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

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25

26

27 **Abstract**

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

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

45

## 46 **1 Introduction**

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

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

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

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

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

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

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

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<sup>1</sup> 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.

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

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

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

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

132

## 133 2 Material and Methods

### 134 2.1 Study site

135 Most of Senegalese soils are ferruginous and very sandy, especially those in cultivated  
136 areas: 85% of total cropped soils contain less than 20% of clay (Stancioff et al. 1986; DAAC  
137 2002). As opposed to clayey soils where the SOM pool in mostly clay fraction, sandy soils  
138 have been shown to be particularly sensitive to organic amendments (Feller et al. 1991). On  
139 the other hand, the total SOM pool of non-degraded sandy soils tends to be smaller than that  
140 of similar clayey soils, which renders their storage potential smaller (Jones 1973; Feller  
141 1995). Another important pattern driving carbon storage is that of rainfall distribution which  
142 follows a southward gradient from 200 mm y<sup>-1</sup> in the North to 1400 mm y<sup>-1</sup> in the South  
143 (Figure 1), with rain falling during a single rainy season of 3 to 6 months (Kelly et al. 1996;  
144 Worldclim 2000).

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

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

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

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

## 167 2.2 Agricultural intensification scenarios

### 168 2.2.1 *Manure availability*

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

### 180 2.2.2 *Description of scenarios*

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

184 *Baseline scenario (Business as Usual or BAU):* The baseline scenario considered was  
185 the continuation of current practices as described in part 2.1. With regards to mineral  
186 fertilizers, it assumes that none is used: the data gathered by the International Fertilizer  
187 Association tend to bolster up this assumption (International Fertilizer Industry Association  
188 2003).

189 The collecting efficiency of the available manure pool for current practices was set at  
190 50% during the dry season (as animals are corralled at night and also deposit manure on fields  
191 during the beginning of the season), and at 0% during the wet season (Fernandez-Rivera *et al.*  
192 1995). This is again a conservative approximation, as deposited manure is not as efficient as  
193 manure collected in stables and manually spread (McIntire and Powell 1994), the latter kind  
194 being the one used for model calibration. The length of the dry season necessary for this  
195 computation was assumed to vary linearly with annual rainfall average from 3 months in  
196 Northern Senegal to 6 months in Southern Senegal.

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

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

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

## 224           2.3 The biophysical model: a statistical model of soil carbon change

### 225                   2.3.1 *Carbon storage dynamics*

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



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

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

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

### 253 2.3.2 Data collection

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

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

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

264 - *Minimal data requirement:* as in most meta-analysis (Jones 1973), the original studies  
265 used here had different methodologies. The most problematic here was the potentially  
266 important discrepancies for SOC content measurements arising from use of varying  
267 methods (Pansu and Gautheyrou 2006). To alleviate any such analytical bias, data  
268 were expressed as the difference in SOC content ( $\Delta C$ ) between each treatment and its  
269 control (which receives no input whatsoever). Only variations in the 0-20 cm layer  
270 have been considered<sup>2</sup>, since the influence of management below this depth has been  
271 found to be of small magnitude (Tiessen et al. 1998; Manlay et al. 2002; Elberling et  
272 al. 2003). The standard of the International Panel on Climate Change (IPCC) is 30 cm,  
273 but it may not be relevant for carbon sequestration projects in agricultural soils as the  
274 costs of monitoring the 20-30 cm depth may override the potential increase in SOC  
275 stocks there, and since only shallow tillage is practised. Finally, the availability of a  
276 control, and of a minimal set of environmental parameters such as average rainfall and  
277 soil texture, also limited the number of studies eligible to the analysis.

278 - *No crop residue return or fallow:* The only kinds of organic amendments retained  
279 were manure and compost. The C:N ratio of crop residues is indeed usually much  
280 higher than compost or manure, which implies notable differences in decomposition  
281 dynamics, and therefore in their effects on SOC and crop yields (Allard et al. 1983; De  
282 Ridder and Van Keulen 1990; McIntire and Powell 1994). For this reason, treatments  
283 with crop residue return were excluded from the analysis. Fallow periods, which  
284 contribute to soil restoration through increased root density and residue return, were  
285 excluded for the same reasons. These exclusions were also reasonable from a socio-  
286 economic point of view: current pressure on land tends to shorten fallow length and  
287 the pressure on organic resources greatly limit the possibility of crop residue recycling  
288 (De Ridder and Van Keulen 1990).

