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Responses of soil crusting, runoff and erosion to fallowing in the sub-humid and semi-arid regions of West Africa

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Abstract

Systems including a long fallow period have proven to be sustainable in the tropics for they enable the transfer of the rich store of nutrients from the vegetation to the ensuing crops. These systems have been mainly studied in the forest zone with a peculiar focus on the maintenance of organic and chemical fertility. By contrast, the effects of the fallow on soil physical properties have not been widely documented especially in the drier areas. The objectives of this paper are: (i) to summarise the fragmented and not readily accessible information on the responses of soil crusting, runoff, water and wind erosion to fallowing in the sub-humid and semi-arid regions of West Africa; (ii) to infer possible scenarios of land use change from the recent past. Two main examples have been taken in northern Ivory Coast and southern Niger. In the Ivorian example, physical properties are restored after a fallow duration of 10 years on sandy clay loam whilst crusts persist over a longer period on sandy soils, partly due to the foraging activities of termites. In the sandy Sahelian soils, cultivation destroys the erosion crusts that develop as the fallow proceeds as a result of dust deposition and colonisation by blue green algae. This crust development is inherent to the Sahelian ecosystem and favours the natural concentration of water resources. The net balance of dust is negative in millet fields ($-0.25\,t\,ha^{-1}$ per year) and positive in young fallows ($+0.68\,t\,ha^{-1}$ per year) so that a slight increase in the field/fallow ratio can transform the region from an accumulation zone to a source zone with consequences on regional fertility transfer. Finally, in both regions the sandy soils have specific dynamics that should be accounted in land management planning. Despite a higher water erosion risk, the sub-humid zone offers a better potential for intensification than the semi-arid zone.

Keywords: Fallow; West Africa; Soil crusting; Runoff; Water erosion; Wind erosion

1. Introduction

In the tropics, farmers have developed agricultural systems that tend to minimise the problem posed by soil fertility depletion and vegetation degradation. Such systems are generally referred to as 'slash and burn', or 'shifting' or 'swidden' cultivation. They have proven to be sustainable and efficient land management systems (e.g., Goudie, 1993) inasmuch as low inherent fertility soils require a long period of fallow to offset the negative impacts of a short period of cultivation. The primary concern of 'slash and burn' activities is not merely the clearing of the land, but rather the transfer of the rich store of nutrients locked up in the vegetation to the ensuing crops. The yields are low per unit of area (ha), but very high per unit of labour ($1\,t\,ha^{-1}$ of paddy for 2 months of work;

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Sevin, 1983). Soil erosion remains very low in this system (<1 t ha^{-1} per year; e.g. Collinet and Valentin, 1985) because many factors contribute to soil conservation. The fire is rarely complete and trunks and branches are voluntarily left on the ground (e.g., Sabhasri, 1978). Moreover, the crop, fertilised by ashes, covers the soil rapidly (de Rouw and van Oers, 1988). To prepare the ground, the farmers use digging sticks. The absence of mechanical tillage allows the maintenance of soil fauna, soil aggregation and surface porosity. Selective manual weeding remove the most noxious weeds and leave those which cover the soil rapidly without competing with the crops (Swamy and Ramakrishnan, 1988; de Rouw, 1995). Whenever shifting cultivation systems are blamed to promote soil erosion (e.g., Gutelman, 1989), they are not really distinguished from the systems with short fallow (Phommasack et al., 1998) or from systems practised by migrants (Piéri, 1989). In these cases, soil management problems do arise. They include weed infestation, land degradation and reduced productivity. The key to efficient and sustainable food production is therefore the duration of the fallow period. This tends to be reduced however as a response to population pressure. The shifting cultivation systems (up to a 25 year rotation) have progressively moved to bush fallow (up to a 6–10 year rotation), to short fallow (with only a 1–2 year rotation), to annual cropping (Boserup, 1965). Considering the ratio R between the cultivation period and the total cycle (cultivation + fallow), Ruthenberg (1980) distinguished the shifting cultivation system ($R < 0.33$), the short fallow system ($33\% < R < 66\%$) and the occasional fallow system ($R > 66$). Nearly one-third of the African farmers still practised shifting cultivation by the end of the 1980s (Schusky, 1989), even though movement of family and/or village communities has become unusual. Bush fallow must be distinguished from grass fallow. The former is characteristic of humid regions; the latter predominates in the drier and more seasonal savannah regions. In West Africa, assuming an efficient weed control, the nutrients released from ashes (Moreau, 1993) might sustain a low agricultural production during 10–5 years in the west forest zone, and no more than 5–6 years in the savannah zone (Piéri, 1989).

In the forest zone, the cultivation causes generally a marked deterioration of the topsoil with a rapid fall in organic matter content, decrease in silt and clay content and a reduction in water holding capacity. For example, Aina (1979) reported that the aggregate stability of two loamy sands from Ife, Nigeria, ranged from one-fifth to one-third those of soils under 15 to 25-year old fallow which contained about four times more organic matter content than the cultivated soils (0.8%). This loss of organic matter not only leads to less stable clods, but also to a significant increase in dispersible clay. By the end of the first cropping year, soil crusts began to decrease the infiltration capacity (Wilkinson and Aina, 1976). In southern Togo, no runoff was observed under natural forest conditions, even though the understorey and the litter have been removed (Poss et al., 1990). Due to the higher organic matter content of the 0–4 cm toplayer (4.2%), aggregates were much more resistant than in a 2-year old fallow (0.9% OM) and in a cropped field (0.7% OM) where heavy runoff was generated only few minutes after the beginning of rainfall and accounted for up to 80% of the total precipitation.

Besides the development of surface crusts, the dramatic decrease in infiltration capacity is favoured by the absence of earthworms in ploughed fields (Kooistra et al., 1990). In the case of continuous cropping, the erosion by water is generally high, especially when the soil is tilled mechanically and left bare (up to 126 t ha^{-1} per year; Roose, 1977). Since most studies have been carried out in the rain forest zone on the maintenance of organic and chemical fertility (Floret and Pontanier, 1993), the effects of shifting cultivation on soil physical properties have not been widely documented (Lal, 1987).

The objectives of this paper are: (i) to summarise the fragmented and not readily accessible information on the responses of soil crusting, runoff, water and wind erosion to fallowing in the sub-humid and semi-arid regions of West Africa; (ii) to infer possible scenarios of land use change from the recent past. The hypothesis that frames this paper is that the responses to fallowing differ among cropping systems depending on the population pressure, climatic zone, and soil texture. In this regard, a peculiar attention have been paid on two contrasting examples: (1) a rather stable system in wet savannah zone in Ivory Coast where population density is still low; (2) a transitional system in Sahelian Niger where population density is increasing much faster and fallow period shortened.

