THE LESSON OF DRENTE'S 'ESSEN'
SOIL NUTRIENT DEPLETION IN SUB-SAHARAN AFRICA AND MANAGEMENT STRATEGIES FOR SOIL REPLENISHMENT[1]

By

Henk Breman[2], Bidjokazo Fofana[3] and Abdoulaye Mando[3]

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2. IFDC-Rwanda, BP 6758 Kigali, RWANDA. (hbreman@ifdc.org);
3. IFDC-Africa (bfofana@ifdc.org; amando@ifdc.org)

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and Agricultural Development

(hbreman@ifdc.org; bfofana@ifdc.org; amando@ifdc.org)

Abstract

The term "replenishment" is used in a misleading way when it is suggested that soils are poor through depletion by farmers and that soils should be restored to their original state for agricultural development. This philosophy created awareness for problems confronted by African farmers. It neglects, however, the heterogeneous redistribution of nutrients that is inherent to agricultural land use. Active and passive transport of organic matter causes centripetal concentration

[1] Drente: Dutch province dominated by poor glacial sands. 'Essen': one-thousand-year old village fields, on which fertility was improved and maintained through active centripetal concentration of organic matter by man (ash, household wastes, mulch, sods, etc.) and his livestock (manure) at the cost of surrounding rangeland and forest. The process finally led to severe degradation of the latter and to moving dunes. The landscape regenerated and Drente regreened when fertilizer use became economically feasible, livestock numbers could be lowered, and milk and meat instead of manure again became the main product of animal husbandry. See also footnote 2.

of nutrients around farms and villages and maintains or even improves the soil fertility of crucial fields at the cost of surrounding land. The advice to use fertilizers on bush fields in view of the use of compost and manure on compound fields is like “putting the cart before the horse”; the value:cost ratio of using inorganic fertilizer on compound fields is higher than that on bush fields given their negative organic matter and nutrient balances. The integrated use of inorganic fertilizers and organic forms of manure triggers a positive spiral of improved nutrient use efficiency and improved soil organic matter status. The increasing value:cost ratio of fertilizer use improves the access to this and other external inputs. Where crop-livestock integration is an important component of the intensifying production system, the centripetal concentration (see footnote 1) can even turn into the opposite, a centrifugal transport that replenishes (planned or unplanned) the depleted surroundings of farms and villages. Active replenishment of depleted soils is no requirement for agricultural development; intensification can start on village fields where fertility is maintained or improved. However, public investment in soils, focusing on reinforcement of the positive effects of the centripetal concentration of organic matter and nutrients, is recommended; it enables farmers to start fertilizer use where even the compound fields at present do not allow it.

Key words

soil fertility depletion and replenishment; nutrient use efficiency; carrying capacity natural resources; compound and bush fields; agricultural development; sub-Saharan Africa

I. INTRODUCTION

Two widespread approaches regarding the presentation of agriculture in sub-Saharan Africa (SSA) impede agricultural development policies. Both concern soil nutrient depletion. First, this depletion is expressed in monetary terms, e.g., to show that exhaustion of soil resources is a crucial component of farmers' income (Van der Pol, 1992) or to quantify the investments required for change (Breman and Sissoko, 1998). Second, it is suggested that the depletion has to be rectified through public investments to enable agricultural intensification and development (Buresh et al., 1997; Breman and Sissoko, 1998; Henao and Baanante, 1999).

These popular descriptions made the world aware of problems faced by African farmers. However, they also hinder effective interventions; the required investments seem immense and discourage donors and national policy makers. Farmers are mistakenly indicated as the cause of their own misery, creating a wrong focus for development efforts. This paper explains the inadequacy of both descriptions, in such a way that it contributes to refocusing and improvement of efforts for agricultural and rural development.

It concentrates on the active and passive redistribution of organic matter and the nutrients contained[2]. Control of this process, limiting the passive component at the benefit of the active one, is of utmost importance for the transition from extensive to intensive agriculture. The paper explains first briefly why agriculture in SSA is still predominantly in the extensive stage and why even a very intensive and intelligent use of organic matter alone will not change this. Then, it shows how the redistribution of organic matter can be exploited to trigger intensification through the improved accessibility of inorganic fertilizer. Finally, the paper describes the conditions that must be fulfilled for successful intensification.

II. NATURALLY POOR SOILS COMBINED WITH DIFFICULT CLIMATES, A REASON FOR THE ARREARS OF AGRICULTURE

II.1 The SSA case

Africa is the world's most ancient land mass. About 90 percent of its soils lost most of their nutrients during millions of years of erosion and leaching; only 10

[2] Active redistribution: collecting, transporting and using materials such as manure, household wastes, straw, and sods to maintain or improve the fertility of certain fields. Passive redistribution: concentration of materials in the surroundings of farms and villages by transport mechanisms having different goals, such as livestock coming to pass the night in kraals, bringing wood and straw for construction, and collecting fruits in the forest for home consumption.

percent of the soils are relatively young and still have nutrient rich sediments. The nutrient impoverished soils produce limited plant biomass; consequently, the soil organic matter content is low. The major European agricultural soils, for example, contain at least twice as much soil organic matter as those in sub-Saharan Africa (Smaling et al., in press).

”Soils in SSA are not in the first place poor through depletion by farmers, but farmers deplete soils because their soils are poor by nature.“ This is the foundation of Breman and Debrah’s (2003) recommendations for reaching food security in this part of the world, justified by decades of research. They explain how it caused the “green revolution” to bypass SSA and that a very unfavorable value:cost ratio (VCR) seriously hampers the use of inorganic fertilizer:

- Extremely poor natural resources cause overpopulation at low absolute population density[3], leading to high prices for external inputs and low prices for agricultural products at the farm gate;
- The efficiency of inorganic fertilizers is low.

Inadequate socio-economic and policy environments worsen the situation. Besides social and political instability, favoring of consumers at the cost of producers is common, while the development of competitive input and output markets is hindered by corruption, lack of quality control, and other factors. The poor resource base of agriculture can be used only partially as an excuse.