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

---

<sup>2</sup> 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

293  
294 Four management variables were available for all sites as potential explanatory  
295 variables for the effect of treatment (average yearly quantity of N, P, K and organic inputs  
296 applied over the last 5 years of treatment). A preliminary step-wise method of model  
297 selection, with the Akaike Information Criterion (AIC) as the selection criteria (Akaike 1973;  
298 StatSoft 2006), showed that only N, P and organic inputs were to be retained for their  
299 explicative power on  $\Delta C$ .

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

310 Figure 2.

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

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

325 The rainfall dataset used to run the biophysical model is the yearly average between  
326 1950-2000. This range is thought to be representative of the region, being wider than the

327 drought that lasted from the 1960s to the beginning of the 1980s. Nevertheless, more recent  
328 averages, or even forecasts such as the climate change scenario available in Hulme et al.  
329 (2001) or in IPCC (2006), could be more relevant depending on the exact objectives of the  
330 model runs.

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

#### 334 2.3.4 Model test

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

### 340 2.4 Socio-economic model

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

#### 347 2.4.1 Cost of transportation of mineral fertilizers

##### 348 • Financial cost:

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

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

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

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

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

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

373 • Environmental costs

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

383 *2.4.2 Cost of application of mineral fertilizers*

384 • Financial costs:

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

386 • Environmental costs:

387 To compute the additional N<sub>2</sub>O emissions resulting from the application of mineral  
 388 fertilizers, the IPCC methodology for national GHG inventories was applied (IPCC 2006).

389 *2.4.3 Cost of manure collection and application*

390 • Financial costs:

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

394

395 • Environmental costs:

396 Emissions of CH<sub>4</sub> or CO<sub>2</sub> resulting from manure decomposition were assumed to be  
397 the same whether livestock is stalled or not, and therefore did not influence the model. A  
398 decrease in N<sub>2</sub>O emissions from cattle manure when it is manually collected and spread  
399 instead of being directly deposited on field by animals was accounted for, following the  
400 standard IPCC methodology (IPCC 2006). The emissions from urine were overlooked,  
401 thereby making the implicit assumption that its decomposition is independent of its  
402 management (either directly deposited in the field or stored in stables and manually spread).  
403 This assumption is probably reasonable since most of the nitrogen in urine is volatilized into  
404 ammoniac notwithstanding its management (Fernandez-Rivera et al. 1995).

#### 405 *2.4.4 Additional revenue from increase in crop yields*

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

409 • Modelling of crop yield change:

410 As for SOC change, we used a statistical approach to model relative change in crop  
411 yield. The same dataset as for SOC change prediction was used to calibrate a statistical  
412 model. As the average yields of each treatment were not always available, the dataset was  
413 here further restricted to 42 points coming from 12 different studies. The model building  
414 methodology was the same as for the biophysical model, which again excluded K inputs from  
415 explicative variables. There, such parameters as clay content and rainfall were not retained, as  
416 they did not improve the model. This tends to show that, although clay content and rainfall  
417 may play a major role in explaining absolute crop yield and absolute crop yield change, they  
418 do not significantly influence relative crop yield change. However, as in McIntire and Powell  
419 (1995), the inclusion of the square of some treatment parameters effectively improved the  
420 model's precision, and was therefore retained to yield the model equation.

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

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

$$426 \quad Y = Y_R \times \frac{100 + (\Delta Y_T - \Delta Y_{BAU})}{100}$$

427 where Y is the yield (in kg ha<sup>-1</sup> y<sup>-1</sup>), Y<sub>R</sub> is the average regional yield (in kg ha<sup>-1</sup> y<sup>-1</sup>), ΔY<sub>T</sub> and  
 428 ΔY<sub>BAU</sub> are the yield changes (in %) from a no-input treatment respectively due to the inputs in  
 429 the new practice and in the baseline scenarios, as computed by the statistical model.

430 • Crop prices:

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

## 437 2.5 Model coupling

### 438 2.5.1 *Hypothesis on carbon prices*

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

### 447 2.5.2 *Accounting for “avoided deforestation”, and valuing it*

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

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

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

468



## 469 3 Results

### 470 3.1 Biophysical model

#### 471 3.1.1 *Parameterization of equation for soil carbon stock change*

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

$$474 \Delta C = \text{organic inputs} \times (-0.56 - 0.036 \times \text{clay} + 0.0015 \times \text{rain} + 0.011 \times P - 0.0031 \times N) + 0.023 \times P - 0.0076 \times N \quad (1)$$

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

#### 479 3.1.2 *Carbon storage found under the different scenarios*

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

485 For the LOWINT and HIGHINT scenarios, the magnitude of SOC change is lower  
486 than for the MAXINT scenario. This way, the national potential for carbon storage was  
487 estimated to  $0.648 \text{ MtC}$  and  $0.832 \text{ MtC}$  for the LOWINT and HIGHINT (Table 2) scenarios,  
488 respectively.

