Agron. Sustain. Dev. (2013) 33:81–96
DOI 10.1007/s13593-012-0081-1

REVIEW ARTICLE

Agroforestry and biochar to offset climate change: a review

Ilan Stavi · Rattan Lal

Accepted: 11 January 2012 / Published online: 23 February 2012

Abstract Expansion of agricultural land use has increased emission of greenhouse gases, exacerbating climatic changes. Most agricultural soils have lost a large portion of their antecedent soil organic carbon storage, becoming a source of atmospheric carbon-dioxide. In addition, agricultural soils can also be a major source of nitrous oxide and methane. Adoption of conservation agricultural practices may mitigate some of the adverse impacts of landuse intensification. However, optimal implementation of these practices is not feasible under all physical and biotic conditions. Of a wide range of conservation practices, the most promising options include agroforestry systems and soil application of biochar, which can efficiently sequester large amounts of carbon over the long-run. In addition, these practices also increase agronomic productivity and support a range of ecosystem services. Payments to farmers and land managers for sequestrating carbon and improving ecosystem services is an important strategy for promoting the adoption of such practices, aimed at mitigating climate change while decreasing environmental footprint of agriculture and sustaining food security.

Keywords Clean development mechanism · Conservation agriculture · Ecosystem services · Global warming · Greenhouse gases · Soil organic carbon

I. Stavi (✉)
Dead Sea & Arava Science Center,
Ketura 88840, Israel
e-mail: istavi@yahoo.com

R. Lal
Carbon Management and Sequestration Center,
Ohio State University,
Columbus, OH 43210, USA

Contents

1 Introduction

Climate change and global warming have worldwide consequences. The most prominent factor driving these phenomena is the increased atmospheric concentrations of greenhouse gases (GHGs) (WMO 2007a). The main GHGs after water vapor are, in descending order, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The current atmospheric concentrations of CO_2, CH_4, and N_2O are 38%, 158%, and 19% higher than those during the pre-industrial era, reaching 387 ppm (vs. 280 ppm), 1,803 ppb (vs. 700 ppb), and 323 ppb (vs. 270 ppb), respectively (WMO 2010). During the twentieth century, average global surface temperature increased by 0.6±0.12°C and is projected to increase by 1.5–5.8°C by the end of the twenty-first century (IPCC 2007).

Emissions of CO_2 are attributed to the increased use of fossil fuels, as well as to the enhanced clearing and burning of forests (Fearnside 2000), and the expanding of agriculture. With the intensification of agriculture, world soils have become a large source of atmospheric CO_2, CH_4, and N_2O (Lal 2002) (Fig. 1). Most agricultural soils have lost from 30% to 75% of their original soil organic C (SOC) pool, namely, 30–40 Mg C ha^{-1}. Consequently, the SOC pool in agricultural soils is

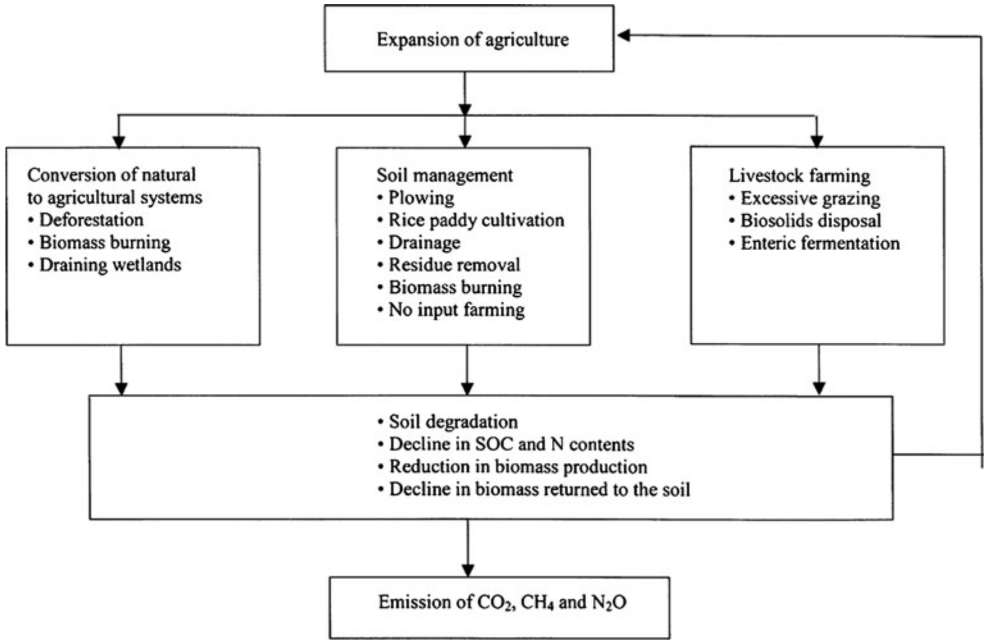

Fig. 1 Agriculture intensification and emissions of greenhouse gases from soils. *SOC* soil organic carbon. Copied with permission from Lal (2002)

much lower than their potential capacity (Lal et al. 2007). Depletion of the SOC pool in arable lands is attributed to lower input of biomass, as well as to higher outputs through oxidation, leaching of dissolved organic carbon (C), and soil erosion (Lal 2004) (Fig. 2). Global CO_2 emissions since 1850 are estimated at 78± 12 Pg from soils compared with 270±30 Pg from fossil fuel combustion (Lal 2004). Depletion of the SOC pool also degrades soil quality (Stavi and Lal 2011),and decreases crop yields (Lal et al. 2007). N_2O is emitted to the atmosphere from a range of natural and anthropogenic sources, including combustion of fossil fuels, biomass burning, and a range of industrial processes (WMO 2007b). Agricultural practices, mainly fertilizer use, also increase N_2O emission from the soil. The rate of N_2O efflux from soil varies with time, and higher rates are associated with periods of high soil moisture, high temperature, and low soil NO_3–N concentration (Perdomo et al. 2009). CH_4 is produced naturally from wetlands and through anthropogenic activity, mainly cultivation of paddy rice (*Oryza sativa* L.), and ruminant husbandry (WMO 2007b; Hobbs et al. 2008). Globally, agricultural lands account for about 25% of the CO_2, 50% of the CH_4, and 70% of the N_2O emissions (Hutchinson et al. 2007).

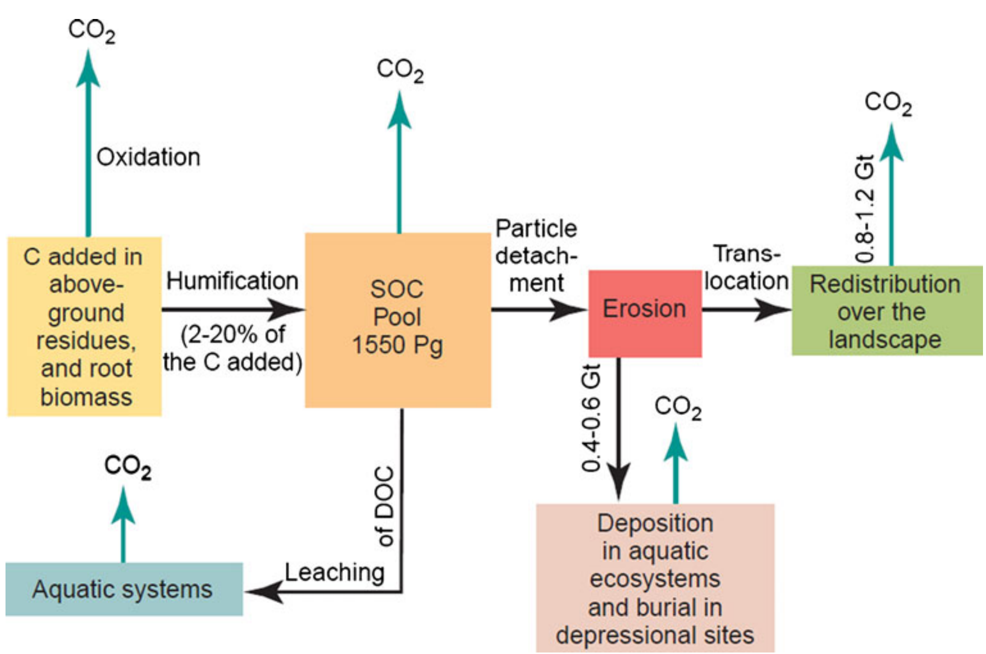

Fig. 2 Soil organic carbon dynamics. *DOC* dissolved organic carbon. Copied with permission from Lal (2004)

Increasing atmospheric concentrations of GHGs have led to a positive radiative forcing of the climate, accelerating warming of the earth surface (IPCC 1995). The radiative forcing has increased by ~23% from 1990 to 2006. The CO_2, CH_4 and N_2O are responsible for ~60%, 20%, and 6%, respectively, of the total radiative forcing of the earth's surface (WMO 2007b). The global warming potential (GWP) of CH_4 and N_2O emissions is, respectively, 21 and 310 times that of CO_2 (Forster et al. 2007). If the CO_2 emission rate had remained at levels of the mid-1990s, it would have led to a nearly constant rate of increase in atmospheric concentrations for at least two centuries, reaching about 500 ppm by the end of the twenty-first century. Stabilizing concentrations of GHGs could be achieved by drastically curtailing global anthropogenic emissions. For stabilization of CO_2 concentration at 450 or 650 ppm, accumulated anthropogenic emissions over the period 1991–2100 should not exceed 630 or 1,030 Pg C, respectively. Stabilizing atmospheric concentrations of CH_4 and N_2O at levels of the mid-1990s would require decreased anthropogenic emissions by ~10% and 50%, respectively (IPCC 1995).

