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Running head: Soil organic carbon sequestration in Senegal

Title: Multi-criteria spatialization of soil organic carbon sequestration potential from agricultural intensification in Senegal

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Abstract

On the eve of the 15th climate negotiations conference in Copenhagen, the pressure to assess all climate mitigation options is mounting. In this study, a bio-physic model and a socio-economic model were designed and coupled to assess the carbon sequestration potential of agricultural intensification in Senegal. The biophysical model is a multiple linear regression, calibrated and tested on a dataset of long-term agricultural trials established in West Africa. The socio-economic model integrates both financial and environmental costs related to considered practice changes. Both models are spatially explicit and the resulting

spatial patterns were computed and displayed over Senegal with a geographic information system. The national potential from large-scale intensification was assessed at 0.65-0.83 MtC. With regards to local-scaled intensification as local projects, the most profitable areas were identified in agricultural expansion regions (especially Casamance), while the areas that meet the current financial additionality criteria of the Clean Development Mechanism were located in the northern part of the Peanut Basin. Using the current relevant mode of carbon valuation (Certified Emission Reductions), environmental benefits are small compared to financial benefits. This picture is radically changed if "avoided deforestation", a likely consequence of agricultural intensification, is accounted for as the greenhouse gases sink capacity of projects increases by an average of a hundred-fold over Senegal.

1 Introduction

The amount of soil organic carbon (SOC) results from an equilibrium between the inputs and outputs to the system, which are driven by various parameters of natural or human origins (Schlesinger et al. 2000). In West African agro-ecosystems, this equilibrium is put in jeopardy as few inputs are available to compensate for harvested biomass, a major output. According to Sanchez (1997), the soils of sub-Saharan Africa would have undergone an average depletion of 660 kg of nitrogen (N) ha^{-1}, 75 kg of phosphorus (P) ha^{-1}, and 450 kg of potassium (K) ha^{-1} over the 1970-2000 period, together with emitting 27 Mt of carbon (C) per year (with an additional 18 MtC y^{-1} lost by erosion and therefore assumed not to be emitted).

Soil carbon loss potentially contributes to another environmental problem: global warming. In Senegal, 32% of greenhouse gases (GHG) emissions come from the agricultural sector (Kante 1997). Since agriculture is part of the problem, it could also be part of the solution to global warming, if agricultural soil carbon stocks are managed to be increased: Parton *et al.* (2004) estimated that 50% of the carbon storage potential of Senegal (as defined by Bernoux et al. (2006), "carbon storage" refers to the change in carbon stored in the system, whereas "carbon sequestration" includes all indirect emissions related to the practice that "stores" carbon) would lie in improved practices in agriculture (that is mainly increased fallowing time combined with manure application). The entry into force of the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC) in 2005 has created an economic value for carbon emitted or stored, paving the way for an internalisation of this potentially important economic externality, if climate change damages are expected to be high. Carbon emitters may therefore consider African agriculture as an opportunity to get carbon credits, in case this activity becomes eligible to the Kyoto framework, or to any other

frameworks rewarding carbon sequestration. Different agricultural practices (amount of inputs, length of fallow, agroforestry, …) result in different stocks of carbon in the soil (Vagen et al. 2005). Considering the prevailing pressure on land in West Africa due to food demand, tenure rights and fire risks, it is particularly relevant to focus on agricultural intensification as a change of practice that is not likely to meet significant economic or social barriers.

Fallowing, manuring and crop residue recycling are traditional practices that sustain soil fertility in West Africa (Kowal and Kassam 1978). The increased or stabilized yields provided by such practices partly rely on the maintaining of a threshold level of soil organic matter (SOM) (Pieri 1992; Pieri 1995). Moreover, several studies have shown that a synergistic effect exists between mineral fertilizers and organic amendments in Sub-Saharan Africa, that leads both to higher yields and SOC content (Pieri 1992; Badiane et al. 2001; Bationo and Buerkert 2001; Palm et al. 2001; Vagen et al. 2005).

These on-field results could seem counter-intuitive at first sight because microbial activity and therefore SOC mineralization is enhanced with increasing mineral form of nitrogen (Corbeels et al. 2006). But nitrogen has the capacity to cycle fairly rapidly between the inorganic and organic forms within the soils and therefore may gave different result than the most expected. Moreover, some recent developments in modelling and laboratory experiments point to more complex mechanisms that could explain field

The aim of the present study was to assess the carbon sequestration potential of the cropped soils of Senegal under a scenario of agricultural intensification. This was done by developing, and coupling, two models: a biophysical model to predict the quantity of carbon sequestrated by a given practice, and a socio-economic model to assess the net present value (NPV)[1] of these practices. This coupled approach is indeed necessary for two reasons:

- the pedo-climatic conditions that are suitable for carbon storage may not coincide with areas where the corresponding practices are socio-economically applicable;
- eligibility to carbon valuation often includes specific criteria. For example, in the Clean Development Mechanism (CDM) framework (UNFCCC 2003), Certified Emission Reductions (CERs) are only granted where their value tips the balance to make the project profitable (financial additionality criteria). On the other hand, the Global Environmental Fund (GEF) has an internal policy of lending money only for projects estimated to cost less than 10 US$ $tCeq^{-1}$. In such circumstances, project-

[1] The Net Present Value (NPV) of a given practice is its cumulated value over a given number of years, each year's value being actualized by a discount rate.

designers will be interested to find where such economically constrained projects may be located. To increase the intelligibility of this work for such project-designers, we purposely used the vocabulary of the CDM framework, and paid a special attention to its eligibility criteria (financial and environmental additionality of the project, “sound reporting, monitoring and verification”, …).

This kind of coupled approach has already been explored locally in the Old Peanut Basin (Tschakert 2004), but not at the country scale in Senegal. Another peculiarity of the present study is that the biophysical model, though simple, has been both calibrated and tested on a set of long-term local agronomic trials. This information is therefore complementary to the one given by more general models such as Century (Parton et al. 2004), as the model narrow range of applicability compared to mechanistic models such as Century is balanced by its specificity to the studied country (Senegal). Indeed, even the adapted version of Century used by Tschakert (2004) in the Old Peanut Basin yields a surprisingly long time-scale for carbon dynamics, and Cerri *et al.* (2004) highlighted the inadequacy of Century for short-term changes prediction in the Amazonian context.

Recently, a system called GEFSOC (Easter et al. 2007; Milne et al. 2007) set out a framework to make regional scale assessment of SOC stocks and change using site scale experimental data, regional GIS databases and simulation models using Century and Roth-C. But the GEFSOC system need in it first stage a model evaluation, based on long term field experiment, of both Century and Roth-C for the range of the different land uses and covering all the conditions (soil type, climate...) found in the studied area. This first stage could be difficult to implement with a large number of climate–soil–management combinations (Cerri et al. 2007). More over this first step is important as it could lead to under or overestimation of the prediction if not perform adequately, and there as there are no automatic, built-in functions for uncertainty analysis in the GEFSOC system this may furnish results with high level of uncertainties (Easter et al. 2007). In our study we decided for a more robust and simple procedure adapted to the available information.

Finally, the coupling of this model to a Geographic Information System (GIS) produces spatialized information, which is essential for many purposes. One example is the aforementioned CDM framework in which project perimeter identification is one of the crucial steps.

2 Material and Methods

2.1 Study site

Most of Senegalese soils are ferruginous and very sandy, especially those in cultivated areas: 85% of total cropped soils contain less than 20% of clay (Stancioff et al. 1986; DAAC 2002). As opposed to clayey soils where the SOM pool in mostly clay fraction, sandy soils have been shown to be particularly sensitive to organic amendments (Feller et al. 1991). On the other hand, the total SOM pool of non-degraded sandy soils tends too be smaller than that of similar clayey soils, which renders their storage potential smaller (Jones 1973; Feller 1995). Another important pattern driving carbon storage is that of rainfall distribution which follows a southward gradient from 200 mm y^{-1} in the North to 1400 mm y^{-1} in the South (Figure 1), with rain falling during a single rainy season of 3 to 6 months (Kelly et al. 1996; Worldclim 2000).

As mentioned in introduction, agriculture and livestock breeding closely interact: during the beginning of the dry season, livestock is left on fields during the day to graze on crop residues and deposit manure (Manlay et al. 2004). Only later in the season when residues are exhausted, or during the wet season when animals are excluded from cropped lands, do they go find food on marginal lands. Moreover, during all the dry season, animals are corralled at night on fields close to human dwellings, so that they fertilize them and so that livestock theft can be prevented. This close kind of interaction is made possible either by farmer ownership of livestock, or through grazing contracts with neighbouring herders (Powell and Williams 1995; Manlay et al. 2004).

Senegal has also hosted many research projects, which yielded large sets of field data. The project “Sequestration Of Carbon in Soil Organic Matter“ co-financed by the USAID and the USGS recently achieved its research, which led to acquisition of spatial data, and the publication of a special issue of the *Journal of Arid Environments* (2004, Vol. 59). The current study is a preliminary contribution to CBP:MMM (“Carbon benefits project, monitoring measuring and modelling”), the second phase of the GEFSOC project, currently under examination by the GEF executive board, and as such benefited from the active collaboration of the Centre de Suivi Ecologique in Dakar.