[3] In the West African Sahel and Soudanian savanna, respectively, 6 and 33 persons per km^{-2} can live from the land in a sustainable way. Overpopulation occurs at population densities above this carrying capacity, and sustainability can only be guaranteed by using external inputs, such as inorganic fertilizers, to increase the carrying capacity of the land. The adoption of agricultural technologies based on external inputs has to occur at a low population density in comparison with such changes elsewhere. For example, in Southeast Africa, it occurred when population densities, the inherent road and market infrastructures and domestic market were 10 times higher.

"VCRs above two or even three to four are no guarantee that farmers will start applying fertilizers in their fields. Kelly et al. (2005) state correctly that reducing risk and uncertainty plays an important part in improving fertilizer incentives in SSA" (Meertens, 2005). The latter, presenting the evolution of VCRs in 15 countries of sub-Saharan Africa, shows that values of 3 or just above 3 are already rare; 11 out of 17 values (maize, cotton and rice) from the early 2000s are lower. Only during the early 1980s, a period of heavy subsidies, were the VCR values considerably higher.

Binswanger and Pingali (1988), trying to explain the particularities of African agriculture, argue that land is still too abundant to attribute it a value and price high enough to trigger the required investments for change. Van Keulen and Breman (1992) reacted that in most of Africa land is not abundant at all; poor soils require extended fallow in time and space.   Therefore, “extreme land hunger” describes the situation better. What occurs if the natural resources degrade (quasi) irreversibly before the favorable density for attributing a value and price to land is reached? (Breman, 2000).

II.2 SSA is not an isolated case

SSA is not the first part of the world where growth of a population undermines the future of that same population. Mazoyer and Roudart (1998) present a worldwide overview of the history of agriculture. They focus attention on the variation, potentials, and limitations of natural resources, and the maximum population density related to different exploitation systems. Slicher van Bath (1960), limiting himself to West Europe, compares the agricultural evolution on rich marine and fluvial clay soils with that on poor glacial sands in the Netherlands. Long before the existence of inorganic fertilizers, farmers on clay could produce more than that required to feed their families. This enabled them to develop market-oriented production systems early, to encourage (most of their) children to look for labor opportunities outside agriculture, to invest in their land, and to develop inheritance systems that maintained their properties. The situation was opposite on poor sands—a farmer could barely produce enough to feed his family, and every family member was obliged to help that happen. Production systems focused on self-sufficiency; upon the death of the farmer, his property was divided among the surviving children. After the fallow system became inadequate in view of population pressure, investments in arable land were limited to the active and passive transport of organic matter and their nutrients. Numerous livestock and men functioned as the primary and secondary tools, and the amounts of manure, hay, leaves, fruits, wood and sod brought to farm and village created fields that were sometimes more than one meter higher than the original level. It was at the expense of range, forest and wasteland that degraded progressively and became moving sands. Entire villages disappeared, and the population reinforced the army of job seekers in the cities. Entirely different landscapes developed on clay and on sand.

Bieleman (1987) studied the history of agriculture on Dutch sands in detail; he limited himself to one rather homogeneous region, the province of Drente. He shows numerous variations in evolution of which the description above is a rather simple generalization, and insists that private initiatives and market opportunities are crucial explanatory factors. Growing markets triggered intensification and diversification, in particular, after the start of industrialization in Europe, in spite of the dominance of production for self-sufficiency and the degradation of (part of) the natural resources. The study underlines that even on the scale of a small Dutch province, the distance to external markets is a factor for differentiation. Tenths of kilometers more could imply centuries of delay in intensification when infrastructure is poorly developed, and carts with animal traction primarily provide transport! Many others factors also stress the importance of the context in its agro-ecological, geographical, socio-economic and political sense. It is illustrative that the relative importance of crops and livestock and the attention they receive from farmers vary with product prices in the Netherlands and in Europe. High dairy prices at the turn of the 19th century caused that increasingly available inorganic fertilizers were first mainly used to improve livestock feeding (Bieleman, 1987).

II.3 How to learn from others and elsewhere?

The agricultural development stage in SSA today is where Drente was one century ago: overpopulated at low absolute population density, using crop-livestock integration to try to maintain crop yields, having limited access to inorganic fertilizer as an alternative, and using market opportunities as challenges for change. A crucial question concerns the time still allowed for using concentration of organic resources through livestock and manpower to maintain crop yield and production while the population density is increasing. The crux is the fraction of land occupied by fields, and the carrying capacity for livestock of the other part. Only temporarily, herd growth can satisfy the increasing manure requirements of extending fields. Fields used for crop production increase at the expense of grazing land, and the manure, which is produced, must be distributed over an expanding area. Besides, extreme grazing pressure threatens other land uses, from which wood production is the most important under the described circumstances (Slicher van Bath, 1960; Mazoyer and Roudart, 1998).

It is tempting to derive an answer from parallels between the situation in Drente in the past, and, for example, Burkina Faso and Rwanda today. In all three cases, livestock effectives increase rapidly with population density and the inherent extension of fields. In Drente, with the doubling of the area occupied by fields, from 10% to 20%, animal density more than doubles from about 30 to 80 tropical livestock units (TLU) km^{-2} (time series 1832 – 1910; derived from Bieleman, 1987, using livestock weights 1.5 times greater than those of tropical animals). In Burkina Faso with the increased area occupied by fields from 5% to

30%, animal density increases from about 10 to 40 TLU km^{-2} (data 1995 per province [de Ridder et al., 2004]). In Rwanda with the increased area occupied by fields from 10% to 40%, animal density increases from about 12 to 33 TLU km^{-2} (data 2002 per province; derived from MINECOFIN, 2003).