The agronomic and environmental advantages of several conservation agricultural practices including reduced and no tillage, crop residue management, cover cropping, perennial pastures, and aerobic rice are widely recognized. However, most practices have a limited potential of C sequestration over the long run. Furthermore, most of these practices are not applicable under diverse physical and biotic conditions. Thus, this article is focused on two promising practices—agroforestry systems and soil application of biochar. Intensive research and development and wide adoption of these two practices could boost their C sequestration capacity and simultaneously, improve a range of ecosystem services, and advance global food security. Therefore, the objectives of this review were to: (1) demonstrate the climatic-related impacts of several conservation agricultural practices, (2) highlight the mitigation potential of climate change by the practices of agroforestry and biochar, and (3) emphasize the need for well-developed regulations, aimed at a widespread adoption of these practices by the agricultural sector.

2 The potential impact of conservation farming

Compared to intensive agricultural practices, conservation farming can reduce emissions of GHGs. Improved management of agricultural lands may simultaneously decrease fuel inputs during the production processes (Hobbs et al. 2008), increase SOC stocks, and maintain ecosystem services (Stavi and Lal 2010) (Table 1). A range of conservation agricultural methods have been often aggregated under guides for "Best Management Practices" aimed at sustaining soil resources (e.g., Ontario Ministry of Agriculture Food & Rural Affairs' website: http://www.omafra.gov.on.ca/english/environment/field/fieldcrop.htm), controlling pollution of off-site water sources (e.g., New Hampshire Department of Agriculture Markets and Food 2002) or maintaining air quality (e.g., Governor's Agricultural Best Practices Committee 2008).

Among the important aspects of conservation farming is the decreased disturbance to the structure of the uppermost soil layers. This is achieved through the practicing of reduced tillage or no-till (NT) method of seedbed preparation coupled with crop residue management. The retention of crop residues on the soil surface decreases raindrop impact, lessens aggregate slaking and dispersion (Stavi and Lal 2010), and protects the soil from water and wind erosion (Govaerts et al. 2007). The retention of crop residues also increases infiltration and decreases evaporation loss, favoring crop yields where water availability limits production. The decreased disturbance of the soil profile aids in maintaining its structure, encouraging proliferation and activity of earthworms and other soil's fauna. These effects promote wildlife biodiversity and support agro-ecosystem health (Huggins and Reganold 2008). At the same time, the reduced disturbance of the soil structure decreases emission rates of CO_2, N_2O, and CH_4 (Ussiri and Lal 2009; Ussiri et al. 2009). The resultant increase in SOC concentration further stimulates soil's structure formation and stability (Govaerts et al. 2007). In economic terms, the number of passes over a field needed to establish and harvest a crop under NT decreases dramatically, requiring 50–80% less fuel and 30–50% less labor (Huggins and Reganold 2008).

However, only about 7% of the globe's croplands are managed under NT. Of these, about 85% are in North and South America. At the same time, adoption rates of NT have remained low in Europe, Africa, and Asia. The introduction of conservation agriculture has been especially difficult in developing countries, where crop residues are often used as animal feed, fuel (Huggins and Reganold 2008), or as construction material. Among many subsistence farmers in Africa, immediate problems such as extreme poverty, food insecurity, and poor agricultural productivity are the most common competing needs for crop residues. As a result, mulching materials are often in critically low supply, increasing vulnerability of soils to erosion and degradation. In addition to these, the retention of crop residues is not always feasible, for example, where mulch is consumed by termites during a very short period after harvest (Giller et al. 2009). Furthermore, the conversion to NT from conventional farming may create a number of agronomic, environmental, and economic challenges. For example, different pest species may emerge, exacerbating infestation of soil-borne fungal diseases that tillage previously kept checked. In addition, the conversion increases the need for chemical weed control, aggravating the risks of contamination of soil and water

Table 1 Some examples of the effects of conservation agricultural practices on SOC stock, emissions of GHGs from soil, and additional ecosystem services

Agricultural practice	Location	Crops	SOC stock\CO_2 emission	N_2O emission	CH_4 emission	Additional ecosystem services	Source
No-till (NT)	USA	Corn	Increased SOC\decreased CO_2 emission	Decreased emission	Decreased emission	NA	Ussiri and Lal (2009); Ussiri et al. (2009)
Reduced tillage	NS (review)	Various	Increased SOC	NA	NA	Erosion control	Lal et al. (2007)
Occasional tillage	USA	Corn	Decreased SOC following occasional tillage	NA	NA	NA	Stavi et al. (2011)
Residue management	Mexico	Corn, wheat	Increased SOC following residue retention	NA	NA	NA	Govaerts et al. (2007)
Manuring \ composting	USA	Corn	Increased SOC but also increased CO_2 emission following composting	Increased emission following composting	Increased emission following composting	NA	Jarecki and Lal (2006)
Cover cropping	NS (review)	NS	Increased SOC	NA	NA	Decreased nutrient leaching, erosion control	Reicosky and Forcella (1998); Unger and Vigil (1998)
Pasture as a component of the multi-year cropping history	Uruguay	Various leguminous and bermuda-grass	Increased SOC	NA	NA	Erosion control	Ernst and Siri-Prieto (2009)
Perennial grasses	USA	A mix of native tallgrasses	Increased SOC	NA	NA	Supporting the soil microbial biomass and food web complexity	Culman et al. (2010); DuPont et al. (2010)
Perennial grain cropping	USA (review)	Various perennial grain crops	Increased SOC	NA	NA	Reduced contamination of water sources, erosion control	Cox et al. (2006); Glover et al. (2007)
Aerobic rice production	India	Rice	NA	Decreased emission	Decreased emission	Water saving	Mandal et al. (2010)
Precision agriculture	NS (review)	NS (review)	NA	NA	NA	Decreased nutrient leaching	Pierce and Nowak (1999)

NS not specified, *NA* not available

resources. Furthermore, it leads to high costs for purchasing of the required apparatuses, which may be prohibitive specifically for small-scale farms (Huggins and Reganold 2008). Moreover, these conservation practices are not applicable under all circumstances. For instance, intensive tillage may be inevitable in cases of soil hardening following continuous NT under dry climatic conditions (Cockroft and Olsson 2000). In addition, in cases of poor drainage, moist conditions, and temperature regimes of temperate to cool, the elimination of crop residues and the practice of intensive tillage may enhance soil drying and warming, favoring crop production (Vetsch et al. 2007). Therefore, in many long-term NT systems, the implementation of occasional tillage may be required to control spread of pathogens, as well as of weeds (Lal et al. 2007). However, occasional tillage may eliminate some of the advantages achieved by long-term NT farming. For example, in a study conducted in the Midwest region of the USA, Stavi et al. (2011) reported reduced physical quality and hydraulic conductivity, and decreased SOC concentration in the tilled layer following occasional tillage in a long-term NT agro-ecosystem.

Another common conservation practice is cover cropping, which is usually practiced during the "off-season." Cover cropping protects the ground surface from erosional processes, increases soil porosity and structure formation, recycles residual fertilizers from the soil profile, and adds organic C to the rhizosphere (Reicosky and Forcella 1998). In cases of leguminous cover crops, they can supply considerable stocks of nitrogen (N) to the soil, which are available for uptake by the subsequent main crops (Unger and Vigil 1998). Similar to residue management and conservation tillage, however, cover cropping may also not be feasible for all geographic zones and climatic conditions. For example, under relatively cool temperatures, cover crops may retard emergence and development of the main crops during the spring (Dabney et al. 2001). Under dry climatic conditions, cover cropping may deplete soil moisture reserves and decrease amounts of available water for the main crops (Unger and Vigil 1998).

