty (1999) examines a typology of eight technology improvements currently in use in 45 sustainable agriculture projects in 17 countries, finding that some 730,000 households have substantially improved food production thanks to cereal yield increases. Also, some studies report results under different climatic conditions: e.g. Kassie et al. (2008) use two sets of plot-level data for their empirical analysis in Ethiopia, one from a low rainfall region (Tigray: 500 farm households, 100 villages, 50 peasant associations and 1,797 plots) and another from a high rainfall region (Amhara: 435 farm households, 98 villages, 49 peasant associations and about 11,434 plots).

To isolate the production effects of the improved cropland management technologies, in many cases the results have been compared with control areas where the practices have not been implemented (e.g. Erenstein et al. 2007; Franzel et al. 2004; Hellin and Haigh 2002; Hödtke et al. (undated); Li et al. 2008). In other cases, the long-term trends in crop yields have been modelled for several alternative technology options and compared to crops produced under conventional management practices, on the basis of extensive farm-experiments (e.g. Garrity 2002, Nelson et al 1998).

In almost all cases included in the literature database, publications have analyzed the results of peasant farming projects which deal with small-size 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.

2.3 Literature review and empirical analysis

We have analysed the effect of adopting improved cropland management technologies on crop productivity through a traditional literature review – examining the publications collected as described above – complemented by the analysis of empirical evidence, using the results from the individual studies contained in the database of publications. 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; Gurevich 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.[9] Most of the studies did not report any measure of variance for the crop yields resulting from the implementation of the improved practices. Thus, only effects on the average yield have been considered.

Since the main goal of the empirical analysis was to determine whether the implementation of various improved cropland management practices elicited quantitatively different responses in crop yields, we considered 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 climate conditions. We also tested whether there are significant differences in mean response among various categories of cropland management technologies (range, standard deviation and coefficient of variation).

Per each management practice – agronomy, integrated nutrient management, tillage and residue management, water management, agroforestry – a crop (or group of crops) is selected and the percentage variation of yield with respect to conventional agricultural practices by agroclimatic conditions (dry/humid) is examined. Some of the studies report the change in crop yields in absolute terms (t/ha), while others report data in percentage yield change due to the introduction of improved practices. To make the results comparable, all data have been transformed into

[9] See also footnote 8 above in the text.

percentage change with respect to the average yield (using the approximate average yield for the specific crop and country and under the prevailing climate characteristics of the project area, when available).

3. Results

This section presents the evidence base of the impact of selected improved cropland management options on crop yields as a result of the literature review (Section 3.1) and of the quantitative analysis of the empirical evidence (Section 3.2).

3.1 Global trends from the literature review

The main benefit of implementing improved cropland management practices is expected to be higher and more stable yields, increased system resilience and, therefore, enhanced livelihoods and food security, and reduced production risk (Conant 2010; Vallis et al. 1996; Pan et al. 2006; Woodfine 2009; Thomas 2008).

In this next section, we summarize findings from a global literature review on yield effects of the adoption of specific improved crop management practices. To the extent possible, we distinguish between agro-ecological and farming system type, as well as long run vs. short run effects. However, the analysis of these factors is highly constrained by the availability of information in the literature cited.

Use of *cover crops* is reported to lead to higher yields due to decreased on-farm erosion and nutrient leaching, and reduced grain losses due to pest attacks. For example: Kaumbutho et al. (2007) showed that maize yield increased from 1.2 to 1.8-2.0 t/ha in Kenya with the use of mucuna (*Velvet Bean*) cover crop; Olaye et al. (2007) showed that there was a significant yield loss of about 31.4-42.4% in the long run and 36.7-48.5% in the short run for continuous maize planting compared to maize cropped using different cover crop types—*Cajanus* spp. (e.g. *Pigeon pea*) and mucuna; Pretty (2000) showed that farmers who adopted mucuna cover cropping benefited from higher yields of maize with less labour input for weeding (maize following mucuna yields 3-4 t/ha without application of nitrogen fertiliser, similar to yields normally obtained with recommended levels of fertilisation at 130 kgN/ha); Altieri (2001) reported that maize yields in Brazil increased by 198-246% with the use of cover crops.

Crop rotations and *intercropping* designed to ensure differential nutrient uptake and use – e.g. between crops, such as millet and sorghum and Nitrogen-fixing crops, such as groundnuts, beans and cowpeas – will enhance soil fertility, reduce reliance on chemical fertilizers, and enrich nutrient supply to subsequent crops (Conant 2010), 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 to 3,414 kg/ha (71% increase in yields) and bean yields to 258 kg/ha (158% increase in yields); Hodtke et al. (undated), as cited by Parrot and Marsden (2002), report that, in Brazil, intercropping maize with legumes led to increases in both grain yield and total nitrogen content by 100%.

Increased crop yields after a *fallow* period have been widely reported (Agboola 1980; Hamid et al. 1984; Saleen and Otsyina 1986; Prinz 1987; Palm et al. 1988; Conant 2010), although the magnitude of yield increment after each successive fallow is variable, and bare fallow may increase soil erosion risk.

The use of *improved crop varieties* is expected to increase average yields because of the greater seed diversity of the same crop. For example, Pretty (2000) showed that introduction of new varieties of crops (vegetables) and trees (fruits) increases yields in Ethiopia by 60%; the International Centre for Tropical Agriculture (CIAT 2008) showed that the average yield increase due to the introduction of new bean varieties in seven African countries was 44% in 2004-2005, although the gains varied widely across countries, ranging from 2% in Malawi to 137% in western Kenya.[10]

Adopting organic fertilization (compost and animal 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; 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; and Scialabba and Hattam (2002) showed that potato yields increased by 250-375% (from 4 to 10-15 t/ha) in Bolivia. Altieri (2001) quotes several examples from Latin America where adoption of organic fertilization and composting led to increases in maize/wheat yields between 198-250% (Brazil, Guatemala and Honduras) and in coffee yield by 140% (in Mexico); Edwards (2000) showed that in the Tigray province of Ethiopia, composting led to yield increases compared to chemically fertilized plots: barley (+9%), wheat (+20%), maize (+7%), teff (+107%), and finger millet (+3%); Rist (2000), as cited in Parrott and Marsden (2002), reports that farmers in Bolivia increased potato yields by 20% using organic fertilizers. Also, enhancing inputs of nitrogen through nitrogen-fixing plants that are not harvested (green manure) is key to maximizing production and ensuring long-term sustainability of agricultural systems (Fageria 2007; Hansen et al. 2007). For example, Kwesiga et al. (2003) showed that in Zambia, including *Sesbania sesban* (an indigenous nitrogen-fixing tree) fallow in rotation led to increases in yields for maize with respect to continuous cropping. Maize yields increased from 6.75 to 7.16 and 7.57 t/ha following 1, 2 and 3 years fallow, showing that short leguminous fallow rotations of 1-3 years have the potential to increase maize yields even without fertilizers, thanks to the nitrogen-fixation capacity and mineralization of the belowground root system.