In spite of parallels, differences between agro-ecological and socio-economic conditions are far too large to obtain even an impression of the respite that the latter countries still have before production systems based on redistribution and increasingly intensive use of locally available organic matter collapse. Drente had to feed more than 60 inhabitants km^{-2} when fields occupied 20% of the land, Burkina has to feed almost 50 inhabitants km^{-2} with an average of 15% of the land occupied by fields; figures for Rwanda are respectively 320 inhabitants km^{-2} and 33%. Where soils in Drente and Burkina Faso are predominantly poor (loamy) sands with limited reserves of organic matter and nutrients, Rwanda has regionally extremely fertile volcanic soils. Average cereal yields in Burkina Faso are about 0.8 t ha^{-1} yr^{-1}. In Drente at the turn of the 19th century, they were 1.3 t, and in Rwanda today the production per hectare and per year exceeds 2 t (two harvests per year!). In Drente 65% of the population depended directly upon agriculture; in Burkina Faso and Rwanda it is about 80 and 85%. Although few people are employed outside agriculture, the extremely high population density implies that the domestic market for agricultural products in Rwanda is nevertheless much larger than that in Burkina Faso. For example, Cour (2001), Tiffen et al. (1994), and Wiggins (1995) stress the opportunities created by large domestic markets for intensification, in West Africa, Kenya, and sub-Saharan Africa as a whole.

Despite the differences in agriculture between Drente, Burkina Faso, and Rwanda, striking parallels exist. In the three cases, livestock increasingly is exploited to maintain the productivity of crops, and in the three cases, it causes erosion that undermines the future of agriculture. Moving sand in Drente in the past was as threatening as moving dunes and sheet erosion in Burkina Faso and eroding hillsides in Rwanda today. In the three regions, cereal yield increases under growing population pressure obtained without external inputs such as inorganic fertilizers are about 7 kg ha^{-1} yr^{-1} (Bieleman, 1987; Breman, 1998), similar to the worldwide situation (De Wit, 1986). The three regions have the same two options for exploiting increased animal pressure that goes hand in hand with extension of fields at increasing population pressure: depleting all land that is not used for crops to its limits while undermining the future, or using it for advancing to fertilizer use as described in next chapters (Breman, 1990).

III. REDISTRIBUTION OF ORGANIC MATTER AND SOIL NUTRIENTS

III.1 Soil depletion

Stoorvogel and Smaling (1990) created awareness regarding the phenomenon of soil fertility depletion in Africa, with their evaluation of the national agricultural nutrient balances. They determined the sum of nutrient inputs through fertilization, use of organic residues and manures, atmospheric deposition, and sedimentation. Then they subtracted nutrient losses through erosion, leaching, volatilization, and crop uptake, followed by export from fields at harvest. Ten years later, Henao and Baanante (1999) repeated and confirmed their work, after improving some of the tools. Both studies evaluate nutrient balances at spatial scales that range from small plots to the whole continent. Henao and Baanante (1999) presented their results per country, as average values per hectare of cropland. Fields in 23 African countries annually lose more than 60 kg ha^{-1} $N+P_20_{5+}K_20$; those in Rwanda with 136 kg ha^{-1} are the highest. Losses in South Africa are negligible; Burkina Faso (with 62 kg $ha^{-1)}$ is at the bottom end of the countries with extremely high depletion. A group of 14 countries has medium level soil nutrient depletion (-30 to -60 kg ha^{-1} yr^{-1}); only 7 have low (<30 kg ha^{-1} yr^{-1}) or no depletion. Factors that cause high depletion are, for example, high erodibility of soils, high rainfall and high population pressure. In particular manure use and inorganic fertilizer counterbalance losses. The countries with no or low depletion have an average annual fertilizer use of 147 kg ha^{-1} $N+P_2O_5+K_2O$. Countries with medium losses use on average 20 kg ha^{-1}, those with high losses only 13 kg ha^{-1}.

Factors determining the use of inorganic fertilizers are profitability, favorable agro-ecological conditions (soil and climate), fertilizer aid by donors, fertilizer subsidies, pan-territorial crop and fertilizer prices, access to input credit and to output markets, and other policy-linked factors such as public investments in irrigation and in soil improvement. Social unrest and lack of political and policy stability seriously hinder fertilizer use (Meertens, 2005; Breman and Debrah, 2003). Also, policies of rich countries can have serious negative impacts on fertilizer use in Africa, e.g., dumping of meat by the EU made high quality fodder production in West Africa impossible, and cotton subsidies in the U.S. and elsewhere threaten intensive cotton production in Africa.

In a recent paper, Henao and Baanante (in press) compare the depletion rate of 1995-97 with 2002-04. Even in this short period, the situation has worsened. One country moved from the group of low depletion to medium depletion; two countries moved from high to medium, but 5 others were added to the list of countries with high depletion.

III.2. Redistribution: a component of the process of depletion of soil fertility

Mazzucato and Niemeijer (2000) created doubt by measuring the organic matter and nutrient content of soils in two villages in Burkina Faso; they compared the results with measures from the past. The two villages had different population pressures and past and present land use pressure. Even in the densely populated village, the soil fertility decline of the fields was not or hardly detectable. This triggered de Ridder et al. (2004) to review literature so that they could revisit the analysis of agricultural production systems in West Africa of the 80s. That analysis (e.g., Van Keulen and Breman, 1990) revealed that the population pressure was already so severe that without the use of inorganic fertilizer, decline in soil fertility of both grazing and arable land would lead to decreasing land productivity and jeopardize food security.

De Ridder et al. (2004, p 2) conclude that "*nutrient budgets show negative trends in stocks, which are probably overestimated because lateral in- and outflows are scale-dependent, difficult to estimate and often ignored.*" They explain that under farming conditions in sub-Saharan Africa, decline in soil fertility of rangeland, and forest can hardly be measured in view of "*highly variable soil management in space and in time. However, at coarser scales, gradients in soil fertility are detected as a result of centripetal transport of organic material.*" In other words, the apparent contradiction between Mazzucato and Niemeijer (2000) and van Keulen and Breman (1990) is explained by the difference in focus. The first authors concentrate on fields while the latter regard the system as a whole. Most soil depletion occurs on rangeland and in forests, not on fields.

