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RESEARCH ARTICLE

Land use change and soil organic carbon dynamics

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Abstract Historically, soils have lost 40–90 Pg carbon (C) globally through cultivation and disturbance with current rates of C loss due to land use change of about 1.6 ± 0.8 Pg C y^{-1}, mainly in the tropics. Since soils contain more than twice the C found in the atmosphere, loss of C from soils can have a significant effect of atmospheric CO_2 concentration, and thereby on climate. Halting land-use conversion would be an effective mechanism to reduce soil C losses, but with a growing population and changing dietary preferences in the developing world, more land is likely to be required for agriculture. Maximizing the productivity of existing agricultural land and applying best management practices to that land would slow the loss of, or is some cases restore, soil C. There are, however, many barriers to implementing best management practices, the most significant of which in developing countries are driven by poverty. Management practices that also improve food security and profitability are most likely to be adopted. Soil C management needs to considered within a broader framework of sustainable development. Policies to encourage fair trade, reduced subsidies for agriculture in developed countries and less onerous interest on loans and foreign debt would encourage sustainable development, which in turn would encourage the adoption of successful soil C management in developing countries. If soil management is to be used to help address the problem of global warming, priority needs to be given to implementing such policies.

Keywords Soil organic carbon · SOC · Land use change · Sequestration · Barriers · Sustainable development · Climate mitigation

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Introduction

Factors controlling the level of soil organic carbon

The level of soil organic carbon (SOC) in a particular soil is determined by many factors including climatic factors (e.g. temperature and moisture regime) and soil-related factors (e.g. soil parent material, clay content, cation exchange capacity; Dawson and Smith 2007). For a given soil type, SOC stock can also vary, the stock being determined by the balance of net C inputs to the soil (as organic matter) and net losses of C from the soil (as carbon dioxide, dissolved organic C and loss through erosion). Carbon inputs to the soil are largely determined by the land use, with forest systems tending to have the largest input of C to the soil (inputs all year round) and often this material is also the most recalcitrant. Grasslands also tend to have large inputs, though the material is often less recalcitrant than forest litter and the smallest input of C is often found in croplands which have inputs only when there is a crop growing and where the C inputs are among the most labile. The smaller input of C to the soil in croplands also results from removal of biomass in the harvested products, and can be further exacerbated by crop residue removal, and by tillage which increases SOC loss by breaking open aggregates to expose protected organic C to weathering and microbial breakdown, and also by changing the temperature regime of the soil. Rate of C input to the soil is related also to the productivity of the vegetation growing on that soil, measured by net primary production (NPP). NPP varies with climate, land cover, species composition and soil type. Moreover, NPP shows seasonal variation due to its dependence on light and temperature, e.g. broadleaf temperate forests are highly productive for part of the year only (Malhi et al. 2002). Over longer time periods, a proportion of NPP enters the soil as organic matter (OM) either via plant leachates, root exudates, or by decomposition of litter and fragmented plant structures (Jones and Donnelly 2004), where it is converted back to CO_2 and CH_4 via soil (heterotrophic) respiration processes. The remaining C is termed net ecosystem production (NEP). However, other processes such as harvest, fire and insect damage also remove C, which when combined with the heterotrophic processes counterbalance the terrestrial CO_2 input from GPP. Any residual C is termed net biome production (NBP) and can be negative or positive depending on whether the terrestrial ecosystem is a source or sink for C (Cao and Woodward 1998; IGBP 1998; Schlesinger and Andrews 2000; Janzen 2004; Jones and Donnelly 2004). Climate and land-use are the main causes of temporal and spatial fluctuations between these opposing fluxes. Very small C inputs to the soil, as dissolved organic C, comes from wet, dry and occult (fog and cloud) deposition (Dawson and Smith 2007). Impacts of land use and land management change on SOC are discussed further below.