#### 489 3.1.3 *Model test*

490 Tested on an independent dataset over seven Senegalese sites, the predicted  
491 values for SOC changes were not significantly different from the field measurements ( $p$ -value  
492 =  $0.13$ ;  $n = 18$ ). Nevertheless, the residual error was important ( $3.6 \text{ mg g}^{-1}$ ;  $5.5 \text{ tC ha}^{-1}$  when  
493 converted into stocks).

#### 494 3.1.4 *Sensitivity analysis to clay content*

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

## 499 3.2 Cost-Benefit Analysis

### 500 3.2.1 *Parameterization of the equation for yield increase*

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

$$503 \Delta Y = (0.0424 - 0.00106 \times P) \times P + 0.00886 \times N + 0.00869 \times OI^2 + 0.0370 \times P \times OI - 0.00978 \times N \times OI \quad (2)$$

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

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

### 512 3.2.2 *Cost-Benefit analysis for the different scenarios*

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

## 521 3.3 Model coupling

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

## 525 3.4 Avoided deforestation

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

531 becomes positive everywhere in Senegal, and its average over Senegal increases to 120 times  
532 the average without accounting for deforestation (Table 1 and Figure 7). For the HIGHINT  
533 scenario the net fixation of GHG would increase by 161 folds (Table 2).  
534

## 535 4 Discussion

### 536 4.1 The limited national potential of increased fertilization for in-situ soil C accretion

537 The average changes in SOC stocks in regions of the Old Peanut Basin such as Kaolack,  
538 Fatick or Diourbel (1.78-3.89 tC ha<sup>-1</sup>; Table 2), are close the 3.17 tC ha<sup>-1</sup> obtained by  
539 Tschakert (2004) with the Century model for a similar treatment in this region. The North-  
540 South gradient in carbon storage potential for the MAXINT scenario (Figure 6a) is also  
541 consistent with the difference between these figures, and higher SOC increases (+9.9 tC ha<sup>-1</sup>)  
542 measured by Manlay *et al.* (2002) in the Kolda region (for an administrative map of Senegal,  
543 see Annex 2). These increases are important compared to the existing SOC stocks of 15-  
544 30 tC ha<sup>-1</sup> in the 0-40 cm layer (Woomer *et al.* 2004).

545 The present estimates of the national potential of carbon accretion of 0.65-0.83 MtC  
546 for scenarios realistic at this scale (LOWINT and HIGHINT) would represent only 7 and 9%  
547 of Senegal's 1994 GHG emissions from activities others than land-use change and forestry,  
548 and 11 and 14% of GHG emissions from all activities, respectively (UNFCCC 2005  
549 according to which land-use change and forestry were net C sinks in 1994). These scenarios  
550 would also barely change the national SOC stocks estimated at 561 MtC by Henry *et al.*  
551 (2009) for the 0-30 cm layer.

552 Estimates for C sequestration for the HIGHINT scenario would be even more modest  
553 since it would represent 3 % of Senegal's 1994 GHG emissions from activities others than  
554 land-use change and forestry, and 5% of GHG emissions from all activities. Estimates for C  
555 accretion are more difficult to relate with the estimate of Senegal's potential of carbon storage  
556 made by Parton *et al.* (2004) under their "improved management practices" scenario. Their  
557 116 MtC potential indeed includes the potential gains from the biomass compartment, and  
558 also those resulting from improved management of pastures and forests. This wide difference  
559 is nevertheless surprising since these authors estimate that agriculture would account for 50%  
560 of this potential, and that in the Intensive Agricultural Region, 90% of the potential comes  
561 from increased SOC. We found several explanations for this discrepancy. The main one is  
562 that the storage potential in our scenario forbids dramatic changes in management practices: it  
563 limits the increase in manure application to the gains in manure from improved collecting  
564 efficiency where Parton *et al.* (2004) assume a doubling of fallow time, coupled with the  
565 application of manure and household wastes (unknown quantities). Their estimate of an  
566 average potential storage of 17.1 tC ha<sup>-1</sup> in the Intensive Agricultural Region is indeed higher  
567 than the value given by Tschakert (2004) for an "optimal" intensification, which requires

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

571 The second source of difference comes from the figures for agricultural cover: as the  
572 present model is spatially explicit, it is bound to use spatialized data (DAAC 2002) which  
573 adds up to 17% of total Senegal under cropping, whereas Parton *et al.* (2004) use the estimate  
574 of 21% from Tappan *et al.* (2004), which is more specific to Senegal, but unfortunately non-  
575 spatialized. Moreover, the range of application was limited here to sandy soils (clay content <  
576 20%), which excluded 15% of total cropland. Overall, the total surface of cropland on which  
577 their estimate is based is therefore 45% higher than the one used in the present study.