Senegal has ratified both the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol. Moreover, it is fairly well rated by *Transparency International* and *COFACE* for its political stability (COFACE 2006; Transparency

International 2006). This set of political and scientific reasons makes it a potentially attractive country for environmental projects, such as CDM or carbon sequestration projects.

2.2 Agricultural intensification scenarios

2.2.1 Manure availability

For the organic inputs of the scenarios, only manure was taken into account, to be consistent with the calibration data of the model. The pool of animals which manure could be tapped through the traditional agriculture-livestock interaction was conservatively limited to those located within 10km of a cultivated area, thereby excluding migrating herds. This computation leaves out 45% of total livestock. Livestock density was assumed to be uniform over the area suitable for livestock grazing (croplands, shrublands and savannas), and could therefore be computed from departmental statistics and a land-cover map (DAAC 2002; Ministère de l'Agriculture et de l'Hydraulique 2004). This pool of animals was then converted into a manure pool using the daily excretion figures of Fernandez-Rivera *et al.* (1995). The resulting figures for manure availability are consistent with previous assessments at national or local scale (Fernandez-Rivera et al. 1995; Breman 1998).

2.2.2 Description of scenarios

Three scenarios were elaborated, and then compared to a baseline scenario with the models designed in this study, in order to assess the opportunities for carbon sequestration by intensifying agriculture:

Baseline scenario (Business as Usual or BAU): The baseline scenario considered was the continuation of current practices as described in part 2.1. With regards to mineral fertilizers, it assumes that none is used: the data gathered by the International Fertilizer Association tend to bolster up this assumption (International Fertilizer Industry Association 2003).

The collecting efficiency of the available manure pool for current practices was set at 50% during the dry season (as animals are corralled at night and also deposit manure on fields during the beginning of the season), and at 0% during the wet season (Fernandez-Rivera et al. 1995). This is again a conservative approximation, as deposited manure is not as efficient as manure collected in stables and manually spread (McIntire and Powell 1994), the latter kind being the one used for model calibration. The length of the dry season necessary for this computation was assumed to vary linearly with annual rainfall average from 3 months in Northern Senegal to 6 months in Southern Senegal.

Dry season stalling (LOWINT): The LOWINT scenario represents a first possibility of intensification at national scale. Animals are stalled during the dry season, which is translated in the model into an improvement of collecting efficiency from 50% to 95% during this period. Crops receive the amount of mineral fertilization recommended by agronomic research (CIRAD et al. 2004). Since these recommendations are crop-specific, a crop repartition pattern was required. As in Liu *et al.* (2004), the share of each crop on each grid element was set at the crop's regional share of cultivated land in 2002-2003 (source: Senegal, DSDIA-DAPS-MAE). Only the main crops were taken into account, and rice was excluded. Rice is indeed so different from other crops in the way it is grown that this study's model is probably irrelevant for it. Therefore, the parts of Senegal classified as rice-growing regions by Le Fur (2000) were excluded from the analysis.

Wet season stalling (HIGHINT): The HIGHINT scenario represents a higher degree of intensification at national scale. Crops receive the same amount of mineral fertilizers as for LOWINT, but animals are stalled all year long, which leads to a 95% collecting efficiency even during the wet season. This scenario could be less plausible than LOWINT, depending on local labour availability: the labour needed for animal stalling (bringing food, cleaning the stalls, spreading the manure, …) is indeed usually less readily available during the wet season, as crops are grown and require a lot of labour (Dugué et al. 2004).

Project-based intensification (MAXINT): The MAXINT scenario is set to assess the opportunities arising from a maximal degree of intensification that can only be realized on a local, project-based basis, on farms well-endowed in livestock. It assumes that any quantity of inputs needed can be brought to the field, notwithstanding the regional availability of such resources or the special needs of the regionally dominant crop. The system considered is a groundnut/millet rotation which receives recommended amount of all inputs: 5 tDM ha^{-1} yr^{-1} of manure (Bosma et al. 1995), 25 kgN ha^{-1} yr^{-1}, and 11.5 kgP ha^{-1} yr^{-1} (CIRAD et al. 2004). Unlike the two other intensification scenarios, it is therefore unfit for a national assessment, but allows the comparison of all sites on an identical basis.

2.3 The biophysical model: a statistical model of soil carbon change

2.3.1 Carbon storage dynamics

To comply with CDM framework, the model must quantify the final difference in SOC between several management techniques only, and therefore it needs not focus on the dynamics that lead to this final difference. However, to select data representing this final

difference and therefore suitable to calibrate the model, a hypothesis on the time to reach equilibrium in topsoil SOC was needed.

Several studies (Bationo et al. 1995; Tiessen et al. 1998) suggest that following a change in land-use the soil surface layer reaches a new equilibrium in SOC after 3-5 years in West African sandy soils. However, other studies assume a much longer timeframe of 25-50 years (Batjes 2001; Tschakert 2004). Among the few long-term trials that fuel the dataset gathered for this study and where SOC had been measured overtime with the same method, the 5-year dynamics hypothesis was verified in Thilmakha (Senegal) and Bambey (Senegal), but not in Bebedjia (Tchad). Bebedjia is very rainy (around 1100 mm y^{-1}), and slightly more clayey (10% clay in the surface horizon) than the first two locations. Therefore, for the modelling purposes of this study, the assumption that the equilibrium for sub-surface SOC was reached after five years of treatment was retained for most of Senegal, but slightly modified for the most n environmental and treatment variables, the general linear model does not strictly apply, forbidding the use of the AIC (StatSoft 2006). A better suited mixed linear model could not be applied either, due to the limited number of repetition within certain sites. It is however well established that soil clay content and annual rainfall play a major role in the SOM dynamics of rainy areas. There, model outputs on total SOC change were still considered to be true, but the equilibrium was assumed to be reached only as fast as a capped maximum speed would allow. This difference in the timeframe of carbon dynamics based on rainfall is consistent with the one observed by Elberling *et al.* (2003).

The storage speed cap was set at 0.5 tC ha^{-1} yr^{-1}, which is approximately the storage speed of the best management practice in the Peanut Basin as computed with the Century model in Tschakert (2004). It is also the value given by the IPCC calculator (IPCC 1996) for Senegal, and by Ringius (2002) for West Africa.

2.3.2 Data collection

An extensive literature survey was undertaken to gather calibration data from long-term agronomic trials conducted in Senegal, and in other West African sites with edaphic conditions similar to those existing in Senegal. Several criteria limited the amount of data retained for the calibration:

- *At least 4 years of treatment:* as the model is geared to predict final SOC stocks changes, calibration data must correspond to the final state of the system that is measured for its SOC. Therefore, consistently with the aforementioned hypothesis, only the studies where treatments had been maintained for at least 4 years were used

for model calibration (for most of them, treatments were actually maintained for more than 10 years).

- *Minimal data requirement:* as in most meta-analysis (Jones 1973), the original studies used here had different methodologies. The most problematic here was the potentially important discrepancies for SOC content measurements arising from use of varying methods (Pansu and Gautheyrou 2006). To alleviate any such analytical bias, data were expressed as the difference in SOC content (ΔC) between each treatment and its control (which receives no input whatsoever). Only variations in the 0-20 cm layer have been considered[2], since the influence of management below this depth has been found to be of small magnitude (Tiessen et al. 1998; Manlay et al. 2002; Elberling et al. 2003). The standard of the International Panel on Climate Change (IPCC) is 30 cm, but it may not be relevant for carbon sequestration projects in agricultural soils as the costs of monitoring the 20-30 cm depth may override the potential increase in SOC stocks there, and since only shallow tillage is practised. Finally, the availability of a control, and of a minimal set of environmental parameters such as average rainfall and soil texture, also limited the number of studies eligible to the analysis.
- *No crop residue return or fallow:* The only kinds of organic amendments retained were manure and compost. The C:N ratio of crop residues is indeed usually much higher than compost or manure, which implies notable differences in decomposition dynamics, and therefore in their effects on SOC and crop yields (Allard et al. 1983; De Ridder and Van Keulen 1990; McIntire and Powell 1994). For this reason, treatments with crop residue return were excluded from the analysis. Fallow periods, which contribute to soil restoration through increased root density and residue return, were excluded for the same reasons. These exclusions were also reasonable from a socio-economic point of view: current pressure on land tends to shorten fallow length and the pressure on organic resources greatly limit the possibility of crop residue recycling (De Ridder and Van Keulen 1990).

These conditions restricted the number of suitable studies for model calibration and testing to the ones indicated in Annex 1. A last restriction was applied by removing two outliers from Saria, which huge organic inputs (40 tDM ha^{-1} y^{-1}) risked to bias the multiple regression (StatSoft 2006).

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[2] For the same reason of data disparity, some readjustments (such depth weighed averages for the layers measured down to 20 cm) were sometimes necessary to obtain a standard depth of 20 cm for all data.