III.3 Quantifying the redistribution phenomenon

Hilhorst and Muchena (2000, p 2), measuring nutrient flows on cropland as detailed as possible all over SSA, focus attention on the role of farmers' management, e.g., by comparing compound fields and outfields. They conclude that: "*moving sources of nutrients around creates 'hotspots' of good quality, fertile soil, even where the sum of nutrient balances in all fields may be negative at the farm level.*" Haileslassie (2005, p 95) arrives at a similar conclusion for mixed farming systems in Ethiopia: "*The positive partial nutrient balances for the intensively cultivated regions of Ethiopia suggest that farmers are applying sufficient inorganic and organic fertilizer to counterbalance the nutrient losses caused by the removal of harvested products and crop residues. In contrast, the full nutrient balances are negative, indicating that the soil nutrient reserves of the country are decreasing*." Ramisch (2005), calculating plot and household-level soil nutrient balances from participatory exercises and soil sampling, observes overall annual community-level nutrient balances of – 9.2 kg ha^{-1} of N, + 0.8 kg ha^{-1} of P, and – 3.4 kg ha^{-1} of K for extreme southern Mali. While considering both crop and livestock systems, his balances are partial; he considers only fields at a distance of 3.5 – 4 km from compounds. He indeed observes centripetal concentration of nutrients; for example, the average N input in fields increases from about 40 kg ha^{-1} at 3.5 km from home to 100 kg ha^{-1} for the home compound. A positive N balance is found only for the compound field (+ 3.8 kg ha^{-1} per year); elsewhere the balance is negative (average – 15 kg ha^{-1} per year). Like Bieleman (1987) in the case of Drente, Ramisch focuses on the strong variation between cases: " *... coefficients attributable to household behaviors* *matched or surpassed those attributable to distance....*"; and "*System differences in household asset ownership, use and resource allocation behavior suggested that much of the diversity seen in the nutrient balances and soil analyses was due to persistent inter-household inequality and the consequent exchanges of agro-pastoral resources*." (Ramisch, 2005, p 353). Livestock appears to be a crucial asset; comparing 3 villages that differ in stocking rate between 7, 17, and 20 TLU km^{-2} (average values dry and rainy season), average annual N balances for fields of -15, - 3 and + 20 kg ha^{-1}, respectively, are observed. Without the frequent manure trade, grazing contracts and purchases of inorganic fertilizer, involving dozens of kg ha^{-1} N, differences annually should still have been larger.

Active and passive transport of organic matter, containing essential mineral nutrients, causes centripetal concentration of these nutrients around farms, villages, and towns. Thanks to this process, the soil fertility of crucial fields can be maintained or even improved at the cost of range-, forest- and wasteland. Islands of (relative) fertility appear, even in regions with very poor soils, comparable to humid run-on spots through redistribution of rainwater by run-off in (semi-) arid regions. The comparison is useful; redistribution of water and nutrients creates agricultural opportunities that are absent at homogeneous distribution of limited amounts.

Krul et al. (1982) observed the phenomenon of centripetal organic matter concentration and tried to quantify it. Total N, C and P appeared respectively

2.75, 3 and 6.8 times higher in the top 10 cm of the soil of a large Sahelian village than at a distance of 6 km; intermediate figures occurred in between. They estimated the export of P by grazing from rangeland far from villages to be in the order of 100 g ha^{-1} yr^{-1}. Their primary interest for P should be emphasized. Since phosphorus is a nutrient that has limited mobility and is not volatile, its centripetal concentration should be higher than that of N, as proven by their observations. It implies that the relative dominance of N-deficiency over P-deficiency, as observed for soils in large parts of West Africa (Breman and Van Reuler, 2002), is accentuated in the redistribution process.[4]

Synthesis of data from three other studies and regions confirms the above trend (Breman, 2002). The top 20 - 30 cm of soil of village fields has a total N, C, and P content of 750, 7,900 and 270 mg kg^{-1},respectively, which is 1.6, 1.7 and 2.6 times higher than observed for the bush or bush fields. Using available-P instead of total-P, the concentration for the village field is 50 mg kg^{-1}, even 8 times higher than that for the bush field.[5] In view of the involved mechanism, grazing and wood production, the land further away than the bush fields will have somewhat lower organic matter and nutrient contents than the bush fields. Krul et al. (1982) showed a decrease of total P from 515 mg kg^{-1} in the village to 153, 95, and 76

[4] Observations such as those of Green and Cole (2006) regarding feedlots in the U.S.A confirm this conclusion: "*A 20,000 head capacity feedyard requires at least eight sections of irrigated corn to dispose of the manure based upon its fertilizer value for nitrogen, but over 48 sections of irrigated corn is required to dispose of the manure based upon its fertilizer value for phosphorus. Consequently, applying manure to croplands to meet the nitrogen requirements oversupplies phosphorus.*"

[5] Samaké (2003, p. 85) observes less difference between the concentration of N and P for extremely poor soils of the Malian Sahel. In the top 15 cm of compound fields, with 280 and 6 mg kg^{-1} of N and P-Bray-I, respectively, the N content appears 2.0 times higher than that of the bush fields, against 2.6 for P-Bray-I.

mg kg^{-1} at 1, 2, and 6 km distances, respectively. The centripetal concentration can be measured, but as others have already stressed, it is generally very difficult to measure a soil fertility decrease in grazing land because organic matter and its nutrients are harvested from large areas in comparison with the land under crops (Turner, 1995; de Ridder et al., 2004). The supply of P by livestock on compound fields, expressed as fraction of total P in the top 25 cm of the soil, is annually about 2% or more; the average depletion of rangeland is only one hundredth of it.