#### 578 4.2 Avoided deforestation: a key element to improved the C balance of fertilization

579 The model runs for carbon balances are widely modified when accounting for  
580 deforestation (Table 1; Table 2). In this case estimates for C sequestration for the HIGHINT  
581 scenario would rise to 561% of Senegal's 1994 GHG emissions from activities others than  
582 land-use change and forestry, and to 872% of GHG emissions from all activities (UNFCCC  
583 2005). This is consistent with the results of Liu *et al.* (2004), who found that of the  
584 52 MgC ha<sup>-1</sup> of carbon stocks lost between 1900 and 2000 in south Central Senegal, 88%  
585 came from live biomass, and only 12% from litter and topsoil SOC (the 0-20 cm depth was  
586 the only soil compartment included in the calculations). Such results are consistent with the  
587 recent regain of interest for the issue of carbon emissions from deforestation (The World  
588 Bank 2008; UNFCCC 2008).

#### 589 4.3 Cost-benefit analysis and carbon sequestration (net of additional GHG emissions)

##### 590 4.3.1 *Profitability of carbon sequestration*

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

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

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

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

#### 609 *4.3.2 Transportation costs*

610 Transportation costs would be all the more relevant for Casamance where their high  
611 level significantly increases the local price of fertilizers (from US\$ 30 ha<sup>-1</sup> y<sup>-1</sup> close to Dakar  
612 to US\$ 41 ha<sup>-1</sup> y<sup>-1</sup> in Western Casamance for recommended amounts of fertilizer). This is  
613 why, as highlighted in other studies about Africa or Indonesia, a priority for better access to  
614 fertilizers is the development of better transportation infrastructures (Vlek 1990; Isherwood  
615 2000; Smaling et al. 2006).

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

### 620 4.4 Methodological considerations

#### 621 *4.4.1 Resolution of spatial data*

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

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

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

#### 638 *4.4.2 Organic matter displacement*

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

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

#### 652 *4.4.3 Yield model*

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

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

#### 663 4.4.4 *The risk issue*

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

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

#### 682 4.4.5 *Model imprecision*

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

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



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

699 *4.4.6 Time window considered in the cost-benefit analysis*

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

707

## 708 **5 Conclusion**

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

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

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

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

736

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<sup>3</sup> Still in the pipeline on 02/12/2008

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

Study	Site	Use	Number of data points	Yearly rainfall (mm y <sup>-1</sup> )	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)	Niuro du Rip, Senegal	Calibration	1	718	11
(Rabot 1984)	Niuro 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*

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

753

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

755 *See figures file for the map*

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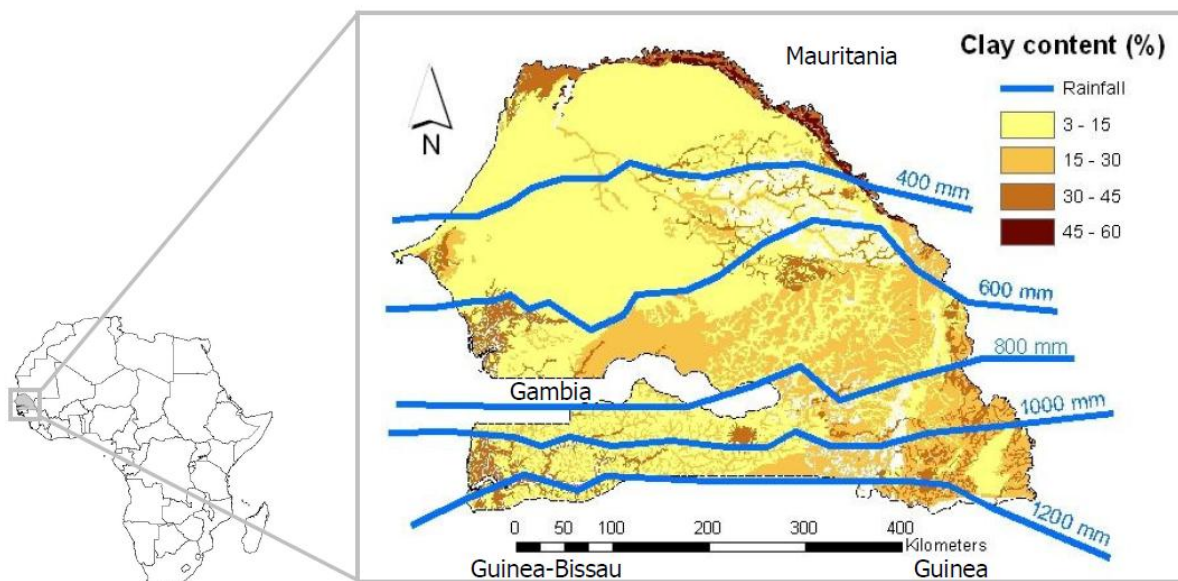
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959 Figures legends