Table 1
Main characteristics of the soil types in the Booro-Borotou Watershed (after Planchon et al., 1987)

Landform	Soil	Munsell colour	Textural class	Topsoil clay content (%)	Slope (%)
Plateaux	Ferralitic with iron pan	2.5 YR 4/4	Sandy clay loam	25	2
Talus	Red ferralitic	5 YR 3/2	Sandy clay loam	33	12
Upper hillslope	Red ferralitic	5 YR 3/2	Sandy clay loam	30	6
Lower hillslope	Yellow ferruginous	10 YR 6/4	Sand	6	7
Thalweg	Hydromorphic	10 YR 7/1	Silty clay loam	26	9

2. Materials and methods

2.1. Study sites

2.1.1. Wet savannah: the site of Booro-Borotou

The Booro-Borotou 136 ha-watershed is located 25 km north of Touba in northwestern Ivory Coast. Mean annual rainfall recorded over a period of 33 years is 1359 mm (standard deviation: 220 mm). The rainy season lasts from April to November. The bedrock consists of undulated injection gneiss. Four main components were differentiated along the hillslope (Table 1): (i) in upper hillslopes, a cuirassed hydromorphic plateau with a low grass savannah, (ii) deep ferrallitic red soils, sandy clay loam, with low woody savannah, (iii) ferruginous sandy yellow soils, with low bush savannah, (iv) hydromorphic soils, silty clay loam, with riparian forest. The low population density (10 inhabitants/km^2), common in the wet savannah zone results from historical reasons (past tribal wars and endemic sanitary problems as sleeping disease, onchocercosis, etc.). More recently, the younger seek work in coastal cities and plantation agriculture. Consequently only a small proportion of the land (8%) is allocated to cultivation in a slash and burn system. Every operation from land clearing to harvesting is performed manually. The fields concentrate on the ferrallitic and ferruginous soils. The crop succession usually includes yam (*Dioscorea typhoides*) as the first crop, followed by rainfed rice (*Oryza sativa*) and groundnut (*Arachis hypogae*), the last crop being cassava (*Manilhot utilissima*). Fields are abandoned after 7 years of cultivation when weeds (mainly *Imperata cylindrica* and *Pennisetum* spp.) can no longer be controlled. The fallow is cultivated again after a period up to 50 years. Among the 37 fallow plots which have been clearly identified and accurately dated (for example from familial events), 16 exceed 35 years (Mitja, 1992). According to the Ruthenberg (1980) classification, this system falls into the category of 'shifting cultivation' ($R = 0.12$). Due to the absence of cattle in the region because of the tse–tse fly, the fallows are not grazed. These general conditions can thus be considered as optimal for the regeneration of soil physical properties under fallow.

2.1.2. Sahel: the site of Banizoumbou

The Sahel comprises two main soil and landform domains: (i) the cuirassed plateaux with shallow soils that can cover very large areas as the Mossi plateau in Burkina Faso, (ii) the late Quaternary aeolian sand deposits that form fixed dunes and hillslopes. This review will mainly focus on the recent results obtained in this sandy environment in Niger (region of Banizoumbou). Examples from the cuirassed plateaux will be taken from Burkina Faso.

The village of Banizoumbou is located 60 km east of Niamey, in southwest Niger. The climate is typically Sahelian with a prolonged dry season from October to May. During this period, north-eastern winds prevail. The short rainy season from June to September (550 mm annual average rainfall, Lebel et al., 1992) corresponds to the cropping period. The crystalline basement complex, part of the Precambrian pan-African shield, as in Booro-Borotou underlies the region. The overlying rocks consist of loamy sandstone of Miocene deposits that have been covered with aeolian sand deposits of late Quaternary age. The catena is typical of the Sahelian landscape (d'Herbès and Valentin, 1997). The impervious soils in the plateaux are shallow gravely loam over cemented ironstone gravel. These plateaux are covered with banded vegetation (Valentin and d'Herbès, 1999). Pearl millet (*Pennisetum glaucum*) is manually cultivated on the deep sandy soils of the hillslope (Table 2). Cultural operations include

Table 2
Main characteristics of the topsoil in the Banizoumbou region (after Peugeot et al., 1997; Rockström and Valentin, 1997; Malam Issa, 1999)

Landform	Textural class	Clay (<2 μm;%)	Silt (2–50 μm, %)	Sand (50 μm–2 mm)	Organic carbon (%)	Slope (%)
Plateaux	Loamy gravel	11.5	20.6	64.6	1.2	>1
Upper hillslope	Sand	3.1	5.7	91.2	0.2	3
Lower hillslope	Sand	3.8	5.8	90.4	0.3	2

sparse sowing in pockets (1 m apart), thinning and two series of weeding operations during the growing season (de Rouw and Rajot, 2004). Neither fertiliser nor pesticide is used.

In the Sahelian zone, the increases in the area of cultivated land and human population over this period are approximately equal. The migration from rural areas to cities or coastal countries has been insufficient to maintain population density in rural areas at a steady state (Le Houérou, 1989). Casenave and Valentin (1989) reported that the area of cultivated land in two watersheds in Burkina Faso increased by factors of 2.2 and 2.3 between 1956 and 1980. Similar rate of population growth and increase in cultivated land have been observed in the Maradi region in southern Niger (Koechlin, 1989), and in central Mali (Haywood, 1981). Assuming the current state of population growth of 3% (i.e. doubling in 23 years), the increase in cultivated land area (extensification) almost exactly matches the increases in population.

A detailed survey in the Banizoumbou region showed that within 1950 and 1995, the land allocated to cultivation (culture + fallow) has increased from 12% of the total area to 71%, i.e. to nearly 100% of the arable area (Loireau, 1998). The population growth has been the main driver of this expanded cropping. Within the same period, the population increased four-fold in Niger, and the cultivated land five-fold.