The parallel increase of the area occupied by fields and the stocking rate of livestock (II.3) imply that the supply of manure and the mineral nutrients that it contains per acreage of cropland is rather constant; whereas, the depletion of grazing land is increasing. The example of P above is based on an estimation using the simple ideal but theoretical case of a concentric distribution of land use types: compound fields (10% of the entire cropland) surrounded by bush fields, surrounded by grazing land (range, forest and wasteland). As radius of the outside circle of grazing land 7.5 km has been chosen, using 15 km as the maximum grazing distance (twice the radius if the herd passes the night at the farm). Grazing is done entirely in the outer circle for which 8-hrs day^{-1} is available. Two-thirds of the manure produced drops on cropland during rest, rumination, and moving. Food intake and quality are those of a typical herd for integrated crop-livestock systems using animal husbandry to maintain crop production (Ketelaars, 1991). The estimation concerns the maximum amount of manure that can be obtained for transporting nutrients from grazing land to arable fields. The maximum supply is about 640 kg manure (DM) per hectare of cropland at homogeneous distribution. Concentrating all on the compound fields, it becomes 6,400 kg ha^{-1} DM. The figure is the same for 10% of the total acreage under crops and a stocking rate of 10 TLU ha^{-1}, as for 30% land under crops combined with a stocking rate of 30 TLU ha^{-1}.

If he succeeds in collecting all manure that is produced during the stay of the herd in the two inner circles, and if nothing is lost during transport, storage and handling, a farmer has the choice between applying 640 kg ha^{-1} of manure (DM) on all his fields or 6,400 kg ha^{-1} on his compound field. However, during storage, the mineralization process starts and organic matter will be lost; this results in an increase in the concentration of mineral nutrients in the composted material. In view of the humidification coefficient of about 0.5, at least one quarter of the manure on DM base will be lost during the average 6 months that it must be stored; what remains is at maximum 480 kg ha^{-1} for all fields or 4,800 kg ha^{-1} for compound fields. Based on data from Sahelian countries, Duivenbooden (1992) finds average mineral nutrient contents for animal manure of 1.3, 0.3 and 1.3 % of DM for N, P and K. In other words, on average about 6, 1.5, and 6 kg.ha^{-1} are available for all fields or doses of 10 times more on compound fields only.

As already stressed above, losses of the relatively mobile nutrients, N and K (mainly through leaching, but in case of N, also through volatilization), in the period between grazing and manure application have been much higher than that of P. The P content of fodder from Sahelian rangeland is one tenth of the N content (Penning de Vries and Djitéye, 1982); in manure it appears to be a quarter (Duivenbooden, 1992). In this context, the term “losses” means “out of control of the farmer.” At least part of the lost nutrients will still serve crop growth, if the losses occurred in the field.

III.4 Reinforcing the redistribution phenomenon

A simple ideal, theoretical case was presented above. A series of studies exist from which the potential role of different variables for reinforcement of redistribution can be derived. Turner (1995) identifies them by using a formula that describes the rangeland: “cropland ratio necessary to support manure-supported continuous cropping." Variables that are emphasized are the production capacity of the land, the fraction of cropland for which fertility is still maintained by fallow, the production of leguminous fodder crops (citing Garin et al., 1990), and the grazing radius. They are positively but not linearly correlated with the acreage of cropland supportable by manure in the place where animals spend the night. This acreage increases also by placing the corrals at the outer edge of the continuously cultivated land instead of in the village.

Without any quantification of their effects, Turner (1995) also mentions livestock, crop, and soil management. Quak et al. (1998) developed modeling and simulation software that enables the quantifying of the contribution of agricultural practices and management to soil organic matter maintenance and nutrient availability. They treat different animal production systems (mobile and sedentary, and mixed grazing herd versus fattening at the farm), different cropping systems and crops (rain-fed and irrigated; cereals, legumes, food, fodder and cash crops), and crop residue management (burning, mulching, burying and composting). It is rather obvious that practices such as sedentary stable feeding, production of high-quality fodder, and the collection and composting of as much manure, crop residues and household wastes as possible all reinforce the redistribution phenomenon and farmers' control over it.

Collection and composting of manure, crop residues and household waste is a crucial variable. This is illustrated by the data on which the above average animal manure nutrient contents of Duivenbooden (1992) are based. Using less than 20 different sources, the N content already varies between 0.35% and 2.50 %, the P content between 0.11% and 0.41 %, and the K content between 0.46% and 4.50 % of manure dry matter. Factors that improve the contents by reducing losses include the use of straw to absorb urine and decrease leaching, concrete floors and anaerobic treatment (pit instead of heap composting; e.g., IFDC, 2002; Lekasi and Kimani, 2005).

A strong and socially rather tricky mechanism for reinforcement of redistribution is the unequal distribution of livestock. The lower the number of farmers concentrating organic matter and its nutrient content from common grazing land on their compound fields, the higher the chance that the soil organic matter status can be maintained locally and the nutrient balance is positive. As stated above (III.2), comparing concentration of nutrients on marginal land with concentration of water in semiarid regions, redistribution of poverty creates opportunities that are absent at homogeneous distribution. This mechanism of reinforcement of redistribution is illustrated well by the study of Ramisch (2005) about "*inequality, agro-pastoral exchanges, and soil fertility gradients*"; the correlation between the N balance and stocking rate has been presented previously (III.2), and the disturbance by manure trade. Key assets for this trade and for focused application of manure, after passive concentration by livestock, appear to be carts and draft power. "... *access to labor, transport, and land constrains efficient household manure use more than the number of livestock*" (Ramisch, 2005, p. 366).

Ramisch asked farmers to classify themselves as 'weak', 'average' and 'strong' regarding their soil fertility management ability, using their local criteria. These criteria appear to be accessibility of manure and inorganic fertilizers, availability of household labor and oxen, and timeliness of planting. The three classes show a heterogeneous distribution in the observed inverse relationship between the degree of heterogeneity of nutrient use and the household N input rate. The 'weak' soil managers, having an average N input rate of 40 kg ha^{-1}, apply their inputs inequitably; the 'strong' soil managers, having an average N input rate of

70 kg ha^{-1}, apply their inputs most equitably. "*Numerous comments made by farmers indicated that it is better to concentrate [scarce] resources than to scatter them.*" "*Households with scarce resources were therefore likely to concentrate it in a 'hotspot' for maximum benefit, while households with access to more of that resource would either increase the number or the area of those 'hotspots', thereby reducing the overall 'patchiness' of their use*" (Ramisch, 2005, p. 365). One could state also that land of 'strong' soil managers becomes the fertile soil 'hotspots' of the village territory.

