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Conservation of soil organic carbon, biodiversity and the provision of other ecosystem services along climatic gradients in West Africa

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Abstract

Terrestrial carbon resources are major drivers of development in West Africa. The distribution of these resources co-varies with ecosystem type and rainfall along a strong Northeast-Southwest climatic gradient. Soil organic carbon, a strong indicator of soil quality, has been severely depleted in some areas by human activities, which leads to issues of soil erosion and desertification, but this trend can be altered via appropriate management. There is significant potential to enhance existing soil carbon stores in West Africa, with benefits at the global and local scales, for atmospheric CO_2 mitigation and supporting, and provisioning ecosystem services, respectively. Three key factors impacting carbon stocks are addressed in this review: climate, biotic factors, and human activities. Climate risks must be considered in a framework of global change, especially in West Africa, where landscape managers have few resources available to adapt to climatic perturbations. Among biotic factors, biodiversity conservation paired with carbon conservation may provide a pathway to sustainable development, as evidence suggests that both may be inter-linked, and biodiversity conservation is also a global priority with local benefits for ecosystem resilience, biomass productivity, and provisioning services such as foodstuffs. Finally, human management has largely been responsible for reduced carbon stocks, but this trend can be reversed through the implementation of appropriate carbon conservation strategies in the agricultural sector, as shown by multiple studies. Owing to the strong regional climatic gradient, country-level initiatives will need to consider carbon sequestration approaches for multiple ecosystem types. Given the diversity of environments, global policies must be adapted and strategised at the national or sub-national levels to improve C storage above and belowground. Initiatives of this sort must act locally at farmer scale, and focus on ecosystem services rather than on carbon sequestration solely.

1 Introduction

Soils represent major reservoirs of terrestrial carbon (C), with global C mass estimated at 1200–1600×10^{15} g of C (Eswaran et al., 1993; Batjes, 1996; Zech et al., 1997), which makes them relevant for atmospheric CO_2 mitigation. In West Africa, soil carbon is also crucial for fertilization and the prevention of erosion and desertification, particularly in drylands (Palm et al., 1997), therefore providing ecosystem services on the local as well as the global scales.

Soil carbon exists in two principal forms, organic (SOC) and inorganic (SIC). At a global scale the relative distribution of both forms depends strongly on climate (Table 1). In general, SOC content increases with precipitation, with optimum levels in humid and cold climates (Eswaran et al., 1999). SIC is more important in soils of arid and semiarid zones (Eswaran et al., 1999; Table 1). Whereas SOC storage is related to biophysical factors and management practices, SIC is relatively resistant to these factors.

Most soil carbon is found in organic form (Table 1; Eswaran et al., 1999), principally stored in the soil organic matter (SOM). Soil organic carbon storage varies within regions and biomes (Table 2). In West Africa, three major climatic and vegetational zones can be broadly distinguished, from north to south and from the inner to the coastal areas, designated as the Sahelian (arid), Sudanian (semi-arid) and Guinean (moist) zones (White, 1983). Vegetation distribution matches the strong climatic gradient, from the humid Guinean forests in the coastal south-western areas, through the savannahs in the semi-arid intermediate belt, into the desert and semi-desert inner continental areas. The dry season of West Africa distinguishes Guinean forests from other tropical zones such as in America or Indo-Malaysia (Hopkins, 1965). In West Africa, the transition between semi-deciduous forests and savannas also express the interaction of climate with biota and human activities (Latham et al., 1970; Jordan, 1983; Jenik, 1994), which in turn vary along the climate-driven soil fertility gradient (Table 2). There is an intricate relationship between climate, biotic factors and soil organic matter formation; these factors influence each other, making SOC formation a complex process, but yet it can be seen that climate, biota, and management are the major drivers acting on the parent material.

In addition to soil organic matter formation, soil organic carbon storage depends on organic carbon stabilization. Processes driving SOC stabilization can be abiotic, including those directly or indirectly depending on temperature and precipitation, or biotic, including productivity and organic matter decomposition (Trumbore, 1997; Thornley and Cannell, 2001; Schulze, 2006). SOC accumulation can also be modified through management. In West Africa, Hien et al. (2006) found 61 Mg C ha^{-1} under natural savannah, 25 Mg C ha^{-1} under crops amended with organic manure, and 16 Mg C ha^{-1} under unmanured crops within a depth of 30 cm.

The West African region is heavily dependent on climate-sensitive sectors like agriculture, pastoral practices, forestry, fisheries, etc. These sectors are also carbon-based systems, emphasizing the pivotal role of both above and belowground carbon in the provisioning of ecosystem goods and services. Soil organic carbon underlies major ecosystem services such as nutrient and soil moisture retention that contribute to plant productivity (Fischer et al., 2006), and also play crucial roles for climate change mitigation. Organic carbon stocks held in various pools (either in plant biomass, litter or soil) constitute major drivers of development in West Africa. However, there is a huge variability in the spatial and temporal distribution of these carbon pools across the region under human activities and climate change impacts.

The dynamic connection between soil resources and household livelihood could be viewed through food insecurity that also contributes to the vulnerability of West Africa to climate impacts according to the IPCC fourth assessment report (IPCC, 2007b). Africa has continuously experienced declining agricultural productivity per head that stands at 0.4% between 2000 and 2004 (UNEP, 2007). This limits the realization of the Millennium Development Goal (MDG 1; MEA, 2005). Decline in soil productivity is invariably linked to changes in the organic carbon pools that prevail in West Africa with increasing human activities of land transformation, especially under increasing population. Liu et al. (2004) highlighted the trend of decreasing total carbon stocks both in vegetation and soils, and predicted that this will continue through the 21st century unless measures practices are put in place. In many cases soil mining and agriculture expansion into marginal areas as a result of increasing land pressures in West Africa have both depleted soils of their carbon and nutrients and led to erosion (Bationo et al., 2007; Fig. 1). Appropriate land use management can reverse this trend and lead to substantial storage of carbon in soils, hence contributing to ecosystem fertility but also greenhouse gas mitigation. From this perspective, soil C management may also play a role in atmospheric CO_2 mitigation, and it is found that there is high potential for sequestration activities in the West and North African region (Table 3). The sum potential for sequestration activities in the West and North African region, including desertification control, is estimated to be between 23 and 31% of the total potential for all global drylands (Lal, 2002).