Three main periods could be distinguished in the Banizoumbou region. Before the 1950s, most of the fields were concentrated around the villages, the use of the manure enabling a rather intense system with short fallow periods. In addition to population pressure, other factors contribute to the need to bring more land into cultivation. Rainfall is very erratic in the region not only in time, with severe and repeated droughts, but also in space so that large differences in rainfall can be registered on the same day in fields a few kilometres apart (de Rouw, 1998). To manage this climatic risk, farmers cultivate fields that are scattered over an area so that some fields may be 5–8 km from each other. Moreover, because of slight variations in soil texture along slopes with the accompanying variations in crusting and water infiltration, farmers tend to cultivate large fields of several hectares along the slope. All this factors encourage extensification rather than intensification. As a result, a higher proportion of land was being left to fallow, the fallow period increasing from a mean of 2.9 years in 1950 to 8.3 years in 1965. The increasing scarcity of land available for cultivation has led farmers latter to abandon long-term fallow so that fallow period was gradually decreased to a mean of 2.6 years. This intensification stage has thus followed an extensification period (Fig. 1). According to the classification of Ruthenberg (1980), this system falls into the short fallow system category, at the limit with the occasional fallow system.

2.2. Methods

2.2.1. Aggregate instability

We used the aggregate stability test proposed by Hénin et al. (1958). The procedure consists of submitting air dried samples to three different treatments: ethanol (to test wet cohesion), benzene (to test wettability), and distilled water. After standard shaking and sieving the amount of ‘stable’ aggregates remaining on the 200 μm sieve is determined for the different treatments and also the amount of clay and silt fraction (<20 μm) that remain in suspension (to test clay + silt dispersability). The instability index (I_s) is then calculated as follows:

$$I_s = \frac{\% < 20\,\mu\text{m}}{((\text{Ag}_a + \text{Ag}_b + \text{Ag}_c)/3) - 0.9(\% > 200\,\mu\text{m})}$$

where Ag_a is the percentage stable aggregates after the ethanol pre-treatment; Ag_b the percentage stable aggregates after the benzene pre-treatment; Ag_c the percentage stable aggregates after the water pre-treatment.

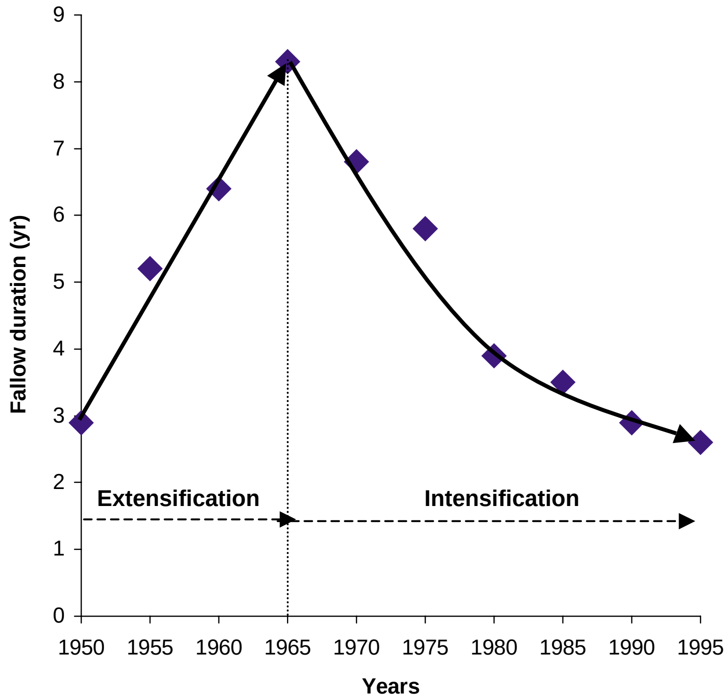

Fig. 1. Evolution of the mean duration of the fallow period between 1950 and 1995. Banizoumbou (Niger), after the data of Loireau (1998).

2.2.2. Faunal activity and soil crusting

In the savannah site, the surface features of the 37 fallows were carefully surveyed on 250 m^2 plots, using the typology proposed by Casenave and Valentin (1992). Six types of surface were identified:

- Surface of termite and earth worm type: TW. It is a surface with a minimum of 20% earth worm casts and a minimum of 30% termite harvesting constructions.
- Surface of worm type: W. It is a surface with a minimum of 20% earth worm casts and less than 30% of termite harvesting constructions.
- Surface with one-layered structural crust: ST1. It is a surface with a maximum of 20% earth worm casts and covered with a one-layered structural crust. Remnants of slaked aggregates make the surface rough. In Booro-Borotou, this crust mainly results from the coalescing of wet earthworm casts.
- Surface of structural two type: ST2. It is a surface with a maximum of 20% earth worm casts, covered with a structural crust made of two microlayers (a coarse, slightly cemented, sand microlayer overlaying a plasmic seal, consisting of finer particles; Valentin and Bresson, 1992).
- Surface of structural three type: ST3. It is a surface with a maximum of 20% earth worm casts covered with a structural crust made of three microlayers (a free coarse sand microlayer, a cemented fine sand microlayer and a plasmic with a high vesicular porosity; Valentin and Bresson, 1992).
- Surface of erosion type: ERO. It is a surface with a maximum of 20% earth worm casts, sealed with an erosion crust. This erosion crust is made of a thin and smooth plasmic seal resulting either of the removal of the sandy microlayers of the two- or three-microlayered crusts, or from the levelling up of the one-microlayered crust (Valentin and Bresson, 1992).

2.2.3. Infiltration, runoff and soil losses

In the savannah site, two rainfalls were simulated at the end of the rainy season, on six 1 m^2 plots (45 min at 60 mm h^{-1} followed 1 h later by a 30 min storm at

$120\,\mathrm{mm\,h^{-1}}$) using the rainfall simulator designed by Asseline and Valentin (1978) to mimic tropical rainfall kinetic energy (e.g., Valentin and Casenave, 1992; Janeau et al., 2003). The six plots were located on fallows of 2, 3, 5, 10, 30 and 40 years on red ferrallitic soils. The steady infiltration rate was calculated as the difference between simulated rainfall intensity and stabilized measured runoff intensity. Sediments were collected from each plot.

To simulate the capability of the 37 fallows to produce runoff, the proportion of the surface types within each fallow (Mitja, 1992) enabled the computation of runoff coefficients, using the classification system of Casenave and Valentin (1992). The runoff coefficient is the ratio between the cumulated runoff and the cumulated rainfall.