Increasing the proportion of nutrients retained in the soil – e.g. through mulching and limiting nutrient leaching – is also expected to have positive effects on crop yields (Smolikowski et al. 1997; Conant 2010; Silvertown et al. 2006). For example, Lal (1987) reported yield increases by incorporating residue mulch of rice husks (about 6 t/ha) on different crops—from 3.0 to 3.7 t/ha on maize, 0.6 to 1.1 t/ha on cowpea, 0.6 to 0.8 t/ha on soybean, 16.4 to 28.3 t/ha on cassava and 10.7 to 17.9 t/ha on yam. Also, soil water contents are generally higher under mulch cover (Unger et al. 1991; Arshad et al. 1997; Barros and Hanks 1993; Scopel et al. 2004).

Tillage systems – which adopt no-tillage, minimum tillage and crop residue management – provide opportunities for increasing soil water retention. Therefore, crop yields are often higher than under conventional tillage (Derpsch and Friedrich 2009), especially in semi-arid and dry sub-humid agroecosystems. For example, substantial increases in rain-use efficiency with implementation of conservation tillage practices in sub-Saharan Africa are reported by Rockstrom et al. (2009). Studies examining maize production in semi-arid Mexico produced similar results (Scopel et al. 2005). Also, in semi-arid areas, no-tillage benefits seem to be higher on severely degraded soils because of low organic matter content and poor physical conditions (Acharya et al. 1998).

There is also evidence of yield and soil improvements from humid tropical and temperate agroecosystems (e.g. Rasmussen 1999; Diaz-Zorita et al. 2002; Bronick and Lal 2005), where primarily minimum and zero-tillage practices are applied. In semi-arid sub-Saharan Africa, documented success with minimum tillage practices is limited and scattered, largely in relation to certain development projects, e.g. in Tanzania and Zambia (Rockstrom and Jonsson 1999), even though significant success has been reported from commercial farms (Oldreive 1993). Conservation farming success in Africa remains concentrated to more humid environments where many studies report positive effects on crop yields compared to traditional tillage management: Hine and Pretty

[10] New varieties were planted on 49% of total bean acreage in 2004-2005, but the proportion varied across countries (DR Congo-Kivu 68%, N. Tanzania 56%, Malawi 68%, Rwanda 43%, and Uganda 31%).

(2008) report increases in maize yields (+34%) and soya (+ 11%) in Argentina; Hine and Pretty (2008) record increases in yields of maize (+67%, from 3 to 5t/ha) in ten years and soya (+68%, from 2.8 to 4.7 t/ha) in Brazil (Paraná and Rio Grande do Sul) and again maize (+ 47%), soya (+83%), and wheat (+82%) in Brazil (Santa Caterina).

Proper *water management* can help capture more rainfall (Vohland and Barry 2009), making more water available to crops, and using water more efficiently (Rockstrom and Barron 2007), which are crucially important for increased agricultural production (Conant 2010; Rockstrom et al. 2010). *Bunds/Zai and Tied Ridge Systems* generate higher yields, particularly where increased soil moisture is a key constraint (Lal 1987). *Terraces and contour farming* practices can increase yields due to reduced soil and water erosion and increased soil quality: Altieri (2001) showed that restoration of Incan terraces has led to 150% increase in a range of upland crops; Shively (1999) finds that contour hedgerows can improve maize yields up to 15% compared with conventional practices on hillside farms in the Philippines; Dutilly-Diane et al (2003) reported an increase millet yields from 150-300 to 400 kg/ha (poor rainfall) and 700-1,000 kg/ha (good rainfall) in Burkina Faso; and from 130 to 480 kg/ha in Niger but also note that bunds lead to increased yields in the low and medium-rainfall areas, but lower yields in the high rainfall area (which had exceptionally high rainfall the year of the survey). Dosteus (2011) reports that building excavated terraces (bench/fanya juu[11]) in the Ulugurus mountains in Tanzania has improved soil composition: for example, soil testing results have shown that the average moisture level in areas with terraces/ fanya juu is higher than in areas without structures (1.6% vs 0.3%) and average soil compaction is lower than in areas with no terraces (1.05 km/m^2 vs 3.05 km/m^2). Consequently, crop performance in areas with interventions has improved in terms of crop growth rate and yields: maize and beans yields harvested on excavated structures increased three times. Also, farmers were able to introduce high value crops like tomato, cabbage and spices (Dosteus 2011). Posthumus (2005) showed that in Peru yields obtained with bench terraces are higher than yields without terraces for maize in Pachuca (640 versus 408 Kg/ha) and for potato in Piuray-Ccorimarca (3,933 versus 850 kg/ha). However, it is also found that the yield increase is nullified by the amount of area lost (20%) due to the terracing, which makes it necessary to fully exploit the terraces (e.g. cultivation of a second crop during the dry season, use of organic fertilizers, or use of irrigation) in order to counterbalance the production loss (Posthumus 2005).

Water harvesting techniques (e.g. run-off collection techniques, water storage tank construction, use of devices for lifting and conveying water, microcatchment water conservation with film mulching) also increase yields: 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 50% increase in productivity in eastern and central Kenya; Pretty (2000) report that cereal yields went up more than 100% in Zimbabwe thanks to the implementation of water harvesting technology.