An additional environmentally friendly practice comprises perennial pastures that are grown as an integral component of the multi-year cropping sequence and include a range of native and introduced grasses, forbs, and legumes for fodder or forage production. The pastures are efficient in reclaiming degraded agricultural lands while providing a range of ecosystem services, such as the increase in species diversity (Sanderson et al. 2004), the support of complex food webs, and the boost in soil health. The deep and dense root systems of pastures support the soil structure formation and C sequestration to a much larger extent than do those of annuals (Ernst and Siri-Prieto 2009; Kell 2011). In a study in Kansas, in the Midwest USA, Culman et al. (2010) studied the impact of perennial grasslands on quality and fertility of the soil up to a 1-m depth. They compared characteristics of soil under native prairie meadows that have never been tilled or fertilized and have been annually harvested for hay for more than 75 years, and of soil under annual cropping systems planted in wheat (*Triticum aestivum* L.), sorghum (*Sorghum bicolor* L.), and soybean (*Glycine max* L.), and chemically fertilized for the past several decades. Culman and colleagues reported that the perennial grasses improved the physical, chemical, and biological quality of the soil. Of special importance were the observed more developed root biomass, greater microbial biomass, more complex food web, higher SOC stock, and increased fertility under the perennial grasses than under the annual cropping systems. In the same region, DuPont et al. (2010) investigated the impact of conversion of a never fertilized, periodically burnt, and annually harvested native tallgrass prairie to a NT annual cropland consisting of soybean, sorghum, and wheat. The conversion was conducted by using herbicides and without tillage. However, DuPont and colleagues reported that the soil under annual crops faced a considerable decrease in readily oxidizable C and in microbial biomass and a substantial modification in soil biota.

In functional terms, a somewhat similar case includes perennial grain crops, such as intermediate wheatgrass (*Elytrigia elongata*), Aleppo millet grass (*Sorghum halepense)*, and Maximilian sunflower (*Helianthus maximiliani*), which develop large and dense root systems (Cox et al. 2006). Compared with the annual grain crops, the perennials are characterized as low-input crops, with a small environmental footprint, and with a high C sequestration capacity (Glover et al. 2007; Kell 2011). These crops are therefore capable of maintaining ecosystem services, particularly on marginal lands or where resources are limited (Glover et al. 2010). However, the perennial grain crops' culture is still in initial stages of development and faces several challenges. Additional research is needed in breeding and husbandry, specifically aimed at increasing crop yields and commercial viability (Cox et al. 2006; Glover et al. 2007, 2010). Shrubby and viney leguminous crops represent an intermediate case of semi-perennials that are vigorous producers of N-enriched vegetation that live longer than the typical annuals (Snapp et al. 2010). In Malawi, Snapp et al. (2010) examined the potential of the grain legume semi-perennials pigeon pea (*Cajanus cajan* L.), mucuna (*Mucuna pruriens* L.), and tephrosia (*Tephrosia vogelii*) in increasing corn (*Zea mays*) production through intercropping (in space) and rotation (on the temporal axis). Overall, they reported that intercropping had no consistent effect on productivity of the agro-ecosystems. However, in the rotational systems, corn grain yields were similar on a 2-year basis when planted continuously and when rotated with the semi-perennials. At the same time, the nutritional value of the rotational systems was much higher due to the high protein yield of the legumes. In addition, both fertilizer efficiency and stability of yield were greater in the rotational systems than in continuous non-fertilized or fertilized corn.

In regard to rice farming, conversion of paddies to aerobic production systems may considerably decrease CH_4 emissions and diminish denitrification losses of N. However, at the same time, such a conversion would considerably increase CO_2 emissions from the soil (Smith et al. 2003; Kögel-Knabner et al. 2010). Furthermore, the conversion to aerobic conditions may exacerbate infestation by weeds and pests, augmenting the need of using herbicides and pesticides.

Advances in development of information technologies and related data processing procedures enable the utilization of precision farming systems, aimed at decreasing the farms' operational costs while reducing the environmental footprint of agriculture (Pierce and Nowak 1999). These advances are especially relevant to nutrient management and can considerably decrease fertilizer input, thereby reducing emissions of N_2O (Smith et al. 2008), diminishing eutrophication of off-site water sources, and increasing economic returns (Hatfield 2000). In addition, precision farming is also useful for weed and pathogen control, reducing the economic and environmental costs associated with the utilization of herbicides and pesticides (Pierce and Nowak 1999). The lower energy input on fuels and chemicals also decreases emissions of CO_2 at the global level. However, wide adoption of precision agriculture in many developing countries is constrained, as the required information technologies and associated facilities are relatively expensive and not accessible for subsistence farmers.

Overall, it seems that the offset potential of climate change by the above discussed conservation practices is site dependent and vary greatly according to the prevalent conditions. While a specific practice may sequester C and decrease emissions of GHGs under certain conditions, it may increase oxidation of SOC and promote emissions of GHGs under other conditions. Moreover, some of the conservation practices are not applicable under wide ranges of physical and biotic conditions. In addition, to some extent, a sort of tradeoff occurs for these practices between C sequestration and adverse agronomic and environmental impacts. For example, conservation tillage systems that require larger efforts in chemical weed control, which in turn increase the risks of contamination of soil and water resources. Similarly, crop residue management may increase infestation of pests, leading to a greater need in applying pesticides. Likewise, application of manure or compost, despite augmenting the SOC stock, also increases the emissions of GHGs from soil and may result in the pollution and eutrophication of off-site water sources. The highly promising perennial crops, which have been proved to sequester large amounts of C and to accomplish a range of ecosystem services, are more efficient in producing animal feed (hay) than food for humans (grains). Therefore, in order to fulfill the increased demand for food production and at the same time to alleviate the increased pressures on the environment, more focus should be given to additional, specific practices that are highly compatible with these challenges. In the next sections, two such practices—agroforestry systems and the utilization of biochar as soil amendment—are discussed.

3 Agroforestry systems

Agroforestry, an important conservation farming option, encompasses several practices such as alley cropping, multi-storey cropping, and silvopastoral systems, where trees or shrubs are intercropped with grain crops, vegetables, or forages (Kandji et al. 2006) (Fig. 3). Additional agroforestry practices include windbreaks and riparian forests, aimed at fulfilling specific objectives, such as wind erosion control or off-site water quality preservation, respectively (Schoeneberger 2009). Agroforestry systems provide a range of products, including food for human consumption, fodder for livestock, timber for building, wood for fuel, and pollen for honey bees (Nair et al. 2010). At the same time, these systems sustain many ecosystem services such as increasing species diversity, enhancing wildlife habitats, fostering natural food webs, fostering water infiltration, improving soil and ecosystem health, augmenting long-term C sequestration, and decreasing emissions of CO_2 (USDA-NRCS 2002; Garrity et al. 2010; Nair et al. 2010). Specifically, these systems are considered as an efficient

Fig. 3 Agroforestry system composed of olive trees for oil, intercropped with alfalfa (*Medicago sativa* L.) for hay. Alfalfa is considered as a perennial forage legume that could last up to several years. At the same time, the forage fertilizes the soil with N and protects the surface from erosional processes. Picture was taken in Yizrael Valley, northern Israel

means in reclaiming degraded lands (Kandji et al. 2006; Soto-Pinto et al. 2010). A wide range of agroforestry systems are presented in Table 2. Despite their being of highly heterogeneous natures, all of these systems reveal a high capacity of sequestering C, along with the improvement of several ecosystem services.

Successful and well-managed integration of trees on farms may optimize the use of water and nutrients (Sileshi et al. 2011), enabling diversified and sustainable crop production (Kandji et al. 2006). In a study of the nutrients dynamics of an alley cropping system in subtropical China, it was reported that Hog plum (*Choerospondias axillaris*) trees and a peanut (*Archis hypogaea*) crop may compete for N fertilizer in the surface soil. However, it was also reported that the trees used leached N in the deep soil not accessed by the shallow-rooted peanuts. The alley cropping system increased N use efficiency compared with a mono-peanut cropping system. These effects increased with time and were more evident for systems with larger trees. These results suggest that the introduction of trees can reduce N loss, but management practices should aim at preventing competition for N with the main crop in the shallow soil depth (Zhang et al. 2008).