In this review we discuss first the global and local relevance of soil organic carbon in West Africa, in the context of climate change mitigation and conservation of soil fertility. These two goals, along with others, may be compatible in some forestry or agriculture applications in West Africa, and we show that temporal C dynamics and sequestration capacity will differ between systems. We also present important climatic, biotic, and human-derived drivers of soil carbon in the region, and we give particular consideration to the role of biodiversity in C storage because of the potential complementarity between C sequestration and biodiversity conservation. Finally we discuss patterns of land use and management, and how social structures may affect the accumulation of soil organic carbon. Overall, this synthesis is aimed towards identifying the processes that have the greatest effect on soil C based ecosystem service provision on the global and multiple levels, and how soil C sequestration might be achieved to suit both local sustainability and climate change mitigation (Fig. 2).

2 Global relevance – climate change mitigation and the carbon cycle

2.1 Contribution to mitigation of global warming

Contemporary carbon dioxide concentrations in the atmosphere have reached levels outside of the range of natural variation of the last 650 000 years, spurring concerns that anthropogenic activities may be causing recent trends of warming in the biosphere. Concentrations have increased from a pre-industrial value of approximately 280 ppm to 379 ppm in 2005, and data from 1990–2005 indicate that the rate of growth in has increased since continuous measurements began in 1960 (IPCC, 2007a).

Between 2000 and 2006, fossil fuel emission has increased by 3.3% year^{-1}. In 2004, 73% of global emissions growth was accounted for by the developing and least-developed economies (Raupach et al., 2007). However, the regional per-capita emissions and per-capita primary energy consumption of most West African countries are 1/10 of the global average (Raupach et al., 2007). Although this raises questions about global equity, it offers the opportunity for a different development model in the region. Climate change mitigation is a shared responsibility, and West Africa is one of the most vulnerable areas (Niasse et al., 2004). There is overwhelming consensus in the global climate change policy arena that mitigation actions provide the most effective carbon dioxide emission offset (Canadell et al., 2007). One efficient way to proceed is through carbon sequestration in soils. Managing soils in a way that minimizes carbon loss while enhancing carbon uptake and storage capacity have important roles to play in the global response to the greenhouse gas crisis. The carbon sequestration potential under proper management of cropland globally is estimated at 0.08–0.12 Pg year^{-1} by erosion control and 0.15–0.175 Pg year^{-1}, for example through conservation tillage (Lal and Bruce, 1999; Lal, 2004). Assuming that degraded grasslands in Senegal may be restored to woody grasslands over 20 years, then C sequestration rates of 0.77 t C ha^{-1} year^{-1} may be achieved (Woomer et al., 2004a). Agroforestry simulations involving *Faidherbia albida* (Del.) Chev. and *Leucaena leucocephala* (Lam.) deWit. in Senegal also resulted in promising carbon gain (+0.22 and +0.12 t C ha^{-1} year^{-1}, respectively), suggesting that improving agricultural practices is key to enhancing food production and mitigating climate change (Tschakert et al., 2004). Woody biomass carbon was found more sensitive to long-term changes in precipitation and temperature than soil carbon (Tschakert et al. 2004). Nonetheless, tropical deforestation averages 13 millions hectares each year, significantly contributing to emissions (Canadell et al., 2007).

Greenhouse gas (GHG) emission from soils is linked to soil degradation (Lal and Bruce, 1999). Soil carbon loss through soil erosion in combination with mineralization of the dislodged carbon is estimated to be 4–6 Pg year^{-1}, with mineralization accounting for 20% of the erosion-induced emissions (Lal, 2003). The semi-arid and sub-humid regions of Africa have the highest potential for carbon sequestration in the world but the soils are severely degraded. West Africa holds significant amounts of SOC, about 4.2–4.5 kg C m^{-2} (Batjes, 2001), but contributed more than 50% of the net emission of C to the atmosphere in 1980 in Africa (Houghton et al., 1987). This contribution was mainly driven by deforestation, and other forms of land use change like expansion of agriculture, over-cultivation of existing agricultural land and extensive gathering of fuelwood. By the end of the last century, 50–70% of West African land was under a management regime with minimal C returns to the soil (Tiessen et al., 1998).

2.2 Short, medium, and long-term impact of climate change mitigation measures in West Africa

Within the context of climate change, of which the main drivers are suspected to be greenhouse gas emission from human activities and land use changes, soil carbon is receiving increasing attention due to the importance of soil carbon pools in comparison to atmospheric carbon. Any change in the belowground pools resulting from changes in land-use (conversion to crop or pasture, afforestation) can have major impacts on carbon concentrations in the atmosphere. Most of these carbon flows are mediated by soil organic matter (Manlay et al., 2007).

Over 30% of CO_2 emissions originate from agricultural and forestry sectors (IPCC, 2007b). The Fourth Assessment Report of IPCC (2007b) indicates cost effective GHG mitigation strategies in forest and agriculture sectors through improved practices, particularly in cropland grazing, rice cultivation techniques, livestock and manure management (to reduce CH_4 emissions), nitrogen fertilisation (to reduce N_2O emissions), irrigation efficiency; as well as restoration of cultivated peaty soils and degraded lands. Forest practices include afforestation, reforestation, forest management, and mapping land use change, water use, erosion control and soil protection. There are significant benefits in management practices that encourage biodiversity conservation in forestry and agricultural landscapes. Besides protecting biodiversity and some keystone species, there is maintenance or restoration of ecosystem services that underlies commodity production and some other vital services like hydrological services (Fischer et al., 2006).

Agricultural production, including access to food, is projected to be severely compromised in many African countries with climate change. Estimates in Senegal suggest a potential decrease of 30% in plant production with climatic changes, and the potential to store 31% carbon from improved management practices (Parton et al., 2004). By 2020, yields from rain-fed agriculture could be reduced by up to 50% in some countries. This would further adversely affect food security and exacerbate malnutrition (IPCC, 2007b). Mitigation efforts over the next 20–30 years will determine humanity's ability to achieve lower stabilization levels and avoid the worst effects of climate change (IPCC, 2007b).

Technological options to increase the carbon pool in soils have to be used with reservation, since some of the practices can release carbon, either due to particular environmental circumstances, or when taking into consideration other carbon pools linked to soils in order to make the global carbon budget of the ecosystem (Lal, 2004). The relationships among the main processes of loss or accumulation of soil carbon are very complex, and there are many human activities affecting them. As examples, three recommended activities – irrigation, chemical fertilization and manure application –

can have drawbacks. Depending on the technology applied, the costs of pumping water, land levelling, and associated expenses can counteract the benefits of irrigation on C storage. Likewise, the irrigation with groundwater may imply the degassing of the CO_2 when taken at the surface and the precipitation of calcite in the soil, which releases CO_2 to the atmosphere (Schlesinger, 2000). Fertilization, needed to balance the stochiometric relations among organic constituents, has implicit costs of production and application that release carbon to the atmosphere, particularly when chemical. The estimates of biomass to be eaten by cattle to produce manure for a given surface are about 6 times the net primary production in this surface (Schlesinger, 2000). Taking this into consideration, crop residue management is more efficient than manure application, although it is a sound option if no alternative use is foreseen for this organic residue.

