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Soil and Crop Growth Variability in the Sahel: Highlights of Research (1990–95) at ICRISAT Sahelian Center

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Collaborating Institutions

IH Institute of Hydrology, Wallingford (UK)

ILRI International Livestock Research Institute, Addis Ababa (Ethiopia), and Nairobi (Kenya)

INRAN Institut national de recherches agronomiques du Niger, Niamey (Niger)

IUCN World Conservation Union, Gland (Switzerland), and Cambridge (UK)

ORSTOM Institut francaise de recherche scientifique pour le developpement en cooperation, Paris (France)

PDAAT Projet de developpement agroforestier et amenagement de terroirs villageois, Niamey (Niger)

TropSoils Soil Management Collaborative Research Support Program, Hawaii (USA)

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Abstract

Soil and crop growth variability in the Sahel are essential to the survival of Sahelian ecosystems and agroecosystems The role of water, plants, animals, farmers, pastoralists, and agronomic researchers in causing, maintaining, and changing such variability, over distances of a few meters up to hundreds of kilometers, was investigated in a 5-year project Examples are given of how the resulting improved understanding of this variability can help increase agricultural production in the Sahel, contribute to sustainable land use, and increase the effectiveness of local agricultural research

Resume

La variabilite du sol et de la croissance des cultures au Sahel est essentielle a la survie des ecosystemes et des agro-ecosystemes saheliens Une etude sur cinq ans a examine le rôle de l'eau, des plants, des animaux, des paysans, des pastoralistes, ainsi que des chercheurs agronomes dans la creation, le maintien et le changement d'une telle variabilite sur les distances allant de quelques metres jusqu'a des centaines de kilometres Les exemples illustrent comment les connaissances ainsi acquises sur cette variabilite pourraient permettre d'accroître la production agricole dans le Sahel, contribuer a l'exploitation durable des terres et augmenter l'efficacite de la recherche agricole regionale

The designations employed and the presentation of the material in this publication do not imply the expression of any opinion whatsoever on the part of ICRISAT or the Agricultural University of Wageningen concerning the legal status of any country, territory, city, or area, or of its authorities, or concerning the delimitation of its frontiers or boundaries Where trade names are used this does not constitute endorsement of or discrimination against any product by either institution

Cover Changes with the seasons of a landscape near the Niger River, just south of Niamey, Niger, April–December 1991

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Summary

In the Sahel, crop growth in farmers' fields varies widely, not only between fields but also between different parts of a single field These differences are generally related to differences in soil properties over short distances (2-50 m) Although such soil and crop growth variability complicates management by farmers as well as research by agronomists, agricultural scientists have historically ignored it This bulletin reports on the results of a 5-year project (1990-95) at the ICRISAT Sahelian Center (ISC) in Niger, investigating various aspects of soil and crop growth variability in the Sahel

The project was financed by the Directorate General of International Cooperation (DGIS), Ministry of External Affairs of The Netherlands Scientific support was provided by the Department of Soil Science and Geology of the Agricultural University of Wageningen, The Netherlands The main conclusions from the project are as follows

1 Soil and crop growth variability in the Sahel occurs on many levels of both time (days to decades) and distance (meters to thousands of kilometers)

2 On the regional and subregional scale, wetland areas deserve particular attention, because they
   - are areas of high production potential,
   - allow more efficient exploitation by livestock of the associated dryland areas small wetlands by providing watering points for nearby dryland grazing areas and large wetlands by providing dry-season grazing to complement the wet-season grazing much further north,
   - can provide a safety net in terms of food production during times of drought,
   - are suffering degradation and hence need coordinated management to preserve their potential for various purposes, including food production and conservation of biodiversity

3 On a local scale, farmers are fully aware of short-distance differences in soil properties and crop growth, caused by, for instance, termite mounds or various trees They aim part of their management strategy at reducing or exploiting such differences

4 Soil and crop growth variability may have an important role to play in reducing risk and increasing yield stability, because water and nutrients alternate in limiting crop production in the Sahel The factor most limiting crop production in a particular field can vary not only from year to year and even day to day, but also from one small part of a field to the next Thus, there is less chance of total

crop failure in the whole field in a particular year On certain soil types, crops may also benefit from differences in the amount of water stored in the soil at the end of one cropping season and carried over to the beginning of the next

5 In a 1-hectare area in a farmer's field, divided into 400 plots of 5 x 5 m, millet grain production in one season ranged from 0 to 2885 kg ha^{1} Root shoot ratios of the millet decreased with increasing above-ground biomass, and total root growth was correlated with soil properties at about 1 0 m depth Total root mass increased with increasing dry matter up to 4000 kg ha^{1}, then decreased again No single factor explained this variability in millet grain production, but correlations were found with total nitrogen and organic carbon and with soil erosion the greater the erosion, the less the grain yield Wild phenotype millet (a genetic throwback) was prominent in areas where the farmer's variety did not grow well, for instance, around acid and eroded patches of soil Millet breeders may want to try incorporating into their cultivars this relative tolerance of poor conditions exhibited by the wild phenotype

6 Soil and crop growth variability is influenced by variability in infiltration of rainfall Even on the very sandy soils of southwestern Niger, infiltration at different points in a farmer's field ranged from 30 to 340% of rainfall This variability is related to differences in topography and crusting of the soil

7 Application of 10 t ha^{1} of cattle manure and urine markedly increased the soil nutrient store at 1 5–2 0 m depth within 12 months organic C increased by 1070 kg ha^{1}, N by 91 kg ha^{1}, and P by 19 kg ha^{1} Similar amounts had probably already been leached to beyond the 2-m depth The degree of leaching was related to plot wetness and topographic position leaching was most pronounced in depressions and on concave slopes, least on convex slopes

8 During 1992, a good rainfall year, the effect on millet yield of applying small amounts (1 5–2 t ha^{1}) of cattle manure and urine also depended on the topographic position of the plot the yield increase was least in depressions and on concave slopes, greatest on convex slopes However, topographic position did not influence the effect of much larger amounts—up to 10 t ha^{1} of cattle manure and urine and 3–4 t ha^{1} of sheep manure and urine The interactive effect of manure rate and topographic position on millet yield in a much drier year remains to be determined

9 Soil parameters vary cyclically during the year, in both the dry and the wet season, irrespective of manure treatment Processes influencing soil properties, such as leaching and termite activity, continue even during the dry season

