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Degradation of soil fertility following cycles of cotton–cereal cultivation in Mali, West Africa: A first approximation to the problem

Giora J. Kidron [a], Arnon Karnieli [b], Itzhak Benenson [c,*]

[a] Institute of Earth Sciences, The Hebrew University, Givat Ram Campus, Jerusalem 91904, Israel
[b] The Remote Sensing Laboratory, Ben Gurion University of the Negev, Sede Boker Campus 84990, Israel
[c] Department of Geography and Human Environment, Tel Aviv University, Tel Aviv 69978, Israel

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ABSTRACT

Common agricultural practice in West Africa involves alternating crop cultivation for 10–12 years and thereafter leaving the field to rest (fallow) for 10–15 years. With increasing population pressure and growing demand for food on the one hand, and the lack of unexploited lands on the other, soils undergo fast degradation.

In an attempt to predict soil degradation, 12 fields were sampled around Kita, Mali. Seven of these fields were under cultivation whereas the remaining fields were fallow or virgin soils. The soil pH, electrical conductivity, N–NO_3, N–NH_4, P, K, and the soil organic matter (SOM) were determined. Of all variables, only nitrogen and SOM showed significant linear relationship with cotton lint at the cultivated fields, with SOM being the only variable showing a clear threshold (of 18 t/ha) that distinguishes between fertile and infertile fields.

Based on field observations a simple model of the family agricultural land use is presented, aiming to provide a link between agriculture practice and soil degradation. The model demonstrates that the current practices of cultivation and fertilization will result in a slow but inevitable decrease of SOM, with SOM reaching, in 25–35 years, a critical level, below which cotton growth will no longer be economical. We thus conclude that the current practice of cultivation is inefficient and a new cultivation practice, which accounts for the cardinal role of SOM should be adopted.

1. Introduction

Two decades ago, common agricultural practice in West Africa involved alternating crop cultivation for approximately 5 years and thereafter leaving the field fallow for over 10 years (Bationo and Mokwune, 1991). However, the scarcity of lands during recent decades forced farmers to increase the cultivation period and to decrease the time during which the land is left fallow (Chappell et al., 1998; Kouyate et al., 2000). In addition, with the increase in family size, farmers have less available funds to invest in fertilization (van der Pol and Traore, 1993). At the same time more and more marginal land is being cultivated (Bationo and Mokwune, 1991). All these phenomena lead to rapid loss of soil fertility, thus resulting in soil degradation (Reenberg et al., 1998) and in an overall decrease in crop yield.

Soil degradation is observed all over West Africa. According to Bationo and Mokwune (1991) and Pandey et al. (2002), crop yield per hectare decreased during the second half of the 20th century. Pandey et al. (2002) report that in Niger, the yield per hectare decreased by 62% for sorghum and 12% for pearl millet from 1960 to 1999. At the same time, all researchers report a sharp increase in cultivated land during the last decades. Thus, according to Fox and Rockström (2003) while only 40% of the land was cultivated in the Yetenga region of northern Burkina Faso in 1973, it reached 80% by 1996.

A decrease in crop yield and the expansion of cultivated area were also reported in Mali (van der Pol and Traore, 1993; Kouyate et al., 2000), where these developments occurred concomitantly with the introduction of cotton. Being a cash crop, cotton fields expanded in Mali steadily since its introduction in the 1950s. With the establishment of Compagnie Malienne pour le Developpement de Textiles (CMDT, the Malian cotton company) in the 1960s, subsidized fertilizers assisted in the further expansion of the cotton fields. However, with the cessation of subsidies in 1982, many farmers preferred clearing new fields rather than investing in costly fertilizers, a process which resulted in accelerated soil degradation (van der Pol and Traore, 1993).

Cotton cultivation in Mali takes place in rotation with cereal and groundnut. This is also the case in the Kita region of Mali, where the climate is suitable for cotton growth. There, 3–4 cycles

* Corresponding author. Tel.: +972 36409178.
E-mail addresses: kidron@vms.huji.ac.il (G.J. Kidron), karnieli@bgu.ac.il (A. Karnieli), bennya@post.tau.ac.il (I. Benenson).

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of rotational cultivation is performed until the soil is left fallow for 10–20 years. The typical rotation begins with a year of cotton and is followed by a year of cereal (sorghum, millet or corn), and an additional year of cereal or groundnut. Whereas cereal is cultivated to provide domestic use, cotton is planted to provide cash, while groundnut serves for cash as well as for domestic use. Groundnut cultivation also assists in checking soil degradation through its nitrogen fixing capability (Bationo and Mokwune, 1991).

During cultivation, manure and chemical fertilizers are added, however not consistently. The manure at the farmer's disposal is limited, and the amount necessary for spreading over a 1 ha field can be collected once in 3 years. The chemical fertilizers are provided by CMDT only for cotton cultivation.

Commonly, both manure and chemical fertilizers are spread over the field during cotton cultivation; the latter yields on average 1.1 t/ha of lint (Vitale et al., 2007). Fertilizers of 150 kg/ha of a complex cotton fertilizer (N—14%, P—12% and K—22%), and 50 kg/ha of urea (N—46%) are provided by CMDT for cotton growth, together with pesticides and seeds. They are lent to the farmer, along with seeds and pesticides, at the beginning of the rainy season on the premise that all cotton will be sold to CMDT and all the cultivation expenses provided by CMDT will be deducted from the farmer's revenue.

Owing to the limited amount of manure at the farmer's disposal and to the fact that fertilizers are provided by CMDT only for cotton growth, cereal and groundnut do not usually receive chemical fertilization. Consequently, soils in Mali may be short of the major nutrients (N, P, K) and of soil organic matter (SOM) which are of great importance for cotton growth (Elliot et al., 1968).