The role of soils in the global carbon cycle

Globally, soils contain about three times the amount of C in vegetation and twice the amount in the atmosphere (IPCC 2000a), i.e. about 1,500 Pg (1 Pg = 1 Gt = 10^{15} g) of organic C (Batjes 1996). The annual fluxes of CO_2 from atmosphere to land (global Net Primary Productivity [NPP]) and land to atmosphere (respiration and fire) are each of the order of 60 Pg C y^{-1} (IPCC 2000a). During the 1990s, fossil fuel combustion and cement production emitted 6.3 ± 1.3 Pg C y^{-1} to the atmosphere, whilst land-use change emitted 1.6 ± 0.8 Pg C y^{-1} (Schimel et al. 2001; IPCC 2001). Atmospheric C increased at a rate of 3.2 ± 0.1 Pg C y^{-1}, the oceans absorbed 2.3 ± 0.8 Pg C y^{-1} with an estimated residual terrestrial sink of 2.3 ± 1.3 Pg C y^{-1} (Schimel et al. 2001; IPCC 2001).

The size of the pool of SOC is therefore large compared to gross and net annual fluxes of C to and from the terrestrial biosphere (Smith 2004). Figure 1 (IPCC 2001) shows a schematic diagram of the C cycle, with part (a) showing the main pools and flows of the natural global C cycle, and part (b) showing the human perturbation to the flows of C between the pools.

Small changes in the SOC pool could have dramatic impacts on the concentration of CO_2 in the atmosphere. The response of SOC to global warming is, therefore, of critical importance. One of the first examples of the potential impact of increased release of terrestrial C on further climate change was given by Cox et al. (2000). Using a climate model with a coupled C cycle, Cox et al. (2000) showed that release of terrestrial C under warming would lead to a positive feedback whereby C release would result in increased global warming. Since then, a number of coupled climate carbon cycle (so called C4 models) have been developed. However, there remains considerable uncertainty concerning the extent of the terrestrial feedback, with the difference between the models amounting to 200 ppm. CO_2-C by 2100 (Friedlingstein et al. 2006). This difference is of the same order as the difference between fossil fuel C emissions under the IPCC SRES emission scenarios (IPCC 2000b). It is clear that better quantifying the response of terrestrial C, a large proportion of which derives from the soil, is essential for understanding the nature and extent of the earth's response to global warming. Understanding interactions between climate and land-use change will also be critically important.

Historical losses of SOC due to land use change

Historically, soils have lost between 40 and 90 Pg C globally through cultivation and disturbance

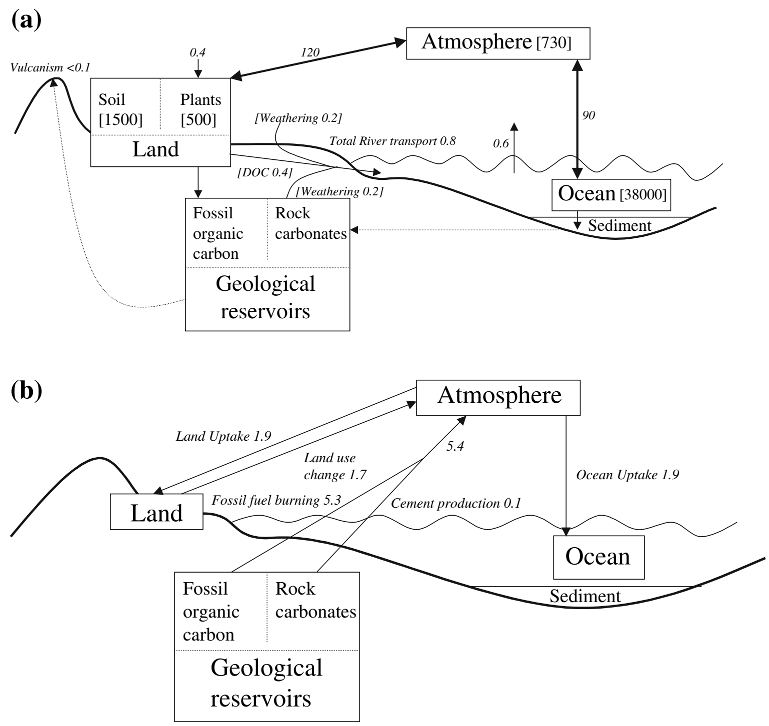

Fig. 1 The global carbon cycle for the 1990s (Pg C). (**a**) the natural carbon cycle (DOC, dissolved organic carbon) and (**b**) the human perturbation (redrawn from IPCC 2001; Smith 2004)