Agroforestry refers to land use practices in which woody perennials are deliberately integrated with agricultural crops, varying from very simple and sparse to very complex and dense systems. It embraces a wide range of practices (e.g. farming with trees on contours, intercropping, multiple cropping, bush and tree fallows, establishing shelter belts and riparian zones/buffer strips with woody species etc.) which can improve land productivity providing a favourable micro-climate, permanent cover, improved soil structure and organic carbon content, increased infiltration and enhanced fertility (WOCAT 2011) reducing the need for mineral fertilizers (Schroth and Sinclair 2003; Garrity 2004). For example, Sharma (2000) as cited by Parrott and Marsdem (2002) reports yield

[11] A *Fanya juu* (“throw it upwards” in Kiswahili) terrace comprises embankments (bunds) which are constructed by digging ditches and heaping the soil on the upper side to form the bunds which are usually stabilized with grass strips (WOCAT, 2007).

increases of 175% on farms in Nepal; Soto-Pinto (2000) studied outputs from shade grown coffee production in Mexico and found that shaded groves had yields 23-38% higher; Verchot (2007) reported an increase in maize yields from 0.7 to 1.5-2t/ha in Malawi. Use of live fences is also expected to increase yields (e.g. Ellis-Jones and Mason (1999) reports increased from 13.5 to 31.7t/ha of cassava yields) although results are controversial: e.g. Hellin and Haigh (undated) reports no difference in yields from adoption of live barriers/fences. A summary of these findings is reported in Table 4.

Last, while we do not present detailed results relating to pasture management, it is worth noting that SLM practices on grasslands can have a positive impact on food security by livestock yields. Research has documented that *improved pasture management* by improving vegetation community structure (e.g. seeding fodder grasses or legumes with higher productivity and deeper roots) can lead to higher livestock yields due to greater availability of better quality forage with potential increased returns per unit of livestock (Sleugh et al. 2000; Hussain 2007). Adopting *improved grazing management* (stocking rate management, rotational grazing, enclosures to allow degraded pasture to recuperate) has also the potential to increase livestock yields. For example, Derner (2008) showed that average daily gains (kg/head/day) decreased with increasing stocking rate and grazing pressure: heavy stocking rates reduced average daily gain by 16% and 12% compared to light and moderate stocking rates, respectively. Haan (2007) reported that grazing cattle return to the pasture over 80% of Phosphorus and other nutrients consumed in forage (Berry et al. 2001), and these nutrients become available to support forage growth and livestock productivity (Bakker et al. 2004). However, as noted above, for the most part there is very limited evidence on changes in livestock productivity from various management options, and even the extent to which there is documented overgrazing (c.f. the review in Vetter 2009) particularly in semi-arid regions. Thus, we do not delve into these issues further here.

Table 4. Impact of improved cropland management practices on crop yields: summary of global trends

Practices	Details of the practices	Impacts on Crop Yields
Improved agronomic practices	Cover Crops	Higher yields due to reduced on-farm erosion and reduced nutrient leaching. E.g. Kaumbutho et al. (2007); Olaye, et al., (2007); Pretty (2000); Altieri (2001)
	Crop rotations	Higher yields when cropped, due to increased soil fertility. E.g. Kwesiga et al. (2003)
	Improved Varieties	Increased crop yield. E.g. Pretty (2000); CIAT African Coordination Kawanda Ag Research Institute (2005); Hine and Pretty (2008)
	Use of legumes in the rotation	Higher yields due to increased N in soil. E.g. Hine and Pretty (2008); Hodtke, et al (undated), as cited by Parrot and Marsden (2002);
Integrated nutrient management	Increased Efficiency of N Fertilizer; organic fertilization; legumes and green manure; compost; animal manure.	Higher yields through through increased soil fertility and more efficient use of N fertilizer. E.g. Hine and Pretty (2008) ; Parrot and Marsden (2002); Scialabba and Hattam (2002) ; Altieri (2001); Edwards (2000); Rist (2000), as cited in Parrott and Marsden
Tillage/residue management	Incorporation of Residues	Higher yields through increased soil fertility, increased water holding capacity. E.g. Lal (1987)
	Reduced/Zero Tillage	Higher yields over long run, particularly where increased soil moisture is valuable. E.g. Hine and Pretty (2008)
Water management	Irrigation	Higher yields, greater intensity of land use. E.g. Khan (2005)
	Bunds/Zai, Tied Ridge System	Higher yields, particularly where increased soil moisture is key constraint. E.g. Lal (1987), Kasie (2008)
	Terraces, contour farming	Higher yields due to reduced soil and water erosion, increased soil quality. E.g. Shively (1999); Altieri (2001); Dutilly-Diane et al (2003); Posthumus (2005)
	Water harvesting	Higher yields. E.g. Parrott and Marsden (2002); Parrott and Marsden (2002), Pretty (2000)
Agroforestry	Live Barriers/Fence	Higher yields. E.g.: Hellin and Haigh (-); Ellis-Jones and Mason (1999)
	Various agroforestry practices	Potentially greater food production, particularly if undertaken on marginal/less productive land within the cropping system. Greater yields on adjacent croplands from reduced erosion in medium-long term, better rainwater management; and where tree cash crops improves food accessiblity. E.g.: Sharma (2000) as cited by Parrott and Marsdem (2002); Soto-Pinto (2000) ; Verchot et al (2007)

Table 4 summarizes the results of the review by major category of practice. There are three important trends that emerge from this analysis related to the potential of these practices to be widely adopted and benefit smallholder farmers as well as the global community.

First, the practices can be adopted in a wide range of different combinations, and this matters very much for impacts on yields as well as externalities across different locations. It depends very much on the entire package that is adopted in terms of yield effects Table 5 exhibits the range of practices in different systems for on location in Brazil – indicating the range of farm effects realized. FAO 2010 and Bassi 2009 provide other examples. This issue of packaging and combining practices is clearly key to obtaining desired results from SLM adoption and creates difficulties in generating comparisons across sites and combinations of technologies.

Table 5. Impact of improved cropland management technology packages on crop yields: an example from Brazil