Therefore, comparison of soil properties determined at different times of the year, such as at sowing and at harvest, may give a false impression of treatment effects on soil properties

10 Termite species that build large mounds, such as *Macrotermes* sp, can have a positive effect on soil fertility, and thus on crop growth

11 Seedlings of *Faidherbia* (*Acacia*) *albida*, planted out into areas of past *Macrotermes* activity, also react positively to the higher fertility In farmers' fields, plantings may therefore be more successful if concentrated on or limited to the surroundings of old *Macrotermes* mounds

12 Away from the millet fields, the vegetated strips in tigerbush areas survive on water supplied by the bare areas upslope of each strip Revegetation of degraded tigerbush areas is therefore unlikely to succeed if seedlings are planted in microdepressions created in a grid pattern Revegetation and exploitation of tigerbush areas are best based on the same ecological principles as the natural tigerbush

13 Recharge to the groundwater is normally about 200-300 mm yr^{1} under millet fields and 10–20 mm yr^{1} under tigerbush and fallow areas Increases in the surface area used for cropping are therefore likely to raise the groundwater table

14 Surface redistribution of rainfall (runoff-runon and subsequent infiltration) in a millet field increases recharge by about 15–20 mm yr^{1} While this is an insignificant amount in normal years in the Niamey area (550 mm annual rainfall), it may be quite significant during drought years or in drier areas

15 Because soil and crop growth variability play such an important role in agriculture in the Sahel, they should not be eliminated from agronomic trial areas by artificial means, such as blanket application of fertilizer This report discusses several ways of handling such variability in the analysis of experimental data

Figure 1 To Sahelian farmers such as this Fulani woman getting stable crop yields is a challenge The soil and crop growth variability in their fields may help maintain yield stability

Introduction

Good spots in a field, poor spots in a field are they just a fact of life for farmers in the Sahel (Fig 1), an irritating phenomenon which can for the most part be ignored by agricultural researchers? Or does short-distance variability in soil and crop growth, when considered in detail, also have something positive to offer? Such detailed investigations of variability have not been common Because of that, soil and crop growth microvariability is only slowly being recognized as constituting, in one form or another, an essential part of subsistence agriculture This bulletin reports the results of a 5-year project (1990-95) at the ICRISAT Sahelian Center (ISC) in Niger, investigating various aspects of soil and crop growth variability in the Sahel The project was financed by the Directorate General of International Cooperation (DGIS), Ministry of External Affairs of The Netherlands Scientific support was provided by the Department of Soil Science and Geology of the Agricultural University of Wageningen

The aim of the project was to show in a general manner—to extension specialists, to staff of development projects, to those who fund agronomic research, and to agricultural researchers—how spatial and temporal variability permeates all of Sahelian agriculture and how the project helped to throw new light on some of that variability

More details on soil and crop growth variability, including extensive references to what other researchers have written on the subject, can be found in the journal articles and conference contributions that have also resulted from the project, these are listed in the References section We gratefully acknowledge the input from farmers, students, and colleagues in collaborating institutions

Although the principles of soil and crop growth variability discussed in this report apply to most of the Sahel, our research was largely carried out at or near ISC, approximately 40 km south of Niamey in southwestern Niger (Fig 2) The climate around Niamey is typical of the southern Sahel The rainy season is clearly defined and lasts from May to September Average annual rainfall is approximately 550 mm and mostly falls during a few intense rainstorms Daily maximum temperatures during the cropping season (rainy season) average between 30 and 40°C, daily minimum temperatures, between 20 and 30°C The ISC campus is situated on a gently undulating wind-deposited sand plain The soils in and around the campus are reddish quartz sands, generally quite deep (>3 m), with a slight increase in clay percentage—from <5% to <10%—with depth Because of this high quartz content, even the topsoil is generally acidic and very low in fertility pH-KCl around 4 0, organic carbon content 0 15%, effective cation exchange capacity (ECEC) 1 0 meq 100 g^{1} The soils are also drought-prone, with an effective