The decrease in the fallow period on the one hand and the reduction in reserve soils on the other hand may pose a real threat to soil quality in Mali. The current research was designed to study the relationships between SOM, N, P, K and cotton yield, to evaluate the pace during which soil degradation may take place, to develop a simple model for anticipating soil fertility and, with the help of this model, to estimate long-term consequences (30–50 years) of the current agricultural practice.

2. Methodology

2.1. Site description

The research sites chosen is located near Kita, approximately 150 km west-northwest of Bamako (13°04′N, 09°49′W). The area is characterized by a flat loessial terrain with inselbergs. Precipitation in the area is about 800 mm falling mostly between June and September. As local rains are monsoonal, intensities are high, consequently resulting in intense nutrient leaching (Bationo et al., 1998; Jaiyeoba, 2003). Leaching may also be intense due to the high sand content of the soils and the fact that most clay minerals are kaolinite (Bationo and Mokwune, 1991). A savanna type of vegetation characterizes the natural landscape, whereas a mixed tree crop system characterizes the cultivated fields, as also described elsewhere (Jaiyeoba, 2003).

Serving as the district capital, Kita provides services for the surrounding rural communities whereby agriculture is the primary source of income. To assess the *in situ* soil degradation, three villages in the Djidia area (Sandjabugu, Kofe, and Kinitonoma-Dmakana) were chosen for which reliable information on the cotton yield and field cultivation history were available. All villages are within a radius of 48 km and had a similar rain regime. In all villages the fields are ploughed and tilled using oxen and thus differences in SOM content that may stem from different cultivation techniques (Riezebos and Loerts, 1998; Mando et al., 2005) were avoided. In all villages, a poor to medium quality manure is used (cereal stover or low quality farmyard manure).

2.2. Field sampling and soils analysis

Field sampling took place during the beginning of May 2006, just before the onset of the rainy season. In each village, 4 plots, approximately 1 ha each, were chosen, two of which were cultivated and two non-cultivated, i.e., fallow or virgin (Table 1). Our samples were restricted to cultivated plots in which cotton was grown during the previous growing season and reliable information existed as to their lint yield (hereafter cotton yield), and their previous cultivation history. As for the fallow plots, only plots for which we had reliable information regarding the length of time during which they were fallow were included in the analysis. For all plots, the current cultivation cycle was preceded by 12–15 years of fallow and included cotton–cereal rotation with cotton being the last crop grown.

In each plot, a pair of randomly chosen pits, 60 cm in depth, were dug at the middle of the plot, approximately 30 m apart, that were used for soil description and sampling. Four samples were taken from each pit, two from a depth of 0–30 and two from a depth of 30–60 cm. The soils were dried at 105 °C, sieved (<2 mm), and then analyzed for particle size composition, pH, electrical conductivity (EC), soil organic matter (SOM) and major nutrients (N, P, K). All measurements were taken according to the guidelines outlined by Sparks (1996). The particle size composition (sand, silt and clay) was determined by wet sieving (for measuring sand) and by the pipette method (for measuring clay and silt). The pH and EC were determined following a water paste, while the organic matter was determined by the modified Wakly–Black method (oxidation with potassium dichromate in sulphuric acid solution to obtain organic C and then multiplied by 1.724 to obtain the soil organic matter). As for the nutrients, owing to our limited sample size and in agreement with the good results received by Bationo and Mokwune (1991), P-Olsen was determined with available $P–PO_4$ being extracted with sodium bicarbonate. As for nitrogen, $N–NO_3$ was extracted in 1:5 soil to water solution and determined by ion analyzer while $N–NH_4$ was extracted with KCl solution. Soluble K was determined by flame photometer following its extraction in 1:5 soil to water solution whereas the exchangeable K was determined following its replacement by ammonium acetate.

As is commonly the case in agricultural studies (Voortman and Brouwer, 2003), the SOM values were obtained from the top soil (0–30 cm), while the nutrient values were obtained from the 0–60 cm soil layer. The relationship between the primary nutrients and the cotton yield were constructed and employed in the model of soil degradation. For convenience, the sum of both inorganic N components, $N–NO_3$ and $N–NH_4$ will be further termed mineral N, whereas the sum of both readily available K, soluble and exchangeable, will be termed available K.

2.3. Basic assumptions of the model of soil degradation

For model construction, we assumed that (1) each cultivated plot undergoes a 3-year cotton–cereal–cereal/groundnut loop; (2) the maximum concentration of SOM or nutrients in the soils are those measured in virgin or fallow plots after long (≈15–20 years) fallow periods; (3) the absolute rates of soil degradation and restoration are constant in time and common for all plots and, therefore, linear dependencies between the cotton yield and soil properties are employed. The linear approximation is dictated by the limited amount of data. Yet, we also present non-linear approximations of soil degradation and restoration dynamics and discuss possible consequences of substituting the linear dependencies with the non-linear dependencies.

The model considers an abstract "family" which possesses two plots, P1 and P2, one of which is cultivated and the other left fallow. In each 3-year period the family decides whether to continue

Table 1
Plot location, number, yield, history and mean (M) and STD (S) of soil properties. P1–P4 Sandjabugu, P5–P8 Kofe, and P9–P12 Konitonoma Dmakana. Mineral N refers to the sum of N–NO_3 and N–NH_4; available K to the sum of soluble and exchangeable K.