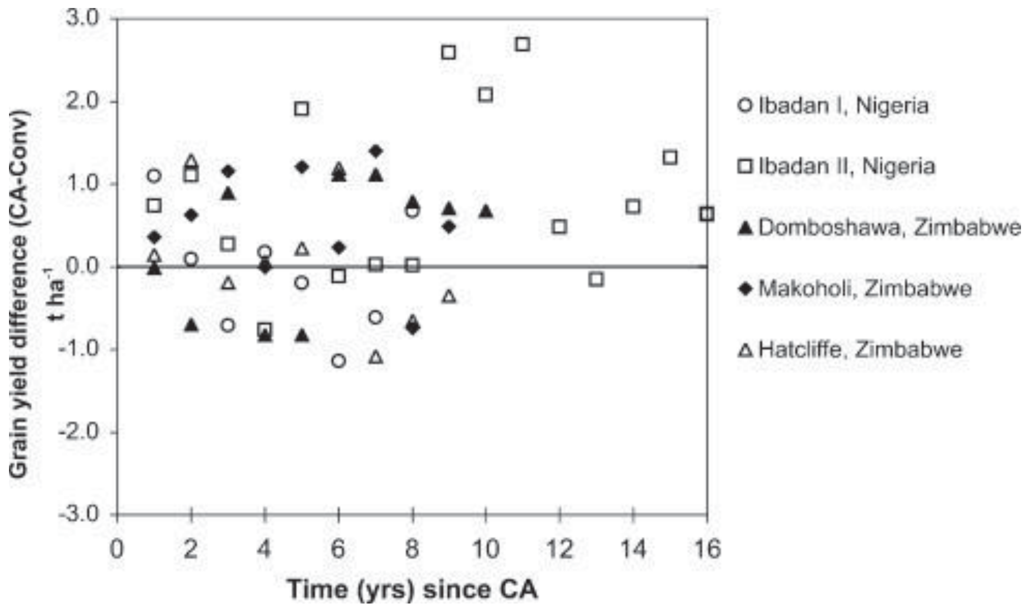
Profitability of adopting SLM practices: some examples of improved cropland management in Brazil					
Activity	Area	Specific practices	Average productivity increase (%)	Average farm net Income increase (%)	Project time horizon (%)
Millet, soybeans, coffee, oranges	S.Paulo	Contour cropping, summer and winter rotation crops, minimum tillage, IPM	50.3	40.7	10
Maize and other grains, beans, banana, cassava	S.Caterina	Conservation agriculture and agro-forestry	205.0	161.0	15
Cotton, maize, pastures	S.Paulo	Terracing, minimum tillage, agro-forestry, integrated nutrient management	45.5	69.3	5-7
Maize and other grains	Parana	Vegetative contours, reduced tillage, terracing, integrated nutrient management	81.7	104.0	7

Source: FAO-Technical Cooperation Department

A second major issue that arises is the timing of yield effects; short run vs. long run. In many of these studies, 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, and farmers unfamiliar with such systems require a period to successfully adopt the practice (e.g. fertilizer application or the construction of water retention structures where incidence and severity of both droughts and floods are expected to increase in the future) (McCarthy et al. 2011; FAO 2009). Long-term impacts are expected to be positive for increasing both the average and 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 presents data from several field studies of conservation agriculture adoption 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.

Figure 1. Effect of conservation agriculture practices on crop yields in Nigeria and Zimbabwe



Source: Giller et al. 2009

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. 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 SLM impacts on yield. This latter conclusion is only speculation and not based on any evidence, but may be important to keep in mind as a possibility when assessing the overall conclusions from the literature.

3.2 Evidence from the empirical analysis

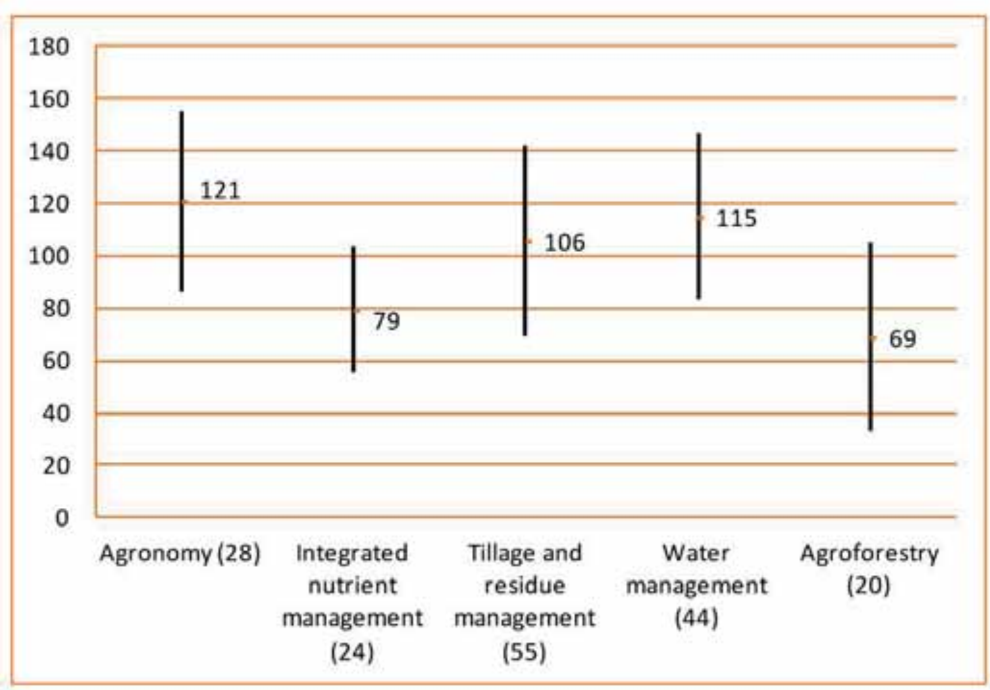
The empirical analysis focuses on the effect of the adoption of improved cropland management practices on the yields of cereals. As for other crops, the number of observations was too limited to be statistically significant (see Tables 2 and 3 above). Our analysis clearly shows that improved cropland management increased cereal productivity. Figure 2 reports the average global marginal increase in cereal productivity with respect to average yield under conventional agriculture (in percentages). However, not all categories of practices had the same impact on average yield increases (and on the variability among the average) as shown in Figure 1.

The data in Figure 1 were further analyzed in relation to the predominant climate and to the geographical area where the practices were adopted.[12] The impact of the adoption of SLM practices was tested in both dry and humid areas. Results show that agronomy practices, integrated nutrient, and water management are more effective at increasing crop yields in humid than in dry areas. On the other hand, the marginal yield increase observed under tillage management and agroforestry practices is higher in dry areas (Table 6).

[12] We also tested if the size of the farm is a variable with some effects on the average yields. As mentioned, most observations reported in the sample refer to smallholders. However, we isolated the effect of the practices on the yields of a few medium-large farms in the sample, and the farm size was found not to be a factor affecting the yields.

Figure 2. Effect of improved cropland management practices: average % marginal increase of cereal yields at global level with respect to conventional agriculture

(95% confidence intervals about the mean are shown, and numbers of observations are in parenthesis)



These results highlight the key role of water as a determinant of crop productivity. For example, 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 result as being most productive. Reduced/zero tillage (often in combination with mulching) will actually increase water availability to plants, improving the capacity of the soil surface to intercept rainfall (by affecting the hydraulic conductivity of the topsoil, soil roughness, and soil surface porosity), reducing direct evaporation, and increasing water storage (Scopel et al. 2001). Agroforestry controls runoff and soil erosion – thereby reducing losses of water – and increases water-use efficiency from crops and trees, which could be improved if used in combination with water harvesting techniques.

