Solid Earth Discuss., 7, 1797–1825, 2015
www.solid-earth-discuss.net/7/1797/2015/
doi:10.5194/sed-7-1797-2015

Solid Earth
Discussions
Open Access

Quantifying the impact of land degradation on crop production: the case of Senegal

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Received: 28 April 2015 – Accepted: 18 May 2015 – Published: 22 June 2015

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Land degradation has been a persistent problem in Senegal for a long time and by now has become a serious impediment to long term development. In this paper, we quantify the impact of land degradation on crop yields using the results of a nation-wide land degradation assessment. For this, the study needs to address two issues. First, the land degradation assessment comprises qualitative expert judgments that have to be converted into more objective, quantitative terms. We propose a land degradation index and assess its plausibility. Second, observational data on soils, land use and rainfall do not provide sufficient information to isolate the impact of land degradation. We, therefore, design a pseudo-experiment that for sites with otherwise similar circumstances compares the yield of a site with and one without land degradation. This pairing exercise is conducted under a gradual refining of the classification of circumstances, until a more or less stable response to land degradation is obtained, In this way, we hope to have controlled sufficiently for confounding variables that will bias the estimation of the impact of land degradation on crop yields. A small number of shared characteristics reveal tendencies of "severe" land degradation levels being associated with declining yields as compared to similar sites with "low" degradation levels. However, as we zoom in at more detail some exceptions come to the fore, in particular in areas without fertilizer application. Yet, our overall conclusion is that yield reduction is associated to higher levels of land degradation, irrespective of whether fertilizer is being applied or not.

1 Land degradation in Senegal

Already in the late 19th and early 20th centuries warnings were issued about severe risks of land degradation in Sub-Saharan Africa (Chevalier, 1900; Stebbing, 1935), as colonial governments had been introducing commercial agriculture, with natural vegetation replaced over large surfaces by monocultures of cash crops. By now these risks have turned into rather dramatic erosion and a consequent threat to food security, bio-

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diversity and economic development, especially in the poorest parts of the continent where farmers lack access to fertilizer and other inputs (e.g. Lal, 2011).

Senegal is a case in point. In an article in Nature, Mulitza et al. (2010) have shown that sharp increases in dust deposition of terrigenous sediments could be related to land degradation processes in Senegal that started in the 1840s, after the promotion by the French colonial power of groundnut cultivation. The incessant demand for agricultural land eliminated the last stretches of original wooded savannas and open woodlands in the early 1900s (e.g. Boahene, 1998). What remained were agricultural parklands dominated by a small range of acacias species (Tschakert and Tappan, 2004) that no longer could protect the soils against wind and water erosion and resulted in less favorable physical and chemical properties in the top soil (Kairé, 2003). During the first half of the 20th century, development of a network of roads and processing centers, and establishment of railroads enabled further expansion of groundnut cultivation, which from 1960, the year of independence until 1980 also benefited from domestic support through state dominated cooperatives and from preferential export arrangements with France, the main customer. The European Union has pursued this relationship until present within the Lomé and Cotonou Conventions (European Commission, 1999; Bergtold et al., 2005).

This resulted in more intensive forms of agriculture, while demand for fertile land gradually came to exceed availability (Mortimore et al., 2005), which gave rise to Senegal's first large wave of rural-urban migration in the period 1971–1980 (e.g. Mbow et al., 2008). Reform policies undertaken in the 1980's and implemented as the Structural Adjustment Program reduced the state involvement but had detrimental effects on soil fertility management as fertilizer subsidies were abolished and even the application of locally produced Phosphorus became too expensive for Senegalese farmers to use (Speirs and Olson, 1992).

An expert judgment-based inventory (e.g. Sonneveld, 2003; Omuto et al., 2014) under the Land Degradation in Dryland Areas (LADA) project (FAO/UNEP) shows that currently 34 % of the national territory and 58 % of the agricultural areas are affected by a degradation process (Sonneveld et al., 2010)[1]. The experts indicated that land degradation seriously impairs agricultural capacity and the quality of eco-system services. Particularly alarming is the fact that the observed increase in the rate of land degradation affects 26 % of the total land area and 40 % of the agricultural areas against 5 and 6 % with improving trends in land quality, respectively. The LADA inventory also reveals that types, causes and impacts of land degradation are diverse. While the Senegalese government has recognized the severity of these problems (Declaration of Abuja; IFDC, 2006; Senegal Emergent Plan in ADB, 2014), the planning of actual interventions seems to be constrained by lack of more than very general knowledge about the actual impact of land degradation on agricultural production under the various condition prevailing in Senegal.

Yet, establishing a relationship between land degradation and productivity loss is not an easy task, for various reasons (Vieira et al., 2015). First, our available crop yield statistics refer to a spatial unit (polygons that combine land use and districts) for which the experts gave an assessment on degree and extent of land degradation but without more specific indication of where crops are cultivated, and where land degradation is prevalent. Second, there are various confounding factors at play that impact on both land degradation and crop production (e.g. Ferreira et al., 2015). Isolating these is especially difficult for Senegal because there are no historical records available on fertilizer application. While an experimental field trial can for given observed biophysical conditions simulate various intensities of land degradation and for every intensity measure the resulting crop yield, under non-experimental conditions, treatment effects cannot be isolated in this way, and estimation biases can hardly be avoided, since correlation between these conditions is inevitable and observed fertilizer application cannot not be corrected for in a satisfactory manner. Instrumental variable estimation

[1]This study tested the consistency of expert judgments by a cross-comparison of mapping units with identical characteristics for annual rainfall, soil suitability, slope, population density and livestock density. The study concluded that experts had a high consistency in their judgment and gave reliable assessment on the degree of land degradation.