2.3.3 Model construction

Four management variables were available for all sites as potential explanatory variables for the effect of treatment (average yearly quantity of N, P, K and organic inputs applied over the last 5 years of treatment). A preliminary step-wise method of model selection, with the Akaike Information Criterion (AIC) as the selection criteria (Akaike 1973; StatSoft 2006), showed that only N, P and organic inputs were to be retained for their explicative power on ΔC.

The selection of environmental explanatory variables could not be so straightforward: due to a split-plot kind of difference between stocks (Jones 1973; Kowal and Kassam 1978; Feller et al. 1991; Feller 1995; Batjes 2001). These two variables were therefore retained in the model as interacting with organic matter inputs. Other environmental variables, such as clay mineralogy, soil thermic and water regimes, vegetation features and intensity of landscape anthropisation that regulates OM availability and biological activity, also influence SOM dynamics. Nevertheless, their influence or variation across Senegal is weaker than that of rainfall and clay content, or is correlated to these, and in any case, no spatially explicit data is available at the scale of Senegal. The structure of the biophysical model, with the level of intervention of each parameter, is summarized on

Figure 2.

Since this regression was based on clay contents ranging 3-15%, the model was not deemed relevant for clay contents exceeding 20%, where SOC dynamics could be significantly altered. Therefore, areas with such soil features (making up 15% of total croplands in Senegal) were excluded from the analysis.

The final results could then be converted into SOC stocks changes using the same depth as considered by the model (0-20 cm), and an average bulk density of 1.52 kg dm^{-3} (average obtained over the same dataset that was used for model calibration). Assuming no spatial variation of bulk density is a rough simplification, which is unavoidable as no spatially explicit database currently exists for bulk density of soils over Senegal. However its impact is likely to be limited, since the range of values for the clay content of the soils considered is narrow, and since texture is a significant driver of soil density (Bernoux et al. 1998). For the national potential for carbon storage, that is an overall estimate of carbon storage in Senegal through agricultural intensification, the LOWINT and HIGHINT scenarios were processed only on agricultural land as determined by MODIS data (DAAC 2002).

The rainfall dataset used to run the biophysical model is the yearly average between 1950-2000. This range is thought to be representative of the region, being wider than the

drought that lasted from the 1960s to the beginning of the 1980s. Nevertheless, more recent averages, or even forecasts such as the climate change scenario available in Hulme et al. (2001) or in IPCC (2006), could be more relevant depending on the exact objectives of the model runs.

The clay content dataset used to run the biophysical model was derived from Stancioff *et al.* (1986), taking the clay content of the barycentre of each texture class as a representative value for the class.

2.3.4 Model test

To assess the overall error of this statistical model, seven studies taking place in Senegal were retained. Their management parameters were entered into the model, together with the average rainfall corresponding to the study's period, and the clay content coming from the map. The model output was then compared with the actual measured values of SOC content change.

2.4 Socio-economic model

The socio-economic model makes a cost-benefit analysis of the agricultural intensification scenarios, taking into account both financial and environmental costs. As appropriate to this study, environmental costs accounted for were restricted to GHG emissions. The data on prices were updated for inflation when necessary (Diarisso 2004). All the intervening factors of the analysis are summarized on
Figure 3 and detailed hereafter.

2.4.1 Cost of transportation of mineral fertilizers

- Financial cost:

In Senegal, most mineral fertilizers are put together in Mbao (close to Dakar) by the *Industries Chimiques du Sénégal (ICS)*, and then distributed to local Senegalese agricultural markets by trucks (Industries Chimiques du Sénégal 2006). ICS uses the local phosphate deposits of Taïba, and imports nitrogen fertilizers and potash through the Dakar harbour.

For both financial and transportation costs, a map representing the distance of each grid element to Dakar by road was required. The itinerary chosen from each point to Dakar was computed using the following hypothesis:

- fertilizers are delivered from Dakar to agricultural markets by the fastest road;
- farmers from any grid element in Senegal then use the fastest road to fetch fertilizers at the closest market.

- no transportation itinerary goes through Gambia, as long waiting times and passage fees to cross the two borders and the Gambia River are prohibitive.

The fastest roads were computed by attributing an average speed of 80 km h^{-1} to journeys on paved roads, 40 km h^{-1} to journeys on laterite roads, 20 km h^{-1} to journeys on tracks, and 5 km h^{-1} to journeys off tracks. These average speeds are broad assumptions, but they generated realistic itineraries. For all these computations, as for all the steps of this study that required a GIS, the ArcGis 9.0 software was used. The grid resolution used for cell-by-cell model runs was 1 km^2.

For any point in Senegal, the financial cost of mineral fertilizers was therefore assumed to be the sum of its price in Dakar (*Source: Ministère de l'Agriculture et de l'Hydraulique - unpublished data, 2005*) and of the transportation price to the field. For this, the average price per ton × kilometer was set at the same level as in Mali (UNCTAD 2000). It seemed relevant to Senegal as gasoline prices were comparable in the two neighbouring countries.

- Environmental costs

For valuation of environmental externalities (costs of emissions), three sources of emissions were identified: manufacturing (Vlek et al. 2004), sea transportation to Dakar (ADEME and MIES 2007), and road transportation to the field (ADEME and MIES 2007). As in N'Guessan (2003), a 25 tons truck was used as the reference, and its emissions were increased by 25% from the original figures to account for the generally older trucks and ill-maintained roads of Senegal (Fall 1998). As Europe is by far the most important trade partner of Senegal with more than 50% of Senegalese imports coming from Europe (Diarisso 2004), the standard maritime route length used for these calculations was 4604 km, corresponding to the standard maritime route from Hamburg to Dakar (Dataloy 2006).

2.4.2 Cost of application of mineral fertilizers

- Financial costs:

The labour cost of applying fertilizers were those estimated by Badiane *et al.* (2001).

- Environmental costs:

To compute the additional N_2O emissions resulting from the application of mineral fertilizers, the IPCC methodology for national GHG inventories was applied (IPCC 2006).

2.4.3 Cost of manure collection and application

- Financial costs:

The collection and application of manure from stables was estimated at US$ 1.42 per ton of manure (Badiane et al. 2001), and the transfer of fodder to stables at US$ 24.86 per ton of manure (CIRAD et al. 2004).

- Environmental costs:

Emissions of CH_4 or CO_2 resulting from manure decomposition were assumed to be the same whether livestock is stalled or not, and therefore did not influence the model. A decrease in N_2O emissions from cattle manure when it is manually collected and spread instead of being directly deposited on field by animals was accounted for, following the standard IPCC methodology (IPCC 2006). The emissions from urine were overlooked, thereby making the implicit assumption that its decomposition is independent of its management (either directly deposited in the field or stored in stables and manually spread). This assumption is probably reasonable since most of the nitrogen in urine is volatilized into ammoniac notwithstanding its management (Fernandez-Rivera et al. 1995).

2.4.4 Additional revenue from increase in crop yields

Another important component of the cost-benefit analysis is the increased revenue from improved yields. This requires (i) to evaluate how crop yield evolves under the different scenarios, and (ii) to specify hypothesis on crop prices.

- Modelling of crop yield change:

As for SOC change, we used a statistical approach to model relative change in crop yield. The same dataset as for SOC change prediction was used to calibrate a statistical model. As the average yields of each treatment were not always available, the dataset was here further restricted to 42 points coming from 12 different studies. The model building methodology was the same as for the biophysical model, which again excluded K inputs from explicative variables. There, such parameters as clay content and rainfall were not retained, as they did not improve the model. This tends to show that, although clay content and rainfall may play a major role in explaining absolute crop yield and absolute crop yield change, they do not significantly influence relative crop yield change. However, as in McIntire and Powell (1995), the inclusion of the square of some treatment parameters effectively improved the model's precision, and was therefore retained to yield the model equation.

Regional statistics (source: Senegal, DSDIA-DAPS-MAE) were retained for the reference yield from which the model computes yield changes (which imply both changed benefits as the crops are sold, and changed costs as the harvesting time is changed in

proportion to the quantity of matter to be harvested). Spatialized crop yields were therefore obtained through the following equation:

$$Y = Y_R \times \frac{100 + (\Delta Y_T - \Delta Y_{BAU})}{100}$$

where Y is the yield (in kg ha^{-1} y^{-1}), Y_R is the average regional yield (in kg ha^{-1} y^{-1}), ΔY_T and ΔY_{BAU} are the yield changes (in %) from a no-input treatment respectively due to the inputs in the new practice and in the baseline scenarios, as computed by the statistical model.

- Crop prices:

For the producer prices of crops, as they were not directly available from any official and easily accessible source (Senegal is surprisingly not listed in the FAO statistical database on agricultural commodity prices), price ratios between crops were assumed to be the same as in Mali (FAO 2006), and these ratios were then combined with current market prices for millet and groundnut in Senegal (D. Baggio, pers. comm.) to get the producer price of each crop.

2.5 Model coupling

2.5.1 Hypothesis on carbon prices

The biophysical and economic models were coupled by attributing the 2005 average price of CERs from registered candidate CDM projects (25.8 US$ $tCeq^{-1}$) to sequestered carbon (Rosenzweig and Forrister 2006). This financial retribution was assumed to be available only five years after the beginning of the project. The CERs were therefore accordingly discounted, using the same discount rate as Sankhayan and Hofstad (2001) for Southern Senegal (5 % y^{-1}). The variable that represented the overall potential was then the change of NPV over five years (using the same 5 % y^{-1} discount rate) between the MAXINT scenario and the baseline (BAU scenario).