2.2.4. Wind erosion and dust balance

In the Sahelian site, saltation flux has been measured during 3 years in a millet field and adjacent young fallow (5–7 years). The equipment included two series of 12 sand collectors (Fryrear, 1986) located at three heights (0.100, 0.225 and 0.350 m) and two meteorological masts. Vertical erosion flux (<20 μm) was estimated using the model of Marticorena and Bergametti (1995) based on horizontal saltation flux and topsoil clay content. Deposition flux (<20 μm) was measured using two passive collectors located at a height of 3 m.

3. Results

3.1. Aggregate instability in the savannah site

The analysis of soil samples from a nearly 'pristine' savannah (or a savannah older than 50 years), cultivated fields and fallow plots of various ages located midslope, showed that structural instability assessed with the method of Hénin et al. (1958) increases during the cultivation period and decreases rapidly after abandonment (Fig. 2). Under these conditions, the duration of the fallow period must exceed a threshold of 10 years to enable the structural stability to be restored (Valentin and Janeau, 1990). This threshold can be reduced to 4 years in the case of fallow 'improved' with fodder crops as *Pennisetum purpureum* or *Panicum maximum*, as shown in Central Africa Republic (Morel and Quantin, 1972). Higher aggregate stability restoration is obtained with *Graminea* compared to plants with taproots and rhizomes (Damour and Killian, 1967). Under similar climate, savannahs with *Andropogon gayanus* produce annually between

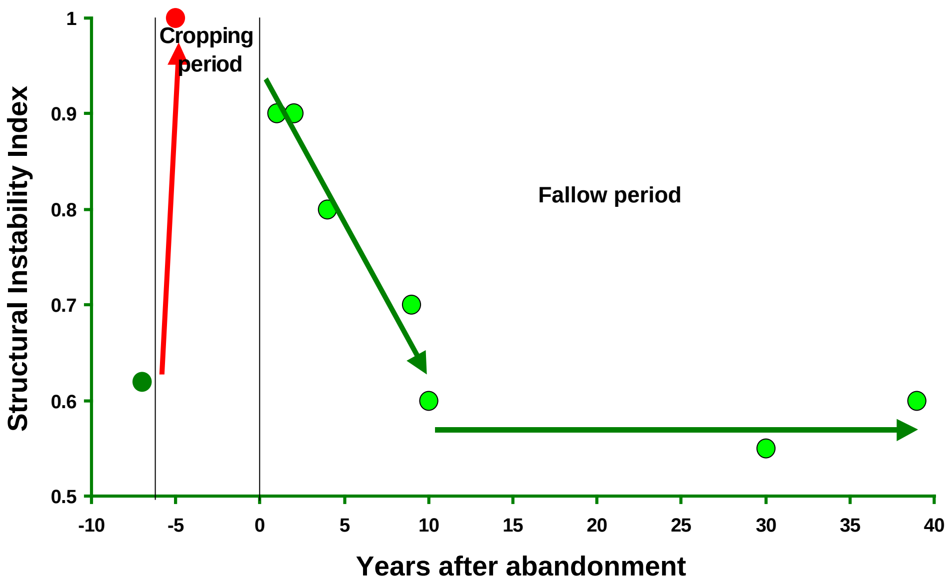

Fig. 2. Variations of the structural stability index (Hénin et al., 1958) during the cropping and the fallow periods. Booro-Borotou (Ivory Coast), after Valentin et al. (1990). For $x > 0, n = 7$; $R^2 = 0.89$, $y = -0.103\log(x) + 0.922$.

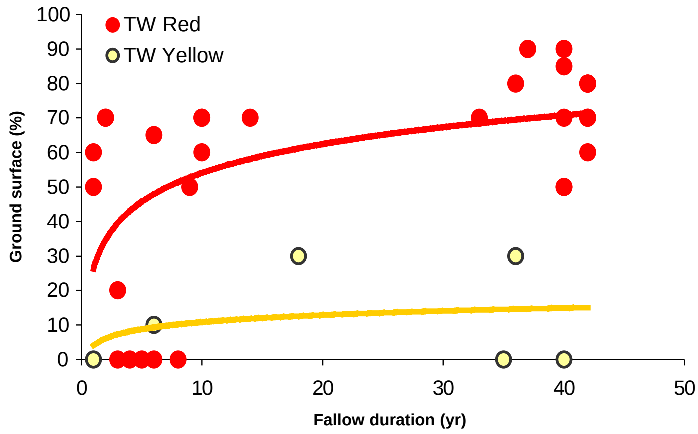

Fig. 3. Evolution of the proportion of the ground surface occupied by termite and worm surface type (TW) on red and yellow soils during the fallow period. Booro-Borotou (Ivory Coast), after the data of Mitja (1992).

3 t ha^{-1} (Nye and Greenland, 1960) and 5.3 t ha^{-1} of root biomass (César and Coulibaly, 1991) whilst crops produce only 0.5–13 t ha^{-1} (Piéri, 1989). Cultivation causes, therefore, a decrease of soil organic matter contents of about 30–40% compared to the initial level (Feller et al., 1991), leading thus to a pronounced increase in aggregate instability.

3.2. *Faunal activity and soil crusting in the savannah site*

As shown in Fig. 3, TW surface can be very rapidly restored in most of the fallows located on the red soils, and occupies 50% of the whole surface after 10 years of fallow. By contrast, TW surface type never covers more than 30% of the whole surface on the yellow soils. At the other end of the spectrum, after 10 years of fallow, ERO has disappeared from the surface of the red soils but cover still 61% in the yellow soils (Fig. 4).

This dynamics of surface features reflects the faunal succession and vegetable reconstitution. Once the cultivated land is left to fallow, the woody cover develops more rapidly on the red than the yellow soils (Mitja, 1992), as shown by the mean height of highest trees (Fig. 5) and the basal tree area (Fig. 6). During

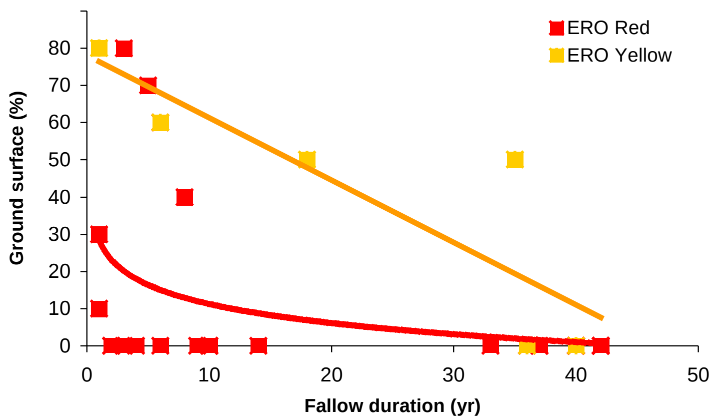

Fig. 4. Evolution of the proportion of the ground surface occupied by erosion crust surface type (ERO) on red and yellow soils during the fallow period. Booro-Borotou (Ivory Coast), after the data of Mitja (1992). Red soils: for $x < 10, n = 12$, mean $y = 24$, for $x = 10$ and $x > 10, n - 19, y = 0$. Yellow soils: $n = 6$, $R^2 = 0.73$, $y = -1.679x + 78.066$.