(e.g. Nkonya et al., 2008) and propensity score matching (Kassie et al., 2008) are no exception to this.

Here we opt for a direct matching approach, whereby we measure differences in crop yields (outcomes) at various levels of land degradation (treatment intensities) under the same external circumstances (conditions), proceeding in two steps. First, we compile a representative land degradation assessment for our spatial entities combining expert assessments on degree and extent of land degradation in a single land degradation factor that can be related to corresponding crop production figures. Second, we compare crop production for sites that share similar biophysical and socio-economic characteristics but one site suffers from land degradation and the other site not. To assess the sensitivity of this relationship for the number of shared conditions we extend the number and degree of detail of the, largely categorical, explanatory variables referring to these conditions.

There is a tradeoff here. The finer explanation will have fewer observations in every treatment class but it will account for more variables, hopefully reducing the correlation of remaining unobserved variables with the treatment intensity i.e. land degradation. Hence, it maps out in a categorical setting what would for ordinary regression on continuous variables be the tradeoff as obtained for a larger number of variables, between good fit and better significance of coefficients. Our assertion will be that relationships that change little under this variation are presumably relatively stable to other, so far unobserved factors as well.

The paper proceeds as follows. Section 2 describes the data used in this study. Section 3 re-interprets expert judgments so as to relate the degree and extent of land degradation to crop production. Section 4 assesses the effect of land degradation on crop yields. Section 5 concludes.

2 Data preparation and methodology

Table 1 summarizes data attributes, geographical dimensions and sources.

Land degradation assessments. The land degradation inventory has been based on judgments of experts who identified for each of the 33 Senegalese districts and per production system area shares and the degree and rate of land degradation. Degree and rate of land degradation are expressed in ordered qualitative classes. Figure 1 presents the degree of land degradation by district and production system zone.

Administrative data. We combine two administrative subdivisions. An (older) administrative subdivision of 30 units that is used as a georeference for district statistics on agricultural production and the current administrative subdivision of 33 units which serves as a spatial reference for production systems, land degradation assessments and population.

Base resource maps. The two major components of the base resource map provided 4 rainfall classes (1 = < 200 mm; 2 = 200–400 mm; 3 = 400–700 mm; 4 = > 700 mm) and 4 soil suitability classes (1 = unsuitable; 2 = moderately suitable; 3 = suitable; 4 = very suitable).

Production system map. The nine production systems and their area in ha and a share of the national total are presented in Table 2.

The *population density* map was obtained from the UNEP data base (Nelson, 2004) and upscaled for each district for the year 2005 with data from the "Agence Nationale de la Statistique et de la Démographie", in Senegal.

The *Tropical Livestock Unit* map was derived from FAO (2007). Global density maps were given for cattle, goats and sheep at 1 km × 1 km scale. These animals comprised 86 % of the total livestock expressed in Tropical Livestock Unit (TLU)[2]. As detailed data per district are missing we upscaled the total TLU nationwide proportionally to the prevailing total TLU densities that were derived from the cattle, goats and sheep.

Roads. The Food Atlas of Africa project (Wesenbeeck and Merbis, 2012) provided the segments on primary, secondary and tertiary road presence. The segments were gridded on the 1 km × 1 km grid. Using the ILWIS distance operator (ILWIS Academic

[2]To compare grazing demand or environmental pressure of different species in common units, animals body weights were converted into TLU equivalents.

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version 3.3) we calculated for each pixel the distance to the primary, secondary and tertiary roads.

Crop production data at district level were for Rice, Maize, Millet, Sorghum, Cassava, Cow Peas, Groundnut, Sesame, derived from FAO (2006). The crops represented 93 % of the total cultivated area (FAOSTAT, 2007). Areas and production levels were up-scaled to the national level to represent the entire cultivated area; yield data remained the same as reported in the Agromaps data base.

The procedure for estimating the yield by grid cell is as follows. We distribute the district output by crop over the cultivated land at grid level, relying on a constrained scaling procedure (Keyzer, 2005), that adjusts grid level output until it meets the district total, within grid level bounds. We set these bounds so as to offer a range around a reference yield (output divided by cultivated land) multiplied by grid level area. The reference yield was given to pixels that were assigned to production system zones where crop production is made possible. Furthermore, we accounted for the spatial variation of the soil quality by multiplying reference yields for soils "Unsuitable", "Not very suitable", Moderately suitable' and "Suitable", with 0.2, 0.6, 0.8 and 1.0, respectively, analogue to the AEZ methodology (e.g. FAO/IIASA, 2000). For our analysis we will concentrate on the yields of millet, as this crop is the most widely cultivated and avails of spatial fertilizer statistics.