3 Local relevance – soil organic matter and nutrient cycling

3.1 Soil quality, soil organic matter, and ecosystem services

In addition to reducing the concentration of greenhouse gases, carbon sequestration in soil provides benefits of improved soil quality (fertility, water holding capacity, resistance to erosion) and ecosystem functioning. Soil performs many functions and delivers ecosystem services vital for human activities. Soil C provides soil quality and resilience of service provision, which include: biomass production; storing, filtering and transforming nutrients and water; reducing soil temperature extremes and soil water loss; improving soil structure, water infiltration and water-holding capacity; hosting the biodiversity pool; acting as a platform for most human activities; providing raw materials; acting as carbon pool; and storing geological and archaeological heritage (Craswell and Leffroy, 2001; Table 4). Soil quality contributes to the ability to provide those services. Soil C sequestration and conservation becomes a strategy to achieve food security through improvement in soil quality (Fig. 2). SOC is an important indicator of soil quality; organic C stocks alone can describe 78% of the variability of maize yields in Nigeria, as shown by Smaling and Dixon (2006). Thus soil carbon, productivity, and degradative processes are closely related (Vågen et al., 2005; Roose and Bathès, 2001).

Soil is a non-renewable resource in that the rate of degradation can be much faster than the formation and regeneration processes. In view of its stability, SOC can have residence times from months (labile organic matter) to tens of thousands of years (passive organic matter). The properties we find most susceptible to rapid changes include those that affect two important soil functions: biomass production and carbon storage (Table 4). According to Stewart et al. (2007), the carbon saturation capacity of the soil is not predetermined for each soil type, but depends strongly on the management practices of the system. These authors suggest that agroecosystems under disturbance may never attain an absolute C saturation level, due to accelerated OM decomposition by tillage (Fig. 3). Otherwise, the soil attainable capacity is finite, and can be filled over 20 to 50 years (Lal, 2004). This is of particular importance when considering strategies to improve SOC stocks, since the maximum attainment period is between 5 to 20 years after adoption of the recommended management practices (Lal, 2004).

3.2 Terrestrial carbon in West Africa: management considerations with local relevance

Management practices are actively being developed in West Africa that target the improvement of soil quality using soil C as a primary indicator of services such as productivity and erosion control. Those management practices consist of addition of high amounts of biomass to the soil, minimal soil disturbance, conservation of soil and water, improvement of soil structure, enhancement of activity and species diversity of soil fauna, and strengthening of mechanisms of elemental cycling (Table 5; Lal, 2004). Lal (2004) demonstrated potential crop yield increase by 20–40 kg ha^{-1} for wheat, 10–20 kg ha^{-1} for maize, and 0.5 to 1 kg ha^{-1} for cowpea through one ton increase in soil carbon pool on degraded cropland. Also, the Greening of the Sahel project in Niger

(USAID) demonstrated that assisted natural regeneration (RNA) provides short-term increases in soil fertility in addition to improving the microclimate (Larwanou et al., 2007).

Restoration of degraded soils has the potential to provide terrestrial sinks of carbon and reduce the rate of enrichment of atmospheric CO_2. Woomer et al. (2004a) report a study in Senegal where the terrestrial carbon stocks ranged from 9 Mg C ha^{-1} in degraded savannas in the north to 113 Mg C ha^{-1} in the remnant forests of the River Senegal valley. The results of Woomer et al. (2004a) further showed that the estimated total carbon stocks were 1019 MT in 1965 and 727 MT in 2000, indicating a loss of 292 MT C over 35 years. Strong differences in soil organic matter between cropland and a remnant of Sudanian forest have also been reported in the Savannah region in Northern Togo (Poch and Ubalde, 2006). Woomer et al. (2004b) also showed that the total system carbon at 40 cm soil depth in the Sahel of Senegal ranged between 12.0 and 31.2 Mg C ha^{-1}, while the total SOC contents ranged between 11.6 and 25.3 Mg C ha^{-1}.

Land degradation and nutrient mining are severe in the Sahelian countries where cereal production fell by 12.7% in 2000 (Pieri, 1995). The application of inorganic fertilizers is rare (8 kg ha^{-1} relative to 107 kg ha^{-1} in developing countries) and it is expected to remain low until 2030 (Tieszen et al., 2004). The SOC pool can be enhanced by the restoration of degraded soils, and the conversion to planted fallows, agroforestry, plantations, improved pastures and mulch farming (Lal, 2005). These practices are capable of sequestering C at a rate of 100 to 1000 kg C ha^{-1} year^{-1}, compared to the total potential of SOC sequestration of 200 to 500 Tg C year^{-1} in tropical forest ecosystems. Unruh et al. (1993) found that the types of agroforestry that included fuelwood production had the most potential to accumulate carbon in sub-Saharan Africa and estimated values of between 6 and 23 Pg C (1 Pg=1×10^9 metric tones), depending on the density of trees. However, if belowground biomass was included the potential for soils to accumulate carbon under agroforestry raised the estimates to between 8 and 54 Pg C. The accumulation of such amount of carbon could offset global emissions from fossil fuels for 1.7 to 9 years and African emissions for 20 to 125 years (Unruh et al., 1993).

The establishment of natural or improved fallow systems such as agroforestry has the potential of increasing SOC, with attainable rates of carbon sequestration in the range of 0.1 to 5.3 Mg C ha^{-1} $year^{-1}$ (Vågen et al., 2005). Vågen et al. (2005) reported that the addition of manure in combination with crop residues and no-till cultivation can attain C sequestration rates of 0 to 0.36 Mg C ha^{-1} $year^{-1}$. They also found that that rates of C sequestration on permanent cropland in sub-Saharan Africa under improved cultivation systems (e.g. no-till) range from 0.2 to 1.5 Tg C $year^{-1}$, while the attainable rates under fallow systems are 0.4 to 18.5 Tg C $year^{-1}$ compared to the potential rates of sequestration of 28.5 Tg C $year^{-1}$ in that region. Tschakert et al. (2004) used a biogeochemical model to simulate soil and biomass carbon over a period of 25 and 50 years that ranged between −0.31 Mg C ha^{-1} $year^{-1}$ for a worst-case millet-sorghum rotation to +0.43 Mg C ha^{-1} $year^{-1}$ on intensively managed agricultural fields. Furthermore, a farmer-centred ex-ante cost benefit analysis of 15 management and land use options, including agroforestry, reported net benefits ranging from −1400 to 9600 Mg C^{-1}. However, human disturbance in Senegal's Sahel Transition Zone accounted for only 22% of biomass C loss in 1993, suggesting that the effects of long-term Sahelian drought continue to play an overriding role in ecosystem change (Woomer et al., 2004b).