III.5 The limits of the redistribution phenomenon.

Droughts, like those of the Sahel during the last three decades, are revelations regarding the degree of overpopulation at certain forms of land use and the surplus value of arable farming in comparison to livestock production for feeding men based on natural resources only. The drought in the overpopulated Sahelian countries changed production systems (Breman et al., 1990; de Grandi, 1996). The relative spatial separation of arable farming and livestock production disappeared, the mobility of pastoral systems decreased or even disappeared, the point of gravity of livestock production moved southward, from the Sahel to the savannah, and the integrated crop-livestock system became general. A change in the priority of goals for keeping livestock accompanied this change. The pastoral systems that dominated land use in the drier parts of Sahelian countries in the past aimed at producing milk and meat. In the present integrated crop-livestock systems, maintenance of crop production through manure, traction and savings dominates over proper animal production. This difference becomes increasingly visible at an increasing stocking rate parallel to increased acreage under crops (II.3), which is caused by the decreasing average fodder quality. "*Where the hogs are many, the wash is poor*"; milk and meat production decrease more than proportionally with decreased fodder quality. At a certain moment, the average quality becomes too low to enable maintenance of the herd; the productivity parameters become too low. The fodder quality limits are 0.9% of N and 52% digestibility (Ketelaars, 1991).

For keeping as much livestock as possible and maintaining their productivity as well as possible, farmers are finally obliged to supplement their grazing animals. First, their own crop-byproducts are used, but finally part of their fields must be used for fodder production, or extra (high) quality fodder must be procured (Slicher van Bath, 1960; Mazoyer and Roudart, 1998). It will make a difference if former pastoralists, who still try to optimize animal production as a goal in itself, handle the crop-livestock system or if arable farmers who focus on crop production handle it. At first glance, the results of Ramisch (2005) seem counterintuitive in this context. Those who make the most effort to improve the fodder situation are arable farmers with rather limited livestock numbers; they collect cowpea leaves, cereal stover, and sweet potato vines. The original pastoralists do not do it. Their grazing strategy is, however, much more effective than those of arable farmers; the first group allows animals to graze longer and even night grazing may still be practiced (Leloup, 1994). The arable farmers must try increasing livestock numbers in spite of the 'opposition' of existing well-managed herds of former pastoralists.

The best chances of rapidly increasing livestock density occur when there is an important market for the proper livestock products—milk and meat. The income obtained enables farmers to decrease the production of human food at the benefit of fodder production. This occurs, for example, in the neighborhood of cities (de Ridder and Slingerland, 2001). Livestock traders may also invest in improved feeding. Leloup (1994) presents the example of cotton seed cake procurement. Bieleman (1987) describes the rapid change in Drente in the 19th century of integrated systems dominated by rye production to those dominated by fodder production, triggered by the rapid increase of demand for milk and meat in industrializing Europe. This change facilitated the transition to inorganic fertilizer use, which in Drente appeared to be economically more feasible for livestock feeding than for rye production. In the Sahelian examples presented, inorganic fertilizers also start to play a role; primarily, cotton pays for it in this case.

The integrated crop-livestock system is indeed an effective tool for maintaining for a long time an increasing population based on natural resource use only. It has, however, its limits—a judgment also supported by those who accepted that the first analyses overestimated the negative trends in soil fertility decline (e.g., Turner, 1995; de Ridder et al., 2004; Ramisch, 2005). The limits are reached when the viability of livestock herds cannot be ensured any longer and/or the degradation of the depleted grazing land gains momentum. The chance that this happens increases rapidly when farmers start to reinforce the redistribution process provoked by their livestock, collecting plant biomass, mulch or even topsoil from grazing land. In Drente the collection of sod was a more important cause of desertification than livestock.

When the limits of integrated crop-livestock systems are reached depends on production systems and management decisions as described under III.3. Those decisions vary with farmers' objectives and with their socio-economic and policy environments. The number of factors involved and linkages between them are high. It is therefore difficult for farmers to make decisions and for others to advise them. Modeling and simulation is increasingly used to increase insight and to support the decision process; multiple goal planning is one of the instruments (e.g., Bakker et al., 1998; Sissoko, 1998; Savadogo, 2000; Stroosnijder and Van Rheenen, 2001; Lopez-Ridaura, 2005). The use of inorganic fertilizers appears to be the tool to allow further population growth while reversing the soil depletion trend and allowing the unlinking of crop and livestock. Farmers' accessibility of input and output markets is key to the adoption of this solution; therefore, policy makers are as responsible for (un)sustainable land use as farmers.