Fertilizer. Data on fertilizer gifts were derived from the Integrated Plant Nutrition Information System (IPNIS; www.fao.org/ag/agl/agll/ipnis/index.asp). The IPNIS data base provides data on NPK fertilizer and organic fertilizer at province level and by major Agro-ecological zone. The data were complete only for millet and groundnut, data for two other reported crops (rice and cow pea) were sparse while no information was given for other crops. Table 3 summarizes the total of inorganic and organic NPK gifts.

Georeferencing spatial data. All spatial data were georeferenced on a 1 km × 1 km grid. Specifications of the coordinate systems are given in Sonneveld et al. (2010). Polygons of the natural resource base map and the production system map that were

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smaller than 1 km were mapped on this grid map with a nearest neighbor operation, using areas in the attribute tables to indicate a proportional share of the grid area.

3 Creation of land degradation index

To compare the impact of land degradation on crop yields between different sites, we relate crop yields to a land degradation index that combines area shares and degradation classes as provided by the experts of the LADA exercise.

To provide a general impression of the relationship, we conduct an exploratory analysis of non-parametric regression using a smoothing method that interpolates point observations on crop yields for the area shares and degree of land degradation so as to reveal the prevalent patterns between the variables. Specifically, we apply a mollifier mapping, a flexible form of curve-fitting that follows the data closely and compensates for the lack of a priori knowledge of an explicit parametric functional form (Keyzer and Sonneveld, 1998) of the land degradation index. The mollifier program implements a kernel density regression to show estimated values in 3-D graphs in a surface plot against two independent variables. Furthermore, the program generates descriptive statistics about the reliability of the estimate and depicts these in the default mode as color shifts in the surface plot and ground plane, respectively – alternatively, the incidence of other covariates can be shown in these dimensions. We apply to the tool to gradually zoom in on the reliable areas of the data domains. Since fertilizer emerges as an important explanatory variable, we included it as covariate.

Climatic conditions are accounted for by expressing the crop yield as a ratio of actual to potential yield that is defined as climate constrained crop output under optimal soil conditions. As noted earlier, the assessment attributes to every production system zone one or several degrees of degradation with a corresponding area share. To isolate degree-specific effects, we select observations with area shares that are higher than 75 % for the dominant degradation degree.

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Figure 2 shows the results for "light" and "moderate" degree of land degradation. The fertilizer gifts appear as color shift in the surface curve, while the observation density appears in the ground plane. The southeast-northwest axis shows an increasing area share of the "light" degradation class. In this direction we see a small increase of crop yield for higher area shares. Rising area shares for the "moderate" class are found along the northeast-southwest axis and show a rapid decline of the crop yield. There is, however, a slight recovery at higher area shares, which correspond with larger fertilizer gifts. We further note that the higher observation densities are concentrated around the lowest area shares.

Next, Fig. 3 shows increasing area shares for the "moderate" and "strong" classes along, the southeast-northwest and northeast-southwest axis, respectively. Crop yields decline rapidly for the "moderate" class to its lowest levels at around 50 % of the area share but rise sharply in areas with high fertilizer gifts. In areas with low fertilizer supplies crop yields decline with increasing area shares of the "strong" degradation, similarly to the "moderate" class. This suggests that "moderate" and "strong" degradation classes have similar impacts on millet yield while the impact of the "light" degradation is definite lower. This leads us to define an aggregate index of degradation types that attributes twice the weight to area shares of "moderate" and "strong" degradation. The "severe" degree of degradation was reported only twice and no clear response to yield ratio could be made. Assuming that "severe" degradation has an impact no less than that of the other classes we weigh its area share at the same level as "moderate" and "strong" degrees.

We acknowledge that the created land degradation index cannot be tested in full, yet, combining classes and area shares in a single land degradation index has been used in many other peer reviewed studies (e.g. Leiwen et al., 2005; Pace et al., 2008; Sonneveld and Dent, 2009), which gives us, jointly with our empirical results, sufficient confidence to apply the index for our analysis.

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4 Land degradation and crop yields

We are now ready to analyze the effect of land degradation on crop production by comparing crop yields for sites that have similar circumstances pairing one with land degradation and one without it. We account for the occurrence of confounding factors by testing if this relationship is sensitive to the level of detail that is used to describe these circumstances. Hence, we gradually expand the number of explanatory variables hopefully reducing the correlation of remaining unobserved variables with the treatment intensity i.e. land degradation and the bias in the estimation of the treatment effect. We suppose that once we find a stable relationship, that is no major change in yield effect after an extension of the list of explanatory factors, the relationship has become insensitive to unobserved factors (errors) and consequently, that the bias has been sufficiently eliminated.

To describe these circumstances, we use three up to seven categorical variables as were identified in the geographical profile to create uniform sites. For these circumstances, we distinguish only two "treatment" levels, "low" and "severe", depending on whether they are below or above the 0.1 threshold point of the land degradation index. From the available combinations we selected those that occupy more than 10 % of the area of a production system zone for which a land degradation assessment was available. Table 4 lists these seven variables and their class categories. The last column shows the place within the seven-digit code that is used to characterize the sites. A zero in this code means that this characteristic is not considered for the combination.