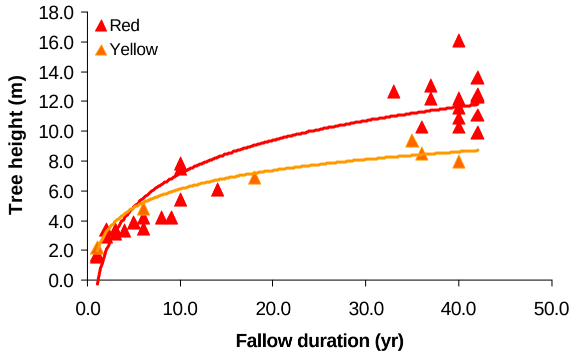

Fig. 5. Evolution of the mean height of the highest trees on red and yellow soils during the fallow period. Booro-Borotou (Ivory Coast), after the data of Mitja (1992). Red soils: $n = 31$, $R^2 = 0.87$, $y = 3.229\log(x) - 0.0300$. Yellow soils: $n = 6$, $R^2 = 0.95$, $y = 1.803\log(x) + 1.902$.

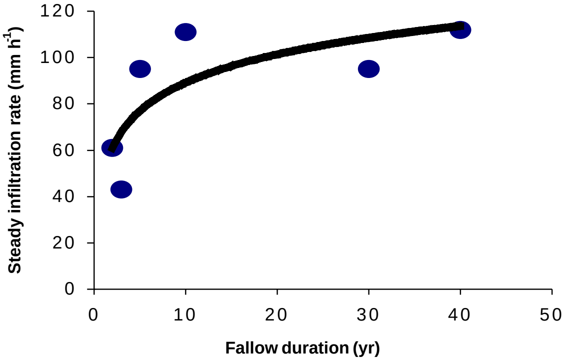

Fig. 7. Evolution of the steady infiltration rate ($\mathrm{mm\,h^{-1}}$) under rainfall simulation on red soils during the fallow period. Booro-Borotou (Ivory Coast), after Valentin and Janeau (1990), $n = 6$, $R^2 = 0.68$, $y = -123.641/x + 110.72$.

the first years of fallow, soil crusting persists because foraging termites as *Trinervitermes* predominate. They harvest grass vegetation around their nests, leaving the soil bare and severely crusted. Among the 38% of the soil surface covered with ERO type surface, nearly one-third could be ascribed to the direct action of termites in a 35 year-old fallow on yellow soils (Janeau and Valentin, 1987). Then fungus-growing termites as *Cubitermes* develop which are considered as having no impact on soil crusting. When the fallow reaches 40 years, humivorous species as *Macrotermes* tend then to prevail. Erosion of their cathedral-shaped nests may cause the sealing of a limited ring around the termite-mounds. But these termites also build tunnels at soil surface as protection against light, thereby perforating the surface, reducing crusting, and favouring infiltration (TW surface type).

3.3. Infiltration, runoff and soil losses in the savannah site

The steady infiltration intensity measured at the end of the second run tended to increase with increasing duration of the fallow period (Fig. 7). In a Nigerian savannah, Wilkinson (1975) reported that infiltration rates increased during the fallow in relation to the square root of time. He also observed that this increase

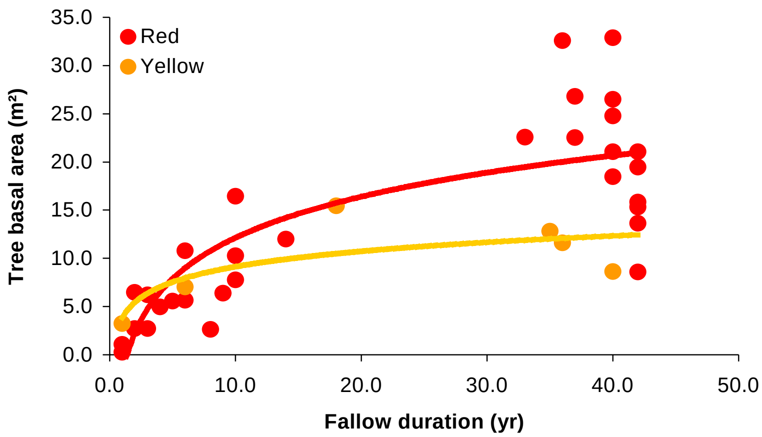

Fig. 6. Evolution of the mean basal area of the trees on red and yellow soils during the fallow period. Booro-Borotou (Ivory Coast), after the data of Mitja (1992).

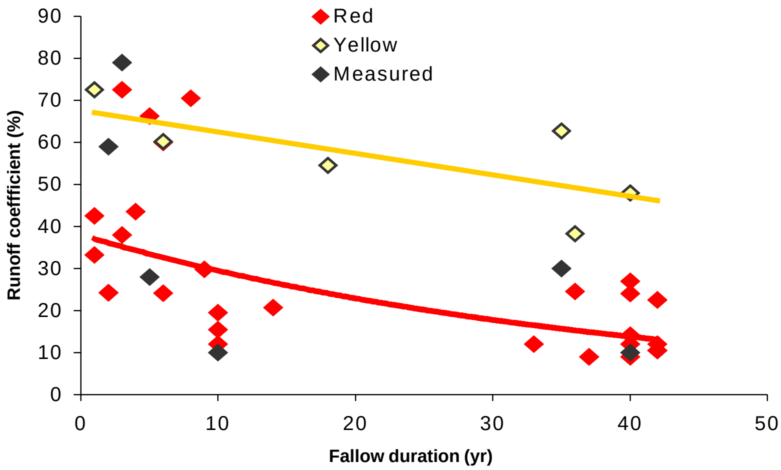

Fig. 8. Evolution of the runoff coefficient rate (%) red and yellow soils estimated from soil surface conditions and measured under rainfall simulation (red soils only). Booro-Borotou (Ivory Coast), after the data of Mitja (1992).

in infiltration rates was primarily due to earthworm activity.