Location, plot#, cotton yield (t/ha), history	Depth, cm		pH	EC dS/ m	SOM t/ha	N–NO_3 kg/ha	N–NH_4 kg/ha	Mineral-N kg/ha	P-Olsen kg/ha	Soluble K kg/ha	Exch. K kg/ha	Available K kg/ha
Sandjabugu, P1, 1.8	0–30	M	5.77	0.30	31.50	9.3	93.3	82.6	10.1	18.8	394.0	412.7
cultivation 5 years,		S	0.52	0.08	2.97	2.2	22.4	24.6	0	1.6	116.5	118.1
manure + fertilizers	30–60	M	5.46	0.25		11.1	76.3	87.4	1.3	12.8	311.6	324.4
		S	0.41	0.05		2.1	17.0	14.9	1.7	4.6	0	4.6
Sandjabugu, P2, fallow	0–30	M	5.62	0.23	28.98	3.2	41.5	44.7	10.1	17.7	423.4	441.0
6 years of fallow		S	0.18	0.01	1.19	0.3	1.6	1.9	2.4	9.1	234.0	243.6
	30–60	M	4.88	0.20		6.8	58.9	65.7	3.8	10.0	311.6	321.6
		S	0.01	0.04		1.0	10.5	9.4	4.2	0	0	0
Sandjabugu, P3, fallow	0–30	M	5.78	0.24	23.52	5.8	54.4	60.1	16.4	16.6	422.1	438.7
20 years of fallow		S	0.05	0.01	1.19	2.0	1.2	3.2	0.6	7.9	156.3	164.2
	30–60	M	4.84	0.20		3.6	60.9	64.6	10.5	8.3	311.6	319.9
		S	0.08	0.01		2.8	5.3	8.1	1.8	1.8	0	1.8
Sandjabugu, P4, 0.6	0–30	M	5.15	0.25	18.27	21.5	50.1	71.6	10.1	15.6	205.0	220.6
Cultivation 10 years.		S	0.41	0.02	2.08	15.1	6.2	21.3	2.4	1.1	0	1.1
Left for fallow due	30–60	M	4.92	0.27		33.5	66.3	99.8	1.3	6.4	152.9	159.3
to poor crop yield		S	0.14	0.08		29.2	5.0	24.2	1.7	1.4	0	1.4
Kofe, P5, fallow	0–30	M	4.68	0.22	32.13	3.2	77.3	80.6	12.6	29.2	504.5	533.6
20 years of fallow		S	0.10	0	2.67	4.5	19.2	14.7	5.9	1.1	39.8	40.9
	30–60	M	4.29	0.19		3.5	94.6	98.1	6.7	13.4	284.8	298.2
		S	0.02	0.03		3.9	13.4	17.3	2.4	1.0	38.0	37.0
Kofe, P6, 2.4 cultivation	0–30	M	5.46	0.41	42.00	50.1	101.2	151.4	19.8	24.5	532.6	557.1
4 years fertilizers + manure		S	0.29	0.04	4.75	8.4	15.9	7.5	7.7	4.3	79.5	84.2
	30–60	M	5.05	0.18		15.5	92.7	108.1	11.8	7.4	339.4	346.7
		S	0.10	0.01		5.2	0.8	4.3	3.6	2.3	115.2	117.5
Kofe, P7, 1.7 adjacent to	0–30	M	6.22	0.27	26.25	32.7	88.1	120.8	16.8	26.1	735.0	761.1
P6 cultivation 4 years		S	0.01	0.01	4.45	3.1	12.5	20.5	3.5	9.7	124.0	134.4
fertilizers only	30–60	M	5.81	0.30		28.6	78.2	106.9	12.6	69.1	2077.4	2146.5
(no manure was added)		S	0.25	0.03		9.7	6.6	16.3	2.4	46.7	1067.9	1114.6
Kofe, P8, virgin	0–30	M	4.84	0.22	44.10	15.4	61.8	77.2	12.6	9.5	258.3	267.8
(never cultivated)		S	0.21	0.05	6.53	5.7	12.1	6.4	4.8	0.4	35.4	75.8
	30–60	M	4.54	0.20		13.1	96.8	109.9	9.2	9.5	429.2	488.7
		S	0.18	0.01		1.0	2.8	1.8	0	3.7	232.0	233.3
Kinitonoma, P9, 0.6	0–30	M	5.69	0.33	19.95	33.6	69.6	103.2	17.7	19.4	286.9	306.2
cultivation 15 years,		S	0.35	0.12	0.30	23.9	1.6	25.5	4.7	12.5	189.4	201.9
manure + fertilizers,	30–60	M	5.62	0.32		15.5	64.2	79.7	8.4	5.4	284.8	290.1
left for fallow due to poor yield		S	0.25	0.01		5.5	5.8	11.3	10.7	1.5	38.0	36.5
Kinitonoma, P10,	0–30	M	5.96	0.67	22.47	105.5	65.4	190.9	16.8	195.5	1213.3	1408.8
1.5 cultivation		S	0.95	0.21	0.30	12.4	5.4	6.9	2.4	194.2	1120.8	1315.0
6 years, manure	30–60	M	5.55	0.26		13.0	42.1	55.1	5.5	7.2	311.6	318.8
+ fertilizers		S	0.06	0.04		1.0	2.7	3.7	3.0	0.7	0	0.7
Kinitonoma, P11, 0.8 adjacent to P10. cultivation 6 years fertilizers only (no manure was added).	0–30	M	5.61	0.42	18.69	52.5	68.8	121.3	18.5	46.2	284.8	330.9
		S	0.01	0.04	2.67	1.7	0.1	1.5	3.5	27.9	38.0	10.0
	30–60	M	5.61	0.26		10.0	48.0	58.0	8.4	7.5	257.9	265.4
		S	0.80	0.05		2.1	2.5	0.4	1.1	2.3	0	2.3
Kinitonoma, P12, fallow	0–30	M	4.01	0.21	40.32	7.9	96.3	104.2	13.0	17.9	422.1	440.0
15 years of fallow,		S	0.16	0.02	1.19	0.8	6.4	7.1	3.0	7.4	156.3	163.6
cleared and prepared	30–60	M	4.58	0.14		12.5	85.6	98.1	0.9	6.0	311.6	317.6
for cultivation		S	0.05	0.01		0.6	31.7	32.3	1.1	0.9	0	0.9

cultivating the current plot or to switch to the fallow plot. A family leaves the plot if *anticipated* yield is below 0.8 t/ha.