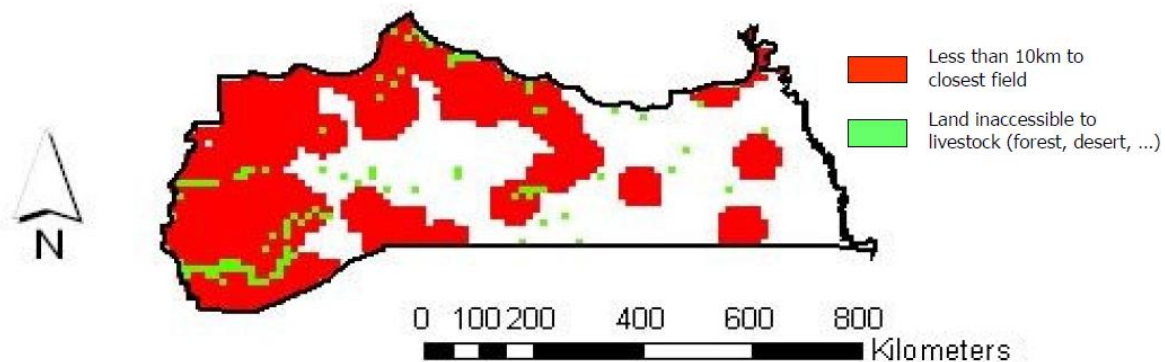
960 Figure 1: Clay content and average yearly rainfall (1950-2000) in Senegal (Stancioff et al.  
 961 1986; Worldclim 2000)



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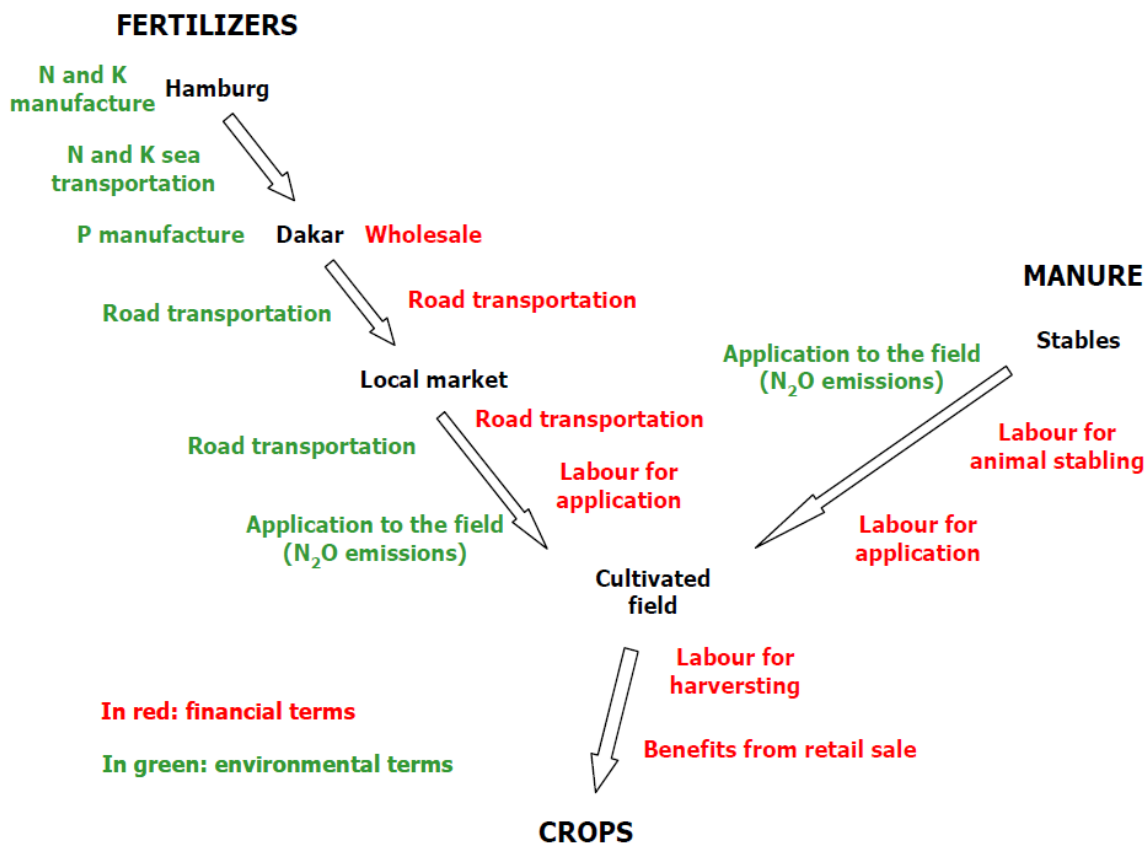
964 Figure 2: Biophysical model design and mode of operation