For the red soils, the runoff coefficient rates based on the surface typology supported the tendency shown by the field rainfall simulation tests (Fig. 8). For the yellow soils, the runoff coefficients remained high even after a fallow period of 40 years. Extrapolating the tendency curve showed that a fallow period exceeding 100 years would be necessary to let runoff coefficient decrease to 20%. This level which is obtained on red soils after 40 years of fallow is commonly observed under ‘natural vegetation’ in the wet savannah zone (Collinet, 1988). The restoration of infiltration properties can be hampered by mechanical cultivation. In the vicinity of the watershed, a field located on red ferrallitic soils had been cleared using a bulldozer, which scraped away the most of the fertile toplayer. Ten years after abandonment due to the infestation by *I. cylindrica* grass, erosion crusts where still present so that the predicted runoff coefficient (60%) was much lower than that measured after manual cultivation (30%, see Fig. 8) and very similar to that predicted for the yellow soils.

As a response to increasing soil cover, soil losses from 1 m^2 plots submitted to rainfall simulation in the savannah site decreased with increasing fallow duration, as a function of 1/duration (Valentin and Janeau, 1990). Applying simulated rainfall on larger plots (50 m^2), Collinet (1988) observed that soil erosion under wet savannah vegetation (or long fallows) ranged from 0.4 to 5.5 t ha^{-1} per year as a function of soil cover. After the bush fire, soil losses increased 80-fold, which explains why the late fires which occur just before the onset of the rainy forest are much more damageable to the soils than the early bush fires (Roose, 1977).

3.4. Soil crusting in the Sahelian site

Examination of the soil surface conditions at 34 plots of 64 m^2 showed that fallowing does not necessarily lead to restoration of soil physical properties (Ambouta, 1994). Just after cropping, erosion crusts (ERO type; Casenave and Valentin, 1992) covered 2% of the area. This area was maintained and even slightly extended during the first 3 years of fallowing to 5%, before increasing to about 13% after 7 years. The number of cycles of cultivation also affected the propensity to form erosion crusts during the fallow period. After a single cultivation, whatever the duration of the fallow period, 13% of the surface was covered with erosion crusts compared to only 1% where there had been more than one period of cultivation. These surprising results can be interpreted in the light of the clay + silt content of the topsoil. The proportion of fine particles tends to decrease during cultivation. Conversely, it increases once the land is returned to fallow (Fig. 9). Similar results were obtained in a similar environment

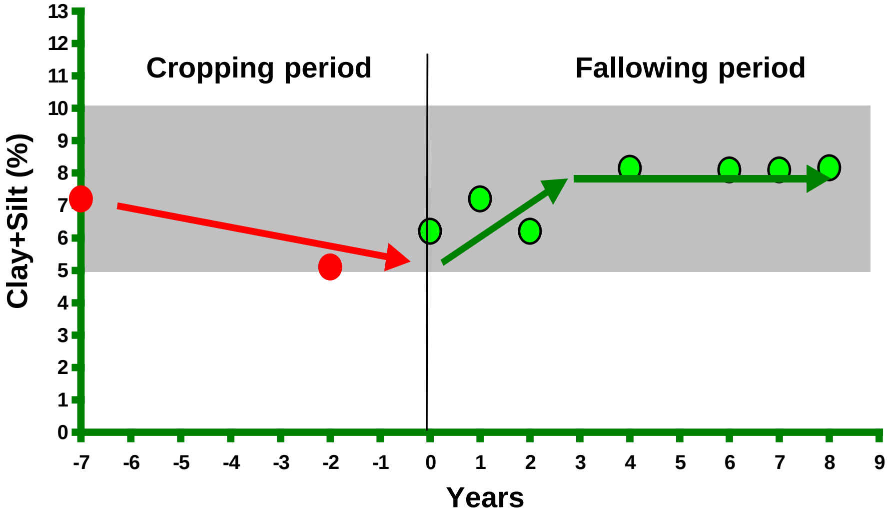

Fig. 9. Variations of the clay + silt content (%) in the topsoil during the cropping and the fallow periods. Banizoumbou, after the data of Ambouta (1994). The grey band indicates the range for crust occurrence between minimal clay+silt content (5%) and optimal content (10%).

in northern Nigeria (Abubakar, 1996). A decrease in the coarsening of soil texture was observed with increasing fallow duration (2, 5, 10 and 15 years). These textural variations caused by land use change can be of paramount importance to crusting processes because no erosion crust could develop when clay + silt contents falls below 5% (Ambouta, 1994). Moreover, the optimal clay + silt content for crust formation is 10% (Poesen, 1986). The clay + silt content ranges thus between the minimal and optimal texture (Fig. 9).

If the selective removal of fine particles during cultivation could have been readily predicted because of water and wind erosion, the enrichment in fine particles during fallowing is more surprising. These fine particles can originate either from the subsoil or from the atmosphere. In the first hypothesis, termites might bring them inasmuch as the activity of *Macrotermes subhyalinus* is very high in the fallow plots of Banizoumbou (Léonard and Rajot, 2001; Léonard et al., 2004). This hypothesis was not firmly supported however by the mechanical analysis of the tunnels that termites build on soil surface. No clear difference was shown between the fine particle content (clay + silt) of these tunnels (mean 12.6, standard deviation 4.7, $n = 15$), the 0–5 cm layer (mean 12.5, standard deviation 3.6, $n = 15$), and the 15–20 cm layer (mean 13.3, standard deviation 5.6, $n = 15$). The hypothesis of atmospheric deposition seems more valid because the mineralogical and chemical composition of the topsoil is very similar to that of the dust (Drees et al., 1993; Herrmann et al., 1996). In these fallow areas, dust deposition has been shown to cause K accumulation. The atmospheric inputs of Ca are also important for the maintenance of pH, base saturation and exchangeable cations (Herrmann, 1996). It has been also shown that dust deposition contributes much more to the nutrient accumulation in the topsoil of the fallow than the transfer of nutrients from subsoil to topsoil by vegetation (Herrmann, 1996). This dust is transported from source areas in the desert, in periodic pulses over the West African savannah and deposited at a decreasing rate and with a decreasing particle-size with transport distance (McTainsh, 1986). Orange and Gac (1990) reported that the total dustfall in the Sahel could reach a deposit rate of 0.2 mm per year. Considering that clay + silt content constitutes between 82% (in northern Nigeria, Møberg et al., 1991) and 97.5% (in Dakar, Senegal, Orange and Gac, 1990) of the dust samples, dustfall can be thus considered as a major source of fine particles in the sandy soils of the Sahel.