Leguminous trees (fertilizer trees) in agroforestry systems can facilitate biological N fixation, augmenting N availability for the main crops, and thereby reducing the requirements for fertilizer inputs (Garrity et al. 2010; Nair et al. 2010). In a study in the sub-Saharan Africa, where rainfall is erratic and highly variable, Sileshi et al. (2011) compared rain use efficiency and crop yield in rain-fed corn when grown as a mono-culture and when intercropped with the N fixation tree Leucaena (*Leucaena leucocephala*) under two different types of agroforestry systems. Treatments included fully fertilized corn alone, non-fertilized (control) corn alone, and corn intercropped with Leucaena and amended with half of the recommended N fertilizer rate. Sileshi and colleagues reported that despite some discrepancies, rain use efficiency was higher for corn intercropped with Leucaena. In addition, the intercropping increased stability of the corn yield over the years. Overall, these results were true compared with corn alone, both with and without fertilizer. Sileshi and colleagues attributed this to the fact that during extremely wet seasons, mineral fertilizers are subject to leaching, resulting in decreased crop yields. At the same time, the considerably increased SOC stock under leguminous trees enhances nutrient retention and availability, yielding greater crops. Sileshi and colleagues concluded that integrated soil fertility management based on intercropping with N fixation trees decreases vulnerability of crops to drought stress and that the augmented SOC stock in these agroforestry systems promotes soil conservation. A number of additional agroforestry systems that involve fertilizer trees and are widespread throughout Africa were described by Garrity et al. (2010), who revealed an overall improvement in soil fertility, increased crop productivity, and augmented C sequestration in above and below ground biomass. However, as noted by Kandji et al. (2006), utilization of leguminous trees or crops may increase N_2O emissions as compared to non N-fertilized agro-ecosystems.

While agroforestry systems contain less C than primary or managed forests, they sequester C over and beyond what would occur under other agricultural activities. In a wide-scale study conducted in Ghana, Wade et al. (2010) compared the C stock of natural forests to that of non-intensive and intensive cocoa (*Theobroma cacao*) based agroforestry systems. The mean total C sequestration capacity was of 155 Mg C ha^{-1} for the forests, 131 Mg C ha^{-1} for the non-intensive systems, and 39 Mg C ha^{-1} for the intensive systems. In addition, Wade and colleagues observed that decreased cropping intensity resulted in an increase in species richness of the native trees left after forest conversion. Henry et al. (2009) reported strong and positive relationships between tree species diversity and above ground biomass-C in several Kenyan agroforestry systems.

In a recently published synthesis study, Nair et al. (2009) reviewed many works dealing with C sequestration by various agroforestry systems. They summarized that root C stocks can range between 1.3 and 20.5 Mg ha^{-1} and that shoot C stocks can range between 6.3 and 172.0 Mg ha^{-1}. Nair and colleagues added that the total SOC stocks in these systems may range between 24 and 90 Mg ha^{-1} in arid and semi-arid lowlands, 21–173 Mg ha^{-1} in tropical highlands, and 10–235 Mg ha^{-1} in humid lowlands. In a synthesis study conducted in Costa Rica and Canada, Oelbermann et al. (2004) reported a greater total input of organic matter in tropical than in temperate agroforestry systems. However, the greater input did not necessarily increase the SOC stock when compared to a temperate system of similar age as a result of faster turnover rates. Oelbermann and colleagues estimated that the C sequestration rate in aboveground biomass is 2.1 Pg C year^{-1} in the tropical biome and 1.9 Pg C year^{-1} in the temperate biome. Furthermore, they commented that capacity to sequester C varies greatly and depends on a range of physical and biotic conditions, as well as on management practices. Zomer et al. (2009) calculated that agroforestry systems support a total population of ~1.5 billion people across more than 1 billion ha in developing countries.

The advantageous nature of agroforestry systems has led to their inclusion in the afforestation and reforestation activities that are eligible for payment under the Clean Development Mechanism (CDM, see: UNFCCC 2003). Hence, trading the sequestered C is a viable economic opportunity for practitioners of agroforestry systems, who are primarily subsistence farmers in developing countries (Nair et al. 2010). Measuring total C stocks before the establishment

Table 2 Impact of agroforestry systems on C stocks and additional ecosystem services

Location	Agroforestry system	Tree species	Inter-tree species	Carbon sequestration/CO_2 emission	Additional ecosystem services	Source
USA	Alley cropping	NS (synthesis)	NS (synthesis)	Increased SOC, decreased CO_2 emission	Erosion control, improved wildlife habitat	USDA-NRCS (2002)
Costa Rica; Canada	Alley cropping	Various (review)	Various (review)	In above ground biomass: 2.1×10^9 Mg C$year^{-1}$ in tropical biomes, and 1.9×10^9 Mg C$year^{-1}$ in temperate biomes; decreased CO_2 emission	Erosion control	Oelbermann et al. (2004)
Africa; South America; southeast Asia; Australia; North America; northern Asia	Agrosilviculture, silvopasture	Various	Various	Total C storage during 50 years: 29–53; 39–195; 12–228; 28–51; 90–198; 15–18 Mg Cha^{-1}, respectively	Erosion control, on-site water conservation	Kandji et al. (2006)
Kenya	Homegardens	Various	Corn, vegetables	Aboveground biomass-C ranged between 13.8 to 17.3 Mg ha^{-1}	Increased biodiversity	Henry et al. (2009)
USA (review)	Alley cropping, silvopasture, riparian forests, windbreaks, snow fence, additional site-specific procedures	NS	NS	Increased biomass-C and SOC stock	Erosion control, Increased off-site water quality, increased biodiversity	Schoene-berger (2009)
Laos; Thailand; Vietnam	Alley cropping, silviculture	Various (a regional project summary)	Various (a regional project summary)	Increased biomass-C	–	Skole et al. (2009)
NS (review)	Various	Various	Various	Increased biomass-C and SOC stock	Decreased nutrient leaching, erosion control, natural pest control	Nair et al. (2009; 2010)
China	Several intercropping systems	Poplar (*Populus deltoids*)	Wheat, soybean, corn	Biomass-C varies among the systems for both trees and crops	–	Fang et al. (2010)
Mexico	Several agrosilvicultural systems	Coffee and a range of introduced and native spontaneously grown tree species	Corn, a range of pasture species	Increased above and below ground biomass-C, dead organic matter, and SOC	–	Soto-Pinto et al. (2010)
Ghana	Cocoa plantations of various cropping intensities, intercropping with other crops	Cocoa and a range of remnant native tree species left after forest conversion	A range of crops	131 Mg Cha^{-1} for traditional (non-intensive) systems vs. 39 Mg Cha^{-1} for intensive system	Native tree species richness increase with decreased cropping intensity	Wade et al. (2010)

NS – Not specified

of agroforestry systems and evaluating their dynamics are necessary steps to get approval for funding. Allometric equations that relate the tree's height and diameter to its biomass allow non-destructive estimates of the above- and below-ground woody stocks (Schoeneberger 2009). Currently, many of the costs associated with developing small holder C offset plantings are related with the need for a large number of field-based measurements. In order to reduce costs, measurements of both biomass-C and SOC should be combined with spatial analyses and relevant information technologies. However, considering the great diversity of agroforestry practices, it is impossible to utilize a single protocol to fit all project types. Further development is needed in advanced methods for quantifying inventory and dynamics of C stocks, as well as in elaborated protocols for C offset in order to allow payments for a wider range of agroforestry projects (Skole et al. 2009). In the USA, several federal and state conservation programs provide financial incentives to landowners for the establishment and management of agroforestry plantings (Schoeneberger 2009). An example is the 2002 Farm Bill (Farm Security and Rural Investment Act of 2002) that has authorized the US Forest Service to allocate 100 million dollars on forestry projects in the private, non-industrial sector. This mechanism functions under the Forest Land Enhancement Program (FLEP) and supports a range of agroforestry practices through several tracks such as cost-sharing, land rental, incentive payments, and technical assistance (USDA 2002).

4 Biochar as soil amendment

Vegetation growth is a very efficient, natural way of CO_2 immobilization, since photosynthesis captures more CO_2 from the atmosphere than any other natural process. However, the efficiency for long-term C sequestration by biomass is limited because large portion of the C is unstable, returning to the atmosphere as CO_2 through decomposition and respiration in a short time of months to years. Therefore, in order to considerably increase long-term C sequestration, biomass has to be converted to a relatively non-degradable form, such as biochar (Lehmann 2007a; Lee et al. 2010).

Biochar is a by-product of the C-negative pyrolysis technology for production of bio-energy from organic materials. The process is conducted under complete or partial exclusion of oxygen and relies on capturing the off-gases from thermal decomposition of organic materials (Lehmann 2007b). Roberts et al. (2010) reported that the net energy of the pyrolysis technology is highly positive, that is, generating much more energy than is consumed. Coupling the pyrolysis process with application of the by-product biochar in soil actually removes CO_2 from the atmosphere, as more C is sequestered than that emitted (Roberts et al. 2010). The biochar is highly resistant to microbial activity, considerably augmenting the recalcitrant fraction of SOC and decreasing emissions of CO_2 from soil (Glaser et al. 2002; Lehmann 2007a). In addition, biochar application was reported to decrease emissions of CH_4 (Rondon et al. 2005), and N_2O (Rondon et al. 2005; Yanai et al. 2007; Roberts et al. 2010) from soils. A range of agro-ecosystems in which biochar was applied in their soil are presented in Table 3. Despite representing a wide range of feedstocks and crops, the overall impact is the increase in SOC stock, decrease in emissions of GHGs, lesser leaching of nutrients, and smaller contamination of off-site water sources.