3. Results

3.1. Soil analysis and determinants of cotton yield

The soil properties of the plots are presented in Table 1. All soils are Ferric Lixisols characterized by a high amount of silt and a small amount of clays. Loam characterizes Sandjabugu (with 41% of sand, 46% of silt and 13% of clay) while silt loam characterizes Kofe (with 25% of sand, 60% of silt and 15% of clay) and Kinitonoma Dmakana (with 28% of sand, 56% of silt and 16% of clay). Electrical conductivity was low in both depths sampled, attesting to intense ion leaching.

All soils were characterized by a pronounced A horizon. Whereas at the virgin soils the A horizon extended for ~15 cm, it extended for up to 25–30 cm at the cultivated plots, mainly as a

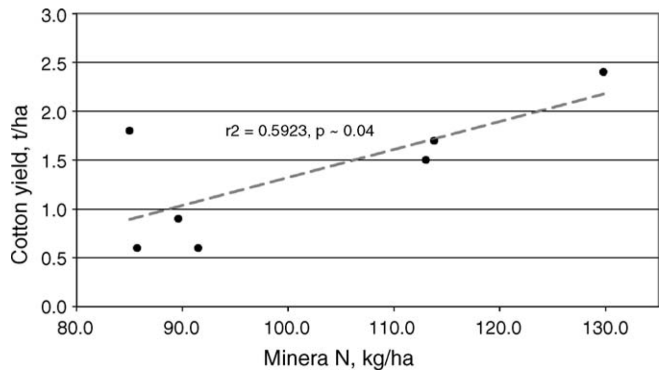

Fig. 1. The relationship between mineral N- and cotton-yield.

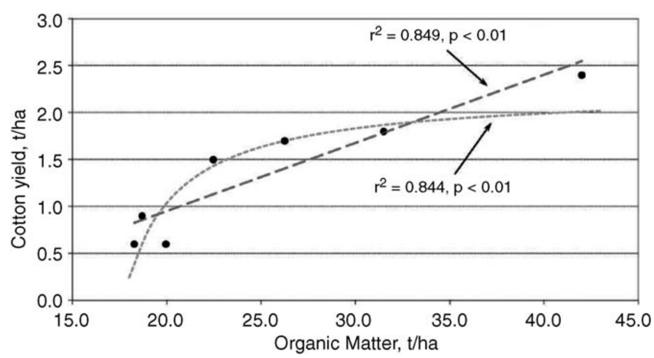

Fig. 2. The linear and hyperbolic relationships between cotton yield and SOM.

result of the manure that also substantially darkened the color of the A horizon.

All plots had slightly low to low pH. However, while the pH values in fallow fields were predominately low (4.5–5.3), they were higher (5.0–6.0) in the cultivated plots, with most plots having pH > 5.5, i.e., above the threshold which necessitates additional liming (Hinkle and Brown, 1968). No relationship was found between soil pH and cotton yield.

While no relationship was found between N–NO_3 and cotton yield ($r^2 = 0.086$, $P > 0.5$), a significant relationship was found between N–NH_4 ($r^2 = 0.589$, $P < 0.05$) and between mineral N ($r^2 = 0.592$, $P < 0.05$) and cotton yield (Fig. 1). No significant relationships were found between P-Olsen ($r^2 = 0.101$, $P > 0.4$) and available K ($r^2 = 0.167$, $P > 0.2$) and cotton yield (not shown). A highly significant relationship was found between SOM and cotton yield, whether linear ($r^2 = 0.849$, $P < 0.01$), or non-linear ($r^2 = 0.844$, $P < 0.01$) (Fig. 2).

Although yielding a significant relationship with cotton yield, the high amounts of mineral N were nevertheless insufficient to serve as an indicator of soil fertility. Both long-standing fallow fields and low-productive fields showed high amounts of mineral N. Thus, plots P4 and P9, which were cultivated for more than 10 years and degraded to the lowest recorded cotton productivity of 0.6 t/ha, had 88.6 ± 4.1 kg/ha of mineral N, similar to that of plots P3, P5, P8 and P12, which were virgin or fallow for 15–20 years, and had an average mineral N of 86.6 ± 16.9 kg/ha. We thus conclude that, under the current cultivation practice, N is not limiting. This conclusion is confirmed by the relationships between SOM and mineral N when constructed separately for the cultivated and the fallow/virgin fields (Fig. 3). Alternatively, given the amount of SOM and basing our model on the linear dependencies presented in Fig. 3, the difference between mineral N at the cultivated and fallow/virgin fields varies between 40 kg/ha for the fields with the lowest level of SOM (22 t/ha) and 35 kg/ha for the highest level of SOM (43 t/ha). Ignoring the dependencies, the average difference between the amount of nitrogen in the soils of the cultivated and fallow/virgin field is 44 kg/ha. These differences are in a good agreement with the 50 kg/ha of mineral N added as chemical fertilizers to the cultivated field.