This still raises a further question: Why the fine particles are not removed by overland flow or wind once deposited on soil surface of the fallows, as they are in the cultivated fields? As long as clay + silt exceeds 5%, blue green algae can colonise the crusts, consolidate them, retain fine particles, and protect them from further water and wind erosion (Malam Issa, 1999). Dust deposition contributes therefore not only to the development of crusts on these sandy soils but also to their protection through colonisation by microphytes in a positive feedback process. By contrast, the repeated weeding operations and the resulting coarsening of the topsoil (de Rouw and Rajot, 2004) hampers crust development in the fields.

On the shallow and more clayey soils of the Mossi plateau in Burkina Faso, Casenave and Valentin (1989) reported that patches with erosion crusts increased 20-fold within less than 25 years as a consequence of increased cultivated land (from 16 to 36%) and reducing fallow land (from 51 to 34%). In a less densely populated region of Burkina Faso these crusted patches increased six-fold within 28 years (Serpantié et al., 1991). Unlike sandy soils, shallow loamy sands, sandy loams and sandy clay loams of the cuirassed plateau are thus prone to severe crusting (erosion crusts) when cultivated.

Similar differences have been observed in northern Senegal between sandy and cuirassed regions submitted to grazing. Soil crusting due to cattle trampling remains marginal on the sandy soils but can be very severe on the plateau environment (Valentin, 1985). In this region, erosion crusts occur widely on sandy soils protected from trampling and grazing. Recent experiments conducted on sandy soils in Niger showed that grazing resulted in a reduction of crusted soils (Hiernaux et al., 1999).

3.5. Runoff in the Sahelian site

In Banizoumbou, runoff was measured during 2 years from two plots (20 m × 5 m), in a milled field and a fallow of 7 years. The two plots were located in a similar soil and topographic position (upper hillslope). Mean runoff coefficient from the fallow (23%) was much higher than from the millet field (5%). The difference was even more pronounced for the maximum runoff coefficient, 66 and 10%, respectively (Peugeot et al., 1997). Along the hillslope, most of the runoff concentrates into gullies which originate from the piedmont of the plateaux. Since the bottom of these gullies are highly permeable (Peugeot et al., 1997) a large proportion of the runoff in these gullies contribute to the watertable recharge (Leduc et al., 2004).

Similar results were obtained in a comparable sandy environment (Oursi, northern Burkina Faso). Higher runoff coefficient was recorded from a fallow plot (51%; Collinet, 1988) than from a millet plot (33%; Piot and Millogo, 1980). In a shallow sandy loam (Saria, Burkina Faso) representative of the Mossi plateau, runoff is more similar to that observed in sub-humid savannah. Maximum runoff coefficient measured (Roose, 1977) decreases from a sorghum field (60%) to a young fallow (1–4 years, 30%) and an old fallow (>30 years; 5%).

3.6. Water erosion in the Sahelian site

As shown from data collected in Niger and in Burkina Faso (Table 3), soil losses remain rather low at the plot scale in the Sahelian region. Sandy loam soils from the plateaux are slightly more vulnerable than the sandy soils to water erosion. At the regional scale, there is virtually no water erosion because most watersheds are closed hydrological systems.

3.7. Wind erosion and dust balance in the Sahelian site

Horizontal fluxes rapidly decreased from the centre of the field to the edge of the fallow where virtually

Table 3
Soil erosion from cultivated and fallow plots in two contrasting Sahelian environment

Landform	Textural class	Soil losses (t ha^{-1} year^{-1})		Source
		Cultivated plots	Fallow plots	
Plateaux	Sandy loam	6.00	0.15–0.50	Roose, 1977
	Sandy loam	0.03–4.80	0.10–6.30	Collinet, 1988
	Loamy gravel	1.24	0.12	Mietton, 1988
Hillslope	Sand	1.60	2.20	Piot and Millogo, 1980
	Sand		0.08–3.20	Collinet, 1988

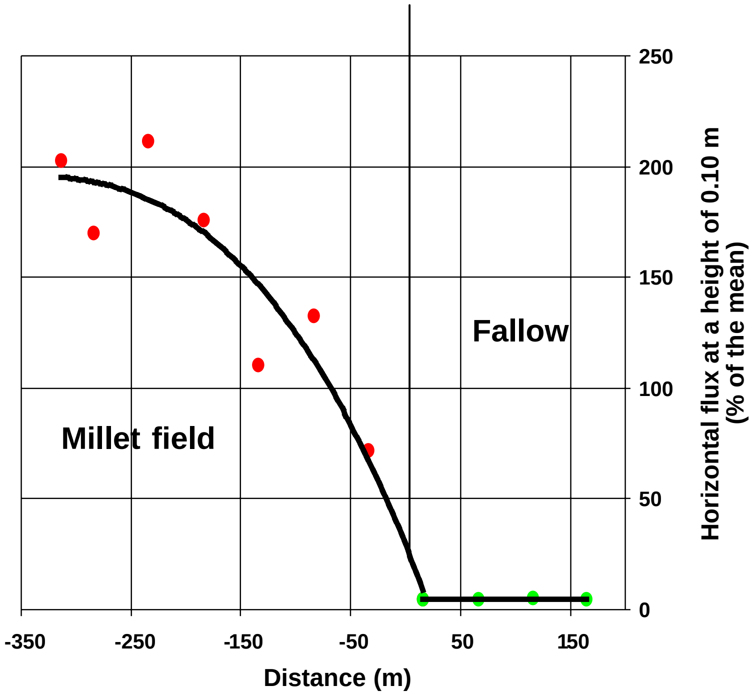

Fig. 10. Saltation measured as horizontal flux in a millet field and an adjacent young fallow. Banizoumbou, after Rajot (2000).

Table 4
Components of the dust balance (<20 μm) in a millet field and a young fallow in Banizoumbou (Niger, after Rajot, 2000)

	Dust deposition ($t\,ha^{-1}\,year^{-1}$)	Dust entrainment ($t\,ha^{-1}\,year^{-1}$)	Dust balance ($t\,ha^{-1}\,year^{-1}$)
Millet field	0.7	0.95	−0.25
Young fallow	0.7	0.02	+0.68

no saltation was recorded (Fig. 10; Rajot, 2000). At the small plot level, in similar conditions, saltation can be responsible for much higher soil losses (160 $t\,ha^{-1}$ per year, Buerkert et al., 1996; 119 $t\,ha^{-1}$ per year, Bielders et al., 2000) than water erosion (<2 $t\,ha^{-1}$ per year, see Table 3). This type of erosion, however, is very scale-limited. The wind-drift sand particles are easily trapped by surrounding vegetation and accumulate in the form of microdunes.