However, it is worth noting that the marginal yield increase shown in Table 6 is only referring to the yield change compared with yields under conventional techniques used before SLM adoption on the same fields and that the change could follow different patterns over subsequent years, depending on several factors (crops, agro-ecological conditions, previous land use, SLM practice type). Also, the sample variability should be considered—as the range of yield changes for agronomy and agroforestry practices in dry areas and for nutrient and water management in humid areas are significant (see Figures 3 and 4).

Table 6. Impact of other SLM practices on cereal yields: summary of global trends

Management practice	Average marginal yield increase with respect to conventional agriculture (%)	
	dry	moist
Agronomy	116	122
Integrated nutrient management	72	118
Tillage and residue management	122	55
Water management	92	164
Agroforestry	81	61

Figure 3. Effect of improved cropland management practices: average % marginal increase of cereal yields in dry areas with respect to conventional agriculture

(95% confidence intervals are shown and numbers of observations are in parenthesis)

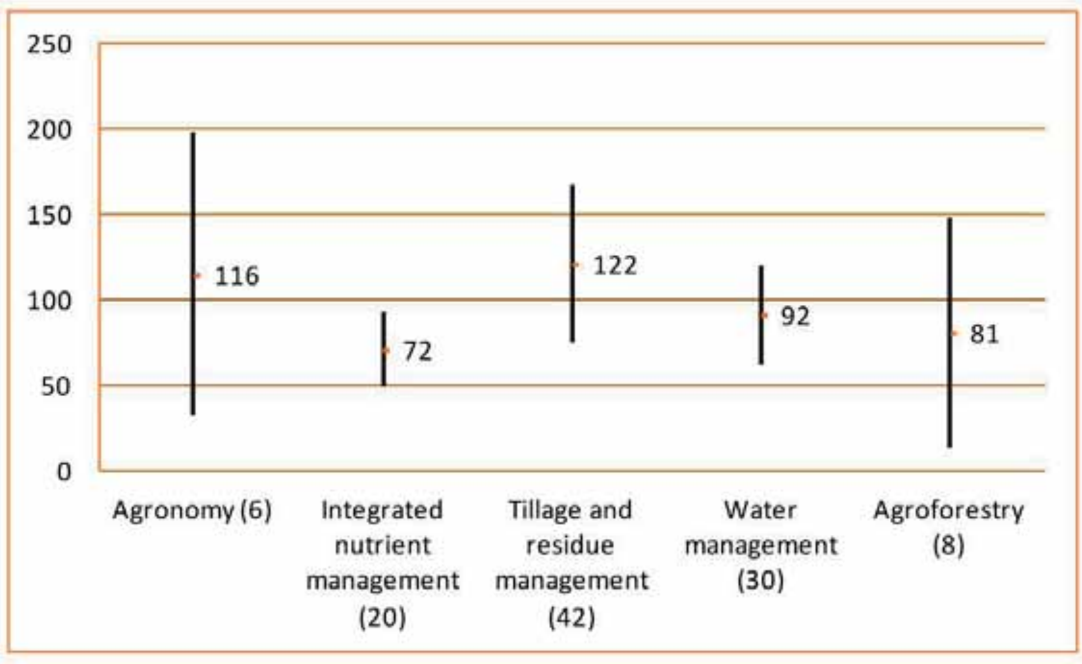
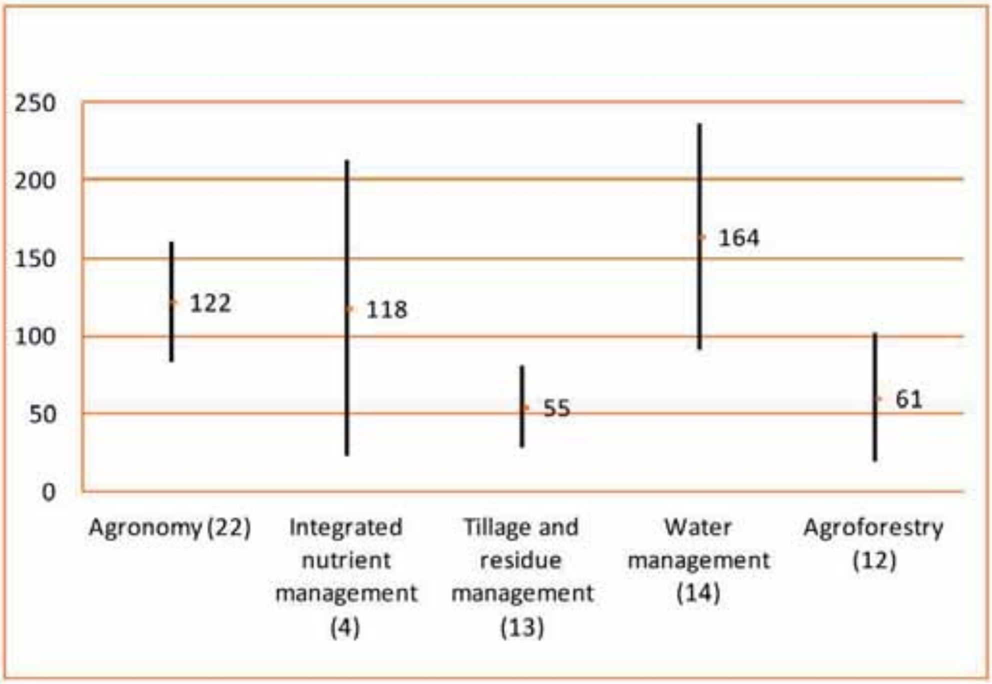