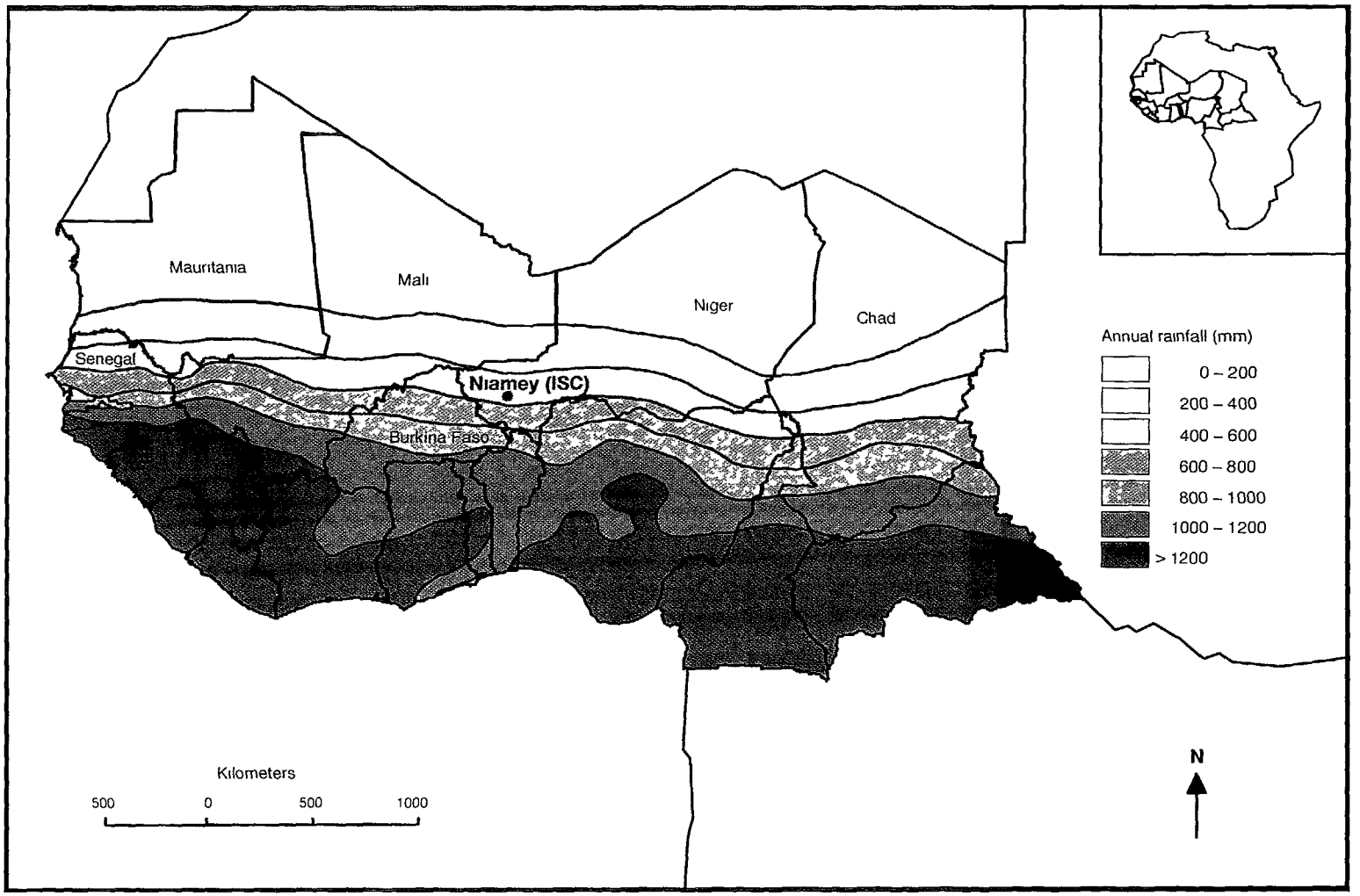

Figure 2 The north-south rainfall gradient in western Africa annual rainfall increases progressively from the edge of the Sahara desert southwards ICRISAT Sahelian Center, where most of the research reported here was done is situated approximately 40 km south of Niamey in Niger

waterholding capacity of about 8% The water table is usually found at >25 m depth (Wallace et al 1994)

The farmers in the area mostly grow pearl millet, often intercropped with cowpea The millet is sown immediately after the first suitable rain, in pockets about 1 5 m apart, and thinned to three plants per pocket during the first weeding, about 3 weeks after sowing Harvest takes place in September, and yields average 300-400 kg ha^{-1}, depending on the amount of manure applied to the fields (Brouwer and Powell 1995) Manure is supplied by cattle and sheep that mostly graze the fallow and bush areas by day and are corralled in the fields by night during the dry season

Variability in time and space

Soil and crop growth variability in the Sahel occurs on many scales in both time and space

Variability in time

The most notorious examples of variability in time are the regionwide droughts, coupled with what appears to be a general decrease in rainfall over the past 25-30 years (Sivakumar et al 1993) Local farmers are well aware of these changes The chief of one of the villages near ISC told us that farmers determine when to sow their millet by digging a hole in the soil by hand in the past, they sowed when the soil had been wetted elbow-deep (40-50 cm), now they sow when the soil has been wetted only wrist-deep (20 cm), as they feel they cannot afford to wait any longer

Farmers also feel that the incidence of drought periods during a rainy season has increased These intraseason droughts, while less spectacular than regionwide droughts, can be nearly as devastating locally A few weeks' drought soon after sowing may kill all the millet or sorghum seedlings in a field An intraseason drought at flowering time can kill all the florets and necessitate the development of new tillers Farmers partly counteract these possibilities by sowing different fields at different times and by growing varieties of different durations, either in separate fields or in the same field, where up to three varieties may be sown (Fig 2) Sandstorms or a sudden occurrence of insect pests can also cause variability on an even shorter time scale

Figure 3 Near Birni N Konni, Niger, farmers spread risk by sowing a millet/sorghum intercrop

Variability in space

Spatial variability likewise occurs over a range of scales On the regional scale there is the north-south rainfall gradient, with annual rainfall increasing progressively from the edge of the Sahara southwards (Fig 2) Pastoralists graze their herds on the grasslands in the north during the wet season, often using for dry-season grazing the major floodplains of the region (Senegal, Niger, Hadejia, Logone, and Chari rivers) Without the availability of these floodplains for grazing, the production potential of the northern grasslands cannot be fully utilized Such traditional uses of the floodplains should be taken into account when these wetlands are developed for other purposes, such as irrigated agriculture (Breman 1992, Brouwer and Ouattara 1995)

On a smaller scale, livestock manure and urine transfer nutrients from the bush and fallow grazing areas to millet and sorghum fields Farmers depend on this transfer of fertility for continuous cropping of the fields near their huts Because of population increases, the area of millet fields is increasing, and the area of fallow and bush land is decreasing This not only reduces the availability of grazing land

and of manure, but also affects the availability of wood for fuel and construction and of plant products used in traditional medicine and for other purposes Here, too, the spatial variability essential for traditional land use is becoming unbalanced due to the growing population pressure and possibly to longer-term climatic changes, such as recent droughts The decreasing rainfall predicted for the western Sahel because of the greenhouse effect (Brouwer and Mullie 1996) will further affect the ecological balance

The livestock involved in the transfer of nutrients to millet and sorghum fields need daily watering, and local wetlands, often quite small, are used for such watering The wetlands also provide opportunities for fishing and hunting, for collection of wild plant products, and for dry-season agriculture (Fig 4) Dry-season agriculture around these small wetlands, whether irrigated or using residual water following floods, generally provides higher-quality foods (vegetables, pulses) as well as cash crops and is particularly important as a fallback following poor rainy seasons The smaller wetlands also often have a higher level of fish production and support higher densities of bird life than larger wetlands The higher production is