Contrary to mineral N, the amount of SOM strongly correlates with cotton yield (Fig. 2). Moreover, the amount of SOM decreases following cultivation, and increases during a fallow period (Fig. 4). Consequently, we chose SOM as a fertility determinant of soil degradation. As the minimal amount of SOM was 18 t/ha (plot P4, Table 1), it was regarded as the minimal SOM level below which the cultivation of the field is economically unjustified and therefore ceased.

3.2. Estimating SOM decay and restoration rates

As a first approximation, let us consider the linear relationships between the soil characteristics and the cotton yield, and the linear representation of the SOM decay during the period of cultivation and SOM restoration during fallow.

Based on Fig. 2, the linear dependence of cotton yield on SOM is given by:

$$\mathrm{Yield\,(t/ha)} = 0.0726 \times \mathrm{SOM(t/ha)} - 0.501 \tag{1}$$

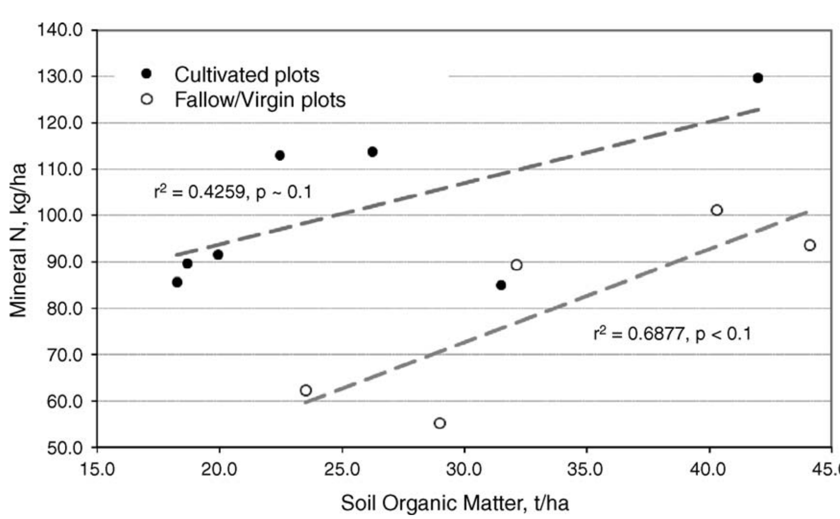

Fig. 3. The relationships between SOM and mineral N for cultivated and fallow/virgin fields.

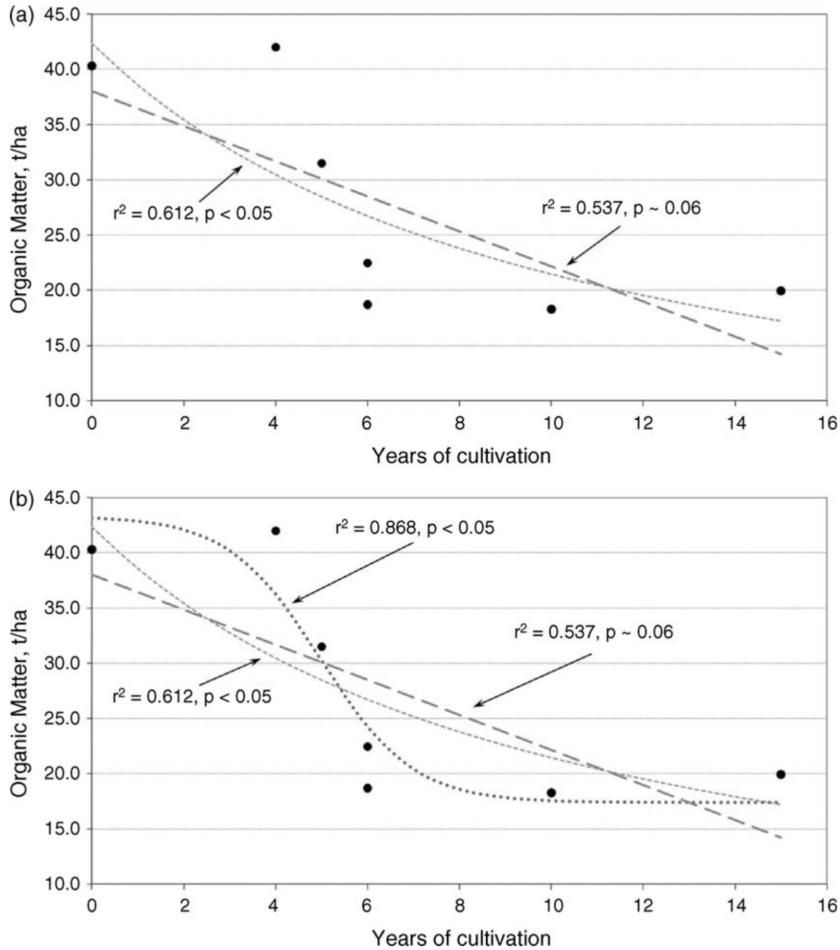

Fig. 4. Available data on (a) SOM decay and (b) SOM restoration and the linear, hyperbolic and logistic approximations of decay and restoration dynamics.

The dependence of the amount of SOM on the length of the cultivation period will be thus sufficient to predict the plot yield dynamics. Assuming a constant rate of SOM decay (i.e., linear approximation of the process) during the cultivation period, this dependence can be expressed as follows (Fig. 4a):

$$\mathrm{SOM}\,(\mathrm{t}) = 38.020 - 1.586 \times t \quad r^2 = 0.54,\ p < 0.1 \tag{2}$$

where t is the cultivation period in years.

As the temporal resolution of the data is a 3-year cultivation loop, average rate of SOM decay during one loop is thus $1.586 \times 3 = 4.758 \approx 4.76$ t/ha.