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966

967 Figure 3: Factors intervening in the socio-economic model



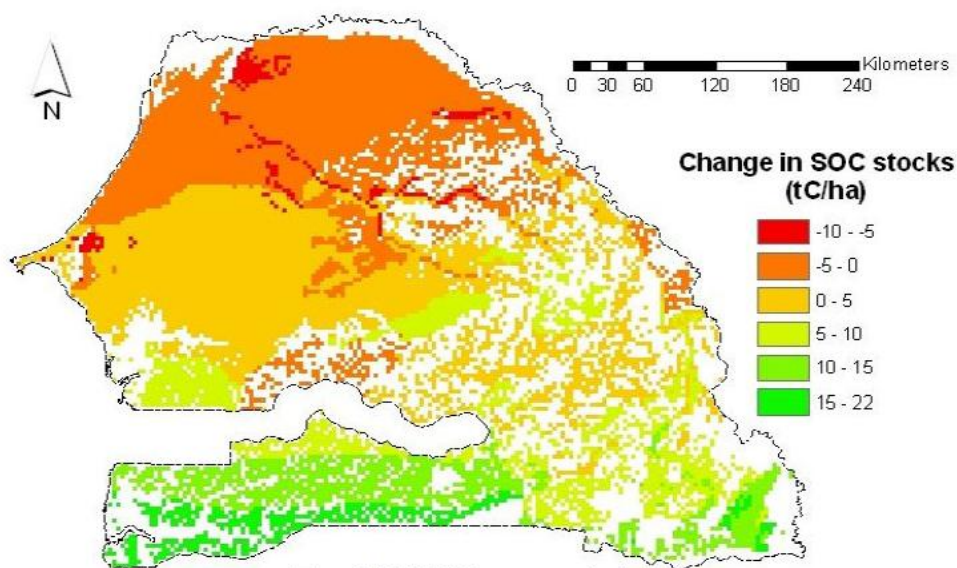
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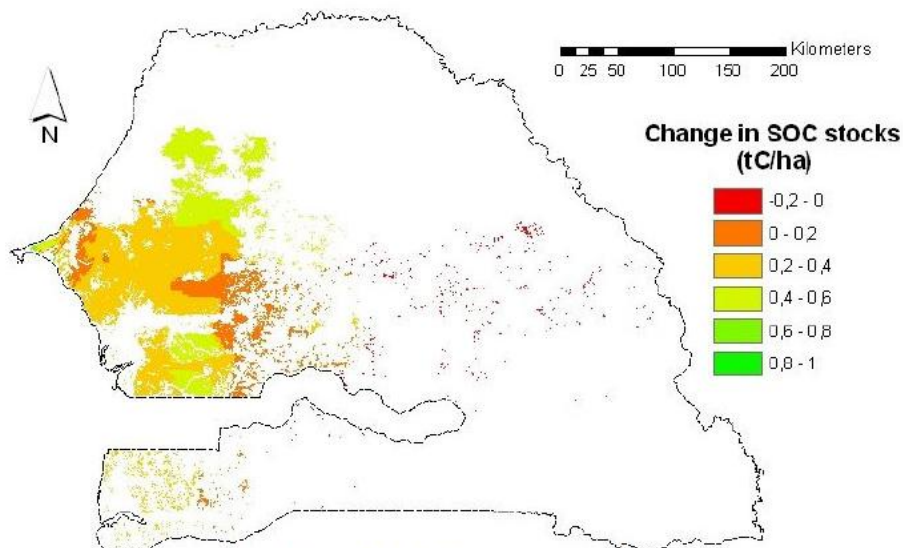
970 Figure 4: Change in Soil Organic Carbon stocks for: (a) the MAXINT scenario; (b) the  
 971 LOWINT scenario;(c) the HIGHINT scenario