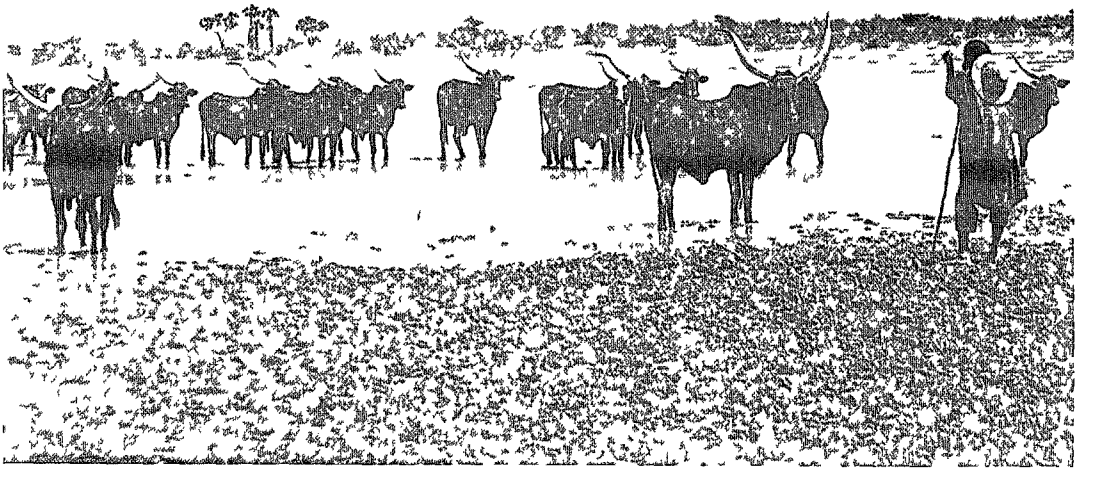

Figure 4 A wetland in the Sahelian zone northeast of Zinder As areas of high potential productivity wetlands should be managed with care to keep them from being degraded

probably related to a higher nutrient loading of smaller wetlands (Brouwer and Mullie 1994a, Mullié and Brouwer 1994)

Unfortunately, there is no coordinated management of these small, highly accessible wetlands, in spite of their high production potential and relatively low production risk As a consequence, many of them are suffering various forms of degradation, such as erosion, sedimentation, salinization, and destruction of the natural vegetation (Brouwer and Mullie 1994b) Research into the sustainable use of small wetlands for agriculture and other purposes may well prove to have a profound impact and be highly cost-effective, given also the probable increase in use of wetlands due to population growth and climatic changes (Brouwer and Mullie 1994a, 1996, Brouwer and Ouattara 1995, Brouwer et al in press)

On an even smaller spatial scale, considerable variability exists between fields Differences between fields relate partly to differences along toposequences, partly to the gradient of decreasing fertility (and decreasing intensity of management) from human habitation outward (Fig 5) Both phenomena are well documented Farmers react to both by sowing different crops or varieties in different fields

Figure 5 Millet growth around this village near Niamey reflects the underlying soil fertility gradient, which is highest close to human habitation

Finally, there is the within-field microvariability, which has been defined as "soil variability over relatively short distances (approximately 2-50 m), with differences in soil properties which do affect hydrological behavior and plant growth, but which are too small in value or extent to warrant separate classification and/or separate mapping" (Brouwer et al 1993b) Most of the effort in our project was focused on this within-field variability, which, after all, is prevalent throughout the Sahel but has received relatively little attention

How farmers perceive and use small-scale variability

Farmers are well aware of short-distance differences in soil properties Part of their management strategy is aimed at exploiting or reducing such differences For instance, some farmers near Gaya, in the Sudanian zone of southwestern Niger, sow sorghum around large old termite mounds in their millet fields Sorghum requires better water and nutrient availability than millet, and farmers know that these can be found around the larger termite mounds Near Niamey, Niger, and near Cinzana, Mali, farmers put branches, weeds, or crop residues on the scars of abandoned large termite mounds they say this assists the rapid breakdown of the hard scar (by attracting other termite species that open up the soil) and that these spots soon produce very good millet or sorghum

In the village of Bellare, close to ISC, we discussed crop growth variability with the village chief Some of his remarks were familiar, others gave new food for thought

- "Good" spots catch sand, "bad" (eroded) spots lose sand and get worse Thus differences in crop growth become more pronounced
- The soil is always "hot" (chaud) under *Faidherbia (Acacia) albida* trees, due to the manure deposited there Hence the crop there experiences problems when it does not have enough water, just as it does in the open field, where manure can burn the crop when there is little rain
- Drought does not have the same effect on all fields, it is worse on "tired" fields
- Millet is not equally sensitive to drought at all stages, it is particularly sensitive at flowering
- Farmers prefer 3 average years to 2 excellent years plus 1 poor one
- A farmer's fields are not always close together This is not a conscious choice to avoid risk—it just happens

- To enable some plants in each pocket to survive drought, some farmers do not thin seedlings, however, without thinning, yields will be relatively poor in good rainfall years

- Good rainfall does not guarantee a high grain yield, nor does poor rainfall necessarily mean a low grain yield Even when crop growth is good, "worms" (*vers*) or grasshoppers can reduce the yield

Another farmer in nearby Diakindi helped us evaluate the effects of trees and shrubs on millet growth variability Such effects seem related to the tree or shrub species, its attractiveness to livestock, its age, and its management Our main observations follow

- Under older trees of *F albida,* millet grows much thicker and darker than in the open field The farmer explained that this well-known "albida effect" is due largely to the manure and urine left by livestock that come to rest in the shade or to feed on fallen or lopped-off fruit and branches Because these trees lose their leaves at the beginning of the rainy season, they do not compete with the growing millet for light The albida effect is not evident under young trees, which are too small to produce much fodder

- Under trees of *Piliostigma reticulata,* millet growth is poor, because of competition for light and water, however, millet growth immediately outside the canopy is very good, because of the manure and urine deposited by animals feeding on the *Piliostigma* pods

- The effect of *Balanites aegyptiaca* trees on millet growth is similar to that of *P reticulata,* though much less marked

- Millet growth under and around trees of *Parinari macrophylla* is poor Neither leaves nor fruit of this tree are eaten by livestock, and it competes with millet for light, water, and nutrients Similarly, millet growth is poor under trees of baobab (*Adansonia digitata*) and karite (*Vitellaria paradoxa*)

- On the slightly raised areas around small bushes of *Guiera senegalensis,* millet grows better than in the open field The farmers, who know that the soil is probably more fertile in these spots, sow their millet more densely immediately around the bushes They then cut back the bushes to near ground level, and often burn them, before the start of the rainy season or at first weeding, to reduce competition with the millet for light, water, and nutrients

- Differences in growth under and around other tree species (*Annona senegalensis*, *Combretum* spp) relate more to preexisting fertility differences, such as old termite mounds, than to direct or indirect effects of the trees