In the same way the linear approximation of SOM restoration during the fallow period is (Fig. 4b):

$$\mathrm{SOM}\,(\mathrm{t}) = 21.018 + 0.962 \times t \quad r^2 = 0.72,\ p < 0.1 \tag{3}$$

The average rate of SOM restoration during a 3-year period (one cultivation loop) equals thus to $0.962 \times 3 = 2.886 \approx 2.89$ t/ha.

Employing the recurrent forms of the dependencies (2) and (3) in terms of 3-year cultivation periods (T) they can be expressed as:

$$\mathrm{SOM}(T+1) = \mathrm{SOM}(T) - 4.76 \tag{4}$$

$$\mathrm{SOM}(T+1) = \mathrm{SOM}(T) + 2.89 \tag{5}$$

during the cultivation and fallow periods, respectively.

For the investigation of the model robustness and in an attempt to better reflect basic theoretical views (La Scala et al., 2008), we have also employed, when possible, the non-linear hyperbolic approximation of the dependencies, which we were able to fit to our limited data:

$$a + \frac{b}{(x+c)} \tag{6}$$

We employed SPSS16 *Nonelinear Regression* procedure (Garson, 2009) for estimating the coefficients of non-linear dependencies.

The application of Eq. (6), results in the following dependency of the cotton yield (in t/ha) on SOM (in t/ha):

$$2.33 - \frac{5.95}{(\mathrm{SOM} - 15)} \tag{7}$$

For the dependency of the annual SOM degradation (in t/ha) on the length of the cultivation period (in years) we obtain the following approximation:

$$\mathrm{SOM} = \frac{433.91}{10.24 + t}, \quad r^2 = 0.612,\ p < 0.05 \tag{8}$$

And the dependency of the annual SOM restoration (in t/ha) on the length of the fallow period (in years) is as follows:

$$49.36 - \frac{300.32}{(9.60 + t)} \tag{9}$$

In addition to the hyperbolic functions, employed for approximation of all three dependencies above, the sharp drop of SOM after 5–6 years of cultivation can be even better represented by a logistic function (Fig. 4a):

$$17.40 + \frac{25.96}{(1 + \exp(t - 4.98))} \tag{10}$$

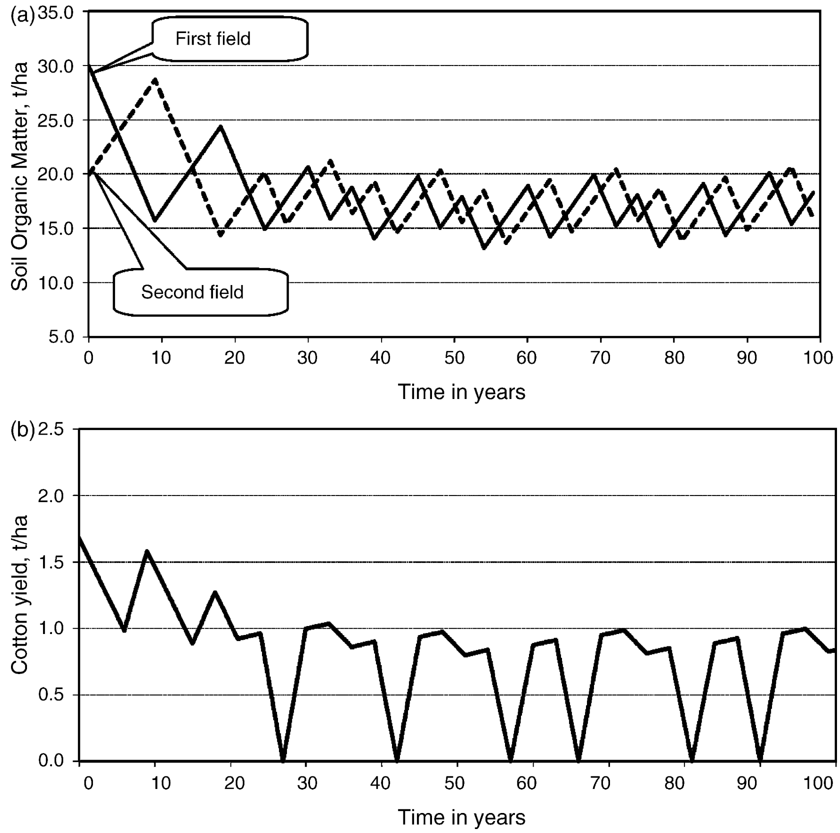

Fig. 5. Model dynamics of (a) SOM in two model fields and (b) overall family cotton yield.

3.3. Estimating long-term rate of family land degradation

Let us now consider the long-term dynamics of the family's land productivity. As it is stated above, we assume that the family possesses two "fields", one cultivated and one fallow and regard the yield of Y_{Th} = 0.8 t/ha as minimal for economically justified cultivation. Dependencies (4) and (5) enable us to easily reproduce the time during which the family must alternate between cultivating of the first and the second field and to estimate the corresponding dynamics of SOM in these fields.

Let us assume a situation during which the yield of the cultivated field drops below 0.8 t/ha (following SOM_1 depletion to below 18 t/ha) and the family has to turn to the second field. Let us assume that the level of SOM in the second field is high, SOM_2 = 30 t/ha, i.e., close to the maximal observed level of SOM after a long fallow period.

As is apparent, the farmer's alternation between the fields results in two-phase dynamics (Fig. 5a and b). During the first phase (12–15 years) the family yield reaches the level of 1–1.2 t/ha and remains at this level for the next 10 years. After the first 25 years of alternating cultivation, neither of the two fields can guarantee a cotton yield of above 0.8 t/ha and *both* fields have to be left fallow for at least one loop, i.e., for 3 years (Fig. 5b). A 3-year cessation in cultivation is sufficient to restore productivity of the first field (Fig. 5a). From then onward, repeating periods of ~9–15 years of cultivation followed by a 3-year period of cessation in cultivation over the entire area are observed (stable dynamics, second phase).