2.5.2 Accounting for "avoided deforestation", and valuing it

Agricultural intensification is likely to decrease pressure on natural ecosystems such as forests and savannas, since demand for agricultural expansion fuelled by population growth is a major driver of deforestation in Senegal (Wood et al. 2004). Therefore, it is relevant to take into account the environmental benefits resulting from this decreasing pressure, especially for national-scale scenarios, which could be used as the practical tools of policies that bestow compensation for reductions in deforestation rates, such as "Compensated Reductions" (Santilli et al. 2005).

For this assessment, land vulnerable to deforestation was defined as the non-agricultural land in the eco-regions undergoing agricultural expansion (Tappan et al. 2004). This included 5 eco-regions (Agricultural Expansion, Casamance, Niayes, Saloum Agricultural, and Southern Pastoral), over which non-agricultural land was divided between forests (17%) and savannas (83%). The area-weighed average change in carbon stocks (soil and aboveground biomass) for these two land uses when converted into cropland was estimated to 37.3 tC ha^{-1} from data collected in Senegal (Liu et al. 2004).

To quantify the impact of agricultural intensification on deforestation, the underlying hypothesis was that agricultural intensification would not impact food and cash demand, meaning that each ton of increased crop production due to agricultural intensification preserves the amount of land necessary to produce one ton of crops in areas vulnerable to deforestation (1.6 ha). The result was then introduced into the cost-benefit analysis for the MAXINT scenario with the same valuation method for carbon as described in 2.4.

3 Results

3.1 Biophysical model

3.1.1 Parameterization of equation for soil carbon stock change

A multiple linear regression on the variables selected by the method exposed in 2.3.3 yielded the following equation:

$$\Delta C = \text{organic inputs} \times (-0.56 - 0.036 \times \text{clay} + 0.0015 \times \text{rain} + 0.011 \times P - 0.0031 \times N) + 0.023 \times P - 0.0076 \times N \quad \textbf{(1)}$$

with ΔC in mgC g^{-1}, organic inputs in tDM ha^{-1} y^{-1}, rain in mm y^{-1}, P (P inputs) in kgP ha^{-1} y^{-1} and N (N inputs) in kgN ha^{-1} y^{-1}. This statistical model significantly explained data variations (R^2 = 0.68***; n = 64) and the standard error was 0.87 mg g^{-1} (1.32 tC ha^{-1} when converted into stocks).

3.1.2 Carbon storage found under the different scenarios

For the MAXINT scenario, the potential for carbon storage follows roughly the southward rainfall gradient, with positive values for most of the country (
Figure 4a). The regional averages range from -3.2 to 15.6 tC/ha (Table 1), with highest increases in absolute amounts in Casamance (Ziguinchor & Kolda) while highest benefits of carbon sequestration on a surface basis were obtained in the Kolda and Tambacounda regions.

For the LOWINT and HIGHINT scenarios, the magnitude of SOC change is lower than for the MAXINT scenario. This way, the national potential for carbon storage was estimated to 0.648 MtC and 0.832 MtC for the LOWINT and HIGHINT (Table 2) scenarios, respectively.

3.1.3 Model test

Tested on an independent dataset over seven Senegalese sites, the predicted values for SOC changes were not significantly different from the field measurements (p-value = 0.13; n = 18). Nevertheless, the residual error was important (3.6 mg g^{-1}; 5.5 tC ha^{-1} when converted into stocks).

3.1.4 Sensitivity analysis to clay content

The biophysical model is quite sensitive to clay for the considered scenarios: a sensitivity analysis performed over a hundred points randomly selected on the map shows an average 92% of variation in SOC change for the MAXINT scenario when clay content is uniformly increased by 3 g $100g^{-1}$ soil.

3.2 Cost-Benefit Analysis

3.2.1 Parameterization of the equation for yield increase

A multiple linear regression on the variables selected by the method exposed in 2.4.4 yielded the following equation:

$$\Delta Y = (0.0424 - 0.00106 \times P) \times P + 0.00886 \times N + 0.00869 \times OI^2 + 0.0370 \times P \times OI - 0.00978 \times N \times OI \quad \textbf{(2)}$$

with ΔY the difference in yield compared to a no-input scenario in %, OI the organic inputs in tDM ha^{-1} y^{-1}, P (P inputs) in kgP ha^{-1} y^{-1} and N (N inputs) in kgN ha^{-1} y^{-1}. This statistical model significantly explained the data variations ($R^2 = 0.66$***; n = 41) and the standard error was 74%.

This error was increased to 94% when tested on an independent dataset over seven Senegalese sites. The seven sites, though offering a good spatial coverage, all received the same level of inputs (72.7 kgN ha^{-1} y^{-1} / 12.8 kgP ha^{-1} y^{-1} / 34.5 kgK ha^{-1} y^{-1} / 1.5 tDM ha^{-1} y^{-1} of manure) which represents a potentially important shortcoming.

3.2.2 Cost-Benefit analysis for the different scenarios

The cost-benefits analysis for the scenarios was positive for most of currently cultivated areas (except for the Northern Peanut Basin), even without accounting for carbon (Figure 5c,d). Results for changes in greenhouse gas (GHG) balances (including all GHG and SOC stock changes), are highly dependent on the considered scenario: the local, project-based MAXINT scenario, yielded net sequestration for all areas where cultivation is practicable (Central and Southern Senegal), whereas the regionally realistic HIGHINT scenario yielded net emissions for most of these areas, except for the Old Peanut Basin and Western Casamance (Figure 5a,b & Table 1).

3.3 Model coupling

When carbon is accounted as a potential source of revenue according to the method previously described, the change of NPV of a farm over five years, due to the MAXINT scenario, becomes positive in a limited area of the Old Peanut Basin (Figure 6).

3.4 Avoided deforestation

For both types of scenarios (regional-scaled such as LOWINT and HIGHINT, or local, project-based such as MAXINT), the environmental benefits are low on a hectare basis, and therefore unlikely to sweep the board. However, when the carbon sequestered through “avoided deforestation” is accounted for, this pattern changes radically. For the MAXINT scenario, the change -on a per hectare basis- in GHG balance compared to the baseline

becomes positive everywhere in Senegal, and its average over Senegal increases to 120 times the average without accounting for deforestation (Table 1 and Figure 7). For the HIGHINT scenario the net fixation of GHG would increase by 161 folds (Table 2).

4 Discussion

4.1 The limited national potential of increased fertilization for in-situ soil C accretion

The average changes in SOC stocks in regions of the Old Peanut Basin such as Kaolack, Fatick or Diourbel (1.78-3.89 tC ha^{-1}; Table 2), are close the 3.17 tC ha^{-1} obtained by Tschakert (2004) with the Century model for a similar treatment in this region. The North-South gradient in carbon storage potential for the MAXINT scenario (Figure 6a) is also consistent with the difference between these figures, and higher SOC increases (+9.9 tC ha^{-1}) measured by Manlay *et al.* (2002) in the Kolda region (for an administrative map of Senegal, see Annex 2). These increases are important compared to the existing SOC stocks of 15-30 tC ha^{-1} in the 0-40 cm layer (Woomer et al. 2004).

The present estimates of the national potential of carbon accretion of 0.65-0.83 MtC for scenarios realistic at this scale (LOWINT and HIGHINT) would represent only 7 and 9% of Senegal's 1994 GHG emissions from activities others than land-use change and forestry, and 11 and 14% of GHG emissions from all activities, respectively (UNFCCC 2005 according to which land-use change and forestry were net C sinks in 1994). These scenarios would also barely change the national SOC stocks estimated at 561 MtC by Henry et al. (2009) for the 0-30 cm layer.

Estimates for C sequestration for the HIGHINT scenario would be even more modest since it would represent 3 % of Senegal's 1994 GHG emissions from activities others than land-use change and forestry, and 5% of GHG emissions from all activities. Estimates for C accretion are more difficult to relate with the estimate of Senegal's potential of carbon storage made by Parton *et al.* (2004) under their "improved management practices" scenario. Their 116 MtC potential indeed includes the potential gains from the biomass compartment, and also those resulting from improved management of pastures and forests. This wide difference is nevertheless surprising since these authors estimate that agriculture would account for 50% of this potential, and that in the Intensive Agricultural Region, 90% of the potential comes from increased SOC. We found several explanations for this discrepancy. The main one is that the storage potential in our scenario forbids dramatic changes in management practices: it limits the increase in manure application to the gains in manure from improved collecting efficiency where Parton *et al.* (2004) assume a doubling of fallow time, coupled with the application of manure and household wastes (unknown quantities). Their estimate of an average potential storage of 17.1 tC ha^{-1} in the Intensive Agricultural Region is indeed higher than the value given by Tschakert (2004) for an "optimal" intensification, which requires

among others 9 tons of manure per hectare, which is already six times the maximal manure available at regional scale in our HIGHINT scenario. For such scenarios with higher inputs in manure such as the MAXINT scenario, our model indeed yields much higher estimates.