IV. Exploiting and optimizing the redistribution phenomenon

IV.1 Integrated soil fertility management

One may wonder if inorganic fertilizer use can indeed be the tool for SSA to allow further population growth while reversing soil depletion. The market-oriented production in an increasingly globalizing world requires from farmers highly competitive production. The problem for regions with poor soils is, however, the unfavorable value-incremental yield:fertilizer cost ratio (VCR) of inorganic fertilizer use (II.1). It is here that the redistribution phenomenon can be of use. The frequently heard and well-intentioned advice to use fertilizers on bush fields in view of the use of compost and manure on compound fields is like “putting the cart before the horse.” The VCR of using inorganic fertilizer on compound fields, combining it with manure and/or compost, is higher than on bush fields with their negative organic matter and nutrient balances. The combined use of inorganic fertilizer with compost or manure is one of the effective forms of integrated soil fertility management (ISFM). ISFM, in this context, aims to improve access to and increased use of inorganic fertilizers. It combines inorganic fertilizers and soil amendments in an integrated way. Soil amendments—sources of organic matter, in particular, but sometimes also phosphate rock and/or lime, improve the soil organic matter status, the accessibility of P and the soil pH, and improve fertilizer use efficiency. The inorganic fertilizer not only increases crop yield, it also contributes to the availability and quality of the key amendment, organic matter in form of crop by-products (IFDC, 2002; 2004 and 2005). Sissoko (1998) identifies a series of policy measures that favor the adoption of ISFM by cotton farmers in Southeast Mali: those that increase the profitability of fertilizer use (see paragraph 3.1), soil improvement (e.g. supporting the use of soil amendments such as phosphate rock), improving land use rights security, responsibility of producers through decentralization and development coordination. After four years of using ISFM by 3000 farmers in seven West African countries on five crops, N-use efficiency increased by an average of 50% (IFDC, 2004). VCRs for traditional use varied between 2-3 or less[6] and 8, depending on systems, crops and regions. The related yields varied between 750 kg ha^{-1} for maize on bush fields and 3,000 kg ha^{-1} for irrigated rice. After four years of using ISFM, VCR values ranged from 4 to12, and yields from 1,800 to 5,500 kg ha^{-1}. The lowest VCR and yield was now found for sorghum, the highest again for irrigated rice. A whole menu of ISFM technologies has been developed; each technology has its own source of organic matter and its own recommendation domains. Details are increasingly published in scientific publications (Fofana et al., 2004; 2005 and in press; Wopereis et al., in press).

Good soils, enabling the economical use of inorganic fertilizers, are the most favorable for the transformation of extensive subsistence agriculture into intensive market-oriented production; they allow for competitive production.

[6] These low values have been derived from on-farm trials; farmers generally do not adopt inorganic fertilizer use at this VCR level (see paragraph 3.1).

Relatively good soils exist everywhere in the form of compound fields[7]. IFDC compared fertilizer use efficiency on compound and bush fields in the Sahel and the Soudanian savannah.

Millet production on compound and bush fields in Karabedji, Niger (Sahel; average rainfall 500 mm per year)

Without using fertilizer, in three successive years, millet grain yields on bush fields varied between 150 and 180 kg ha^{-1} and on compound fields between 490 and 570 kg ha^{-1}. Both N and P were limiting. Maximum N use efficiencies were found by using doses of 30 kg ha^{-1} for both elements that led to average yields of 1,220 and 1,940 kg ha^{-1} for outlying and compound fields, respectively. Every kilogram of N produced 35 kg of millet grain on the bush fields compared with 47 kg on the compound field (Fofana et al., in press).

Maize production on compound and bush fields in Northern Togo (Soudanian savannah; average rainfall 900 mm per year)

While comparable results have been obtained for individual sites and years, the average difference in N-use efficiency that has been observed on four farms in three successive years is less pronounced than for millet in the Sahel. Using doses of 50 kg ha^{-1} of N at 15 or 30 kg ha^{-1} of P produced maximum N efficiencies. Every kilogram of N produced 22 kg of millet grain on the bush fields compared with 25 kg on the compound field. The greatest differences between

[7] Market gardening around cities is in this context regarded as an extreme case of compound field production. It is the food transport for the urban population that replaces the centripetal concentration or organic matter by cattle, while organic urban waste replaces household waste and manure.

outfields and compound fields occurred during a year with low and erratic rainfall. For doses of 50 kg ha^{-1} of N, every kilogram of N produced 10 kg of maize grain on bush fields compared with 18 kg of maize grain on compound fields.
A much higher difference appears to exist between the N-recovery, which is on average 30% higher on the compound fields in comparison with that of the bush fields. Different dose:N-uptake curves are found for the two types of fields. Yields increase proportionally with the N doses for the bush fields, but for the compound fields a saturation curve is found. In other words, N was not the limiting factor any more above 50 N, and absorbed N is increasingly less efficient when used for grain production (derived from Wopereis et al., in press).

To better understand the differences in results for the Sahel and the savannah, one should realize that the C and N content of the savannah soils are about five times higher than those in the Sahel[8]. On the compound fields, in particular, important amounts of N became available from the soil; the uptake rate by crops was 50 kg ha^{-1} or more. Without any fertilizer, this leads to average maize yields of 2,100 kg ha^{-1} compared with 900 kg ha^{-1} on bush fields. The implication for the topic of this paper is that i) ISFM has indeed comparative advantages for marginal land (Breman, 1990); and ii) that there is a limit to the benefits of redistribution. The latter appears also from the behavior of farmers in the villages studied by Ramisch (2005; see III.3). It must be possible to improve the effects of N application in the savannah, but it requires detailed studies about limiting

[8] In the Sahelian case the top soils of compound and bush fields had an organic C content of 1.6 and 1.5 g kg^{-1}, respectively, and a total N content of 135 and 118 mg kg^{-1}. For the savanna case these figures were 13.4 and 6.3 for C and 968 and 511 for N.

factors and, presumably, more sophisticated and more expensive fertilizer use, paying attention to more nutrients, time and place of application, and fragmentation of doses.

The increased effects of soil improvement on fertilizer use efficiency in the case of drought should be stressed more. Too often, it is suggested that the use of inorganic fertilizer is very risky in case of drought. The results obtained in Niger and the effects in a dry year in the savannah show that using ISFM can suppress this risk. This effect of integrated management of inorganic fertilizer and organic soil amendments appears far before the soil organic matter status is improved enough to explain the drought effect through a higher water-holding capacity (de Ridder and van Keulen, 1990). Other possible explanations are the organic matter contribution to improved water infiltration, the nutrient-holding capacity of the soil (see below), or the improved root development observed by Cissé (1986).