4 Biotic drivers of soil carbon in West Africa

Generally speaking, there are five main soil-forming factors: time, climate, relief, parent material, and biota (Jenny, 1941). Biota must clearly include humans, who now dominate more than three quarters of the Earth's surface, such that wildlands now only account for 10% of the entire planet's primary productivity (Ellis and Ramankutty, 2008). Biota, human or otherwise, plays an important role in soil-forming processes, via mechanisms such as human-attributed disturbance or inputs in the form of organic residues of plants and other organisms or, in general, through their effects on biogeochemical processes (Schulze, 2006).

4.1 Biodiversity and ecosystem services

Biodiversity is a biotic factor that has particular relevance for C sequestration and conservation in tropical zones and biodiversity hotspots, one of which is the Guinean forest zone of West Africa (Mittermeier, 2004). In this context, biodiversity protection in West Africa may serve keystone or rare species, but biodiversity also maintains and restores vital ecosystem services such as commodity production and hydrological services (Fischer et al., 2006).

There is reason to explore how species richness, functional diversity and dominant plant traits are relevant for C conservation and sequestration in West Africa. Biodiversity is related to sustainability and resilience of ecosystems and the provision of ecosystem goods and services (MEA, 2005). Though ecologists are really just beginning to understand the mechanistic effects of diversity on ecosystem function (Reich et al., 1997; Mittelbach et al., 2001; Hooper et al., 2005) there is consensus that biodiversity underlies ecosystem services (MEA, 2005; Rodriguez et al., 2006.; Kirwan et al., 2007), and that with biodiversity loss ecosystem function is threatened, as well as the goods and services ecosystems provide (Chapin et al., 1997; Loreau et al., 2001; Hooper et al., 2005). On the other hand, plant functional trait (de Bello et al., 2005; Sebastià, 2007) and species (Sebastià et al., 2008) diversity may both be compromised under a scenario of climate change.

4.2 Effects of plant species and functional diversity on carbon storage

A relationship between soil C storage and species richness has been reported in experimental grassland systems (Tilman et al., 2006), in boreal forests (Hollingsworth et al., 2008), and in managed grasslands in the Savannah region of Northern Togo (Sebastià et al., 2008). It has been hypothesized that the loss of any species will result in negative ecosystem effects from the perspective of species-identity effects (Jonsson and Malmqvist, 2003). Vascular plant species identity effects can be dominant controls over ecosystem services such as productivity via such mechanisms as intra and inter-specific interactions (Ramseier et al., 2005; Jonsson and Malmqvist, 2003). However, there seem to be emerging properties in diverse systems that go beyond particular species identity effects on ecosystem services (Kirwan et al., 2007), and could be linked to species complementarity and functional diversity. There is much room for exploration on how diversity of organism function may affect ecosystem processes, and modelling frameworks linking species and functional diversity with ecosystem properties and the resulting ecosystem services are being developed (Fig. 4; Diaz et al., 2007).

Functional diversity may be a stronger predictor of ecosystem processes than species number (Tilman et al., 1996). A decoupling has been found between species and functional diversity responses to environmental change (de Bello et al., 2006). Previous work using leaf traits has already demonstrated that traits-based analysis can describe consistent variation in measurements for leaf form, function, chemistry and longevity across large scales and multiple biomes (Reich et al., 1997). Methods that use community-aggregated functional traits for modeling important ecosystem processes relevant for soil carbon storage, such as photosynthesis, decomposition, and respiration, might be applied to describe the dominant controls on C sequestration (Eviner and Chapin, 2003; Diaz et al., 2007).

Previous studies on the ecosystem effects of biodiversity have used net primary productivity (NPP) as an integrated measure of ecosystem function and ecosystem service provision (Costanza et al., 2007; Kirwan et al., 2007). Biomass productivity via photosynthesis is the primary mechanism by which CO_2 can enter terrestrial ecosystems (Catovsky, 2002). Of particular relevance for tropical zones is the finding by Costanza et al. (2007) that biodiversity showed the strongest regulating effect on productivity in high-temperature zones (Fig. 5). Dominant ecosystem plant traits also directly influence C sequestration potential via respiration by leaves, from woody material and litter, from soil roots, and microbial respiration which is influenced by litter quality with additional subsequent effects on the process of decomposition (Schulze, 2006; De Deyn et al., 2008). Thus, functional trait diversity may have an effect on soil carbon storage through processes other than productivity, including decomposition and nutrient cycling. Shifts in plant guilds and functional types have been related to soil carbon storage (Fornara and Tilman, 2008) and nutrient dynamics (Sebastià, 2007) in ecosystems.

The trait pool in West Africa is partly affected by sustained human intervention in the landscape over millennia, contributing to an observed "dominant ruderal strategy" in the distribution of vascular plants in Guinean forests associated with the toleration of open and dry conditions (Holmgren and Poorter, 2007). Human activities fracture forest and savannah ecosystems, favouring plant traits related to the colonization of open areas (Holmgren and Poorter, 2007). Changes in the plant community implies changes in the amount and quality of litter inputs to the soil, thus such shifts driven by land use can lead to low fertility and desertification (Milton and Dean, 1994; Ringius, 2002).

5 The human footprint on soil organic carbon: management and land use in West Africa

5.1 Land use change and soil carbon evolution

Globally, the annual loss of CO_2 due to land use changes and fossil fuel combustion since the 1850 are 1.6 and 5.5 Pg C year^{-1}, respectively (Post et al., 1990). Humans have already dramatically altered the biosphere through land use (Vitousek et al., 1986; Ellis and Ramankutty, 2008), and it is projected that emissions from land use changes would increase to 3 Pg C year^{-1} under a scenario of climatic change, with corresponding increases in temperature and aridity that would transform organic soils from being sinks to sources of CO_2 (Post et al., 1990). In dry environments there is even greater risk that human activities may result in land degradation.

Deforestation in West Africa has led to increases in secondary savannas (Badejo, 1998), which implies changes in the litter inputs as described in the previous section.