The second source of difference comes from the figures for agricultural cover: as the present model is spatially explicit, it is bound to use spatialized data (DAAC 2002) which adds up to 17% of total Senegal under cropping, whereas Parton *et al.* (2004) use the estimate of 21% from Tappan *et al.* (2004), which is more specific to Senegal, but unfortunately non-spatialized. Moreover, the range of application was limited here to sandy soils (clay content < 20%), which excluded 15% of total cropland. Overall, the total surface of cropland on which their estimate is based is therefore 45% higher than the one used in the present study.

4.2 Avoided deforestation: a key element to improved the C balance of fertilization

The model runs for carbon balances are widely modified when accounting for deforestation (Table 1; Table 2). In this case estimates for C sequestration for the HIGHINT scenario would rise to 561% of Senegal's 1994 GHG emissions from activities others than land-use change and forestry, and to 872% of GHG emissions from all activities (UNFCCC 2005). This is consistent with the results of Liu *et al.* (2004), who found that of the 52 MgC ha^{-1} of carbon stocks lost between 1900 and 2000 in south Central Senegal, 88% came from live biomass, and only 12% from litter and topsoil SOC (the 0-20 cm depth was the only soil compartment included in the calculations). Such results are consistent with the recent regain of interest for the issue of carbon emissions from deforestation (The World Bank 2008; UNFCCC 2008).

4.3 Cost-benefit analysis and carbon sequestration (net of additional GHG emissions)

4.3.1 Profitability of carbon sequestration

The models predict the intensification scenarios to be profitable in almost all Central and Southern Senegal (Figure 5c,d). However, they also show that intensification does not always coincide with carbon sequestration: for the HIGHINT scenario, the GHG balance is lower (more emissions) than the baseline for all areas but the central Senegal (which has low emission levels due to its proximity to Dakar) and Ziguinchor and Kolda due to their high potential for carbon storage). In Eastern Senegal and most of southern Senegal, emissions due to fertilizer use override gains from carbon storage (Figure 5a).

Facing such positive figures for profitability, one could wonder why farmers do not intensify. The reason probably dwells in the time-discrepancy between the time when money

is needed to buy fertilizer, and the time when benefits from yield increases are reaped. In a context of lacking credit possibilities, and chaotic supply, this has been shown to be an important obstacle (Vlek 1990; Tschakert 2004). Climate variability seriously affects the impact of fertilization on crop yields, and may also be part of the answer (see 4.4.4).

One could therefore look at the income generated by carbon retribution as a source of savings that that would enable farmers to buy fertilizers at the beginning of the growing season. However as Tschakert (2004), in the present study these retributions are insufficient since the yearly gains from carbon never compensate for even the lowest yearly price of fertilizers as predicted by the model (US$ 28 ha^{-1} y^{-1}, data not shown).

4.3.2 Transportation costs

Transportation costs would be all the more relevant for Casamance where their high level significantly increases the local price of fertilizers (from US$ 30 ha^{-1} y^{-1} close to Dakar to US$ 41 ha^{-1} y^{-1} in Western Casamance for recommended amounts of fertilizer). This is why, as highlighted in other studies about Africa or Indonesia, a priority for better access to fertilizers is the development of better transportation infrastructures (Vlek 1990; Isherwood 2000; Smaling et al. 2006).

A potential pitfall in these estimates of transportation costs is that they are independent of the total flow of fertilizer. Possible efficiency gains linked to large increases in fertilizer flow (through improvements in the road network infrastructure for example) are thereby ruled out.

4.4 Methodological considerations

4.4.1 Resolution of spatial data

The sources of spatial data are of different resolutions, but those that would have to be refined in priority may depend on the kind of scenario. For national-scale assessments, the “socio-economic” data such as the desirable quantity of fertilizer inputs are generally given at a much coarser resolution than the “environmental” data (region or department versus square kilometre). The priority would therefore be to refine the scenarios, in particular by accounting for rice cultivation and fallowing, and by taking better care of the feasibility of each scenario. Indeed, fodder and labour availability for animal stalling during an entire season was taken for granted here as grazing animals are only able to consume 20% of residues (the rest being trampled on, polluted by excrements, burnt, or carried away by termites) (Bosma et al. 1999)

and as stabled animals eat less (more than 33% so according to CIRAD et al. 2004). However, local patterns could countervail these broad generalities.

On the contrary, for evaluations of local project feasibility, it is assumed that such "socio-economic" data could be accurately forecast as project managers know what they intend to do with the land. Clay content however still varies at very small scales due to erosion, parent material, and deposition (Cerri et al. 2004). Therefore, refining first the clay content map would therefore be most advisable.

4.4.2 Organic matter displacement

An important hypothesis of this paper is that the organic matter used to increase SOC in agricultural fields would not have also done so in their original location. Otherwise, the environmental benefit to the atmosphere would be null.

For manure naturally deposited on pastures, there are reasons to think this hypothesis is valid (Poulton 1996), even if no experimental demonstration in the West African context has been identified to support it. Indeed, manure patchily deposited by grazing animals is probably much less efficiently incorporated to the soil than manure collected from stables and evenly spread over the field (Bationo et al. 1995). Also, organic inputs would probably be more protected from decomposition in depleted agricultural soils than in pastures where the threshold of SOC protection by clays may already be attained (Breman 1998; Six et al. 2002). Finally, manure has been shown to actually increase SOC content only if associated with mineral inputs in South Senegal (Manlay et al. 2002), something unlikely to happen in pastures unless they are also fertilized with synthetic inputs.

4.4.3 Yield model

The model used to compute yield increases is very simple. Whereas more complex models can offer better predictions (Christianson et al. 1990; Aune and Lal 1995; McIntire and Powell 1995), they are often too demanding in parameters to be used on such a broad scale as this study's and in developing countries were data is scarce. Therefore, many well described effects of treatments or the environment on yields are either very summarily or not at all included in this model.

Nevertheless, it is satisfying to verify that where Baidu-Forson and Bationo (1992) equate a 17.5 kgP ha^{-1} treatment to a 8.7 kgP.ha^{-1} treatment complemented by 5 tDM ha^{-1} of manure in terms of yields, the model predicted similar yield increases of respectively 95% and 91% for these two treatments compared to a no-input treatment.

4.4.4 The risk issue

The Net Present Value of a practice is not the only parameter that will determine its chances of adoption (Tschakert 2004). As underscored by Bartel (2004), the most important for smallholders may be to minimize risk before maximising profits. It was therefore interesting for us to assess the risk associated to each practice. Badiane *et al.* (2001) found that the combination of organic and mineral inputs decreased the risk coming from yield variability. Therefore, the different scenarios are likely to decrease risk in the areas where they increase the NPV, but some critical elements were lacking to perform a thorough risk analysis.

Another risk is that of non-permanence of carbon storage, although this risk falls on the eventual recipient of CERs, who is not necessarily the farmer himself. Although part of it is included in the diminished price of the CERs themselves compared to other carbon credits (Rosenzweig and Forrister 2006), the market is probably not able to cope with all risks, especially such complex ones as an eventual large scale SOC mineralization due to increased temperature (Ringius 2002; Bellamy et al. 2005) in the most vulnerable continent to climate change (Boko et al. 2007). On the other hand, as mentioned by Olsson and Ardo (2002), the risk of future release of sequestered carbon is less important in agriculture than in forestry since (1) SOM preservation is the interest of the farmer, as it contributes to soil fertility, and (2) it is less subject to external hazards such as fire.

4.4.5 Model imprecision

The standard errors of both SOC and yield prediction models, as assessed on our limited independent dataset, are quite high (±5.5 tC ha^{-1} for SOC change, and ±94% for yield increase). This could be expected as it includes both the inherent imprecision of the statistical model and the one arising from cartographic data, especially high for clay content which varies on a much smaller scale than the map is able to represent (Cerri et al. 2004). Due to the non-homogeneous distribution of test points both spatially over Senegal, and qualitatively over the environmental parameters (clay content and rainfall), these error estimates have to be considered with caution.

Overall, the model error seems nevertheless low enough to provide broad indications on the most adequate locations for carbon sequestration projects. It would be interesting to perform the same kind of analysis with some more standard models such as Century (Parton et al. 1987). Indeed, it is difficult to get a sense of the overall precision of these from existing studies: Cerri *et al.* (2004) obtained a standard error as low as ±17% for forest conversion to

pasture in Brazil, but this does not include the uncertainty stemming from the use of mapped data. For more diverse and more specific kinds of managements such as those studied here, the standard error is often left untested (Tschakert 2004; Woomer et al. 2004).

4.4.6 Time window considered in the cost-benefit analysis

The time window considered for the cost-benefit analysis is five years, which makes sense as a minimal time to get credits from carbon sequestration projects. But while future financial benefits after five years may be irrelevant due to high discount rates, this may not be easily replicable for the environmental balance: indeed, the intensification treatments would have to be maintained overtime, thereby emitting always more greenhouse gas for the same amount of SOC storage, unless integrated, nutrient-conservative management strategies are identified and adopted.