Farmers near Dosso, 150 km southeast of Niamey, use microvariability similarly Bushes of *Pergularia* (probably *P tomentosa*) are deliberately left, even planted on purpose, in fields with millet, cowpea, and sesame Crops are said to grow better near the shrubs, perhaps because they trap sand and reduce erosion The shrub has medicinal value and is also used as a dye

Another clear example of site-specific management, which we noted near Dosso, is the sowing of pumpkins at the end of the rainy season in the loose sand deposited by floods the sand acts as a mulch and reduces the evaporation from the underlying heavier soil

Of course, farmers not only use spatial variability to their advantage, they also try to reduce it In various parts of the Sahel, they apply crop residues, livestock manure, weeds, millet chaff, chaff compost, domestic waste, and town refuse to eroded areas, either on the surface or in shallow holes (Fig 6) The organic matter

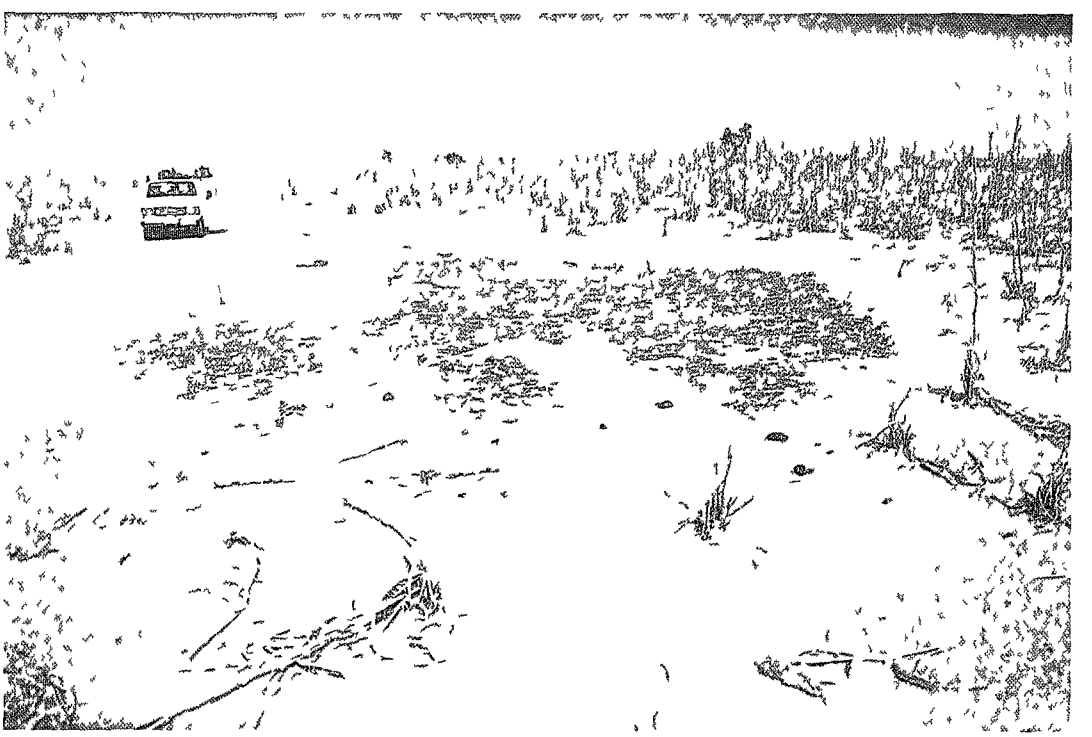

Figure 6 An eroded area near Ouallam, 100 km north of Niamey, being reclaimed by application of sheep manure

catches sand, adds nutrients, and encourages soil biological activity that breaks up crusts and increases the infiltration of rainfall

Similar techniques are also used in "good" parts of a field near Cinzana, Mali, the millet being sown where small holes had been filled with collected weeds the year before Another practice is for small villages to be moved every few years to a poor growth area in one of the fields The household waste left behind helps regenerate soil fertility and reclaim unproductive areas (Fig 7)

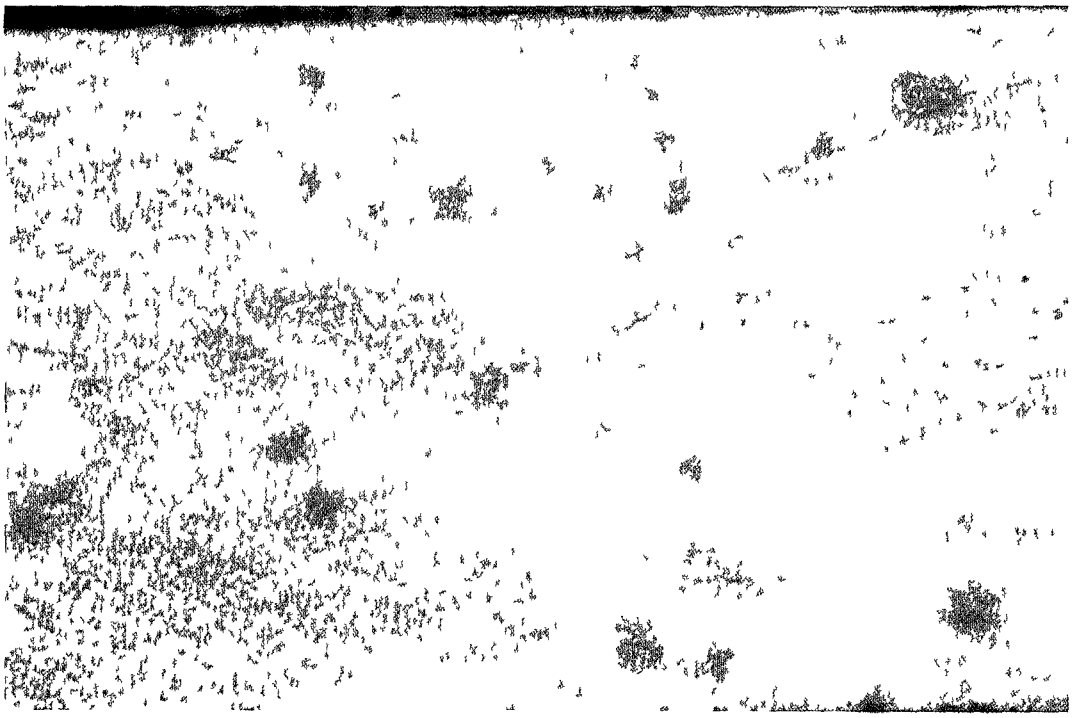

Figure 7 Excellent millet growth at a site where the village huts once stood The household refuse left behind improves fertility in poor growth areas