The better the initial conditions of the "post-fallow" field, the longer the period of convergence to stable dynamics and vice versa. Thus, once SOM_1 = 25 t/ha and SOM_2 = 40 t/ha the length of the first fertile period is 18 loops (54 years), while once SOM_1 = 18 t/ha and SOM_2 = 25 t/ha, it will last only 5 loops (15 years). At the same time, the length of the period of cultivation during the phase of stable soil dynamics always remains the same, 9–15 years, followed by 3 years of fallow.

The model sensitivity of the two main parameters—(1) the rate of SOM exploitation during the period of cultivation and (2) the rate of SOM restoration during the fallow period, is "one-directional". Slower decay and/or faster restoration rates result in a longer period of convergence, while having a limited effect on the reduction of this period. Indeed, as can be seen in Fig. 6, the lower rate of SOM exploitation or higher restoration rate (right side of Fig. 6) substantially extends the length of the first phase and that of the first cultivation period of the second phase. However, the impact of the increase in the SOM exploitation rate or the decrease in the SOM restoration rate (left side of Fig. 6) is essentially limited.

4. Discussion

4.1. Mineral N and SOM as determinants of cotton yield

Contrary to previous reports (Bationo and Mokwune, 1991; Chien et al., 1993), and albeit the potential role reported for P in cotton yield (Jones and Bardsley, 1968), no significant relationship was found between P-Olsen and cotton yield. Similarly, no significant relationship was obtained between available K and cotton yield, which may be explained by the high K content in the soil. The high K content may result from bush burning that takes place when fallow fields are cleared for cultivation (Lombin and Fayemi, 1976). This is in agreement with Bationo and Mokwune (1991) and Vanlauwe and Giller (2006) that concluded that a clear link between available K and crop yield in West Africa is often unlikely. This is also in agreement with Zougmoré et al. (2002) that did not observe a decrease in P and K following ~20 years of cultivation.

The positive linear relationship between mineral N and cotton yield stemmed from a high correlation between N–NH_4 and cotton

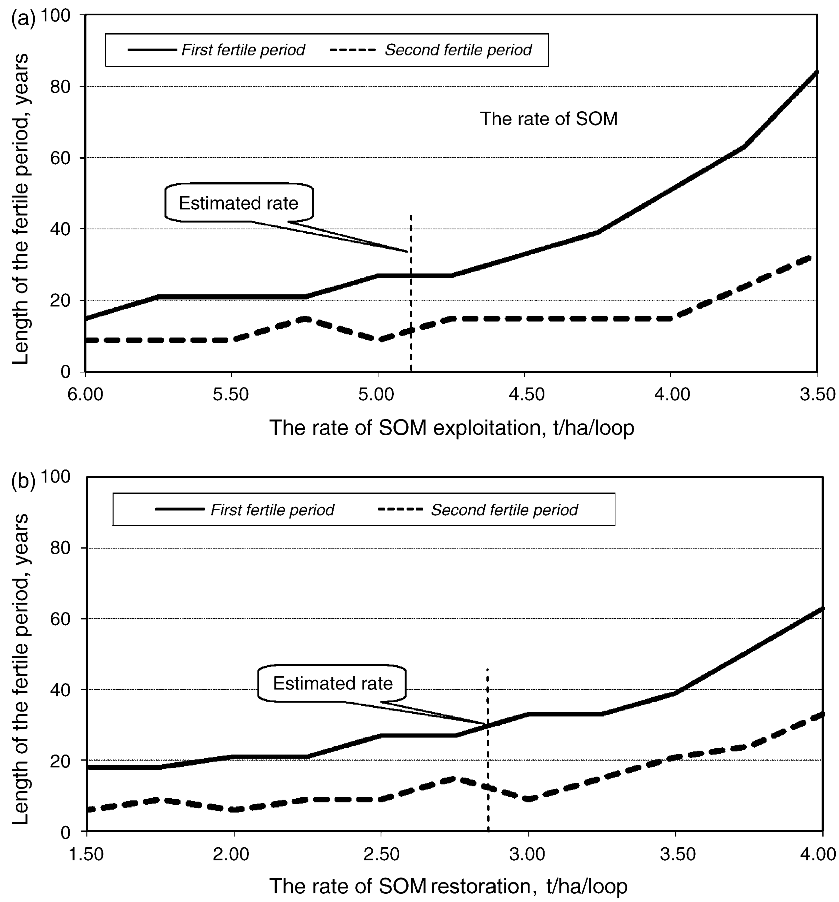

Fig. 6. Dependence of the length of the first and second fertile periods on (a) the rate of SOM exploitation during the cultivation period (given the rate of SOM restoration during the period of fallow is 2.89 t/ha per loop) and (b) the rate of SOM restoration during the period of fallow (given the rate of SOM exploitation during the period of cultivation is 4.76 t/ha per loop).

yield. Apparently, despite the preference of cotton to utilize N–NO_3 (Tucker and Tucker, 1968), anion leaching may have masked a clear relationship between N–NO_3 and cotton yield. Yet, N amendment apparently sufficed to meet the cotton demand for nitrogen. Indeed, as can be seen in Fig. 3, the difference between the amount of mineral N in cultivated and fallow fields is in very good agreement with manure amendment and the 50 kg of mineral N provided by CMDT through chemical fertilization.