Despite the recalcitrant nature of biochar, about 40% of the total biomass-C of the feedstock is lost during the pyrolysis process, and an additional 10% is mineralized over a few months after biochar application in soil. Nevertheless, the remaining 50% of the total C is relatively stable (Laird et al. 2009). The degree of stability of the biochar-C depends on its specifications. While C in biochar produced by high-temperature pyrolysis is either recalcitrant or degradable at an extremely slow rate, some of the C in biochar produced under low temperatures is biodegradable. In addition, compared with fallow soils, application of biochar increases rates of CO_2 emissions from the amended soil. This response may be explained by several factors, such as lower bulk density, improved aeration, and higher pH, providing a favorable habitat for soil microorganisms (Laird et al. 2009).

Biochar application positively impacts soil fertility, for example, through its effect on cation exchange capacity (CEC). Increase in CEC is attributed to the existence of carboxylic groups on the surfaces of the biochar itself, as well as due to exposed carboxylic groups of organic acids absorbed by the biochar, both of which contribute negative surface charge to the biochar (Liang et al. 2006). In addition, biochar can effectively absorb ammonia (NH_3), reducing its loss through volatilization. However, the biochar itself contains a limited amount of available mineral nutrients in its ash content, and therefore, its application in soil is usually done in conjunction with fertilizer management (Lee et al. 2010). Nonetheless, the high capacity to absorb nutrients enables their retention in the rooting zone, increasing fertilizer efficiency while decreasing the leaching of nutrients and reducing contamination of underground water sources (Glaser et al. 2002; Laird et al. 2010a). In addition, the high porosity of biochar augments physical quality of the soil, increasing its water-holding capacity and hydraulic conductivity (Laird et al. 2010b). The combined effect of biochar application is the enhancement of soil fertility and productive capacity, resulting in increased crop yields (Marris 2006).

The improved structure formation and stability of the soil are expected to decrease frequency and magnitude of soil

Table 3 Impact of biochar application on emissions of GHGs from soil and additional ecosystem services

Location	Crops	Feedstock type\biochar application rate or quantity	CO_2 emission	N_2O emission	CH_4 emission	Additional ecosystem services	Source
NS (review)	Various	Various\various	Considerable reduction	NA	NA	Decreased nutrient leaching	Glaser et al. (2002)
Colombia	Soybean/*Brachiaria humidicola*	NA\7.5–30 gkg^{-1} soil	NA	50–80% reduction	Significant reduction	NA	Rondon et al. (2005)
NS (review)	NS	NS	Significant reduction	NA	NA	NA	Lehmann (2007a)
Japan	Sorghum ap.	Municipal bio-waste\1:5 and 1:20 solutions	NA	Up to 89% reduction	NA	NA	Yanai et al. (2007)
NS (review)	NS	NS	Lower than that of non-carbonized organic materials' amended soils, but higher than that of fallow soils	Up to 70% Reduction	NA	Decreased contamination of off-site water sources by mineral or organic pollutants	Laird et al. (2009)
USA	None	NA\5–20 gkg^{-1} soil	Signifiant reduction	Signifiant reduction	NA	NA	Rogovska et al. (2009)
NS (review)	Various	Various\various	NA	NA	NA	Sorption of organic pollutants	Smernik (2009)
UK	None	Hardwood\1/3 of biochar/soil mix; 1/3 of soil-compost mix	NA	NA	NA	Remediation of contaminated soil and decreased phyto-toxicity	Beesley et al. (2010)
China	None	Bamboo\1/15, with various NH_4Cl solutions	NA	NA	NA	Decreased N leaching	Ding et al. (2010)
USA	None	Mixed hardwood\5–20 gkg^{-1} soil	NA	NA	NA	Decreased leaching of N, P, Mg, and Si	Laird et al. (2010a)
NS (review)	Various	Various crops and yard waste \various	Up to 66% reduction	Assumed 50% reduction	NA	NA	Roberts et al. (2010)

NS not specified, *NA* not available

loss through erosional processes. However, the impact of biochar on soil erosion has been only very scantly studied and, therefore, requires much more research. In their study, Foereid et al. (2011) modeled the loss of biochar through erosional processes. Foereid and colleagues assumed that larger pieces of biochar are more prone to erosion. They reported positive relations between rate of soil erosion and content of biochar in sediments. In addition, they found that on a 2,000-year time scale, the largest loss (75%) of biochar is through soil erosion, followed by decomposition (20%) and downward movement (0.5%). Overall, it could be expected that retention of biochar on the soil surface with no incorporation into the soil would increase its vulnerability to erosion by either water or wind force. Therefore, also in long-term NT agro-ecosystems, biochar should be incorporated into soil. This could be done by the means of occasional inversion tillage.

According to the International Biochar Initiatives, 154 biochar projects have been carried out in 43 developing countries in 2011. These projects have taken place in a range of operational and functional scales, including household (26%), farm (41%), village (12%), cooperative (11%), and regional (10%) levels. The feedstocks include a range of organic residues and wastes including timber mill waste, plant material derived from invasive species, leaves, livestock manure, plantation prunings, field stover, rice husks, and waste of fruits such as cacao, coffee, and coconut. The biochar production scale varies from small to large and technologies vary from batch retort kiln to continuous-process kiln (Kelpie 2011). Considering an application rate of between 10 and 100 Mg biochar per hectare (Chan et al. 2007) and that biochar's C concentration is between 50% (Lehmann et al. 2006) and 78% (Gaskin et al. 2008), and assuming a total area of 1,411 Mha cropland around the world (Lee et al. 2010), then the global capacity for storing biochar-C under this landuse is between 7 and 110 Pg. Lee et al. (2010) noted that additional infinite amounts of biochar could be sequestered in abandoned mines, underground reservoirs, and geological formations.

Similar to other bioenergy sectors, feedstocks for the pyrolysis technology can include a range of agricultural and organic wastes, such as forestry residues, prunings from fruit trees, domestic wastes, livestock- and human-derived sludge, and municipal sewage. In addition, designated agricultural crops that do not require high inputs in water and fertilizer and that could be grown on marginal lands that cannot be used for food production could also be utilized for bioenergy crops (Tilman et al. 2009). At the same time, residues of agricultural crops, such as wheat straw or corn stalk, must not be considered as viable biofuel feedstocks. This is because the retention of residues on the soil maintains the SOC stock, supports the soil food chain, protects the soil surface from raindrop impact and erosional processes, preserves the soil quality, and sustains the productive capacity of the agro-ecosystem (Lal and Pimentel 2009).

The basic concept of biochar production is simple, and therefore, it can be easily produced locally by farmers, including those with low economic power (Glaser et al. 2002). Some examples for low-cost means for production of charcoal were detailed by the FAO (1987), describing the construction of earth pits, earth mounds, brick kilns, and metal kilns. Another low-cost technique is the two-barrel kiln that can be constructed by using reused materials (Fig. 4), which can be used to produce biochar from a range of agricultural wastes (Fig. 5). Such a low-cost kiln has been used during the last year in the Dead Sea & Arava Science Center of Israel in order to demonstrate the ease of biochar production. The rate of producing biochar in this kiln has been approximately 5 kg from ground date palm fronds during a 1-h process and about 20 kg from cattle manure during a 4-h process. Actually, the simplicity of the kiln and its low-cost enable the running of up to five kilns simultaneously by one person, reaching a maximal biochar production capacity of about 25 kg from fronds over 1 h, or 100 kg from manure over 4 h.

However, it may be noteworthy to mention that in many parts of the world, several socio-cultural obstacles prevent a much wider expansion of the biochar management practice. Of the main obstacles, gender barriers (Kelpie 2011) and land tenure issues are especially remarkable. In addition, there are several gaps in understanding various aspects related to the production process, as well as to the application in soil. For example, much research is needed to quantify the interactions among biochar, soil properties, management practices, and emissions of CO_2 and N_2O (Laird et al. 2009). In addition, the potential impacts on soil quality and crop yields under a range of soil's nutritional stati, as well as under alkaline soil conditions, are yet unclear. Furthermore, the production of biochar from many types of feedstocks and under a wide range of pyrolysis processes makes validations rather difficult. Therefore, standardization of biochar is crucial to enable comparisons among the different feedstocks and production procedures.