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

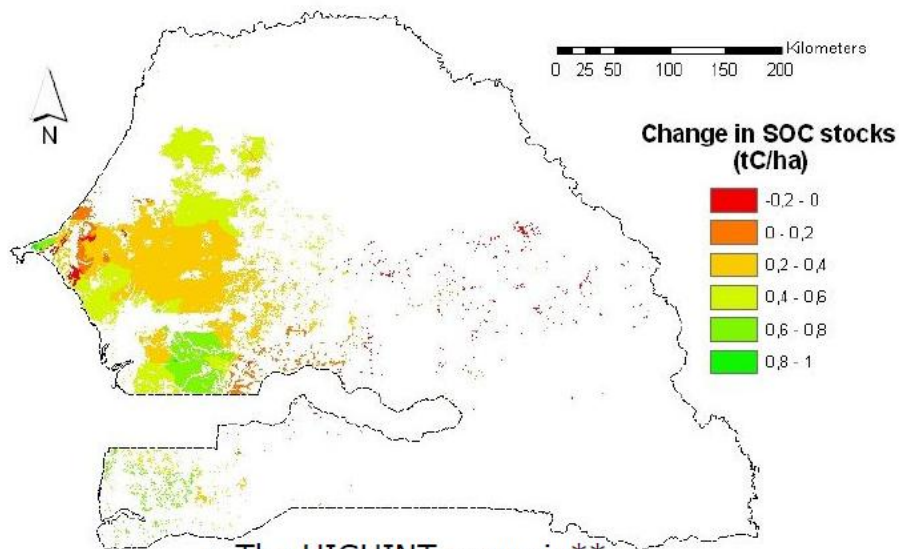
975 \*\* White areas within national boundaries correspond either to the model restriction previously mentioned, or to  
 976 non agricultural land-uses as identified by (DAAC 2002).