Declines in soil fertility are also found as consequence of overgrazing, and management for livestock is associated with bush burning (Van der Werf, 1983; Adepetu, 1994). In particular, agriculture adds to CO_2-driven climate risks because it favours SOM mineralization over sequestration (IPCC, 2007b). Exposing the soil and breaking down soil aggregates puts SOC at the disposal of microbial activity and to the action of the atmospheric agents (Batjes and Bridges, 1992). This is the main process of liberation of CO_2 due to land use changes from forest and pasture to croplands and plantations, which are known to have high consequences in terms of soil carbon loss (Fig. 6; Guo and Gifford, 2002). Within the semi-arid region of Senegal known as the groundnut basin (dominated by sandy soils), agricultural expansion from north to south has resulted in a decline in SOC and nitrogen, and continued expansion of the traditional groundnut-millet cultivation system into woodlands may within 40 years result in a loss of up to 1.1 kg C m^{-2} (Elberling et al., 2003). While soil C levels are smaller in the drier northern areas, the absolute values of short-term losses of soil C are approximately the same (0.06 kg C m^{-2} per year; Elberling et al., 2003). Despite the rapid losses of soil C in the region, the combination of modelling with land use classification estimated between 54 kg C ha^{-1} $year^{-1}$ may be sequestered for the study area with ridge tillage, increased application of fertilizers, and residue management. Encouragingly, this is about one-third the rate of C sequestration used for large-scale estimates of C sequestration potential in West Africa (Doraiswamy et al., 2006).

6 Fires, land degradation processes and soil carbon

Frequent fires and over-exploitation can lead to land degradation, a major constraint to African development. It is estimated that over 500 million hectares of land have undergone soil degradation since the 1950s which include 65% of agricultural land in Africa (GEF and IFAD, 2002). The impact of fires on SOM depends on the intensity of the fire and the distribution of SOM in depth. Although the direct effects entail a decrease of SOM and the liberation of CO_2, this affects only the first centimetres of the soil, unless the fires recur with high frequency. The indirect effects in the medium and long term are, however, more important, and they can be positive for the storage of carbon (conversion of C of the biomass to recalcitrant forms of coal, increase of the chemical fertility in acid soils that increases their production potential) or negative (increase of erosion, reduction of infiltration). The latter (negative) is the principal effect of fire in semiarid zones, where the fires occur often in forest grounds where the organic matter is in the surface horizons, in erodible areas, and where the climate does not favor the regeneration of the forests. In the light fraction of SOM ($<50\,\mu$m) there are amounts of coal particles coming from fires or burning, which are part of the recalcitrant coal. This coal, which was believed anecdotal in the estimations of the SOC, constitutes the major fraction – on the order of 30–35% in soils affected over long periods by slash and burn practices (Skjemstad et al., 2002). The time of residence, however, not only depends on the nature of the fraction, but also on the climate, the mineralogy of the clays and the soil depth, among other factors.

Soil erosion is associated with C emissions, although not all the implied mechanisms act in the same direction. The primary mechanisms of erosion are the liberation and transportation of the SOM by wind or water during which SOM is mineralized faster, which results in a decrease in situ of the physical, chemical and biological quality of the soil and therefore of its potential to sequester carbon (Table 6). The effects are a decrease in situ of the physical, chemical and biological quality of the soil and therefore of its potential to sequester carbon. However, depending on the place where the SOM is deposited the organic matter can be sequestered (sediments of lakes, reservoirs) or can be accumulated in certain soils improving their quality (toeslopes, floodplains, deltas). These areas become sinks of carbon in so far as the organic matter remains there with periods of recurrence longer than those of the places where it was eroded. However, the erosion can not be considered as a simple process of organic matter redistribution in the landscape since there are some irreversible losses by mineralization (Lal, 2001).

6.1 Soil carbon and socio-economic structure

Soil carbon preservation in West Africa, as elsewhere, depends on socio-economic structures and well-designed support policy measures. In addition, stakeholders are key as the agents of change towards sustainable practices enhancing C conservation. In Senegal, local farming systems in Old Peanut Basin have embarked on different pathways of change to adapt to their evolving environment, despite some general trends of resource degradation (Tschakert and Tappan, 2004). A study in Ghana (Sagoe, unpublished doctoral dissertation) revealed that communities with strong social ties and networks are more likely to embrace land management activities that would improve soil organic carbon, biodiversity, and livelihood. Within the studied communities, common culture and kinship were found to be enabling factors, whereas communities with weak social ties were found to be less developed and unwelcoming to innovation. In assessing the real hazards of various households (Fig. 7), most household concerns (96%) were related to financial capital, followed by natural capital (40%) which includes land, soil productivity and biodiversity (Sagoe, unpublished doctoral dissertation).

Gender also played a key role in land use and land use change of households in the studied communities; male headed households had greater access to human capital than the female headed households. In the female-headed households, the majority of household heads were found to be single-parent divorcees, widows, or never-married persons, and these households cannot afford the human and financial capital needed for soil organic carbon interventions (Sagoe, unpublished doctoral dissertation).

Since any factor or process that influences land use would invariably affect soil organic carbon, social issues such as gender disparity in access to land, crop grown, ethnicity, cultures and financial implications must be considered. This may only be achieved if communities are included in early stage of development-related decision-making or activity design. A “win-win” scenario that suits the goals of a diverse group of stakeholders will not emerge easily. Other constraints such as poverty and over-exploitation of forests may have already affected such a degree of landscape fragmentation (Fairhead and Leach, 1998) that smallholders would be disadvantaged in any initiatives related to C conservation paired with biodiversity conservation, as already observed in Central America (Tschakert et al., 2007). Furthermore, C sequestration mitigation in West African productive ecosystems should not result in inappropriate trade-offs for food production nor added social tensions or risks (Perez et al., 2007; Tschakert et al., 2007). If success is measured on the long rather than short term, which seems necessary given the disruptability of prominent terrestrial C stores such as forest and soils, then participation or buy-in from local stakeholders may be the difference between project success and failure.

7 Concluding remarks

The soil is the largest reservoir of carbon in the terrestrial carbon cycle. As such, understanding the spatial and temporal distribution of carbon sources and sinks in the terrestrial biosphere is crucial for countries to make informed decisions about limiting their emissions and also responding to other national development challenges like land degradation and food security. Soil scientists now recognize SOM as a major factor controlling the capacity of soil resources to deliver agricultural and environmental services and sustain human societies at both local (e.g. fertility maintenance) and global (e.g. mitigation of atmospheric carbon emissions) scales. As such, climate change mitigation programs in West Africa will have direct impacts in other sectors.

Sub-Saharan Africa has a high potential for C sequestration, largely in the opportunity to restore lands degraded by agricultural expansion, deforestation, erosion, and desertification. Strategies for soil C sequestration must be sensitive to the diversity of ecosystem types which range from rainforest to semi-desert, and also to cultural and social factors that can either promote or hinder C conservation. Ethically as well as practically, sustainable C sequestration policies will be built with the understanding that SOC and SOM provide important ecosystem services beyond CO_2 mitigation, and therefore that local and global ecosystem service provision will covary for some

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services. Given the diversity of the environment, global policies are necessary at a national scale to plan strategies to improve C storage above and belowground, depending on the availability of resources as SOM or residues; water; social structure, and so on. The policies must act locally at farmer scale, and focus on the ecosystem services rather than on carbon sequestration solely.