5 Regulations

Until the late 1990s, the CO_2 produced during burning of fossil or woody fuels was considered valueless, and the cheapest means to dispose it was merely to let it be emitted into the atmosphere. In the same manner, the increased oxidation of SOC caused by the conversion of native ecosystems into cultivated lands was not treated and considered as a legitimate environmental cost of agricultural production. As long as the emission of GHGs is free of any costs, the economic rationale of the relevant sectors is to increase agricultural production with the associated increased emissions of CO_2. Likewise, emissions of CH_4 through cultivation of rice paddies and

Fig. 4 A home-made kiln, produced of reused barrels. An ~80-l barrel, filled in with ground date palm fronds is laid upside down within an ~160-l barrel. The gap between the barrels is filled with (unground) fronds that are used as fuel. About 5 kg biochar are produced during a 1-h process. Using the same method, ~20 kg biochar are produced from cattle manure during a 4-h process. Notice the piles of dry date palm fronds in the background, acquired from the date palm orchard (in the far background). Picture was taken in the Arava Valley, southern Israel

Fig. 5 Biochar made of ground date palm fronds. Produced using the home-made kiln shown in Fig. 4. Picture was taken at the Dead Sea & Arava Science Center, Israel

animal husbandry, as well as emissions of N_2O through fertilizers use, are expected to increase.

Considering that the capacity of the atmosphere to absorb GHGs prior to the emergence of catastrophic climatic changes is limited, some actions are inevitable (IPCC 2007; Lal 2007). For example, relying more on renewable (solar/wind/geothermal) and other alternative (biomass-derived) energy sources, enhancing efficiency of energy use, and increasing C sequestration (Kyoto Protocol 1998). Large rates of C sequestration may be achieved by means of vegetative biomass (van Minnen et al. 2008) and soils (Lal et al. 2007). Nevertheless, as stressed by Hardin (1968) in his essay, “The Tragedy of the Commons”, which deals with the (mis-) management of land resources, leaning exclusively on technical solutions without relying on change in human behavior and values, might not suffice. Therefore, education and sharing of knowledge, along with the use of incentive-based means, are crucial. Indeed, history has shown that economic incentives are very effective in reducing emissions of GHGs. Since the 1960s, the only reliefs from global gas emissions have corresponded with economic downturns or high energy prices. Similarly, C taxation is expected to reduce demands, encouraging individuals, companies, and countries to decrease energy consumption or to replace high C-emission fuels with more efficient ones (Meyerson 1998). Currently, coupling the impacts of rising energy prices and climate change has already had a dramatic impact. Food prices are increasing sharply along with the price of consumer products and services, threatening the economic wellbeing of billions of people. The current steep rise in oil prices boosts inflation, which has long been regarded as the most unequal “tax” as it redistributes wealth from low income to high income groups. It is virtually certain that these circumstances will worsen in the years ahead, endangering the Western world’s vision of a wealthier and more equitable society (Carvalho et al. 2011).

The inter-governmental consideration of C as a valuable commodity under the Kyoto Protocol (1998) has initiated the required shift in the willingness and motivation of individuals, private sectors, and governments towards responsible behavior. The CDM described under Article 12 in this protocol allows developed countries, which have been committed to GHGs reduction to purchase emission credits by investing in mitigation projects in developing countries (Nair et al. 2010). Under this mechanism, developing countries may generate Certified Emissions Reductions, which can be sold to committed developed countries. This mechanism aimed at stimulating clean development in developing countries by providing finance for environmentally friendly technologies, while developed countries gain access to low-cost mitigation projects (Whitman and Lehmann 2009). Afforestation and reforestation are among the eligible means under the CDM, aimed at increasing above- and below-ground biomass production, as well as at accumulating plant residues and sequestering SOC (UNFCCC 2003). Agroforestry has been also included under this framework, providing farmers in developing countries with attractive economic benefits (Nair et al. 2010). However, considering the current market price for C, a wide implementation of agroforestry projects seems unfeasible due to the small size of many farms that do not achieve a critical land area to enable compensation for the concomitant costs. Higher financial compensations for C sequestration in agroforestry projects, which at the same time improve ecosystem services, would allow clearer win–win scenarios for small holder farmers, encouraging them to implement these practices (Henry et al. 2009).

An example for the mode of operation of the financial bodies may be the case of the BioCarbon Fund, launched by the World Bank, and aimed at funding “projects that sequester or conserve C in forests and agro-ecosystems” in order to “deliver cost-effective emission reductions, while promoting biodiversity conservation and poverty alleviation.” Despite that “the BioCarbon Fund can consider purchasing C from a variety of land use[s] and forestry projects,” the only eligible practices are “afforestation and reforestation, [and] reducing emissions from deforestation and [land] degradation.” Nonetheless, the BioCarbon Fund “is exploring innovative approaches to [sequester] agricultural C” (BioCarbon Fund’s website: http://wbcarbonfinance.org/Router.cfm?Page=BioCF).

To date, except for agroforestry, other agricultural landuses and management practices are not eligible for funding through the CDM. Even the promising practice of biochar application in soil is not eligible for payment under this framework (Marris 2006; Whitman and Lehmann 2009). Thereby, an inter-governmental intervention should adjust the global C finance market’s framework to include the biochar management practice. The incentive benefits should be high enough to promote the implementation of this practice by farmers. For example, Roberts et al. (2010) calculated that valuing an Mg of CO_2 at a minimum of ~$60 would encourage farmers in the USA to pyrolyze switchgrass for co-production of bio-energy and biochar. In addition, a considerable increase is necessary in authorizational payments for maintaining ecosystem services such as soil erosion control, water quality preservation, and biodiversity conservation. This would promote the adoption of such environmentally friendly farming practices, aimed at sustaining global food security and alleviating poverty while reducing environmental footprint and minimizing GHGs emissions.

6 Conclusions

The impact of agriculture in emissions of GHGs is enormous. Intensively managed croplands have emitted considerable amounts of CO_2, CH_4, and N_2O, tremendously increasing their atmospheric concentrations. Furthermore, some of the intensive farming practices have increased soil erosion as well as contamination of off-site water sources. At the same time, conservation agriculture practices may decrease emissions of GHGs, mitigate climate change, on the environment. However, as emphasized in this review, the agronomic efficiency of some of the conservation practices are site-dependent and not relevant to all geographic zones and climatic conditions. Nevertheless, specific conservation practices—agroforestry systems and application of biochar in soil—can boost sequestration of organic C and, in addition, increase fertilizer efficiency, enhance productive capacity, and advance global food security. At the same time, these practices support a range of ecosystem services such as decreased soil erosion, reduced contamination of off-site water sources and increased species diversity and ecosystem health, and therefore, can be utilized in reclamation of degraded lands. Future regulations should facilitate national and international schemes of payments for these agricultural practices, encouraging their wide implementation throughout the world.

References

Beesley L, Moreno-Jiménez E, Gomez-Eyles JL (2010) Effects of biochar and greenwaste compost amendments on mobility, bioavailability and toxicity of inorganic and organic contaminants in a multi-element polluted soil. Environ Pollut 158:2282–2287. doi:10.1016/j.envpol.2010.02.003

Carvalho MD, Bonifacio M, Dechamps P (2011) Building a low carbon society. Energy 36:1842–1847. doi:10.1016/j.energy.2010.09.030

Chan KY, Van Zwieten L, Meszaros I, Downie A, Joseph S (2007) Agronomic values of greenwaste biochar as a soil amendment. Aust J Soil Res 45:629–634. doi:10.1071/SR07109

Cockroft B, Olsson KA (2000) Degradation of soil structure due to coalescence of aggregates in no-till, no-traffic beds in irrigated crops. Aust J Soil Res 38:61–70

Cox TS, Glover JD, Van Tassel DL, Cox CM, Dehaan LR (2006) Prospects for developing perennial grain crops. BioScience 56:649–659

Culman SW, DuPont ST, Glover JD, Buckley DH, Fick GW, Ferris H, Crews TE (2010) Long-term impacts of high-input annual cropping and unfertilized perennial grass production on soil properties and belowground food webs in Kansas, USA. Agr Ecosyst Environ 137:13–24. doi:10.1016/j.agee.2009.11.008

Dabney SM, Delgado JA, Reeves DW (2001) Using winter cover crops to improve soil and water quality. Commun Soil Sci Plan 32:1221–1250. doi:10.1081/CSS-100104110

Ding Y, Liu YX, Wu WX, Shi DZ, Yang M, Zhong ZK (2010) Evaluation of biochar effects on nitrogen retention and leaching in multi-layered soil columns. Water Air Soil Pollut 213:47–55. doi:10.1007/s11270-010-0366-4

DuPont ST, Culman SW, Ferris H, Buckley DH, Glover JD (2010) No-tillage conversion of harvested perennial grassland to annual cropland reduces root biomass, decreases active carbon stocks, and impacts soil biota. Agr Ecosyst Environ 137:25–32. doi:10.1016/j.agee.2009.12.021

Ernst O, Siri-Prieto G (2009) Impact of perennial pasture and tillage systems on carbon input and soil quality indicators. Soil Tillage Res 105:260–268. doi:10.1016/j.still.2009.08.001