How researchers view small-scale variability

Traditionally, agronomists have viewed microvariability as a nuisance it distorts treatment averages and complicates the interpretation of experimental results Large coefficients of variability and large residuals mean that often no statistically significant differences are found between treatments Hence, microvariability within experimental areas has often been ignored

Alternatively, the variability over the entire experimental area is reduced by artificial means, such as blanket applications of fertilizer (Fig 8) As a result, many

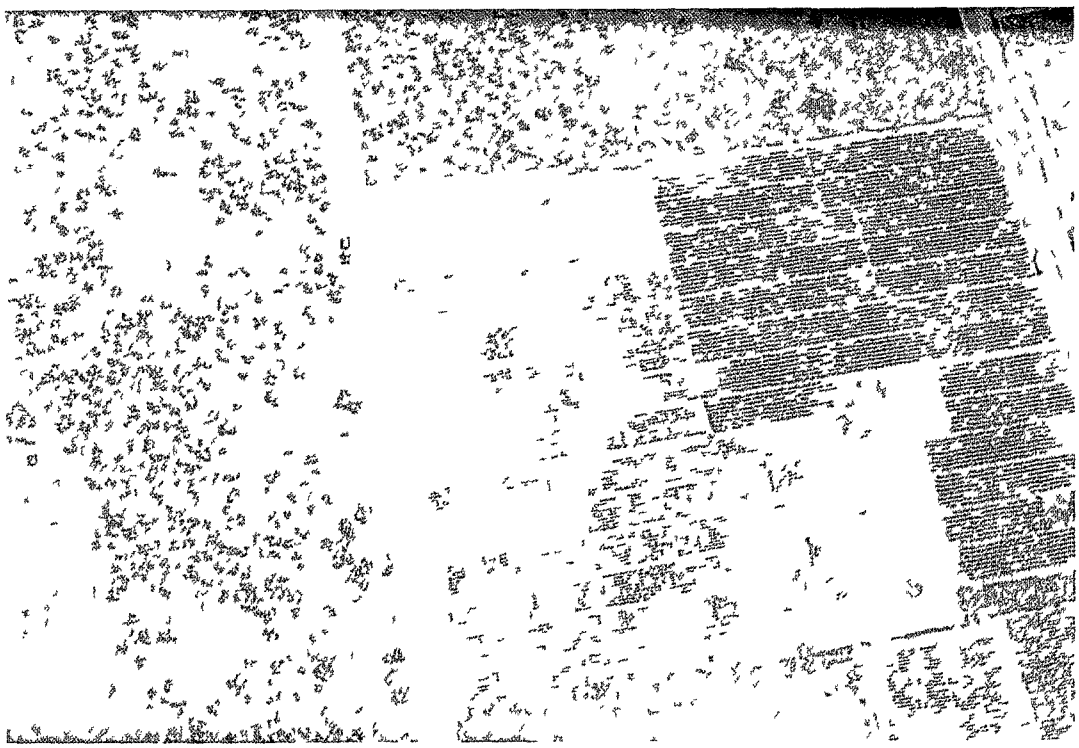

Figure 8 Millet growth in experimental fields, left natural soil variability, at right variability has been reduced by blanket application of phosphorus

experimental stations in the Sahel have a fertility status markedly different from that of the surrounding farmers' fields, for example, 90% of the fields surveyed at one station have an available P level 3-30 times that found in most farmers' fields and well above the response threshold for millet

However, agronomists have begun to recognize that many types of variability are essential components of subsistence agriculture Use of different crops and varieties and of different management methods is considered an integral part of the farmers' risk-reduction strategies in an environment they cannot control—a means of reaching a certain minimum yield each year rather than a high average over several years

Brouwer et al (1993b) showed that soil and crop growth microvariability, too, may contribute to risk reduction and yield stability in the Sahel They showed that different parts of a field may give the best yield in different years, and related this to uneven and unequal availability of water and nutrients in a field Some parts of a field may be relatively fertile but also relatively dry, other parts may be less fertile but wetter Depending on the rainfall during a particular year, the chief factor