IV.2 Optimizing redistribution

Use and optimum management of (soil) organic matter must be different in case of being the main source of nutrients or being the soil amendment for efficient inorganic fertilizer use (e.g., Palm et al., 2001). Although the interactions between inorganic fertilizers and organic matter are not yet known in detail, several processes are known through which organic matter contributes to effective management of inorganic macronutrient fertilizers (Vanlauwe et al., 2002). Besides the above-mentioned improvement of water absorption potential, it concerns processes that lead to the improvement of the nutrient absorption potential: increased cation exchange capacity (C.E.C.) and increased anion exchange capacity, pH buffering, occupation of phosphate fixation sites, and maintenance of micronutrient balances through chelation and ion exchange.

The mechanisms behind these phenomena are such that it appears sufficient to ensure that minimum SOM values are maintained through organic matter management. Pieri (1989) formulates such critical threshold values in relation to the soil textures, paying attention to the soils' potential for erosion. Breman (2002), influenced by the work of Janssen et al. (1990), suggests a SOM content in relation to the nutrient-holding capacity of soils; the C.E.C. value should be at least 10 cmol kg-1. Also, in that case, the threshold and the required amounts of organic matter will be texture dependent, considering the contribution of clay particles to the C.E.C. The idea of a threshold is supported by the behavior of farmers as described by Ramisch (2005, p. 365), presented in III.3. Those households that "*would either increase the number or the area of those 'hotspots,' thereby reducing the overall 'patchiness' of their use*" are the richer ones using also most inorganic fertilizers.

Not only is less organic matter required when used as a soil amendment in an ISFM context compared with its use as manure, but its quality is also different.

Organic matter with a lower nutrient content and a lower mineralization rate is required (Palm et al., 2001). This concerns material that contributes more easily and quickly to SOM maintenance or formation; it has a high C-sequestration capacity. The availability of such organic matter is much higher than that of the quality class that can be used as a direct alternative for inorganic fertilizer. However, part of the organic matter will be 'too inert' to serve effectively in an ISFM context in combination with inorganic fertilizers (Henkens, 1975; Palm et al., 2001; Breman et al., 2004). This organic matter can only be used for erosion control and for C-sequestration.

Armed with this knowledge and with the knowledge of farmers and scientists about spatial crop growth variability (e.g., Voortman and Brouwer, 2003; Voortman et al., 2004), the progressive transition from passive to active redistribution can be guided and exploited for the intensification of agriculture by inorganic fertilizer use. Goal- and location-specific recommendations can be made for the integrated use of inorganic fertilizers and available sources of organic matter, promoting different ISFM technologies for different farm sites[9]:

- One should be less concerned about negative organic matter and nutrient balances of whole village territories and adjacent rangelands, and even about the degradation of the latter. Rather one should be concerned about bottlenecks for market-oriented, competitive production, such as limited

[9] It goes without saying that besides benefiting from the (relative) good soils of compound fields for starting intensification, farmers should also exploit good soils such as those of depressions and valleys, where nutrients from elsewhere are concentrated thanks to water . Schreurs et al. (2002) promote and illustrate the use of strategic sites in general.

access to inorganic fertilizers, lack of market transparency, and inadequate agricultural policies.

- Intensification should start on compound fields[5] and focus first on N-fertilizer, combining it with manure and compost, and if required with P (K, S,. ..).
- Compound fields on which inorganic fertilizer is used can be extended more than the traditional ones on which manure and compost serve as nutrient sources.
- At least part of the space[10] created by extension of compound fields should be used for fodder production on bush fields. If the VCR of fertilizer use allows it, other ISFM technologies can be introduced on bush fields, particularly those based on agroforestry, fodder and cover crops, and pasture-crop rotation. It reinforces the redistribution process and the availability of organic matter for the extension of compound fields without (rapid) depletion of bush fields. Both N and P are required (more often than on compound fields--K, S, and micronutrients, e.g., for productive leguminous crops).
- N doses must be relatively low to avoid the negative interaction with N from SOM and other organic resources that easily suppress the benefit of high N recovery (Wopereis et al., in press; Fofana et al., in press).

[10] 'Space' should be read in several senses: more food can be produced thanks to higher yields and larger surface, while the higher fertilizer use efficiency leads to a higher net production and income.

Small ruminants, the most important tool for organic matter *casu quo* mineral nutrient transport where population pressure is high and depletion of forest-, range-, and wasteland is advanced, become redundant, and their harmful influence on the environment can be controlled when the redistribution phenomenon itself is not used to maintain production but where it serves intensification as described. The centripetal transport can even turn into a centrifugal transport and replenish (planned or unplanned) the depleted surroundings of farms and villages. A form of unplanned redistribution in countries with intensive agriculture and high levels of fertilizer use is acid rain, a fraction of which is caused by extremely intensive livestock raising. In the Netherlands, its effect on entirely depleted and degraded land reached the point that the law had to be changed to protect the last moving dunes as a monument to the history of agriculture. These laws, very similar to those developed today for stopping desertification in the Sahel, were elaborated centuries ago to stop environmental degradation caused by human activities in regions with poor sandy soils (e.g., Gelderland Province, 1862; see Handelingen Provinciale Staten Gelderland 1982).

IV.3 Enabling Socio-Economic and Policy Environments

Active replenishment of depleted African soils is no requirement for agricultural development. However, public investments in soils can contribute largely to the success of ISFM. Such investments are about one tenth of those in small-scale irrigation with at least comparable rates of return and can be direct (cheap soil amendments) or indirect—supporting farmers through subsidies or loans for carts and animal traction (Breman et al., 2003). They should focus on reinforcement of the positive effects of the redistribution phenomenon, enabling farmers to start fertilizer use where even the compound fields at present do not allow it[11]. It forms one of the four main public supports for agricultural and rural development. The others are investments in infrastructure and transport, the creation of an enabling environment for private input and output market development (transparency!), and regional cooperation, considering the benefits of scale and temporary and differentiated market protection (Breman and Debrah, 2003). Such policies improve the VCR of using inorganic fertilizer by offering farmers lower fertilizer prices and higher crop prices, which reinforce the approach presented for increased fertilizer use efficiency.

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[11] A useful form of support concerns reinforcement of active organic matter management and redistribution, e.g., through subsidized carts and draught oxen.

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