5 Conclusion

This study shows that the potential for carbon storage through the proposed scenarios applicable at national scale is relatively low (0.65-0.83 MtC) compared to previous estimates. Large inputs of manure can change the picture (MAXINT scenario) and make it coincide better with existing local estimates, but these would not be available at a larger scale than a few well-endowed farms, unless livestock resources are increased. And in that case, the methane emissions from the additional livestock would probably override the amounts of carbon stored in the soil. However, accounting for "avoided deforestation" as a likely side-effect of agricultural intensification completely changes the picture, with carbon balances positive everywhere, and amounting to about a hundred-fold increase compared to the original figures, thus representing a major source of revenue with the proposed valuation method.

Through this valuation method, the internalisation of a restricted set of environmental costs and benefits, namely GHG emissions, was attempted. But the considered scenarios are likely to impact other aspects of the environment: mineral fertilizer application carries the risk of water table pollution and soil acidification, and manure application can help prevent soil drought, soil acidification, and erosion. The further internalisation of these aspects would be of great interest.

The means of reducing greenhouse gas emissions explored in this study's scenarios are far from being comprehensive. At least three complementary ways of sequestering carbon would deserve an explicit role in the models and scenarios: agroforestry, intercropping and no tillage cropping schemes. Other more indirect ways could also be considered, such as methane capture from manure decomposition in stables. All these unexplored potentials would have to be analysed in depth before any definitive conclusion on the carbon sequestration potential of agriculture as a whole can be drawn for Senegal.

Inclusion of considerations out of the Kyoto protocol scope such as resource use efficiency (carbon intensity), per capita emissions or historical responsibility could also broaden the view on how Senegalese farming systems interact with global change.

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[3] Still in the pipeline on 02/12/2008

Annex 1 – Sources used for building the soil carbon accretion and yield increase models (summary table)

Study	Site	Use	Number of data points	Yearly rainfall (mm y^{-1})	Clay content (%)
(Fernandes 1999)	Bambey, Senegal	Calibration	2	446	4
(Pieri 1979; Pieri 1992)	Bambey, Senegal	Calibration	1	412	3
(Richard and Djoulet 1985)	Bebedjia, Chad (Trial N)	Calibration	3	1120	9
(Richard and Djoulet 1985)	Bebedjia, Chad (Trial R – Serial 64)	Calibration	3	1120	10
(Richard and Djoulet 1985)	Bebedjia, Chad (Trial R – Serial 65)	Calibration	3	1120	10
(Richard and Djoulet 1985)	Bebedjia, Chad (Trial S1 – Serial 68)	Calibration	5	1120	11
(Richard and Djoulet 1985)	Bebedjia, Chad (Trial X – Serial 1968)	Calibration	6	1120	10
(Sarr 1981)	Nioro du Rip, Senegal	Calibration	1	718	11
(Rabot 1984)	Nioro du Rip, Senegal	Calibration	1	718	9
(Bationo et al. 1993; Bationo and Buerkert 2001)	Sadoré, Niger	Calibration	1	560	3
(Agbenin and Goladi 1997)	Samaru, Nigeria	Calibration	5	1062	10
(Jones 1971)	Samaru, Nigeria (DNPK trial)	Calibration	8	1062	10
(Jones 1971)	Samaru, Nigeria (MVR trial)	Calibration	3	1062	10
(Jones 1971)	Samaru, Nigeria (PFM trial)	Calibration	3	1062	10
(Singh and Balasubramanian 1979), (Ogunwole and Ogunleye 2005)	Samaru, Nigeria	Calibration	5	1062	10
(Hien 2004)	Saria, Burkina Faso (EEC trial)	Calibration	7	794	14
(Pieri 1992; Hien 2004)	Saria, Burkina Faso (EFF trial – monoculture)	Calibration	3	765	14
(Pichot et al. 1981)	Saria, Burkina Faso (EFF trial – monoculture)	Calibration	4	765	14
(Feller et al. 1981)	Bambey, Senegal	Test	7	412	3,3*
(Rabot 1984)	Missirah, Senegal	Test	1	800	23,1*
(Manlay et al. 2002)	Sare Yorobana, Senegal	Test	5	960	3,3*
(Rabot 1984)	Sinthiou, Senegal	Test	1	900	9,5*
(Badiane 1993)	Thilmakha, Senegal	Test	1	363	3,3*
(Cissé 1986; Pieri 1992)	Thilmakha, Senegal	Test	2	344	3,3*
(Rabot 1984)	Velingara, Senegal	Test	1	1150	9,5*

* Not a direct measurement. Clay content estimated from the clay content map of Senegal

Annex 2. Administrative map of Senegal (source: http://www.culture.gouv.sn/)

See figures file for the map

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Figures legends

Figure 1: Clay content and average yearly rainfall (1950-2000) in Senegal (Stancioff et al. 1986; Worldclim 2000)