Fang S, Li H, Sun O, Chen L (2010) Biomass production and carbon stocks in poplar-crop intercropping systems: a case study in northwestern Jiangsu, China. Agroforest Syst 79:213–222. doi:10.1007/s10457-010-9307-x

FAO (1987) Simple technologies for charcoal making. http://www.fao.org/docrep/x5328e/x5328e00.htm

Farm Security and Rural Investment Act of 2002. Public Law 107–171—May 13, 2002. http://www.fas.usda.gov/excredits/FoodAid/Farm_Bill_2002.pdf

Fearnside PM (2000) Global warming and tropical land-use change: greenhouse gas emissions from biomass burning, decomposition and soils in forest conversion, shifting cultivation and secondary vegetation. Clim Chang 46:115–158. doi:10.1023/A:1005569915357

Foereid B, Lehmann J, Major J (2011) Modeling black carbon degradation and movement in soil. Plant Soil 345:223–236. doi:10.1007/s11104-011-0773-3

Forster P, Ramaswamy V, Artaxo P, Berntsen T, Betts R, Fahey DW, Haywood J, Lean J, Lowe DC, Myhre G, Nganga J, Prinn R, Raga G, Schulz M, Van Dorland R (2007) Changes in atmospheric constituents and in radiative forcing. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 129–234

Garrity DP, Akinnifesi FK, Ajayi OC, Weldesemayat SG, Mowo JG, Kalinganire A, Larwanou M, Bayala J (2010) Evergreen agriculture: a robust approach to sustainable food security in Africa. Food Sec 2:197–214. doi:10.1007/s12571-010-0070-7

Gaskin JW, Steiner C, Harris K, Das KC, Bibens B (2008) Effect of low-temperature pyrolysis conditions on biochar for agricultural use. T ASABE 51:2061–2069

Giller KE, Witter E, Corbeels M, Tittonell P (2009) Conservation agriculture and smallholder farming in Africa: the heretics' view. Field Crop Res 114:23–34. doi:10.1016/j.fcr.2009.06.017

Glaser B, Lehmann J, Zech W (2002) Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal—a review. Biol Fert Soils 35:219–230. doi:10.1007/s00374-002-0466-4

Glover JD, Cox CM, Reganold JP (2007) Future farming: a return to roots? Sci Am 297:82–89

Glover JD, Reganold JP, Bell LW, Borevitz J, Brummer EC, Buckler ES, Cox CM, Cox TS, Crews TE, Culman SW, DeHaan LR, Eriksson D, Gill BS, Holland J, Hu F, Hulke BS, Ibrahim AMH, Jackson W, Jones SS, Murray SC, Paterson AH, Ploschuk E, Sacks EJ, Snapp S, Tao D, Van Tassel DL, Wade LJ, Wyse DL, Xu Y (2010) Increased food and ecosystem security via perennial grains. Science 328:1638–1639. doi:10.1126/science.1188761

Govaerts B, Mezzalama M, Unno Y, Sayre KD, Luna-Guido M, Vanherck K, Dendooven L, Deckers J (2007) Influence of tillage, residue management, and crop rotation on soil microbial biomass and catabolic diversity. Appl Soil Ecol 37:18–30. doi:10.1016/j.apsoil.2007.03.006

Governor's Agricultural Best Practices Committee (2008) Guide to agricultural PM10 best management practices—agriculture improving air quality. Arizona Department of Environmental Quality, Phoenix

Hardin G (1968) The tragedy of the commons. Science 162:1243–1248

Hatfield JA (2000) Precision agriculture and environmental quality: challenges for research and education. USDA-NRCS, Iowa

Henry M, Tittonell P, Manlay RJ, Bernoux M, Albrecht A, Vanlauwe B (2009) Biodiversity, carbon stocks and sequestration potential in aboveground biomass in smallholder farming systems of western Kenya. Agr Ecosyst Environ 129:238–252. doi:10.1016/j.agee.2008.09.006

Hobbs PR, Sayre K, Gupta R (2008) The role of conservation agriculture in sustainable agriculture. Philos T Roy Soc 363:543–555. doi:10.1098/rstb.2007.2169

Huggins DR, Reganold JP (2008) No-till: the quiet revolution. Sci Am 299:70–77. doi:10.1038/scientificamerican0708-70

Hutchinson JJ, Campbell CA, Desjardins RL (2007) Some perspectives on carbon sequestration in agriculture. Agr Forest Meteorol 142:288–302. doi:10.1016/j.agrformet.2006.03.030

IPCC (1995) Climate change. Second assessment report. IPCC, Geneva

IPCC (2007) Climate change: impacts, adaptation and vulnerability. Fourth assessment report. IPCC, Geneva

Jarecki MK, Lal R (2006) Compost and mulch effects on gaseous flux from an alfisol in Ohio. Soil Sci 171:249–260

Kandji ST, Verchot LV, Boye A, van Noordwijk M, Tomich TP, Ong C, Palm C (2006) Opportunities for linking climate change adaptation and mitigation through agroforestry systems. In: Garrity D, Okono A, Grayson M, Parrott S (eds) World agroforestry into the future. World Agroforestry Center, Nairobi

Kell DB (2011) Breeding crop plants with deep roots: their role in sustainable carbon, nutrient and water sequestration. Ann Bot 108:407–418. doi:10.1093/aob/mcr175

Kelpie W (2011) IBI Developing country biochar systems survey: methodology and results. International Biochar Initiatives

Kögel-Knabner I, Amelung W, Cao Z, Fiedler S, Frenzel P, Jahn R, Kalbitz K, Kölbl A, Schloter M (2010) Biogeochemistry of paddy soils. Geoderma 157:1–14. doi:10.1016/j.geoderma.2010.03.009

Kyoto protocol to the United Nations framework convention to climate change (1998) United Nations, New York

Laird DA, Brown RC, Amonette JE, Lehmann J (2009) Review of the pyrolysis platform for coproducing bio-oil and biochar. Biofuels, Bioprod Biorefin 3:547–562. doi:10.1002/bbb.169

Laird D, Fleming P, Wang B, Horton R, Karlen D (2010a) Biochar impact on nutrient leaching from a Midwestern agricultural soil. Geoderma 158:436–442. doi:10.1016/j.geoderma.2010.05.012

Laird DA, Fleming P, Davis DD, Horton R, Wang B, Karlen DL (2010b) Impact of biochar amendments on the quality of a typical Midwestern agricultural soil. Geoderma 158:443–449. doi:10.1016/j.geoderma.2010.05.013

Lal R (2002) Soil carbon dynamics in cropland and rangeland. Environ Pollut 116:353–362. doi:10.1016/S0269-7491(01)00211-1

Lal R (2004) Soil carbon sequestration impacts on global climate change and food security. Science 304:1623–1627. doi:10.1126/science.1097396

Lal R (2007) Tragedy of the global commons: soil, water and air. CSA News V52 N10, 10–11.

Lal R, Pimentel D (2009) Biofuels: beware crop residues. Science 326:1345–1346. doi:10.1126/science.326.5958.1345-c

Lal R, Follett RF, Stewart BA, Kimble JM (2007) Soil carbon sequestration to mitigate climate change and advance food security. Soil Sci 172:943–956. doi:10.1097/ss.0b013e31815cc498

Lee JW, Hawkins B, Day DM, Reicosky DC (2010) Sustainability: the capacity of smokeless biomass pyrolysis for energy production, global carbon capture and sequestration. Energy Environ Sci 3:1695–1705. doi:10.1039/C004561F