The selection of the number of variables for crossing seeks to strike a balance between accuracy and policy relevance. Use of many variables reduces the effect of unobserved variables but will rapidly increase the number of combinations. There will be more observations without a match in this case and hence reduces representativeness of the estimation. Conversely, with fewer variables accuracy of comparison will be less but the number of matches higher. Figure 4 illustrates the tradeoff, by plotting the percentage of combinations that could be compared for two land degradation condi-

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tions and their area share is plotted against the number of variables used for crossing. The seven variables combined comprise 36 % of the registered combinations while the two combined variables cover almost 90 %; in between we find a more or less linear increase of successful combinations under a decreasing number of selected variables. Concerning area share, differences are less pronounced. The seven variables combined cover an area share of 64 %, while other combinations report 89 % or higher shares. Hence our assessment compares yields under "low" and "severe" degradation conditions for sites that are defined by combinations of three, four and, finally, seven variables.

Figure 5 shows the pair-wise comparison of average yields for "low" (green bars) and "severe" (sandy brown bars) land degradation at uniform sites defined by a combination of three variables (rainfall, soil and slope). In all cases, lower yields are reported for "severe" degradation, varying from declines of less than 1 to 66 %, with an average of 25 %. Yield drops are most pronounced for low rainfall regimes and unsuitable soils, but also for the combination of high rainfall and moderately suitable soils. Thus, we do not detect any definite relationship between severity of yield decline and specific combinations of rainfall, soil and slope.

Figure 6 shows the comparison for sites defined by combining four variables (rainfall, soil, slope, fertilizer). As we observed in Sect. 3, fertilizer can mitigate land degradation effects on yield and we decided to separate the pairs for "low" (Fig. 6a) and "moderate" (Fig. 6b) fertilizer gifts. For low fertilizer gifts, 4 out of the 6 combinations show a declining yield under "severe" land degradation, varying from 3 to 52 % with an average of 30 %. The two cases with higher yields had "moderately suitable" and "suitable" soils. This might indicate that the productivity of better soils is not yet affected. However, we cannot exclude that other factors like soil conservation activities affect the outcome as well. In case of moderate fertilizer gifts, we obtain in all six cases a decline in yield that varies from 9 to 69 % with an average of 33 %. This is remarkable as the non-parametric estimation in Sect. 3 seemed to indicate that fertilizer has a compen-

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sating effect on land degradation. Yet, this more refined comparison tells us that land degradation effects cannot be mitigated by fertilizer.

Finally, we discuss the pair-wise comparison, at sites that have seven variables in common (rainfall, soil, slope, population, TLU, fertilizer and markets). For low fertilizer gifts (Fig. 7), 6 out of the 8 combinations show a declining yield under "severe" land degradation compared to the "low" level. Average yield decline for these six cases was 25 %, varying from 1 to 51 %. The two cases where higher yields are reported for "severe" degraded land correspond to better soils. However, one site, also endowed with "suitable" soils, shows declining yields for severe degraded areas. As noted earlier, this would suggest that better soils also have higher resistance against land degradation, albeit that other unobserved effects might be at play as well.

As regards the sites with moderate fertilizer gifts (Fig. 8), we find declining yields for degraded soils that vary from 7 to 69 % with an average of 23 % for all sites. Here also, the moderate fertilizer gifts cannot compensate for reduction in yield due to land degradation. Absence of historical records on fertilizer application obstructs a more direct evaluation of impacts and nutrient dynamics at every location. Yet, the lower yields on degraded areas with fertilizer gifts are presumably caused by the long term depletion of P and K stocks that are not easily compensated for through fertilizer volumes and mixes that were commonly applied. For example, currently applied 72 $kg\,ha^{-1}$ NPK for groundnuts is lower than recommended rates of 150 $kg\,ha^{-1}$ NPK and 200 $kg\,ha^{-1}$ for gypsum (Thuo et al., 2011; Ntare et al., 2008).

5 Conclusions

We have studied the effect of land degradation on crop yields in Senegal, in two steps. First, combining qualitative expert judgments and data on areas affected by land degradation, we created an index to quantify the impact of land degradation on crop yields. Non-parametric estimation suggests that this land degradation index can summarize key information in that higher values correspond to lower crop yields in the way one would expect on the basis of the literature. Second, we have estimated a treatment effect by matching sites with common biophysical and socio-economic characteristics and different intensity of land degradation. Such matching is inevitably plagued by unobserved factors that bias the estimation. We have assessed the sensitivity to such factors by conducting the matching at different level of detail for shared characteristics, until a stable relationship was obtained.

In this way, a negative effect of land degradation could be established in qualitative, descriptive terms. In view of the inherently qualitative nature of the underlying data this categorical nature of the assessment can hardly be considered a limitation as compared to any parametric statistical test. After this, pairwise comparison revealed, with a small number of shared characteristics, the tendency that "severe" land degradation levels are being associated with declining yields as compared to similar sites with "low" degradation levels. As we zoomed in with more detail about shared characteristics, some exceptions came to the fore, however, in particular in areas without fertilizer application. Yet, overall we concluded that yield fall with land degradation, irrespective of whether fertilizer is being applied or not.