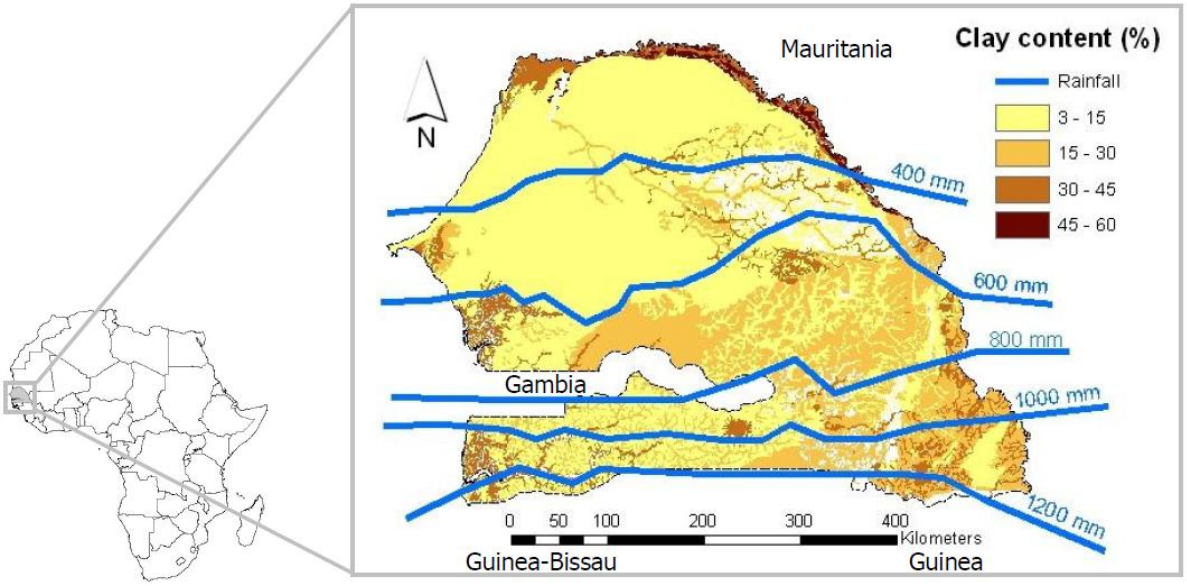


Figure 2: Biophysical model design and mode of operation

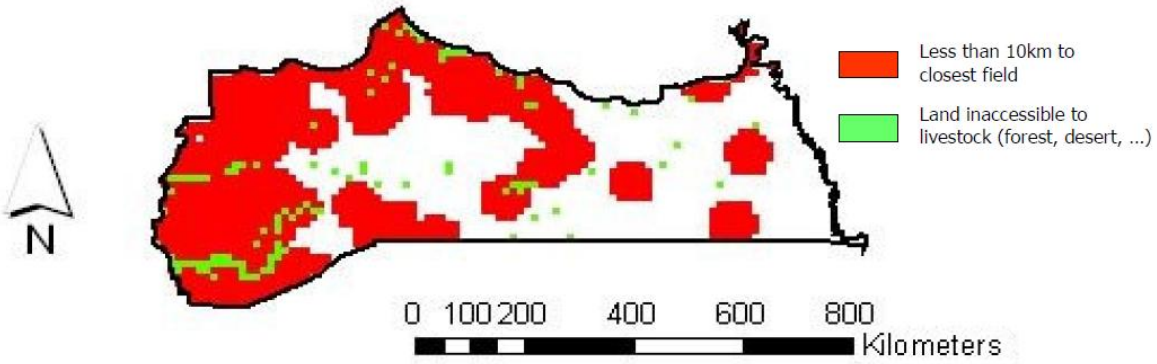


Figure 3: Factors intervening in the socio-economic model

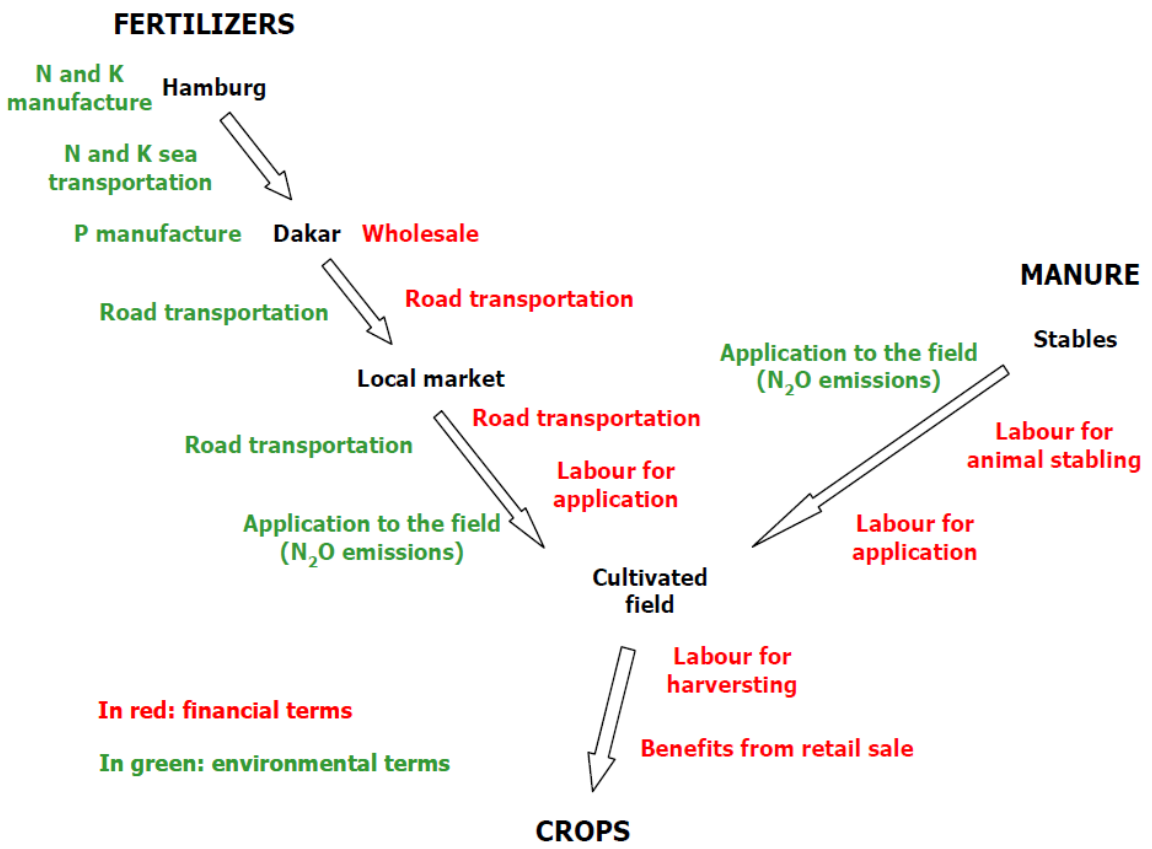
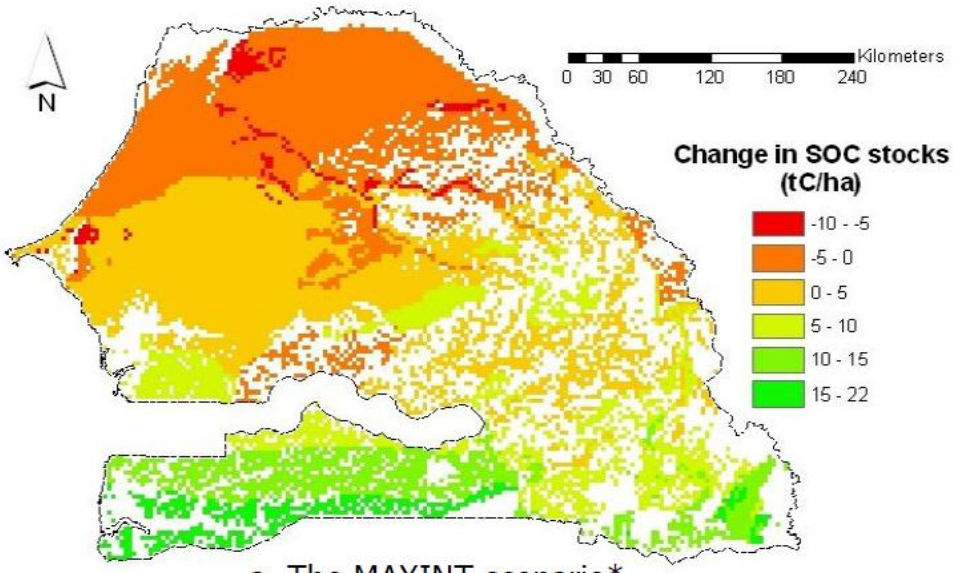


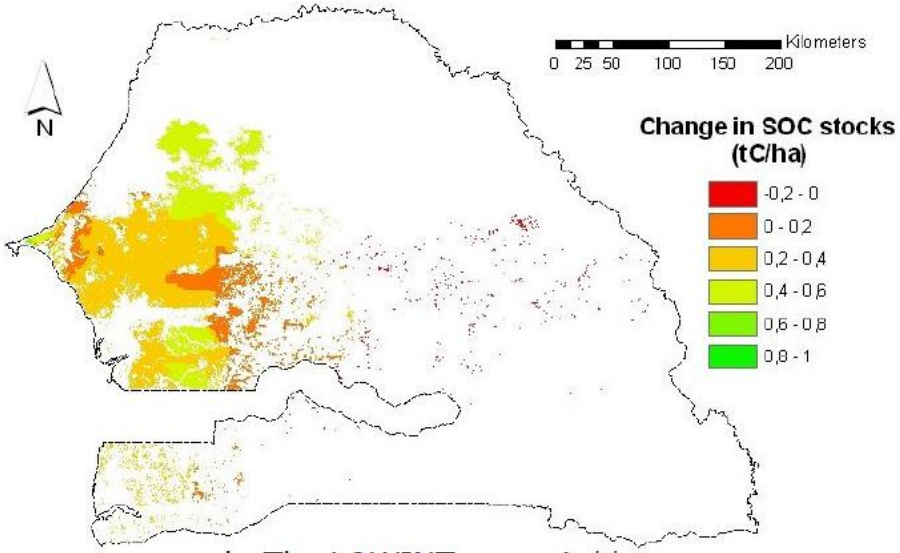
Figure 4: Change in Soil Organic Carbon stocks for: (a) the MAXINT scenario; (b) the LOWINT scenario;(c) the HIGHINT scenario

* White areas within national boundaries are either clayey soils (> 20% clay), rocks, or wetlands, over which the model was not run; the negative values for Northern Senegal should be taken with caution due to increasing imprecision of the model at low rainfall averages (extra- rather than inter-polations).

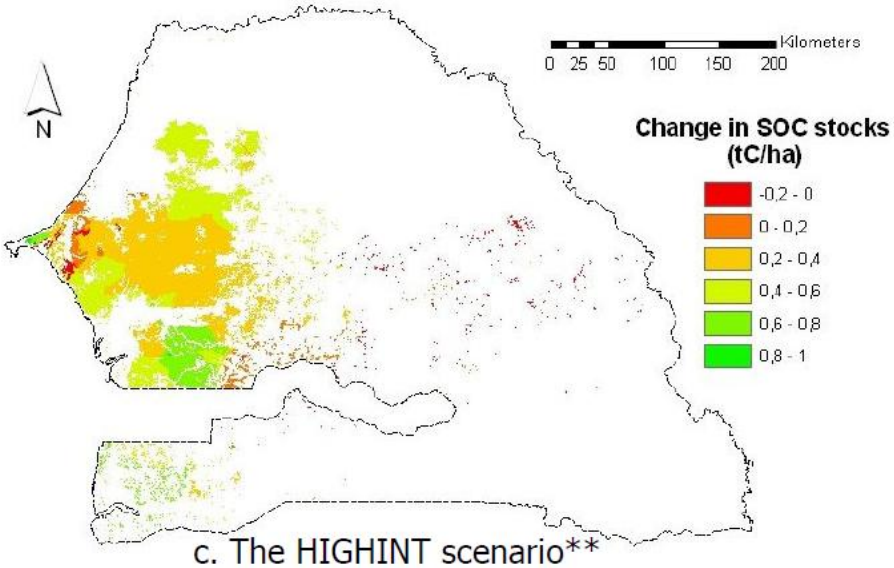
** White areas within national boundaries correspond either to the model restriction previously mentioned, or to non agricultural land-uses as identified by (DAAC 2002).



a. The MAXINT scenario*



b. The LOWINT scenario**



c. The HIGHINT scenario**

977

Figure 5: Results of model coupling for two scenarios: (a) Change in greenhouse gas (GHG) balance for the HIGHINT scenario; (b) Change in GHG balance for the MAXINT scenario; (c) Change in financial benefits for the HIGHINT scenario; (d) Change in financial benefits for the MAXINT scenario

* Negative figures indicate net releases of GHG; the change in GHG balance includes emissions from fertilizer manufacture, transportation, and use, emissions from manure use, and SOC changes