(Houghton 1999; Houghton et al. 1999; Schimel 1995; Lal 1999). It is estimated that land use change emitted 1.6 ± 0.8 Pg C y^{-1} to the atmosphere during the 1990s (Schimel et al. 2001; IPCC 2001).

Land use change and soc loss

Land use change significantly affects soil C stock (Guo and Gifford 2002). Most long term experiments on land use change show significant changes in SOC (e.g. Smith et al. 1997, 2000, 2001a, 2002). This is likely to continue into the future; a recent modeling study examining the potential impacts of climate and land use change on SOC stocks in Europe, land use change was found to have a larger net effect on SOC storage than projected climate change (Smith et al. 2005a).

In a meta-analysis of long term experiments, Guo and Gifford (2002) showed that converting forest land or grassland to croplands caused significant loss of SOC, whereas conversion of forestry to grassland did not result is SOC loss in all cases. Total ecosystem C (including above ground biomass), does however, decrease due to loss of the tree biomass C. Similar results have been reported in Brazil, where total ecosystem C losses are large, but where soil C does not decrease (Veldkamp 1994; Moraes et al. 1995; Neill et al. 1997; Smith et al. 1999), though other studies have shown a loss of SOC upon conversion of forest to grassland (e.g. Allen 1985; Mann 1986; Detwiller and Hall 1988). In the most favorable case, only about 10% of the total ecosystem C lost after deforestation (due to tree removal, burning etc.) can be recovered (Fearnside 1997; Neill et al. 1997; Smith et al. 1999).

The largest per-area losses of SOC occur where the C stock are largest, e.g. in highly organic soils such as peatlands, either through drainage, cultivation or liming. Organic soils hold enormous quantities of SOC, accounting for 329–525 Pg C, or 15–35% of the total terrestrial C (Maltby and Immirizi (1993), with about one fifth (70 Pg) located in the tropics. Studies of cultivated peats in Europe show that they can lose significant amounts of SOC through oxidation and subsidence; between 0.8 and 8.3 t C ha^{-1} y^{-1} (Nykänen et al. 1995; Lohila et al. 2004; Maljanen et al. 2001, 2004). The potential for SOC loss from land use change on highly organic soils is therefore very large.

In short, SOC tends to be lost when converting grasslands, forest or other native ecosystems to croplands, or by draining, cultivating or liming highly organic soils. SOC tends to increase when restoring grasslands, forests or native vegetation on former croplands, or by restoring organic soils to their native condition. Where the land is managed, best management practices that increase C inputs to the soil (e.g. improved residue and manure management) or reduce losses (e.g. reduced impact tillage, reduced residue removal) help to maintain or increase SOC levels. Management practices to increase SOC storage are discussed in the next section.

The most effective mechanism for reducing SOC loss globally would be to halt land conversion to agriculture, but with the population growing and diets changing in developing countries (Smith et al. 2007b; Smith and Trines 2007), more land is likely to be required for agriculture. To meet growing and changing food demands without encouraging land conversion to agriculture will require productivity on current agricultural land to be increased (Vlek et al. 2004). In addition to increasing agricultural productivity, there are a number of other management practices that can be used to prevent SOC loss. These are described in more detail in the next section.