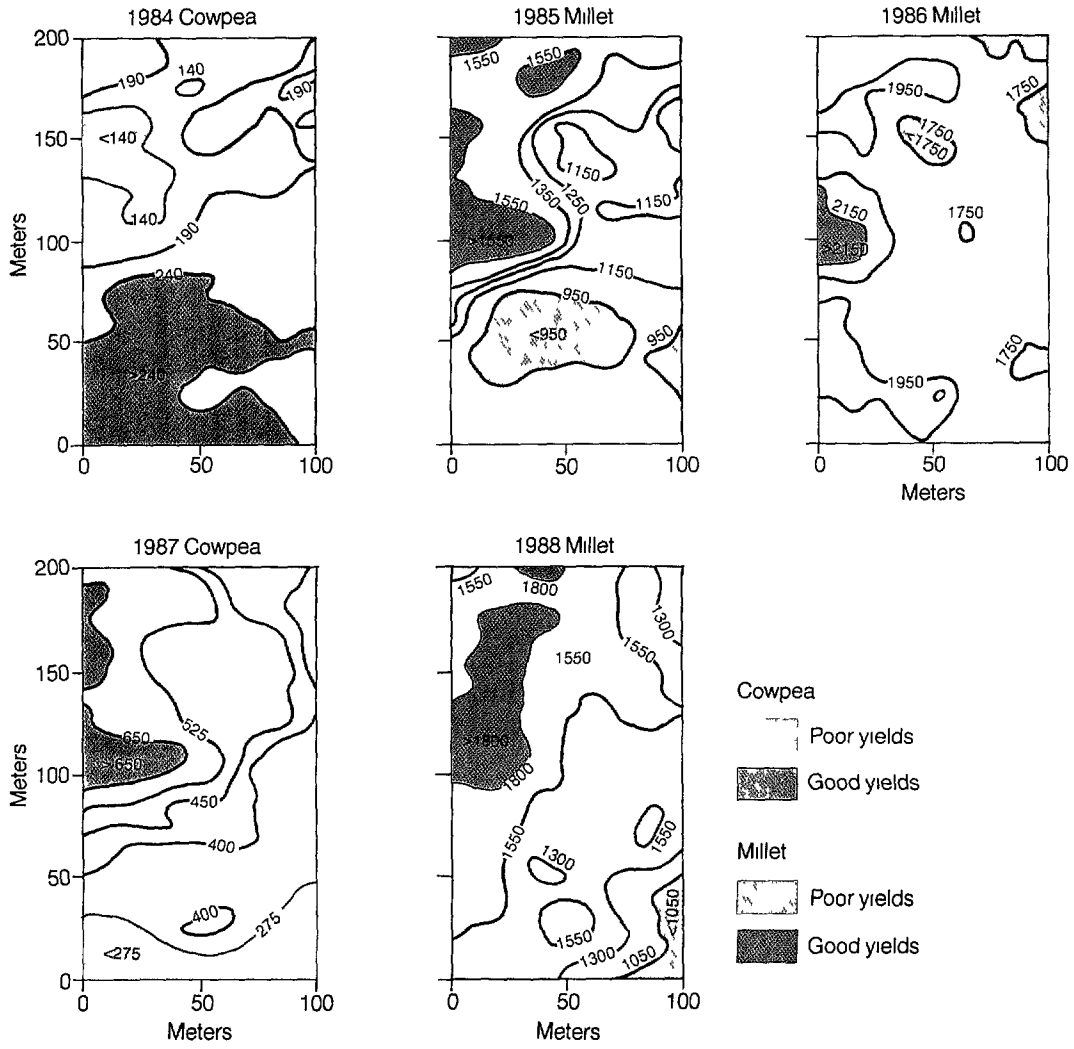

Figure 9 Year-to-year variability in grain yields (kg ha⁻¹) in the same field, areas that gave poor yields in most years (1985-88) gave relatively good yields in a drought year (1984) (Source L Fussell, unpublished data)

limiting production may be either nutrients or water, and either the most fertile or the wettest parts of a field may produce best

Figure 9 illustrates this for a field at ISC the areas of relatively poor yield during most years (1985-88) were areas of relatively good yield during a drought year (1984) On certain soil types, crops may also benefit from differences in the amount of water stored in the soil at the end of one cropping season and carried over to the beginning of the next

This conclusion of Brouwer and colleagues is to some extent contrary to the conventional opinion that the major factor limiting agricultural production is lack of water in the northern part of the Sahel and lack of available nutrients further south In fact, water and nutrients alternate in limiting crop production Within a field, they can alternate not only from year to year (good rainy season vs poor rainy season), but also from week to week and even from day to day (before and after a rainstorm following a dry period) (Brouwer 1996) In fact, water may be limiting in some parts of a field (where the crop is already wilting), while nutrients may be limiting in other parts (where there is still some water stored in the soil)

This spatial variability also has a temporal aspect Because higher soil fertility generally means more rapid development, a crop will develop unevenly where there is significant microvariability This means that the whole crop will not be equally sensitive to the same environmental factors at the same time drought around flowering time is less likely to wilt all the florets on all the inflorescences, and the occurrence of a particular pest or disease may not wipe out the whole harvest (Brouwer et al 1993b) Risk reduction through diversity is an ecological principle that is also relevant in agricultural environments

Crop growth variability in a farmer's field

Because what happens in farmers' fields should determine to a large extent the research done on-station, an on-farm study was initiated, managed by the University of Hohenheim and with major input from ICRISAT A 100 × 100 m area in a farmer's millet field was divided into 400 plots of 5 × 5 m For each plot, data were collected on sowing date, pocket density, development, and yield of the local millet variety and the wild phenotype, or "shibra", density and yield of intercropped cowpea, manure deposition, and soil crusting For each 10 x 10 m area, bulked soil samples from three depths were analyzed for parameters such as pH, organic C, N, P, exchangeable bases, and acidity A contour map and a map showing features such as shrubs, trees, termite mounds, and footpaths were also made Soil samples were taken at several points to a depth of 2–3 m for root density measurements

As expected, the soil at the site showed large relative, if small absolute, differences in various parameters For instance, for the 100 samples from the 0-0 2 m depth, pH-KCl ranged from 3 85 to 4 74 (average 4 07), organic C from 0 09 to 0 20% (average 0 14%), and ECEC from 0 65 to 1 65 meq 100 g^{-1} (average 0 95 meq 100 g^{-1}) (Wallace et al 1994)

Sowing density also varied enormously the average density for millet was 4600±1260 pockets ha^{-1}, for cowpea, 886±463 pockets ha^{-1} This was partly due

directly to soil differences, partly to the farmer's taking these soil differences into account when sowing and therefore managing different parts of the field differently

The differences in soil and sowing density were reflected in the biomass production total above-ground dry biomass of millet at harvest averaged 3350±1964 kg ha^{-1} (range 27-13 954 kg ha^{-1}, on a 5 x 5 m plot basis) Of this, on average, 7% consisted of the wild shibra millet rather than the local variety Cultivated millet grain production averaged 650±391 kg ha^{-1} (range 0-2885 kg ha^{-1}) (Wallace et al 1994) There was a good log-log correlation between millet tiller weight and leaf area index (Levy et al 1996) There was also a good decreasing relationship between root shoot ratio and above-ground biomass Root shoot ratios ranged from 0 7 to 1 5, the high ratio of 1 5 in one plot coinciding with a high aluminum concentration and the presence of a very hard soil crust

Total root length, on the other hand, was found first to increase with increasing above-ground dry matter production, then to decrease This we interpret to mean that up to an above-ground biomass of about 4000 kg ha^{-1}, soil conditions limited root as well as shoot growth Above this threshold, soil conditions in most plots investigated apparently improved enough to support more shoot mass with less root length (Table 1) In addition, with increasing above-ground dry matter, root length density increases occurred at ever greater depth (Table 1) This supports the view that the total depth of soil with characteristics suitable for millet roots—that is, the depth of soil deposited by the wind relatively recently—plays a role in determining root as well as shoot growth Indeed, total above-ground dry matter is better correlated with root length density at 0 90-1 05 m depth than at any other depth (r^2=0 61) At this depth, root length density appears to be negatively correlated with Al^{+++} concentration (inhibiting root growth?) and water-soluble P (a high concentration of water-soluble P enables the plant to take up more P with less root length) and positively correlated with nitrate-N