The good relationship between SOM and cotton yield is not surprising when considering the role of SOM as a source and a sink for the major nutrients, secondary nutrients (such as Ca and Mg) and micronutrients (Hinkle and Brown, 1968; Bationo et al., 1993; Kouyate et al., 2000; Breman et al., 2001; Voortman and Brouwer, 2003; Voortman et al., 2004; Vanlauwe and Giller, 2006). Similar observations were made by Benjaminsen (2001), who compared nitrogen content and organic matter in fallow and virgin soils to those of cultivated fields: while mineral N was not depleted, SOM was 40% lower in the cultivated fields in comparison to the fallow fields (see also Mando et al., 2005). As was also the case in other studies (Bationo et al., 1998; Zougmoré et al., 2002; Oenema et al., 2006; Yang, 2006) the use of SOM as an adequate key proxy for the soil fertility level and as a predictor for cotton yield was called for. A SOM-based linear model was thus adopted.

4.2. Adequacy of the simplified model of soils degradation

In line with other research (Mohamed et al., 2000; Hengsdijk and van Keulen, 2002; van Ittersum et al., 2003; van Hofwegen et al., 2007), our basic model adopts the simplest, i.e., linear dependencies. We employ the non-linear dependencies (given by Eqs. (7)–(10)) to estimate the robustness of the model. As may be expected, non-linear dependencies do not influence the results qualitatively. Indeed, cotton cultivation becomes unjustified and the family is forced to leave the field fallow once the SOM drops below ~18 t/ha, and this condition remains valid for both linear and non-linear versions of the model.

Yet, the length of the cultivation period for cotton growth depends on whether linear or non-linear dependencies are employed. In comparison to the basic linear case, which results in 9–15 years of continuous cultivation in the second phase (Fig. 5b), the period of cultivation following the adoption of the non-linear dependencies is usually shorter, being up to only 6–12 years. Our data are insufficient to justify the non-linear representation of soil dynamics (La Scala et al., 2008) and thus, a linear model was adopted for the current research.

Even for the linear model, soil fertility will drop below the productivity threshold within a relatively short time. According to our model, cotton cultivation will no longer be economical in 20–25 years under average current-day conditions and in 35–40 years under optimal conditions. These results are in good agreement with other reports (Kaya et al., 2000; Dalton and Masters, 1998), and specifically with Ouédraogo et al. (2006, 2007) who showed a sharp loss of SOM during the cultivation period. It is also in good agreement with van der Pol and Traore (1993), who concluded that soil degradation in West Africa will take place within 30–40 years. It is also worth noting that van der Pol and Traore's (1993) estimated the annual rate of SOM depletion to amount to 0.6 t/ha, which is very close to that obtained in our research (1.586 t/ha per 3 years).

The model also highlights that the ratio of 1:1 between cultivated and fallow lands is insufficient for continuous agriculture over the area (Fig. 5b). Comparing the rates of SOM decay (4.8 t/ha) and restoration (2.9 t/ha) per 3 years (the duration of the cultivation cycle), one can roughly estimate that for persistent agriculture the area of the family-owned fallow lands should be $4.8/2.9 \approx 1.65$ times larger than that of the cultivated land.

One however should note that the estimated amount of SOM depletion of 1.59 t/ha is an annual average for a cultivation practice that alternates between cotton (once in 3 years) and cereal/groundnut cultivation (2 more years). Since cotton causes more rapid SOM decay than cereal and, especially, groundnut (Bationo and Mokwune, 1991; Bado et al., 2006), more frequent cotton cultivation would result in an accelerated rate of soil degradation. In this regard, our findings show that providing chemical fertilizers once in 3 years, according to the CMDT-induced scheme has an advantage over the ''supply by demand'' policy. The 3-year cotton–cereal–groundnut cultivation cycle, enforced by the CMDT policy, impedes the natural tendency of the family to gain immediate economic rewards by frequent cotton cultivation and also reduces the risk of soil acidification (Juo et al., 1995; Bationo et al., 1998; Kouyate et al., 2000). Furthermore, by the concomitant supply of chemical fertilizers with manure, nutrient leaching is impeded and a prolonged period of nutrient availability is thus guaranteed (De Ridder and van Keulen, 1990; Juo et al., 1995; Bationo et al., 1998; Breman et al., 2001; Vanlauwe and Giller, 2008).

Yet, despite the deceleration of soil degradation, the CMDT-enforced 3-year cycle of fertilization cannot prevent the crisis. As we demonstrated, SOM drops periodically below 18 t/ha, forcing the farmer to leave the field fallow. Cultivation can be renewed only following SOM restoration. Although limited data facilitate only linear approximation, our findings highlight the need for a change in the fertilization scheme and moreover, in the agricultural policy in Mali and probably also in other countries in the Sahel.

5. Conclusions

We investigated twelve fields near Kita, Mali, and demonstrated that of four variables sampled—soil organic matter (SOM), mineral N, available K and P-Olsen, only nitrogen and SOM exhibited a significant linear relationship with cotton yield, with SOM being the only variable showing a clear threshold (of 18 t/ha) between fertile and infertile fields. Based on the SOM depletion, a simple model was constructed to link between agricultural practice and soil degradation. The model demonstrates that the current practice of growth and fertilization will result in a slow but inevitable decrease in SOM, with SOM reaching the critical threshold of 18 t/ha in 25–35 years, depending on its initial value. These results are robust in regards to the analytical expressions chosen for the dependency of the yield on SOM and on the curves of the SOM decay (during cultivation) and restoration (during fallow). Although limited data facilitate only linear approximation, our findings indicate that the current practice of cultivation is inefficient and a new cultivation practice, which accounts for the cardinal role of SOM, should be adopted.

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