Thus, intervention is called for to arrest further damage to physical soil properties and avoid further depletion of soil nutrients. At the same time, lack of information seems to be a major hurdle. More research is urgently needed to identify remedies. The solution might be more complex than merely applying more fertilizer, as some studies point to micro-nutrients (Voortman, 2010), while other clearly indicated a Nitrogen deficiency (e.g. Saito et al., 2013). Furthermore, restoring Phosphorus and Potassium is not an easy task as the soils will first restore their buffer capacity, and will not release a steady flow of nutrients until they reach new equilibrium.

A follow up study might consider including information on land conservation practices applied at the sites, so as to allow for comparison of sites with and without such interventions, other circumstances remaining equal. For this, variables of two kinds would need to become part of the data set: (1) specific conservation techniques that are tailored to the biophysical characteristics and land use systems, and (2) features of

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the institutional setting, which might otherwise remain a source of confounding factors, and are known to have been decisive for past success and failure of sustainable land management programs (Bouma, 2008). Inclusion of these variables would allow for identification of the most advisable interventions and hence contribute to more tangible targeting of environmental measures, in line with the recently signed Partnership for Action on Green Economy (UNEP, 2014).

Acknowledgements. This research was sponsored by the FAO-GEF-UNEP Land Degradation in Dryland Areas (LADA) project. The authors like to thank FAO counterparts Freddy Nachtergaele, Sally Bunning and Riccardo Biancalani for useful comments on an earlier draft.

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Table 1. Data, geographical resolution and source.

Data	Resolution	Source
Expert assessments on land degradation	Polygons	Sonneveld et al. (2010), CSE (2008)
Administrative subdivision (2009)	Polygons	CSE (2008)
Administrative subdivision (2005)	Polygons	CSE (2008)
Natural resources: soils, altitude classes, land use	Polygons	CSE (2008)
Slope	Grid 1 km × 1 km	FAO/IIASA (2000)
Production systems	Polygons	CSE (2008)
Population density	Grid 1 km × 1 km	Nelson (2004)
Livestock (cattle, buffalo, sheep and goats)	Grid 1 km × 1 km	FAO (2007)
Presence of primary, secondary and tertiary roads	Segment	Wesenbeeck and Merbis (2012)
Distance to primary, secondary and tertiary roads	Grid 1 km × 1 km	Wesenbeeck and Merbis (2012)
Millet production ($kg\,ha^{-1}$)	District	FAO (2006)

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Table 2. Production system, area (in ha) and share of total land area in percentage.

Production system	area in ha	share of total
Peri-urban	245 234	1.2
Irrigated	200 572	1.0
Floodplains	160 068	1.0
Agro-pastoral	2 541 424	12.7
Rainfed	1 891 141	9.4
Transhumant	3 357 948	16.8
Forestry	7 678 003	38.3
Nature Reserve	2 995 748	15.0
No assessment made	962 385	4.8

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Table 3. NPK gifts ($kg\,ha^{-1}$) for millet groundnut, rice and cow pea.

Region	AEZ	Millet	groundnut	rice	cowpea
Dakar	Niayes	95			
Diourbel	Centre Nord Bassin Arachidier	4	15		
Fatick	Sud Bassin Arachidier	4	28		
Kaolack	Sud Bassin Arachidier	3	28		
Kolda	Basse et Moyenne Casamance	207	6	0	
Kolda	Sénégal Oriental/Haute	83	28		
Sant Louis	Fleuve	0		247	
Sant Louis	Zone Sylvo-pastorale	0			0
Tambacounda	Sénégal Oriental/Haute Casamance	83	28		
Thies	Centre Nord Bassin Arachidier	4	28		
Thies	Niayes	94	28		
Ziguinchor	Basse et Moyenne Casamance	186	6	0	

Source: IPNIS; accessed November 2009.

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Table 4. Variables and encoding of categories used to make uniform sites.

Variable	Encoding of categories	Place in code
Rainfall	1 = < 200 mm; 2 = 200–400 mm; 3 = 400–700 mm; 4 = > 700 mm	1
Soils	1 = unsuitable; 2 = not suitable; 3 = moderately suitable; 4 = suitable	2
Slope	1 = no slope ; 2 = undulating	3
Population density	1 = < 600 p km^{-2}; 2 = 600–9000 p km^{-2}; 3 = > 9000 p km^{-2}	4
TLU density	1 = < 21 TLU km^{-2}; 2 = 21–32 TLU km^{-2}; 3 = > 32 TLU km^{-2}	5
Fertilizer use	1 = < 50 kg ha^{-1}; 2 = 50–150 kg ha^{-1}; 3 = > 150 kg ha^{-1}	6
Access markets*	1 = 1st cat. < 10 km; 2 = 2nd cat. < 10 km; 3 = 3rd cat. < 10 km; 4 = > 10 km	7

* Access to markets expressed as distance to road categories.