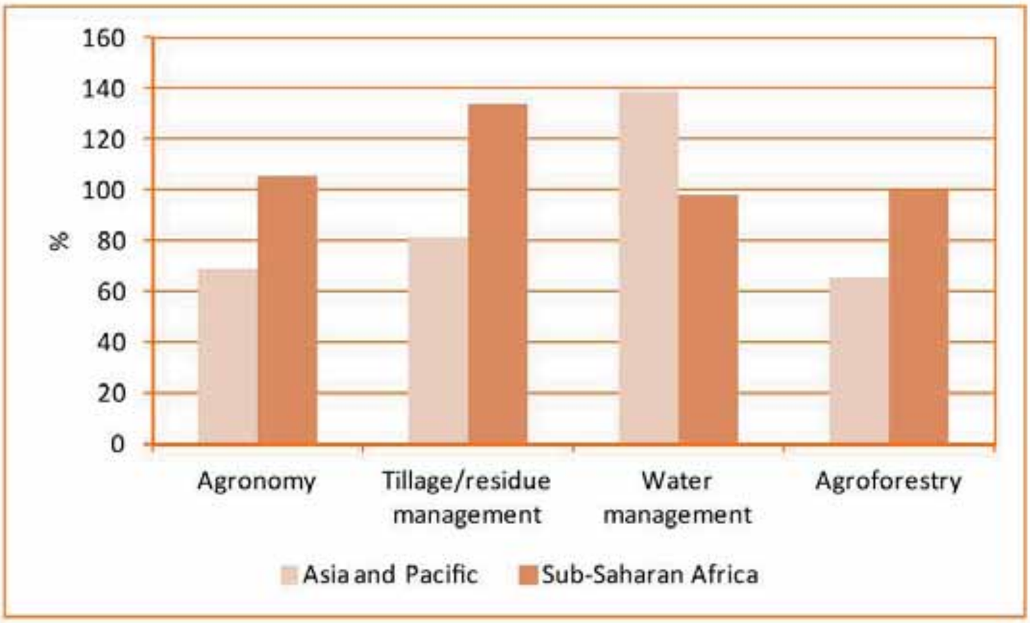
Figure 4. Effect of improved cropland management practices: average % marginal increase of cereal yields in humid areas with respect to conventional agriculture

(95% confidence intervals are shown and numbers of observations are in parenthesis)



Differences in the impact of cropland management practices at regional level were also taken into account. Interestingly, the impact was higher in sub-Saharan Africa than in Asia for most of the practices with the exception of water management (see Figure 5).

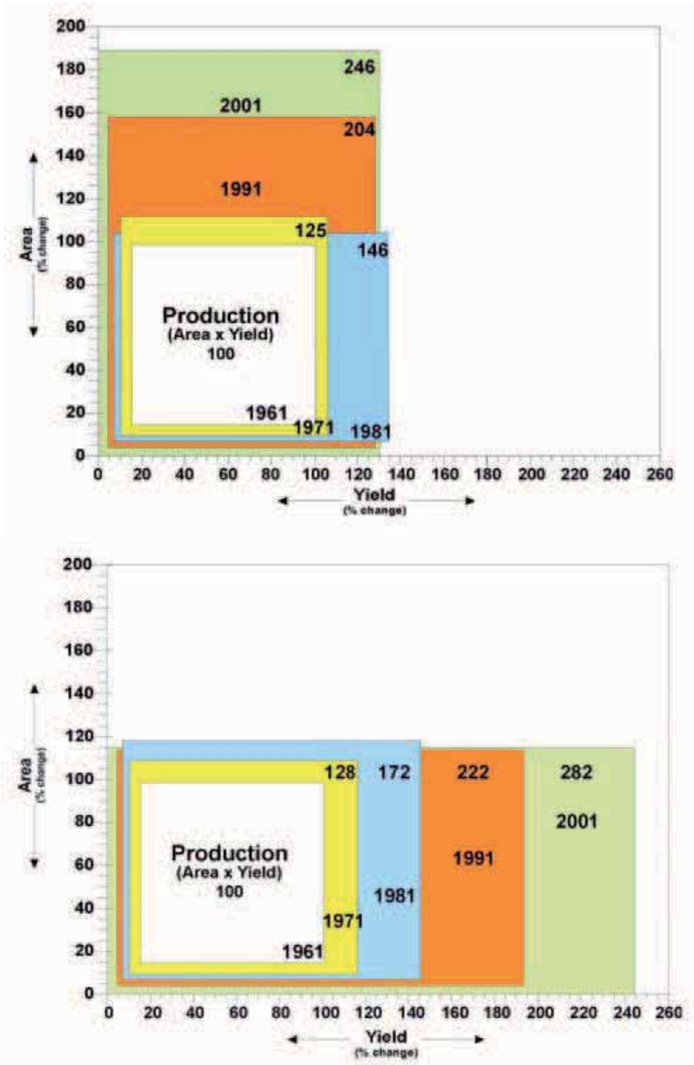
Figure 5. Regional differences in the impact of improved agricultural practices on crop yields



This could be explained by considering that in Asia soil capacity may have reached a productivity limit after the 'Green Revolution' which was based on improved crop varieties, synthetic fertilizers, pesticides, irrigation and mechanization. There is in fact evidence, albeit largely anecdotal, of increasing production problems in those places where yield growth has been most marked. For example, evidence in Southeast Asia suggest there are serious and growing threats to the sustainability of the yields of the Green Revolution lands (Pingali and Rosegrant 1998). And there is even evidence of declines in the rates of yield growth (Cassman 1999; Mann 1999; Pingali and Heisey 1999).

Crop production in Asia has increased mainly as a result of increased yields, while in sub-Saharan Africa this happened mainly by expanding the area of land under farming (Figure 6).

Figure 6. Regional differences in the increase of agricultural production



Source: Henao and Baanante 2006

The benefit from adopting improved practices is not therefore surprising for Asia and sub-Saharan Africa (where there is more potential to increase crop yields). However, limited access to and affordability of fertilizers and other inputs (e.g. improved planting material) has forced African farmers to cultivate less fertile soils on more marginal lands; these in turn are generally more susceptible to degradation and have poor potential for production (Henao and Baanante 2006). Thus, there is very limited scope for further expansion in sub-Saharan Africa without highly detrimental impacts on natural resources (e.g.

deforestation) and there is the need to increase productivity through the adoption of sustainable practices.

3.3 Synergies between food security and climate change mitigation

The literature review and the quantitative analysis of the empirical evidence have shown under which conditions improved cropland management practices can increase crop productivity therefore contributing to food security. The same practices can also deliver significant CC mitigation co-benefits in the form of reduced GHG emissions and increased C sequestration.

Improved agronomic practices have, in fact, the potential to generate higher inputs of C residue, leading to increased soil C storage (Follett et al. 2001)—introducing rotation with N fixing crops will increase biomass production, and improving land cover by avoiding use of bare fallow and using cover crops can avoid CO_2 release. Integrated nutrient management can: (i) decrease N_2O emissions on-site by reducing leaching and volatile losses; (ii) improve nitrogen (N) use efficiency through precision farming and fertilizer application timing;[13] (iii) increase C storage by increasing biomass and improving soil equilibrium to store more C; and (iv) improve soil fertility through manure management. 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, so that more soil organic carbon is reported under organic than conventional farming systems (Leiva et al. 1997).