Lehmann J (2007a) A handful of carbon. Nature 447:143–144. doi:10.1038/447143a

Lehmann J (2007b) Bio-energy in the black. Frontiers Ecol Environ 5:381–387. doi:10.1890/1540-9295(2007)5[381:BITB]2.0.CO;2
Lehmann J, Gaunt J, Rondon M (2006) Bio-char sequestration in terrestrial ecosystems—a review. Mitig Adapt Strateg Glob Change 11:403–427. doi:10.1007/s11027-005-9006-5
Liang B, Lehmann J, Solomon D, Kinyangi J, Grossman J, O'Neill B, Skjemstad JO, Thies J, Luizão FJ, Petersen J, Neves EG (2006) Black carbon increases cation exchange capacity in soils. Soil Sci Soc Am J 70:1719–1730. doi:10.2136/sssaj2005.0383
Mandal DK, Mandal C, Raja P, Goswami SN (2010) Identification of suitable areas for aerobic rice cultivation in the humid tropics of eastern India. Curr Sci India 99:227–231
Marris E (2006) Black is the new green. Nature 442:624–626. doi:10.1038/442624a
Meyerson FAB (1998) Population, development and global warming: averting the tragedy of the climate commons. Popul Environ 19:443–463
Nair PKR, Nair VD, Kumar BM, Haile SG (2009) Soil carbon sequestration in tropical agroforestry systems: a feasibility appraisal. Environ Sci Policy 12:1099–1111. doi:10.1016/j.envsci.2009.01.010
Nair PKR, Nair VD, Kumar BM, Showalter JM (2010) Carbon sequestration in agroforestry systems. Adv Agron 108:237–307. doi:10.1016/S0065-2113(10)08005-3
New Hampshire Department of Agriculture Markets and Food (2002) Manual of best management practices (BMPS) for agriculture in New Hampshire
Oelbermann M, Voroney RP, Gordon AM (2004) Carbon sequestration in tropical and temperate agroforestry systems: a review with examples from Costa Rica and southern Canada. Agr Ecosyst Environ 104:359–377. doi:10.1016/j.agee.2004.04.001
Perdomo C, Irisarri P, Ernest O (2009) Nitrous oxide emission from an Uruguayan argiudoll under different tillage and rotation treatments. Nutr Cycling Agroecosyst 84:119–128. doi:10.1007/s10705-008-9231-x
Pierce FJ, Nowak P (1999) Aspects of precision agriculture. Adv Agron 67:1–85. doi:10.1016/S0065-2113(08)60513-1
Reicosky DC, Forcella F (1998) Cover crop and soil quality interactions in agroecosystems. J Soil Water Conserv 53:224–229
Roberts KG, Gloy BA, Joseph S, Scott NR, Lehmann J (2010) Life cycle assessment of biochar systems: estimating the energetic, economic, and climate change potential. Environ Sci Technol 44:827–833. doi:10.1021/es902266r
Rogovska N, Fleming P, Laird D, Cruse R, Parkin T (2009) Carbon dioxide and nitrous oxide emissions from biochar amended soils. In: Proceedings of the North American Biochar Conference. Boulder
Rondon M, Ramirez J, Lehmann J (2005) Charcoal additions reduce net emissions of greenhouse gases to the atmosphere. In: Proceedings of the 3rd USDA Symposium on Greenhouse Gases and Carbon Sequestration. Baltimore
Sanderson MA, Skinner RH, Barker DJ, Edwards GR, Tracy BF, Wedin DA (2004) Plant species diversity and management of temperate forage and grazing land ecosystems. Crop Sci 44:1132–1144
Schoeneberger MM (2009) Agroforestry: working trees for sequestering carbon on agricultural lands. Agroforest Syst 75:27–37. doi:10.1007/s10457-008-9123-8
Sileshi GW, Akinnifesi FK, Ajayi OC, Muys B (2011) Integration of legume trees in maize-based cropping systems improves rain use efficiency and yield stability under rain-fed agriculture. Agr Water Manage 98:1364–1372. doi:10.1016/j.agwat.2011.04.002
Skole DL, Thongmanivong S, Butthep C, Lan DX (2009) Developing small holder agroforestry carbon offset protocols for carbon financial markets –twinning sustainable livelihoods and climate mitigation. Final report for APN Project. Asia-Pacific Network for Global Change Research
Smernik RJ (2009) Biochar and sorption of organic compounds. In: Lehmann J, Joseph S (eds) Biochar for environmental management. Earthscan, Washington, pp 289–293
Smith KA, Ball T, Conen F, Dobbie KE, Massheder J, Rey A (2003) Exchange of greenhouse gases between soil and atmosphere: interactions of soil physical factors and biological processes. Eur J Soil Sci 54:779–791. doi:10.1046/j.1365-2389.2003.00567.x
Smith P, Martin M, Cai Z, Gwary D, Janzen H, Kumar P, McCarl B, Ogle S, O'Mara F, Rice C, Scholes B, Sirotenko O, Howden M, McAllister T, Pan P, Romanenkov V, Schneider U, Towprayoon S, Wattenbach M, Smith J (2008) Greenhouse gas mitigation in agriculture. Philos T Roy Soc 363:789–813. doi:10.1098/rstb.2007.2184
Snapp SS, Blackie MJ, Gilbert RA, Bezner-Kerr R, Kanyama-Phiri GY (2010) Biodiversity can support a greener revolution in Africa. PNAS 107:20840–20845. doi:10.1073/pnas.1007199107
Soto-Pinto L, Anzueto M, Mendoza J, Ferrer GJ, de Jong B (2010) Carbon sequestration through agroforestry in indigenous communities of Chiapas, Mexico. Agroforest Syst 78:39–51. doi:10.1007/s10457-009-9247-5
Stavi I, Lal R (2010) Challenges and opportunities of soil organic carbon sequestration in croplands. In: Lichtfouse E (ed) Sustainable agriculture reviews, vol 5. Biodiversity, biofuels, agroforestry and conservation agriculture. Springer, Berlin, pp. 149–174. doi:10.1007/978-90-481-9513-8_5
Stavi I, Lal R (2011) Variability of soil physical quality in uneroded, eroded, and depositional cropland sites. Geomorphology 125:85–91. doi:10.1016/j.geomorph.2010.09.006
Stavi I, Lal R, Owens LB (2011) On-farm effects of no-till versus occasional tillage on soil quality and crop yields in eastern Ohio. Agron Sustain Dev 31:475–482. doi:10.1007/s13593-011-0006-4
Tilman D, Socolow R, Foley JA, Hill J, Larson E, Lynd L, Pacala S, Reilly J, Searchinger T, Somerville C, Williams R (2009) Beneficial biofuels—the food, energy, and environment Trilemma. Science 325:270–271. doi:10.1126/science.1177970
UNFCCC (2003) Modalities and procedures for afforestation and reforestation project activities under the clean development mechanism in the first commitment period of the Kyoto Protocol. 19CP9/FCCC/CP/2003/6/Add2. Bonn
Unger PW, Vigil MF (1998) Crop cover effects on soil water relationships. J Soil Water Conserv 53:200–206
USDA (2002) Inside agroforestry. Incentives for agroforestry. 2002 Farm Bill. National Agroforestry Center, Lincoln
USDA-NRCS (2002) Alley cropping—practical introduction. US Department of Agriculture—Natural Resources Conservation Service, Practice Code 311
Ussiri DAN, Lal R (2009) Long-term tillage effects on soil carbon storage and carbon dioxide emissions in continuous corn cropping system from an alfisol in Ohio. Soil Tillage Res 104:39–47. doi:10.1016/j.still.2008.11.008
Ussiri DAN, Lal R, Jarecki MK (2009) Nitrous oxide and methane emissions from long-term tillage under a continuous corn cropping system in Ohio. Soil Tillage Res 104:247–255. doi:10.1016/j.still.2009.03.001
van Minnen JG, Strengers BJ, Eickhout B, Swart RJ, Leemans R (2008) Quantifying the effectiveness of climate change mitigation through forest plantations and carbon sequestration with an integrated land-use model. Carbon Balance Manage 3:3. doi:10.1186/1750-0680-3-3
Vetsch JA, Randall GW, Lamb JA (2007) Corn and soybean production as affected by tillage systems. Agron J 99:952–959. doi:10.2134/agronj2006.0149

Wade ASI, Asase A, Hadley P, Mason J, Ofori-Frimpong K, Preece D, Spring N, Norris K (2010) Management strategies for maximizing carbon storage and tree species diversity in cocoa-growing landscapes. Agr Ecosyst Environ 138:324–334. doi:10.1016/j.agee.2010.06.007

Whitman T, Lehmann J (2009) Biochar—one way forward for soil carbon in offset mechanisms in Africa? Environ Sci Policy 12:1024–1027. doi:10.1016/j.envsci.2009.07.013

WMO (2007a) Greenhouse gas bulletin 2006: atmospheric carbon dioxide levels highest on record. World Meteorological Organization, Geneva

WMO (2007b) Greenhouse gas bulletin 2006: the state of Greenhouse gases in the atmosphere using global observation through 2006. World Meteorological Organization, Geneva

WMO (2010) Greenhouse gas bulletin: the state of greenhouse gases in the atmosphere based on global observations through 2009. World Meteorological Organization, Geneva

Yanai Y, Toyota K, Okazaki M (2007) Effects of charcoal addition on N_2O emissions from soil resulting from rewetting air-dried soil in short-term laboratory experiments. Soil Sci Plant Nutr 53:181–188. doi:10.1111/j.1747-0765.2007.00123.x

Zhang B, Wang XX, Wang MZ (2008) Fertilizer nitrogen recovery from different soil depths in an alley cropping system consisting of peanut (*Archis hypogaea*) and *Choerospondias axillaries* in subtropical China. In: IAEA (TECDOC-1606) Management of Agroforestry Systems for Enhancing Resource use Efficiency and Crop Productivity, Vienna, pp. 167–174

Zomer RJ, Trabucco A, Coe R, Place F (2009) Trees on farm: analysis of global extent and geographical patterns of agroforestry. ICRAF Working Paper No. 89. World Agroforestry Centre, Nairobi