a. The MAXINT scenario\*



b. The LOWINT scenario\*\*



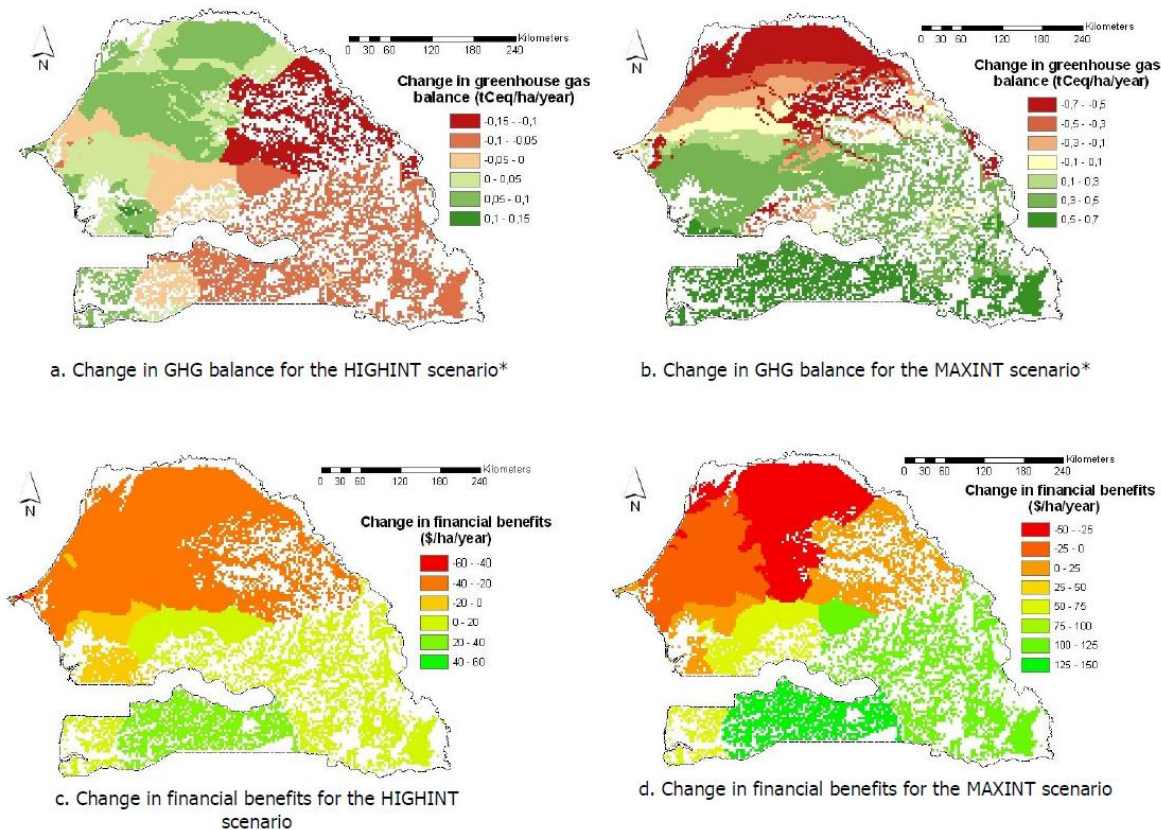
c. The HIGHINT scenario\*\*



978

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

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

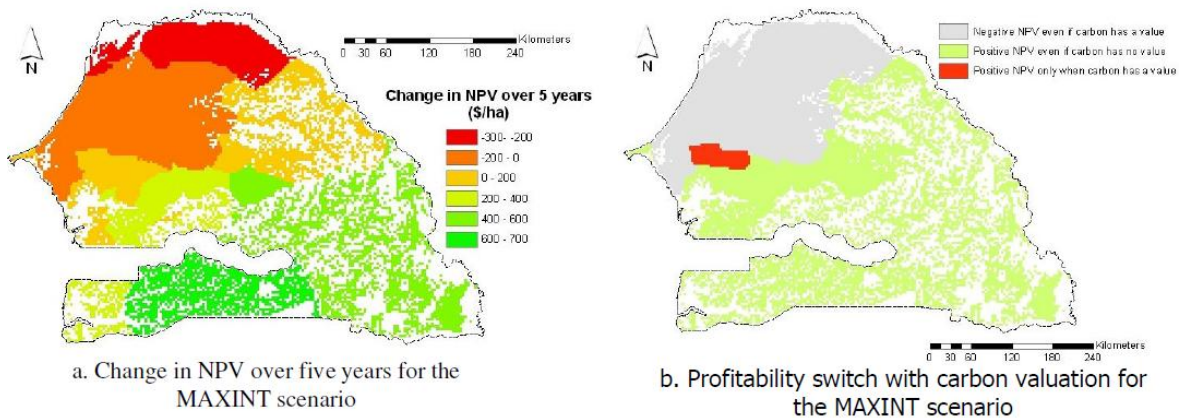


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986

987 Figure 6: Valuation of potential carbon sequestration at US\$ 25.8 tCeq<sup>-1</sup> for the MAXINT  
 988 scenario:

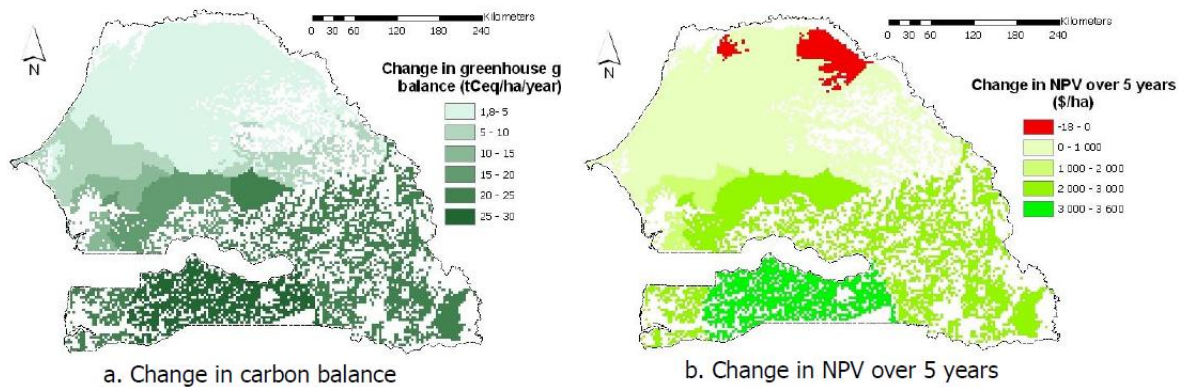
989 (a) Change in NPV over five years for the MAXINT scenario; (b) Profitability switch with  
 990 carbon valuation for the MAXINT scenario



991

992

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



995

996



997 **Tables**

Region	Percent of region subject to analysis (%)	Average change in SOC stocks (tC/ha)	Average GHG balance		Average change in financial balance (\$/ha/y)	Average change in NPV over five years with C valuation (\$/ha)
			(tCeq/ha/y)	including "avoided deforestation" (tCeq/ha/y)		
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
<b>Senegal</b>	65	3.03	0.11	13.27	40.1	183.4

998  
999 Table 1: Change in soil carbon sequestration amounts and benefits across regions of Senegal,  
1000 in the MAXINT scenario with respect to the BAU scenario (NPV: Net Present Value)

1001

Region	Part of region subject to analysis (%)	Carbon storage		GHG balance			
		Average (tC/ha)	Total (tC)	without accounting for "avoided deforestation"		with accounting for "avoided deforestation"	
				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
<b>Senegal</b>	10.99	0.38	832 546	0.03	64 930	4.82	10 461 280

1002

1003 Table 2: Change in soil carbon storage amounts in Senegal in the HIGHINT scenario with  
1004 respect to the BAU scenario (for the grid elements where storage is positive)

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