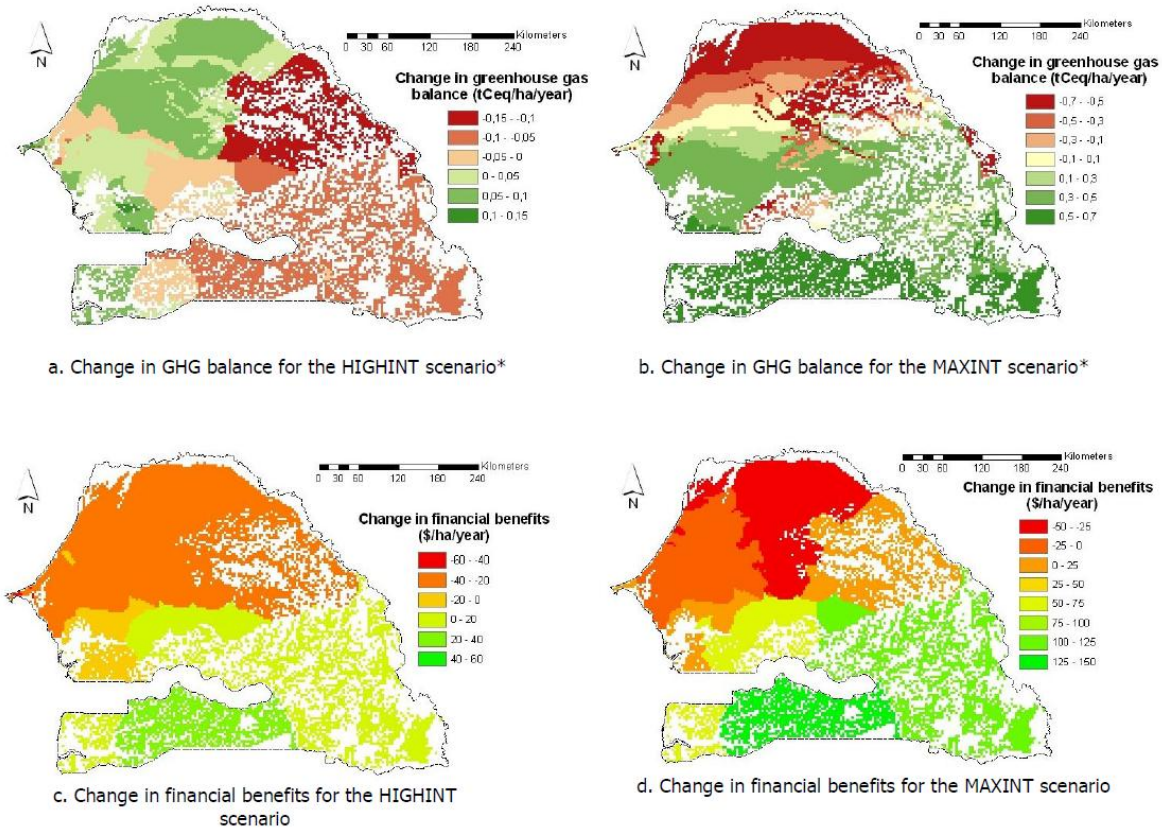
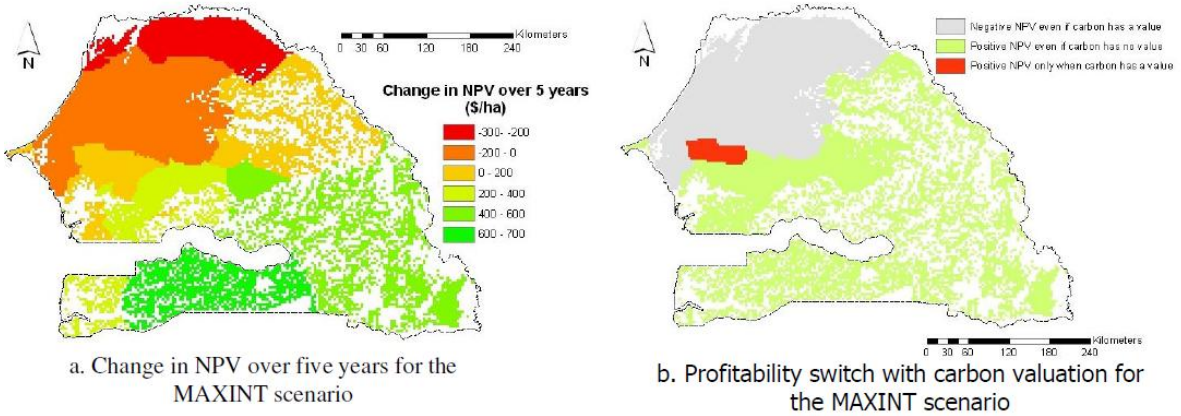


Figure 6: Valuation of potential carbon sequestration at US$ 25.8 $tCeq^{-1}$ for the MAXINT scenario:

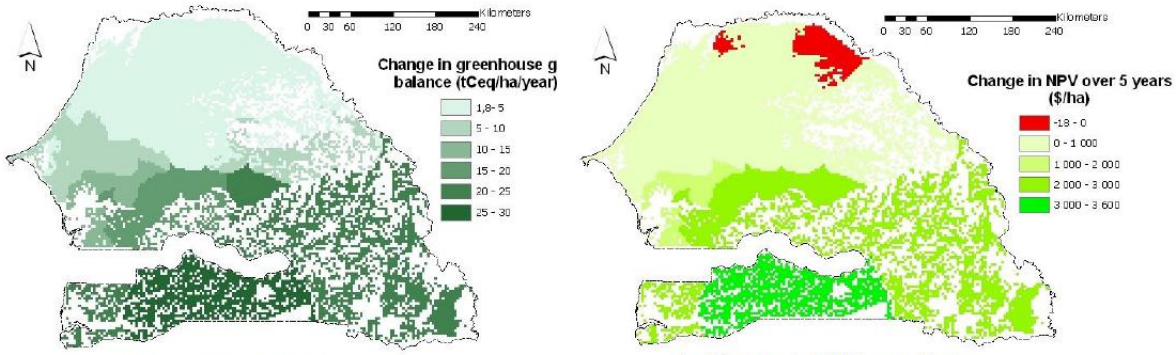
(a) Change in NPV over five years for the MAXINT scenario; (b) Profitability switch with carbon valuation for the MAXINT scenario



a. Change in NPV over five years for the MAXINT scenario

b. Profitability switch with carbon valuation for the MAXINT scenario

Figure 7: Results from model coupling with accounting "avoided deforestation" for the MAXINT scenario: (a) Change in carbon balance; (b) Change in NPV over five years



a. Change in carbon balance

b. Change in NPV over 5 years

Tables

Region	Percent of region subject to analysis (%)	Average change in SOC stocks (tC/ha)	Average GHG balance (tCeq/ha/y)	Average GHG balance including "avoided deforestation" (tCeq/ha/y)	Average change in financial balance ($/ha/y)	Average change in NPV over five years with C valuation ($/ha)
Dakar	59	-0.64	-0.07	5.61	3.2	6.1
Diourbel	100	1.78	0.31	9.15	-7.3	-0.8
Fatick	69	3.89	0.46	14.29	22.1	141
Kaolack	71	3.17	0.33	19.35	58.8	285.4
Kolda	64	12.75	0.56	28.99	139.3	654.1
Louga	97	-1.05	-0.24	4.24	-25.1	-131.5
Matam	55	0.01	-0.08	4.99	20	77.9
Saint-Louis	73	-3.18	-0.58	2.47	-43, 6	-245.3
Tambacounda	47	5.91	0.43	22.93	116.4	543.3
Thiès	90	0.39	0.05	5.58	-15.3	-60.7
Ziguinchor	44	15.64	0.58	20.23	65	337.7
Senegal	65	3.03	0.11	13.27	40.1	183.4

Table 1: Change in soil carbon sequestration amounts and benefits across regions of Senegal, in the MAXINT scenario with respect to the BAU scenario (NPV: Net Present Value)

Region	Part of region subject to analysis (%)	Carbon storage		GHG balance			
				without accounting for "avoided deforestation"		with accounting for "avoided deforestation"	
		Average (tC/ha)	Total (tC)	Average (tCeq/ha/y)	Total (tCeq/y)	Average (tCeq/ha/y)	Total (tCeq/y)
Dakar	27.58	0.71	10 553	0.10	1 503	7.06	104 495
Diourbel	82.38	0.30	123 905	0.01	4 855	4.86	2 019 220
Fatick	54.61	0.35	149 539	0.02	7 631	5.00	2 149 470
Kaolack	30.94	0.43	200 442	0.04	17 572	4.93	2 280 350
Kolda	0.93	0.28	5 492	-0.02	-458	5.22	102 899
Louga	16.18	0.46	187 749	0.06	22 921	4.38	1 798 800
Matam	0.01	0.03	5	-0.07	-14	4.97	995
Saint-Louis	0.03	0.44	264	0.05	29	4.37	2 625
Tambacounda	0.09	0.01	55	-0.07	-374	4.97	26 353
Thiès	50.48	0.32	106 519	0.02	6 061	4.81	1 614 680
Ziguinchor	10.00	0.64	48 023	0.07	5 201	4.84	361 393
Senegal	10.99	0.38	832 546	0.03	64 930	4.82	10 461 280

Table 2: Change in soil carbon storage amounts in Senegal in the HIGHINT scenario with respect to the BAU scenario (for the grid elements where storage is positive)