Proper water management can enhance biomass production, increase the amount of above-ground and root biomass returned to the soil, and improve soil organic C sequestration potential by increasing available water in the root zone (Kimmelshue et al. 1995).

Tillage management practices – with minimal soil disturbance and incorporation of crop residues – decrease soil C losses through enhanced decomposition and reduced erosion. Systems that retain crop residues tend to increase soil C because these residues are the precursors of soil organic matter. For example, conservation tillage which leaves at least 30% of ground covered by crop residue mulch during seedbed preparation (Lal 1997b) increases soil organic C content when land is converted from conventional (plow-based) use. Based on average benefits of all conservation tillage systems, the C sequestration potential of adopting a conservation tillage system is about 0.15t/ha (Lal 1997a,b). Adoption of reduced tillage may also save fossil fuels at the rate of about 8 KgC/ha/year (Lal and Bruce 1999).

Different estimates of the mitigation potential of agroforestry exist (Dixon 1995; Montagnini and Nair 2004; Palm et al. 2000; Watson et al. 2000). Agroforestry systems can increase C storage in the vegetation and in the soil and may also reduce soil C losses stemming from erosion (Lal 2001b; 2004b; Bruce et al. 1999; Olsson and Ardö 2002; Paustian et al. 2004; Paustian et al. 1997; Lal and Bruce 1999; Lal 2003). The standing stock of C above ground is usually higher than the equivalent land use without trees, and planting trees may also increase soil carbon sequestration (Oelbermann et al. 2004; Guo and Gifford 2002; Mutuo et al. 2005; Paul et al. 2003). However, the effects on N_2O and CH_4 emissions are not well known (Albrecht and Kandji 2003).

Table 7 summarizes the annual mitigation potential in each climate region for the above-described SLM options expressed in units of CO_2 equivalent per hectare and per year: it shows average net mitigation through an increase in soil C stocks or N_2O and CH_4 emissions reductions. Such estimates were derived from studies conducted in regions throughout the world, standardised using a linear mixed-effect modelling approach and integrated by results of simulation models (IPCC 2007).

[13] Judicious nutrient management is crucial to humification of C in the residue and to SOC sequestration. Soils under low-input and subsistence agricultural practices have low SOC content which can be improved by judicious use of inorganic fertilizers, organic amendments and strengthening nutrient recycling mechanisms (Lal and Bruce 1999).

Table 7. Mitigation potential of sustainable cropland management technologies[14]

Climate zone	Management Practices	All GHGs (tCO2e/ha/year)
Cool-dry	Improved Agronomic Practices	0.39
	Integrated Nutrient Management	0.33
	Tillage/Residue Management	0.17
	Water Management	1.14
	Agroforestry	0.17
Cool-moist	Improved Agronomic Practices	0.98
	Integrated Nutrient Management	0.62
	Tillage/Residue Management	0.53
	Water Management	1.14
	Agroforestry	0.53
Warm-dry	Improved Agronomic Practices	0.39
	Integrated Nutrient Management	0.33
	Tillage/Residue Management	0.35
	Water Management	1.14
	Agroforestry	0.35
Warm-moist	Improved Agronomic Practices	0.98
	Integrated Nutrient Management	0.62
	Tillage/Residue Management	0.72
	Water Management	1.14
	Agroforestry	0.72

Source: IPCC 2007

Combining the results of the literature review and empirical analysis with the mitigation potential analysis from IPCC (2007), it is possible to highlight where the synergies lie between food security and CC mitigation (Table 8).

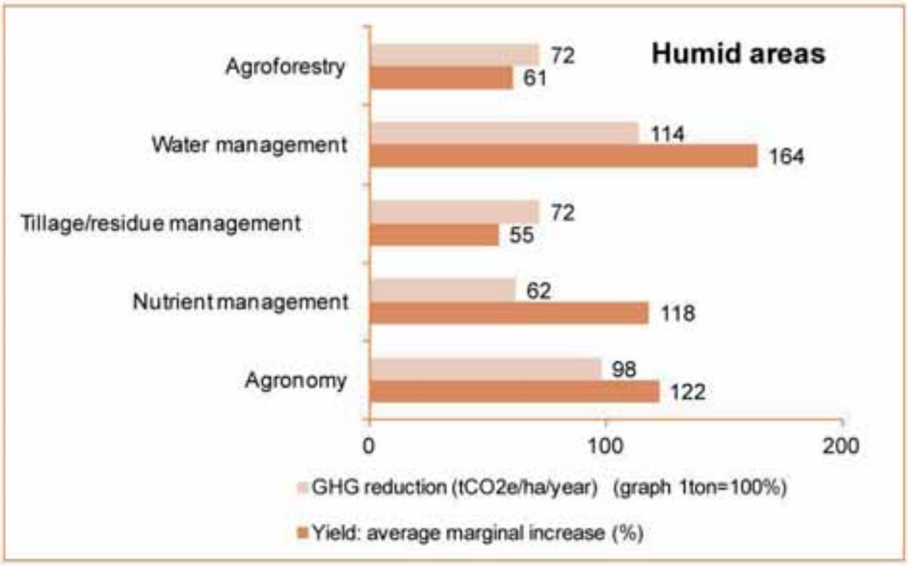
Figure 6 highlights that in dry areas the impact of the majority of the practices is more relevant in terms of increased food security than in the form of CC mitigation (with the only exception of water management which can deliver significant mitigation co-benefits also in dry areas). On the other hand, in humid areas, there is evidence of the synergies between increased crop productivity (food security potential) and CC mitigation.