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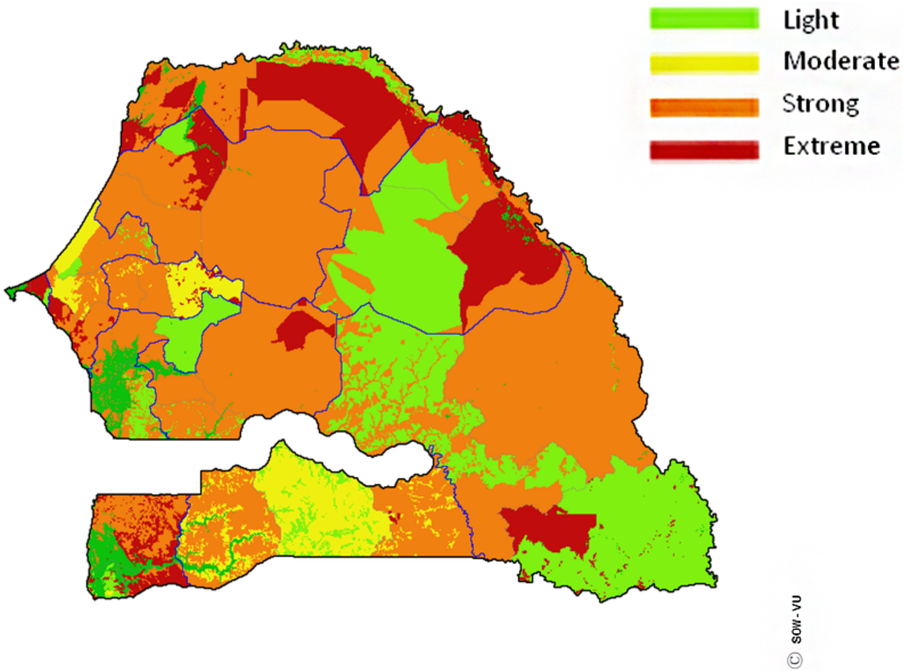

Figure 1. Average degree of land degradation.

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Quantifying the impact of land degradation on crop production

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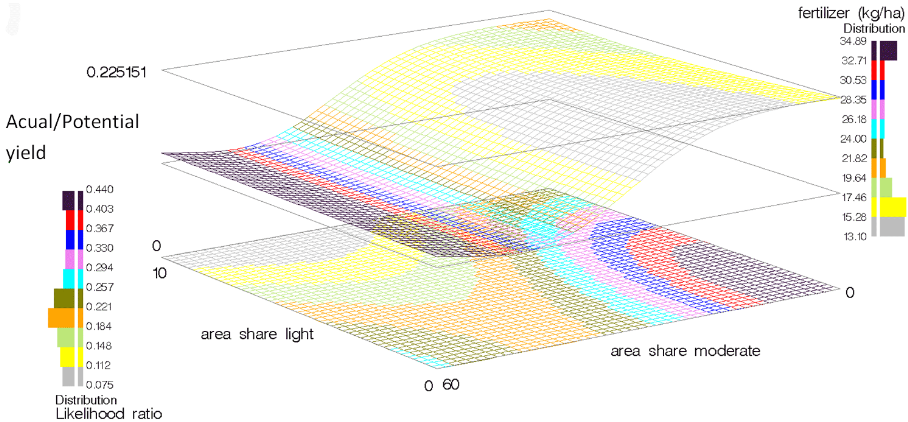

Figure 2. Yield ratio (actual/potential yield) against area share under light and moderate degradation; covariates: fertilizer gifts and likelihood ratio.

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Quantifying the impact of land degradation on crop production

B. G. J. S. Sonneveld et al.

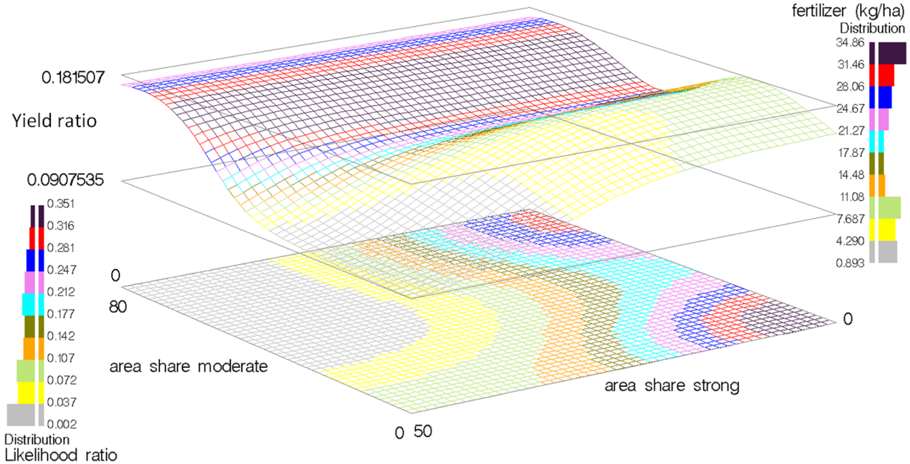

Figure 3. Yield ratio (actual/potential yield) against area share under moderate and strong degradation; covariates: fertilizer gifts and likelihood ratio.