In essence, the need addressed here is a synthesis of the commonalities shared between global and local goals, and it is hoped that this will aid future research and policy efforts on the conservation of soil C and biodiversity. What is advocated is applied work that specifically seeks to pair C sequestration for mitigation purposes with local development issues related to soil quality. We do not suppose that such “win-win” scenarios may emerge easily, but we must continue with the notion that such opportunities should and do exist.

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Table 1. SOC and SIC storage in the world. Modified from Eswaran et al. (1999).

Order	Area	Organic Carbon		Inorganic Carbon		Total Carbon	
	%	Pg	%	Pg	%	Pg	%
Gelisols	8.6	316	20.4	7	0.8	323	12.9
Histosols	1.2	179	11.6	0	0.1	180	7.2
Spodosols	2.6	64	4.1	0	0.0	64	2.6
Andisols	0.7	20	1.3	0	0.0	20	0.8
Oxisols	7.5	126	8.1	0	0.0	126	5.1
Vertisols	2.4	42	2.7	21	2.3	64	2.6
Aridisols	12.0	59	3.8	456	48.0	515	20.6
Ultisols	8.4	137	8.8	0	0.0	137	5.5
Mollisols	6.9	121	7.8	116	12.2	237	9.5
Alfisols	9.6	158	10.2	43	4.5	201	8.0
Inceptisols	9.8	190	12.2	34	3.6	224	9.0
Entisols	16.2	90	5.8	263	27.7	353	14.2
Miscellaneous	14.1	24	1.5	0	0.0	24	1.0
Total	100.0	1 526	100.0	940	100.0	2 468	100.0

Table 2. Carbon stocks and other fertility indicators of granitic soils in different agro-ecological zones in West Africa spanning the N-S climatic gradient. Modified from Bationo et al. (2007).

Agro-ecological zone	pH (H_2O)	OC ($g\,kg^{-1}$)	Total N ($g\,kg^{-1}$)	Total P ($mg\,kg^{-1}$)
Equatorial forest	5.3	24.5	1.6	628
Guinea savanna	5.7	11.7	1.39	392
Sudan savanna	6.8	3.3	0.49	287

Table 3. Potential of the West Africa North Africa (WANA) region (Lal, 2002) and the global dryland systems to sequester C under various strategies. Modified from Lal (2002).

Strategy	West Africa and North Africa region (Tg C year^{-1})	Global dryland system (Tg C year^{-1})
Desertification Control	40–100	200–300
Reclamation of salt-affected lands	9–18	200–400
Agricultural intensification on undegraded soils	6–12	10–20
Fuel C offset	88–175	300–500
Soil C sequestration under biofuel planting	25–75	NA
Total	168–380	710–1220

Table 4. Ecosystem services derived from soil organic carbon pool. Modified from Lal (2004).

On-site benefits	Off-site benefits
Improvement in soil quality Increase in available water capacity Increase in nutrient retention Improvement in soil structure and tilth Buffering against changes in pH Enhancement of soil biotic activity Improvements in soil moisture and temperature regimes	*Improvement of water quality* Decrease in transport of pollutants Biodegradation and denaturing of pollutants and contaminants Reduction in sediment load and siltation of water bodies Decreased in non-point source pollution Reduction in hypoxia risk in water bodies Less damage to coastal ecosystems Low risk by floods and sedimentation Decrease in transport of pollutants out of the ecosystem
Increase in agronomic/forest productivity Increase in crop yield Increase in use efficiency of input (fertilizers and water) Decrease in losses of soil amendments by runoff, erosion and leaching Improvements in soil conditions	*Improvement in air quality* Reduction in rate of enrichment of GHG Decrease in wind-borne sediments
Sustainability and food security Increase in sustainable use of perturbed soil and water resources Food security increase Additional income from trading C credits Improvement in nutritional value of food and avoidance of hidden hunger	*Improvement in biodiversity* Increase in soil biodiversity Improvement in wildlife habitat and species diversity on restored ecosystems Improvement in aesthetic and cultural value
	Desertification control Restoration of desertified lands Reversal of degradation trends Strengthening elemental recycling mechanisms

Table 5. Technological C-sequestration options for humid and semi-arid climates. Modified from Lal (2004).

Technological options	Humid tropical climate	Semi-arid tropical climate
	$\mathrm{T\,C\,ha^{-1}\,year^{-1}}$	
Cropland		
No-till/conservation tillage	0.2–0.5	0.1–0.2
Cover crops and elimination of bare fallow	0.1–0.2	0.05–0.1
Manuring (10–20 $\mathrm{Mg\,ha^{-1}\,year^{-1}}$)	0.2–0.4	0.1–0.2
Complex rotation with deep rooted plants	0.1–0.2	0.02–0.05
Integrated pest management	0.02–0.05	0.01–0.2
Irrigation and water management	-	0.2–0.4
Agroforestry	0.2–0.5	0.1–0.2
Rice paddies	0.2–0.5	0.05–0.1
Grazing land		
Improved pastures	0.5–1.0	0.1–0.2
Fertility management	0.2–0.4	0.05–0.1
Grazing management	0.4–0.6	0.1–0.2
Forest land		
Timber harvest	0.2–0.4	0.1–0.2
Site preparation	0.1–0.2	0.05–0.1
Improved species	0.4–0.8	0.1–0.2
Stand management	0.1–0.2	0.05–0.1
Degraded soils		
Soil erosion by water	0.2–0.4	0.1–0.2
Soil erosion by wind	–	0.05–0.1
Salt affected soils	–	0.2–0.5
Mine soils	0.2–0.4	0.1–0.2
Wetland restoration	0.2–0.4	0.1–0.2

Table 6. Carbon deposits by rainfall, carbon losses by erosion, runoff and leaching, and carbon stock in the topsoil (30 cm) under natural and cropped field conditions, in runoff plots at Adiopodoumé, Korhogo (Ivory Coast) and Saria (Burkina Faso). Modified from Roose and Bathès (2001).