Land use change and land management to restore or sequester soc

The global potential for sequestration of SOC

Soil C sequestration can be achieved by increasing the net flux of C from the atmosphere to the terrestrial biosphere by increasing global C inputs to the soil (via increasing NPP), by storing a larger proportion of the C from NPP in the longer-term C pools in the soil, or by reducing C losses from the soils by slowing decomposition. For soil C sinks, the best options are to increase C stocks in soils that have been depleted in C, i.e. agricultural soils and degraded soils, or to halt the loss of C from cultivated peatlands (Smith et al. 2007a).

Early estimates of the potential for additional soil C sequestration varied widely. Based on studies in European cropland (Smith et al. 2000), US cropland (Lal et al. 1998), global degraded lands (Lal 2001) and global estimates (Cole et al. 1996; IPCC 2000a), an estimate of global soil C sequestration potential is 0.9 ± 0.3 Pg C y^{-1} was made by Lal (2004a, b), between a 1/3 and 1/4 of the annual increase in atmospheric C levels. Over 50 years, the level of C sequestration suggested by Lal (2004a) would restore a large part of the C lost from soils historically.

The most recent estimate (Smith et al. 2007a) is that the technical potential for SOC sequestration globally is around 1.3 Pg C y^{-1}, but this is very unlikely to be realized. Economic potentials for SOC sequestration estimated by Smith et al. (2007a) were 0.4, 0.6 and 0.7 Pg C y^{-1} at carbon prices of 0–20, 0–50 and 0–100 USD t CO_2-equivalent^{-1}, respectively. At reasonable C prices, then, global soil C sequestration seems to be limited to around 0.4–0.7 Pg C y^{-1}. Even then, there are barriers (e.g. economic, institutional, educational, social) that mean the economic potential may not be realized (Trines et al. 2006; Smith and Trines 2007). The estimates for C sequestration potential in soils are of the same order as for forest trees, which have a technical potential to sequester about 1–2 Pg C y^{-1} (IPCC 1997; Trexler 1988 [cited in Metting et al. 1999]), but economic potential for C sequestration in forestry is similar to that for soil C sequestration in agriculture (IPCC WGIII 2007).

Many reviews have been published recently discussing options available for soil C sequestration and mitigation potentials (e.g. IPCC 2000a; Cannell 2003; Metting et al. 1999; Smith et al. 2000; Lal 2004a; Lal et al. 1998; Nabuurs et al. 1999; Follett et al. 2000; Freibauer et al. 2004; Smith et al. 2007a). Table 1 summarizes the main soil C sequestration options available in agricultural soils.

Most of the estimates for the sequestration potential of activities listed in Table 1 range from about 0.3 to 0.8 t C ha^{-1} y^{-1}, but some estimates are outside this range (IPCC 2000a; Lal 2004a; Smith et al. 2000; Follett et al. 2000; Nabuurs et al. 1999; Smith et al. 2007a). When considering soil C sequestration options, it is important also to consider other side effects, including the emission of other greenhouse gases. Smith et al. (2001b) suggested that as much as one half of the climate mitigation potential of some C sequestration options could be lost when increased emissions of other greenhouse gases (nitrous oxide; N_2O and methane; CH_4) were included, and Robertson et al. (2000) has shown that some practices that are beneficial for SOC

Table 1 Examples of soil carbon sequestration practices as considered by Smith et al. (2007a)

Activity	Practice	Specific management change
Cropland management	Agronomy	Increased productivity
		Rotations
		Catch crops
		Less fallow
		More legumes
		Deintensification
		Improved cultivars
	Nutrient management	Fertilizer placement
		Fertilizer timing
	Tillage/Residue management	Reduced tillage
		Zero tillage
		Reduced residue removal
		Reduced residue burning
	Upland water management	Irrigation
		Drainage
	Set-aside and land use change	Set aside
		Wetlands
	Agroforestry	Tree crops inc. Shelterbelts etc.
Grazing land management	Livestock grazing intensity	Livestock grazing intensity
	Fertilization	Fertilization
	Fire management	Fire management
	Species introduction	Species introduction
	More legumes	More legumes
	Increased productivity	Increased productivity
Organic soils	Restoration	Rewetting/Abandonment
Degraded lands	Restoration	Restoration

sequestration, may not be beneficial when all greenhouse gases are considered. Smith et al. (2007a) showed that soil C sequestration accounts for about 90% of the total global mitigation potential available in agriculture by 2030.