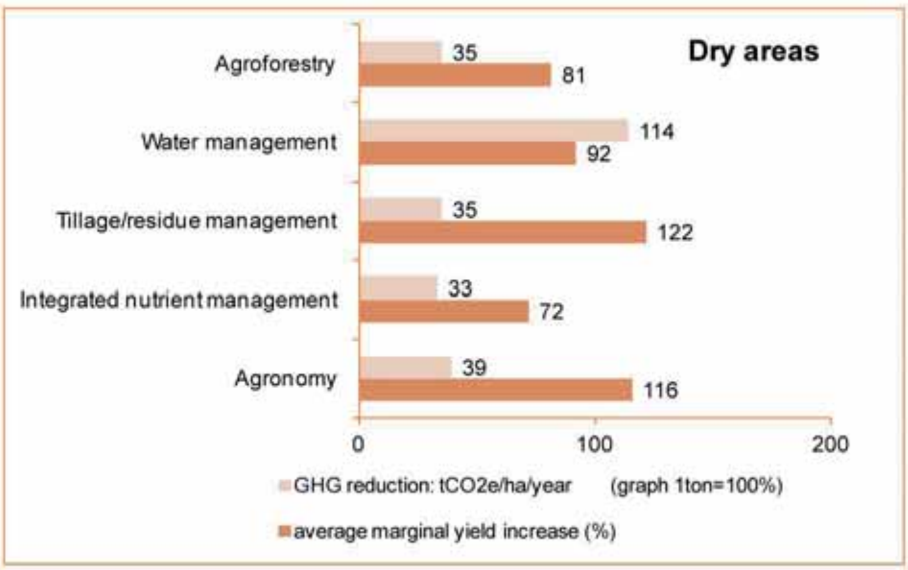
[14] The mitigation potential is expressed in terms of tCO_2e, which already accounts for the fact that some management options may cause other GHGs (CH_4 and N_2O) emissions that may partially offset the CO_2 emission reductions determined by the implementation of the practice. IPCC (2007) does not reports confidence intervals the for specific mitigation coefficients of single management practices as reported in the table. 95% confidence intervals are reported only with reference to average mitigation coefficients (all practices, by region) which are not used in the present analysis. The Climatic Zones are defined based on the classification of IPCC which makes reference to: annual mean daily temperature, total annual precipitation, total annual potential evapo-transpiration (PET) and elevation (IPCC, 2006).

Table 8. Food security and CC mitigation potential of improved cropland management practices in dry and humid areas

	MANAGEMENT PRACTICE			
	FOOD SECURITY POTENTIAL Average marginal yield increase with respect to conventional agriculture (cereals) (%/year)		MITIGATION POTENTIAL All GHGs (change in soil C stock + emissions) (tCO2e/ha/year)	
	dry	moist	dry	moist
Agronomy	116	122	0.39	0.98
Integrated nutrient management	72	118	0.33	0.62
Tillage and residue management	122	55	0.35	0.72
Water management	92	164	1.14	1.14
Agroforestry	81	61	0.35	0.72

Figure 6. Synergies between food security and CC mitigation for improved cropland management practices in humid and dry areas





4. Conclusions

We looked at changes in smallholder agriculture aimed at promoting food security through the adoption of improved cropland management practices and investigated under which conditions we can expect the highest mitigation co-benefits. Main conclusions are summarized in what follows.

Most practices (agronomy, integrated nutrient management, tillage/residue management, agroforestry) show significant CC mitigation potential in humid areas but smaller mitigation co-benefits in dry lands. Only water management is found to be effective in delivering significant food security benefits and mitigation co-benefits both in dry and humid areas. However in dry areas, the marginal benefit to food security from SLM is high – thus the marginal contribution of mitigation (soil carbon sequestration) is high. This has important implications for the potential and means of capturing synergies between mitigation and food security. The higher "productivity" (e.g. t/ha emissions reduction) in humid areas provides an economic basis for supporting higher transaction costs in mitigation crediting programmes – which is key to accessing many forms of 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 lead to large productivity gains. SLM implemented over a large enough scale, therefore, gives significant mitigation benefits, although it also requires crediting mechanisms designed for these circumstances.

Geographic differences influence the magnitude of crop productivity increases in response to the adoption of improved practices. Specifically, SLM 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 where the Green Revolution seems to have reached a productivity limit of soils). On the contrary, differences in farm size are not found to be a factor determining the impact on yields. However, most publications cited here conducted the analysis at smallholder level (only a very small number of observations refer to medium and large-scale farming) thus it is difficult to derive conclusions of general validity on the relationship between farm size and yield effects.

- The validity of our results differs across the technologies considered. Data on tillage and residue management, as well water management practices, show less variability and more consistent results than those related to other technologies. For example, agronomy practices and integrated nutrient management show a relatively high variability in the results, as they constitute heterogeneous technology packages and include practices which are significantly different in terms of soil fertility and overall agronomic effects – e.g. use of cover crops, which is often associated with tillage in CA systems, very much differ from crop rotations and use of improved crop varieties – and the use of organic fertilization techniques and green manure very much differ from technologies aimed at increasing N efficiency. Also, the effect of agroforestry practices on the yields of crops is not well documented and sometimes controversial.

- 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, potato) and legumes (e.g. beans, soybeans). Also, the studies consulted refer mainly to warm dry and warm humid areas and other climates are much less represented (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 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. Therefore, 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 CC research.

- More research is needed. Firstly, the review should be expanded (e.g. exploring grey literature, national surveys and project reports) in order to: (i) increase the number of observations and types of crops analyzed, thus improving the statistical significance of the empirical analysis; (ii) refine the analysis reporting results at the level of single practices instead of group 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); and (iii) improve evidence across different agro-ecological zones and land-use systems. Secondly, there is a need to compare this analysis with literature which looks at the establishment, maintenance and opportunity costs of SLM adoption in order to highlight the trade-offs of SLM implementation (e.g. see Antle et al. 2007; McCarthy 2011; Ringius 2002; Tennigkeit and Wilkes 2008; Tschakert 2004). Thirdly, it would be interesting to replicate the same analysis focusing on grassland productivity, sustainable grazing and pasture management, and livestock production. Fourthly, the analysis reported in the paper groups specific practices into five categories and presents results for those categories. However, there may be some types of specific practices which are worthy of further analysis, and some of these may cut across categories. For example, the use of leguminous crops in agronomy, nutrient management and agroforestry may lead to higher average yields than treatments using other crop types.

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Meeting the food demand of a global population expected to reach 9.1 billion in 2050 and over 10 billion by the end of the century will require major changes in agricultural production systems. Improving cropland management is key to increasing crop productivity without further degrading soil and water resources. At the same time, sustainable agriculture has the potential to deliver co-benefits in the form of reduced GHG emissions and increased carbon sequestration, therefore contributing to climate change mitigation. This paper synthesizes the results of a literature review reporting the evidence base of different sustainable land management practices aimed at increasing and stabilizing crop productivity in developing countries. It is shown that soil and climate characteristics are key to interpreting the impact on crop yields and mitigation of different agricultural practices and that technology options most promising for enhancing food security at smallholder level are also effective for increasing system resilience in dry areas and mitigating climate change in humid areas.

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