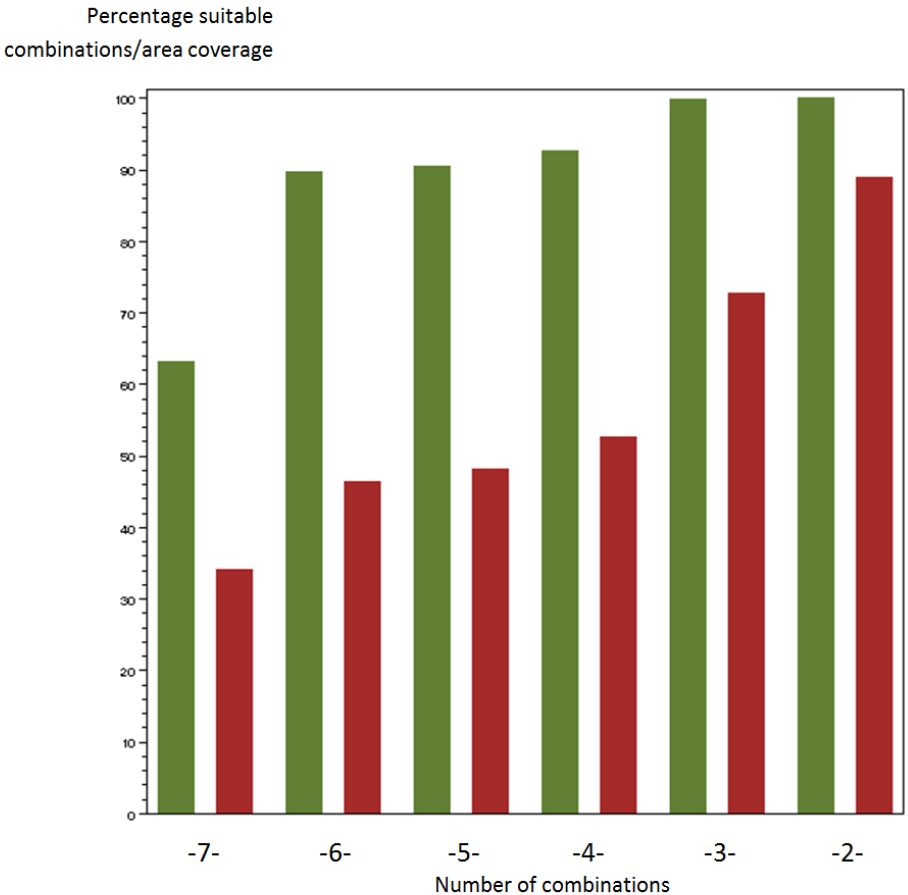

Figure 4. Percentage area coverage (green bar) and available combinations for pair-wise uniform sites (red bar) defined by number of selected variables.

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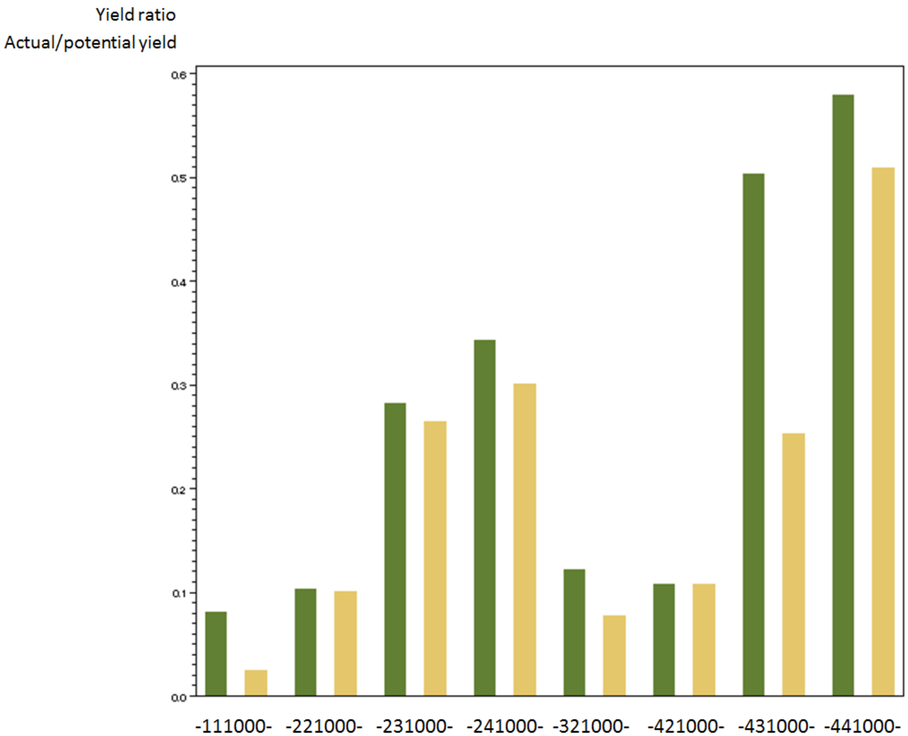

Figure 5. Comparing yields under "low" (green) and "severe" (light brown) degradation for uniform sites defined by three variables (rainfall, soil and slope). Place and category of codes on *x* axis are explained in Table 4.