Other considerations for soil carbon sequestration

One also needs to consider the trade off between different sources of carbon dioxide. For example, N fertilizer production has an associated C cost, and some authors have argued that the additional C sequestration for increased production is outweighed by the C cost in producing the fertilizer (Schlesinger 1999). However, other studies in developing countries suggest that when accounting for increased production per unit of land allowed by increased fertilizer use, and the consequent avoided use of new land for agriculture, that there is a significant C benefit associated with increased fertilizer use in these countries (Vlek et al. 2004).

Soil C sinks are not permanent and will continue only for as long as appropriate management practices are maintained. If a land-management or land-use change is reversed, the C accumulated will be lost, usually more rapidly than it was accumulated (Smith et al. 1996). For the greatest potential of soil C sequestration to be realized, new C sinks, once established, need to be preserved in perpetuity. Within the Kyoto Protocol, mechanisms have been suggested to provide disincentives for sink reversal i.e. when land is entered into the Kyoto process it has to continue to be accounted for and any sink reversal will result in a loss of C credits. This process is termed “sink reversibility” (IPCC 2000a).

Soil C sinks increase most rapidly soon after a C enhancing land-management change has been implemented, but soil C levels may decrease initially if there is significant disturbance e.g. when land is afforested. Sink strength, i.e. the rate at which C is removed from the atmosphere, in soil becomes smaller with time, as the soil C stock approaches a new equilibrium. At equilibrium, the sink has saturated: the C stock may have increased, but the sink strength has decreased to zero (Smith 2004). This process is termed "sink saturation" (IPCC 2000a).

The time taken for sink saturation (i.e. new equilibrium) to occur is variable. The period for soils in a temperate location to reach a new equilibrium after a land-use change is around 100 years (Jenkinson 1988; Smith et al. 1996) but tropical soils may reach equilibrium more quickly. Soils in boreal regions may take centuries to approach a new equilibrium. As a compromise, current IPCC good practice guidelines for greenhouse gas inventories use a figure of 20 years for soil C to approach a new equilibrium (IPCC 1997; Paustian et al. 1997).

Meeting atmospheric CO_2 concentration stabilization targets

The current annual emission of CO_2-carbon to the atmosphere is 6.3 ± 1.3 Pg C y^{-1}. Carbon emission gaps by 2100 could be as high as 25 Pg C y^{-1} meaning that the C emission problem could be up to four times greater than at present. The maximum annual global C sequestration potential is about 0.4–0.7 Pg C y^{-1} (Smith et al. 2007a) meaning that even if these rates could be maintained until 2100, soil C sequestration would contribute a maximum of about 1–3% towards reducing the C emission gap under the highest emission scenarios. When we also consider the limited duration of C sequestration options in removing C from the atmosphere, we see that C sequestration could play only a minor role in closing the emission gap by 2100. It is clear from these figures that if we wish to stabilize atmospheric CO_2 concentrations by 2100, the increased global population and its increased energy demand can only be supported if there is a large-scale switch to non-C emitting technologies in the energy, transport, building, industry, agriculture, forestry and waste sectors (IPCC WGIII 2007).

This demonstrates that soil C sequestration alone can play only a minor role in closing the C emission gap by 2100. Nevertheless, if atmospheric CO_2 levels are to be stabilized at reasonable concentrations by 2100 (e.g. 450–750 ppm), drastic reductions in emissions are required over the next 20–30 years (IPCC 2000b; IPCC WGIII 2007). During this critical period, all measures to reduce net C emissions to the atmosphere would play an important role—there will be no single solution (IPCC WGIII 2007). IPCC WGIII (2007) show that there is significant potential for greenhouse gas mitigation at low cost across a range of sectors, but for stabilization at low atmospheric CO_2/GHG concentrations, strong action needs to be taken in the very near future, echoing the findings of the Stern Review (Stern 2006). Given that C sequestration is likely to be most effective in its first 20 years of implementation, it should form a central role in any portfolio of measures to reduce atmospheric CO_2 concentrations over the next 20–30 years whilst new technologies, particularly in the energy sector, are developed and implemented (Smith 2004).