Location	C deposits by rainfall	C losses				C stock (topsoil 30 cm)
		Erosion	Runoff	Leaching	Total	
	kg ha^{-1} yr^{-1}	kg ha^{-1} yr^{-1}				kg ha^{-1}
Adiopodoume (2100 mm rainfall)						
Sub-equatorial forest	155.6	13.0	1.2	73.9	88.1	45 670
Cereals	27.3	1801.0	64.8	7.0	1872.8	34 180
Korogho (1300 mm rainfall)						
Sudanian savanna	46.1	5.5	2.1	12.6	20.2	22 570
Maize, with fertilizers	14.9	64.1	17.6	2.5	84.2	20 583
Saria (800 mm rainfall)						
Sudano-sahelian savanna	22.4	22.4	1.1	1.5	11.1	14 545
Cereals	11.2	11.2	5.4	0.3	115.4	13 205

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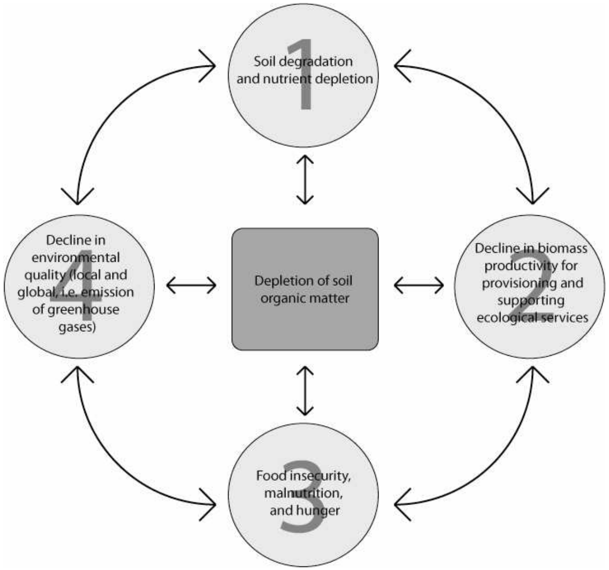

Fig. 1. Diagram showing the cycle associated with soil carbon depletion witnessed in African cereal farming systems. Soil carbon depletion impacts: 1) soil fertility, 2) ecological services, 3) food security with impacts on livelihood, and 4) environmental quality and safety. The cycle can be broken by improving soil fertility by enhancing the soil organic matter pool using sustainable technologies for improved management of water and nutrients, including no-till farming, composts, mulching, cover crops, water harvesting, and agroforestry. Modified from Lal (2004).

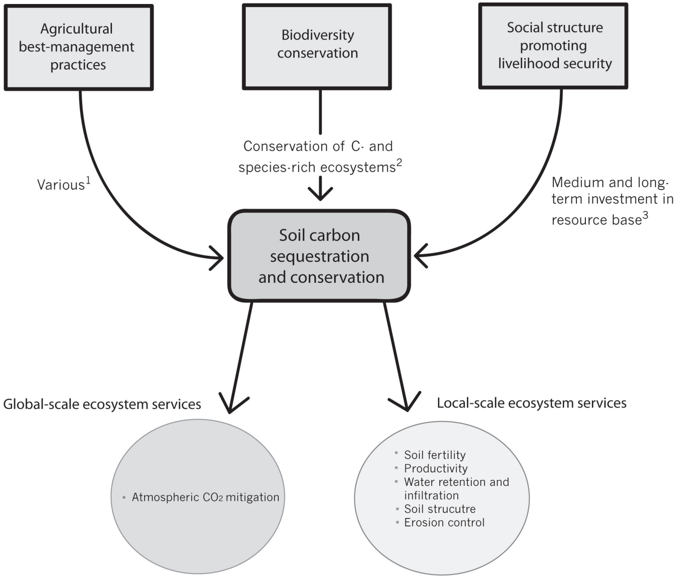

Fig. 2. Conceptual diagram of three factors of high importance with can positively influence carbon sequestration in West Africa, promoting ecosystem service provision at the global and local scales. 1: Agricultural best practices may vary depending on ecosystem type or environmental conditions, but commonly-discussed practices to preserve soil C include erosion control, conservation tillage, improved fallow systems, and integration of manure or crop residues. 2: Pairing biodiversity conservation with C-conservation initiatives may be possible in tropical zones with high biodiversity. 3: Social factors influence a smallholder's ability to invest labour and resources in C-conservation or sequestration.

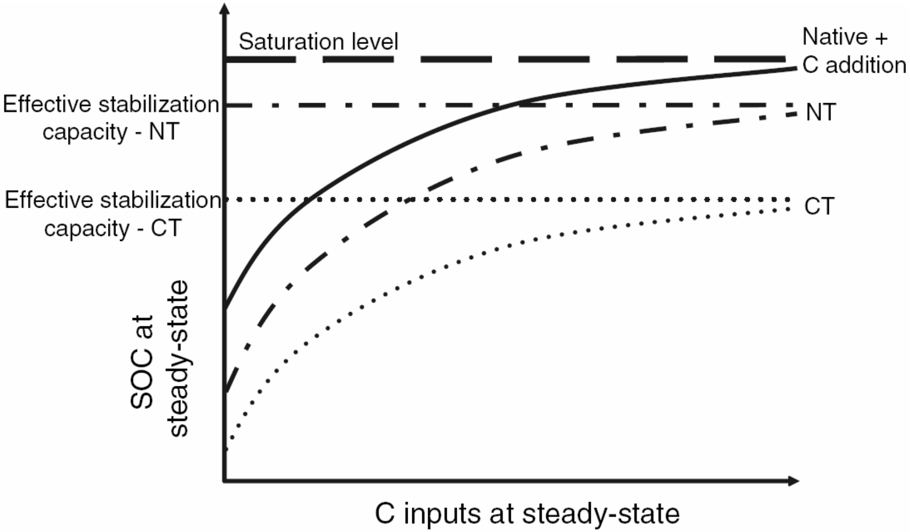

Fig. 3. Soil carbon accumulation dynamics under theoretical decomposition regimes produced by management scenarios. NT, no-tillage; CT, conventional tillage. Steady-state SOC content will be greater for NT than for CT under the same C input level, since NT has a reduced specific decomposition rate compared to CT. Effective stabilization capacity is the upper limit to C storage as a function of the different specific decomposition rates. These systems are not considered saturated due to C decomposition conditions dominating C stabilization. Source: Stewart et al. (2007); copyright Springer.