Dust erosion was much higher in the field (0.95 $t\,ha^{-1}$ per year) than in the fallow (0.02 $t\,ha^{-1}$ per year). As a result, the net balance between dust deposition and erosion was positive in the fallow and negative in the field (Table 4). These data substantiate the above-mentioned hypothesis of topsoil enrichment in fine particles due to dustfall. These data also suggest that regional dust balance is highly dependent on the field/fallow ratio. Rajot (2000) calculated that in the present conditions of the Banizoumbou region, a slight decrease in the proportion of the fallow land (6%) would be responsible for the change of the region from a dust well into a dust source.

4. General discussion

4.1. Fallowing and restoration of the soil physical properties

Three main types of dynamics can be distinguished: (i) soil crusts develop during the cultivation period and are disrupted by faunal activity and vegetation growth during the fallow period. This is observed in the sandy clay loam and the sandy loams of the sub-humid region and the Sahel as well; (ii) physical properties are restored, but much more slowly, as observed in the sandy soils of the sub-humid region; (iii) erosion crusts are disrupted during the cultivation period and develop again during the fallow period. This situation occurs on the Sahelian sandy soils.

Even in this latter situation, fallowing favours the restoration of conditions prior to cultivation, because erosion crusts are inherent to the sandy soils in the Sahel where the pristine surface consists of a mosaic of patches of vegetation and of bare crusted ground (e.g., Valentin, 1985). In such an environment, the fact that fallowing favours soil crusts and runoff production must not be regarded as detrimental for the ecosystem. The runon can substantially supplement the rainfall input that is often insufficient for plant growth. This concentration of water resource is a condition for plant production in the dry regions (e.g., Noy-Mer, 1973). At the landscape scale, the mosaic of a runoff generating fallows and runon-fields is also part of a water-harvesting system (Rockström and de Rouw, 1997; Rockström and Valentin, 1997; Rockström et al., 1999). This system on crusted sandy soils presents some analogies with the natural vegetation banded systems in the loamy gravel soils of the plateaux which can also be regarded as a water-harvesting system (Valentin and d'Herbès, 1999).

4.2. Predictable scenarios

On the red sandy clay loams of the sub-humid region, soil crusting, runoff and water erosion should be dramatically increased when the fallow duration tends to zero. This rapid deterioration is supposed to occur when the population density exceeds 70 people/km^2 (Planchon and Valentin, 2004). This very rapid growth of population could be due to migrations induced by droughts and dryland degradation. It should peculiarly affect the sub-humid and semi-arid border zone (Scherr and Yadav, 1996). This pessimistic view can be yet counterbalanced. Once the upper layer removed, erosion will be naturally reduced because the gravel will be exposed and protect the soil from further erosion (Valentin, 1996). Furthermore, because this gravel is not a constraint to cotton in the sub-humid region, more farmers should adopt more intensive systems using fertilisers and pesticides. This trend should be favoured, as already observed in northern Ivory Coast and southern Burkina Faso regions, by incentives and credit facilities (Sivakumar and Valentin, 1997). As a result of this intensification, more land should be allocated for savannah. More fragile soils, as the yellow sandy downslope soils, and the hydromorphic soils of the plateaux, could be therefore left uncultivated (Mitja et al., 1990).

The future of shallow soils in the plateaux of the semi-arid region should be similar to that of the red sandy clay loams of the sub-humid regions, except that climate is too dry for cotton and large-scale irrigation cannot be realistically considered in the near future. Replacing the natural fallow with an artificial fallow, or applying agroforestry techniques would require extra work that population are most often unable to afford. Soil denudation, decline in organic matter, coupled with and increased pressure on arable land should thus substantially increase the risks of physical degradation, accelerating the migration of population to wetter regions.

In the sandy Sahel, the evolution can be even more problematic because depleting the fine particle content through continuous cultivation will further exhaust soil fertility. In addition, the reduced crusted areas will decrease runon, increasing therefore greatly the risk of crop failure due to droughts. At the regional level, the limit between the net dust erosion zone and the net dust accumulation zone which roughly follows the 200 mm rainfall isohyet (Herrmann, 1996) is expected to shift rapidly to the 600 mm rainfall isohyet as a response to continuous cropping. Within few decades, a broad band of the Sahel can thus be turned from a sink zone to a source zone, with possible effects on large-scale fertility transfer, change in albedo and solar radiation. High concentrations of mineral aerosols could produce a warming of the upper atmospheric layers and a cooling at surface level, reducing the formation of clouds and changing their spatial distribution, affecting thus the climate (Bergametti, 1992).

Because trampling has similar effect than weeding operations upon soil surface properties, intense grazing cannot be considered as an alternative to cultivation in the sandy Sahelian zone. A combination of cattle breeding and cultivation seems a more promising way to combat wind erosion in this environment, because local animal manure supply favours surface heterogeneity which is a key element for the maintenance of the ecosystem (de Rouw and Rajot, 2004).

5. Conclusions

In West Africa, the issue of fallowing becomes crucial as the former shifting cultivation systems are gradually substituted by systems including short or no fallow. Reviewing studies conducted in the sub-humid and semi-arid zones led to emphasize the following points:

- In addition to climate, soil texture must be carefully accounted for when addressing the issue of physical properties restoration. In particular slight variations in sand content can have major consequences on soil crusting, runoff and erosion.
- The restoration of physical properties similar to those prior to clearing are hampered when low inherent fertility of sandy soils has been too much depleted by cropping.
- Fallowing does not invariably imply a reduction of soil crusts and runoff production. In the case of the sandy soils in the sub-humid region, erosion crusts are favoured by the foraging activities of *Trinervitermes*. In the Sahel, dust deposition and the development of blue algae encourage the expansion of erosion crusts.
- A slight decrease in the areal crop/fallow ratio can have substantial effect upon dust erosion, with possible fertility and climatic consequences at the regional level.
- The sub-humid zone offers a better potential to intensification (Cotton Belt) than the semi-arid zone where soil, climate and economic conditions are less favourable.

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