Overcoming barriers to implementation

There are a number of barriers that mean that the economic potential for C sequestration might not be reached (Smith et al. 2007a, b). These barriers may prevent best management practices from being implemented. Trines et al. (2006) divided these into five categories: economic, risk-related, political/bureaucratic, logistical and educational/societal barriers. Trines et al. (2006) considered barriers preventing a range of agricultural and forestry greenhouse gas mitigation measures (including soil C sequestration) in developed countries, developing countries and countries with economies in transition and Smith and Trines (2007) considered the particular barriers prevalent in developing countries.

- Economic barriers include the cost of land, competing for land, continued poverty, lack of existing capacity, low price of C, population growth, transaction costs and monitoring costs.
- Risk related barriers include the delay on returns due to slow system responses, issues of permanence (particularly of C sinks) and issues concerning leakage and natural variation in C sink strength.

- Political and bureaucratic barriers include the slow land planning bureaucracy and the complexity and lack of clarity in C/greenhouse gas accounting rules, resulting in a lack of political will.
- Among logistical barriers considered by Trines et al. (2006) were the fact that land owners are often scattered and have very different interests, that large areas are unmanaged, the managed areas can be inaccessible and some areas are not biologically suitable.
- The education/societal barriers relate to the sector and legislation governing it being very new, stakeholder perceptions and the persistence of traditional practices.

Competition with other land uses is a barrier that necessitates a comprehensive consideration of mitigation potential for the land-use sector. It is important that forestry and agricultural land management options are considered within the same framework to optimise mitigation solutions. Costs of verification and monitoring could be reduced by clear guidelines on how to measure, report and verify GHG emissions from agriculture.

Transaction costs, on the other hand, will be more difficult to address. The process of passing the money and obligations back and forth between those who realise the C sequestration and the investors or those who wish to acquire the C benefits, involves substantial transaction costs, which increases with the number of landholders involved. Given the large number of small-holder farmers in many developing countries, the transaction costs are likely to be even higher than in developed countries, where costs can amount to 25% of the market price (Smith et al. 2007b). Organisations such as farmers' collectives may help to reduce this significant barrier by drawing on the value of social capital. Farmers in developing countries are in touch with each other, through local organisations, magazines or community meetings, providing forums for these groups to set up consortia of interested forefront players. In order for these collectives to work, regimes need to be in place already, and it is essential that the credits are actually paid to the local owner.

For a number of practices, especially those involving C sequestration, risk related barriers such as delay on returns and potential for leakage and sink reversal, can be significant barriers. Education, emphasising the long term nature of the sink, could help to overcome this barrier, but fiscal policies (guaranteed markets, risk insurance) might also be required.

Education/societal barriers affect many practices in many regions. There is often a societal preference for traditional farming practices and, where mitigation measures alter traditional practice radically (not all practices do), education and extension would help to reduce some of the barriers to implementation.

But the most significant barriers to implementation of mitigation measures in developing countries (and for some economies in transition) are economic. These are mostly driven by poverty and in some areas these are exacerbated by a growing population. In developing countries many farmers are poor and struggle to make a living from agriculture, with food security and child malnutrition still prevalent in poor countries (Conway and Toenniessen 1999). Given the challenges many farmers in these regions already face, climate change mitigation is a low priority. To begin to overcome these barriers global sharing of innovative technologies for efficient use of land resources and agricultural chemicals, to eliminate poverty and malnutrition, will significantly help to remove barriers that currently prevent implementation of mitigation measures in agriculture (Smith et al. 2007b). Capacity building and education in the use of innovative technologies and best management practices would also serve to reduce barriers.