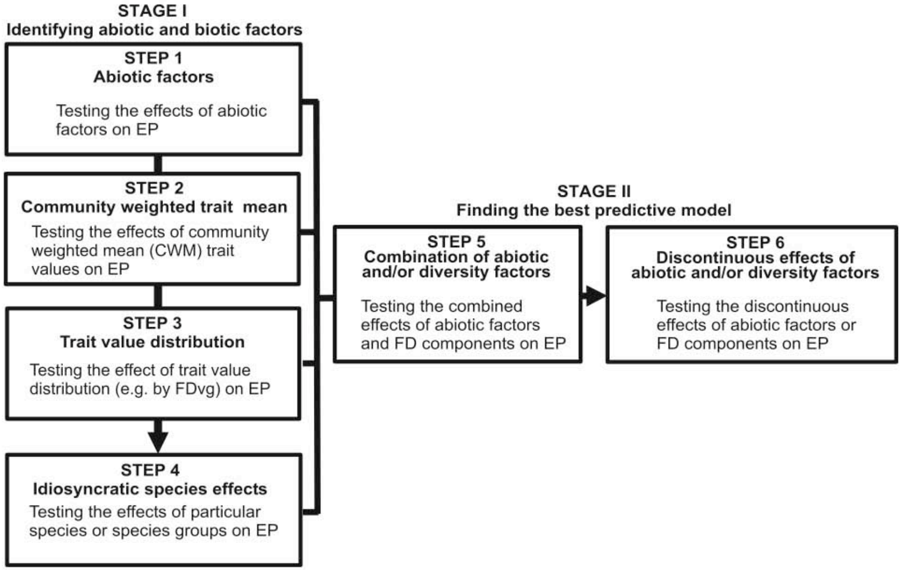

Fig. 4. Diagrammatic representation of the steps proposed to reduce uncertainty in the prediction of ecosystem properties (EP) and ecosystem services (ES) on the basis of plant functional diversity (FD). In stage I, the models tested at each step link EP with driving factors of different nature: abiotic factors (AFi), community-aggregated trait value or CWM of any one functional trait (CWMi), distribution of values of any one trait present in a community (FDvgi), and local abundance of any one species present in the community (Ab spi). In stage II, combined models are built. Source: Diaz et al. (2007); copyright 2007 National Academy of Sciences, USA.

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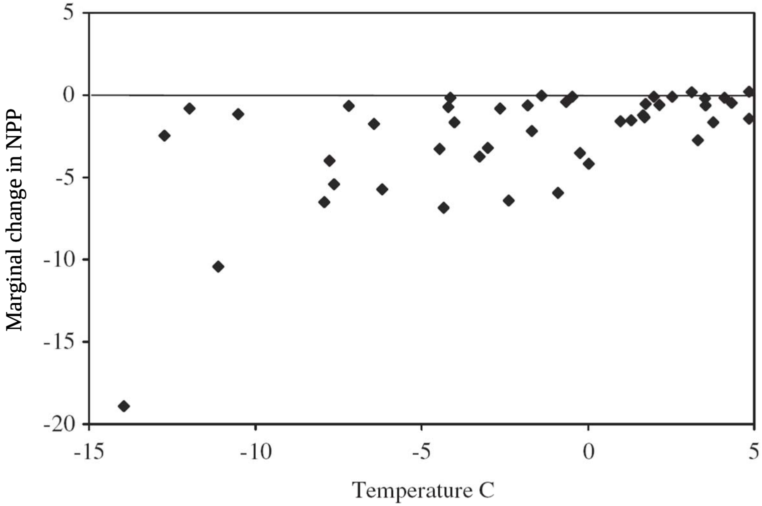

Fig. 5. Marginal change in Net Primary Production (NPP) with biodiversity in the high temperature model. Source: Costanza et al. (2007); copyright Elsevier.

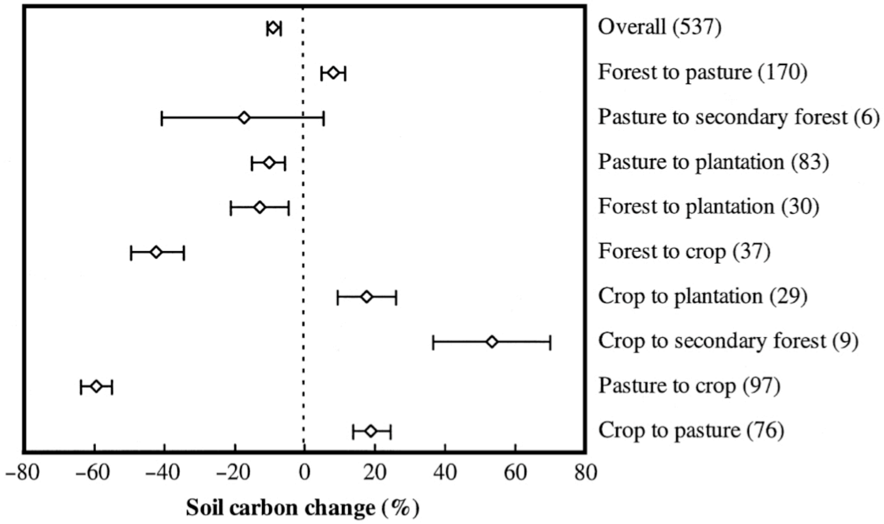

Fig. 6. Soil carbon response to variation in land use. Mean and 95% confidence intervals are shown. Source: Guo and Gifford (2002); copyright Blackwell Publishing.

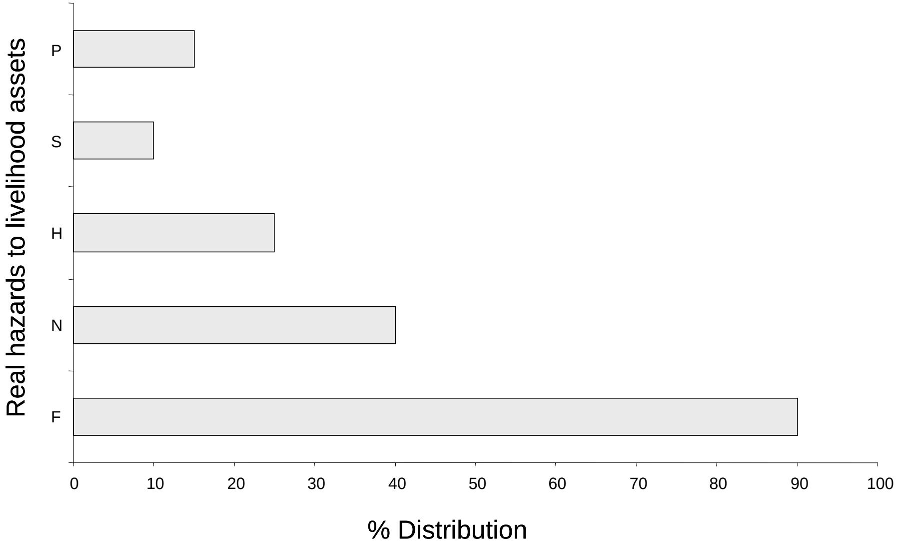

Fig. 7. Percentage distribution of real world hazards to livelihood assets. Impacts of Risks/Stressors on Types of Capital: F=Financial; N=Natural; H=Human; S=Social; P=Physical. Source: Sagoe, unpublished doctoral dissertation.