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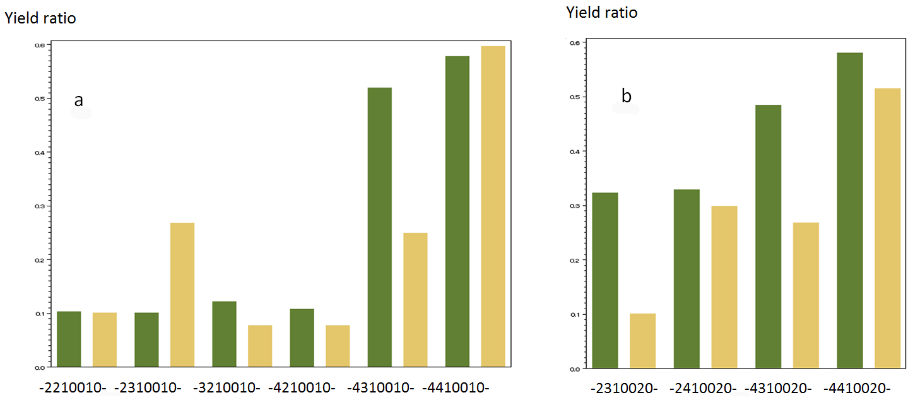

Figure 6. Comparing yields under "low" (green) and "severe" (light brown) degradation for uniform sites defined by three variables (rainfall, soil and slope) for "low" **(a)** and "moderate" **(b)** fertilizer gifts. Place and category of codes on *x* axis are explained in Table 4.

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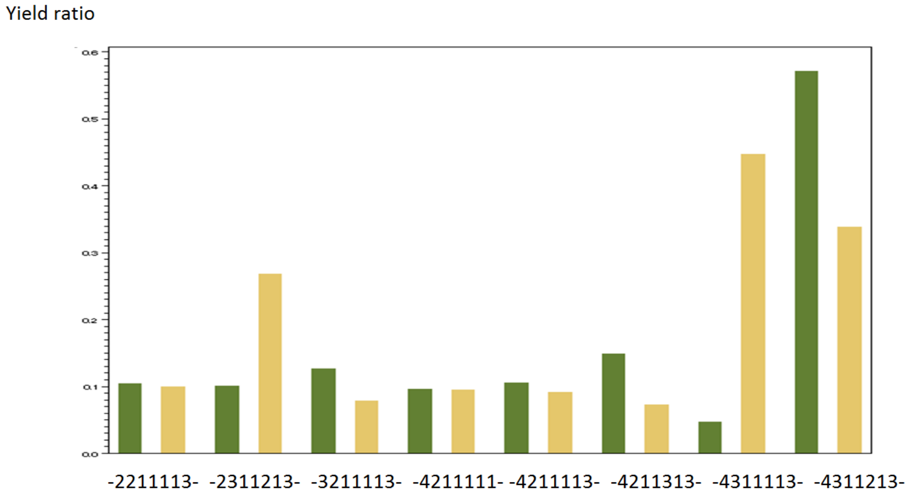

Figure 7. Comparing yields under "low" (green) and "severe" (sandy brown) degradation for uniform sites defined by six variables (rainfall, soil, slope, population, TLU, markets) for "low" fertilizer gifts. Place and category of codes on *x* axis is explained in Table 4.

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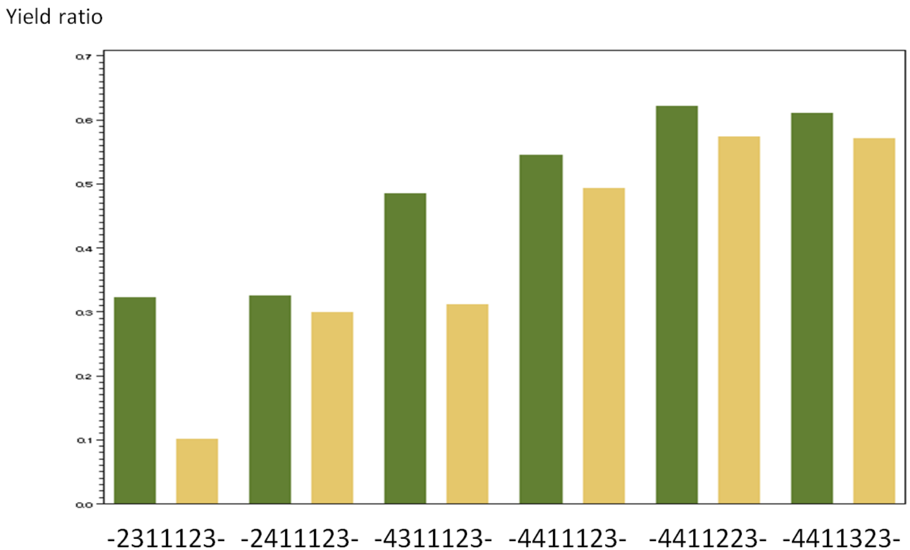

Figure 8. Comparing yields under “low” (green) and “severe” (sandy brown) degradation for uniform sites defined by six variables (rainfall, soil, slope, population, TLU, markets) for “moderate” fertilizer gifts. Place and category of codes on x axis are explained in Table 4.

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