More broadly, macro-economic policies to reduce debt and to alleviate poverty in developing countries, through encouraging sustainable economic growth and sustainable development, would serve to lower or remove barriers: farmers can only be expected to consider climate mitigation when the threat of poverty and hunger are removed. Mitigation measures that also improve food security and profitability (such as improved use of fertiliser) would be more favourable than those which have no economic or agronomic benefit. Such practices are often referred to as "win–win" options, and strategies to implement such measures can be encouraged on a "no regrets" basis (Smith and Powlson 2003), i.e. they provide other benefits even if the mitigation potential is not realised.

Maximizing the productivity of existing agricultural land and applying best management practices would help to reduce greenhouse gas emissions (Smith et al. 2007b). Ideally agricultural mitigation measures need to be considered within a broader framework of sustainable development. Policies to encourage sustainable development will make agricultural mitigation in developing countries more achievable. Current macro-economic frameworks do not support sustainable development policies at the local level whilst macro-economic policies to reduce debt and to alleviate poverty in developing countries, through encouraging sustainable economic growth and sustainable development, are desperately needed.

Ideally policies associated with fair trade, reduced subsidies for agriculture in the developed world and less onerous interest rates on loans and foreign debt all need to be considered. This may provide an environment in which climate change mitigation in agricultural in developing countries could flourish. The UK's Stern Review (http://www.sternreview.org.uk; Stern 2006) warns that unless we take action in the next 10–20 years, the environmental damage caused by climate change later in the century could cost between 5 and 20% of global GDP every year. The barriers to implementation of mitigation actions in developing countries need to be overcome if we are to realise even a proportion of the 70% of global agricultural climate mitigation potential that is available in these countries. Since we need to act now to achieve low atmospheric CO_2/GHG stabilisation targets (IPCC WGIII 2007), overcoming these barriers in developing countries should be a priority (Smith and Trines 2007).

Conclusions

Land management can profoundly affect soil C stocks and careful management can be used to sequester soil C. As with all human activities, the social dimension needs to be considered when implementing soil C sequestration practices. Since there will be increasing competition for limited land resources in the coming century, soil C sequestration cannot be viewed in isolation from other environmental and social needs. The IPCC WGIII (2007) have noted that global, regional and local environmental issues such as climate change, loss of biodiversity, desertification, stratospheric ozone depletion, regional acid deposition and local air quality are inextricably linked. Soil C sequestration measures clearly belong in this list. The importance of integrated approaches to sustainable environmental management is becoming ever clearer.

The key to increasing soil C sequestration, as part of wider programs to enhance sustainability, is to maximize the number of winners and minimize the number of losers. One possibility for improving the social/cultural acceptability of soil C sequestration measures, would be to include compensation costs for those who are disadvantaged when costing implementation strategies. By far the best option however, is to identify measures that increase C stocks whilst at the same time improving other aspects of the environment, e.g. improved soil fertility, decreased erosion, or greater profitability, e.g. improved yield of agricultural or forestry products. There are a number of management practices available that could be implemented to protect and enhance existing C sinks now, and in the future. Smith and Powlson (2003) developed these arguments for soil sustainability but the policy options are equally applicable to soil C sequestration. Since such practices are consistent with, and may even be encouraged by, many current international agreements and conventions, their rapid adoption should be encouraged as widely as possible.

Carbon sequestration measures should be considered within a broader framework of sustainable development. Policies to encourage sustainable development will make soil C sequestration in developing countries more achievable. Current macro-economic frameworks do not currently support sustainable development policies at the local level. Policies to encourage fair trade, reduced subsidies for agriculture in developed countries and less onerous interest on loans and foreign debt would encourage sustainable development, which in turn would provide an environment in which C sequestration could be considered in developing countries (Trines et al. 2006; Smith and Trines 2007).

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