So far, correlation analysis of millet grain production and soil factors has failed to identify any single causal factor for millet yield variability (Stein et al in press) The highest correlations were found for total N at 0-0 2 m depth (r=0 41) and at 0 2-0 4 m depth (r=0 31) and organic C at the same depths (r=0 37 for both) Negative correlations (r=-0 25, approximately) were found with ECEC values at all depths These negative correlations are probably related to increases in clay content with depth and erosion of the surface soil Where the soil is more eroded, it is less fertile, but also has a higher clay content, and thus a higher ECEC, close to the surface The negative correlation with CEC is in fact a negative correlation with microtopography where the CEC is higher at the surface, there has been more erosion and thus a lowering of the soil surface Erosion on these soils generally also

Table 1 Average characteristics of various millet shoot growth classes, Bellare, August–September 1992

Dry matter class 16/9 (harvest) (kg ha^{-1})	0-1000	1000-2000	2000-3000	3000-4000	4000-5000	5000-6000	6000-7000	7000-8000	8000-9000	9000-10000	>10000
Number of plots (n=400)	35	56	91	104	43	34	16	11	3	3	4
Frequency	0 09	0 14	0 23	0 26	0 11	0 09	0 04	0 03	0 01	0 01	0 01
Dry matter (kg ha^{-1})											
Total above-ground	571	1525	2493	3504	4426	5424	6497	7492	8430	9343	11316
Straw	397	1038	1669	2347	2985	3715	4416	5329	6093	6498	8136
Grain	94	296	514	725	897	1071	1312	1363	1477	1836	2089
Harvest index	0 15	0 21	0 21	0 21	0 21	0 21	0 21	0 19	0 20	0 20	0 18
Roots (kg ha^{-1})	360	560	770	940	930	880	820	790	760	740	725
Root shoot ratio	0 63	0 37	0 31	0 27	0 21	0 16	0 13	0 11	0 09	0 08	0 06
Root length density (cm cm^{-3}) at soil depth (cm)											
0–15	0 30	0 80	1 15	1 20	1 00	0 80	0 70	0 55	0 50	0 40	0 40
15–30	0 20	0 45	0 75	0 90	0 75	0 55	0 35	0 35	0 35	0 35	0 35
30–45	0 10	0 25	0 40	0 50	0 45	0 35	0 30	0 25	0 20	0 20	0 20
60–75	0 05	0 12	0 18	0 25	0 30	0 32	0 28	0 22	0 18	0 14	0 12
90–105	0 01	0 03	0 05	0 07	0 09	0 11	0 13	0 15	0 17	0 19	0 21
120–135	0 01	0 02	0 04	0 06	0 07	0 09	0 07	0 05	0 03	0 01	0 01
150–165	0 01	0 02	0 03	0 03	0 04	0 05	0 06	0 04	0 02	0 01	0 01
180–195	0 01	0 02	0 02	0 02	0 02	0 02	0 03	0 02	0 01	0 01	0 01
Total root length 0–203 cm (km m^{-2})	1 25	3 07	4 71	5 57	5 20	4 58	3 87	3 35	2 96	2 66	2 66

means a hardening of the soil surface All hard areas, either partly eroded termite mounds or eroded depressions, show relatively poor millet growth and grain production (Brouwer et al 1994, Stein et al in press)

Using a new mathematical method to quantify the similarity between the spatial patterns of millet production and various soil parameters, we found an even better correlation between ECEC at 0 7-0 9 m depth and millet grain production, showing clearly the effect of ECEC on millet root growth at that depth (Stein et al in press)

Where cultivated millet growth was poor, shibra growth was proportionally greater, in the poorest millet growth class, the shibra produced up to 35% of the straw and 21% of the grain Although this wild phenotype is generally considered a weed, it is often used to make couscous, when it is harvested before it is quite ripe, to keep the seeds from falling to the ground

Short-distance variability in rainfall infiltration

Besides the soil physical and chemical properties, variability in the availability of water also affects crop growth This is often ignored in agronomic experiments in the Sahel, for example, in the calculation of water balances of different varieties of a particular crop, or of a single variety under different types of management Where changes in soil water storage are measured in such experiments, they are usually measured with a single neutron probe access tube in each plot In addition, these calculations assume that all the rain infiltrates where it falls

But this assumption may not be correct Even on very sandy soils, both puddles and relatively dry spots are visible during rainfall (Fig 10) This indicates local redistribution of rainfall through short-distance overland flow within the field, even if there is no runoff from the field One way of quantifying local

Figure 10 Not all rain infiltrates the soil where it falls even on very sandy soils, puddles and dry spots are visible during rainfall

infiltration of rainfall is to measure soil water storage immediately before and after a rainstorm and compare the change in soil water storage with the amount of rain caught in a raingauge, assuming that the wetting front in the soil has not penetrated beyond the maximum depth of measurement The ratio of change in storage to actual rainfall is called the rainfall concentration factor (RCF) An RCF of <1 0 implies net runoff at the point of measurement, an RCF of >1 0 implies net runon (Gaze et al 1996)

In collaboration with the Institute of Hydrology and the University of Reading in the UK, we studied infiltration of rainfall in a traditionally managed millet field near ISC during 1992-94 The soil was >90% sand The RCF values varied widely (0 3-3 4) between the neutron probe access tubes, with about 20% of the values being outside the range 0 6-1 2 (Gaze et al 1996) There was a fair amount of consistency between storms, with spots at the extremes of infiltration showing consistently high or low RCF values However, changes in crop cover and degree of crusting, as well as differences in rainfall amount and intensity, will all affect the RCF values calculated for a particular access tube (Gaze et al 1996)

Clearly, not all rain infiltrates where it falls, even on very sandy soils It is important to recognize this from the point of view of water balance calculations where in the range of 0 3-3 4 does the RCF of a particular access tube fall? It is also important from the point of view of soil and crop growth variability what effects will such differences in infiltration have on water storage and nutrient leaching and how will they affect yields and yield stability?

Applying manure for optimum crop production

In the farmer's field we studied, plots on the eastern side of the experimental area showed excellent millet growth Adjacent to these plots, just outside the experimental area, is a well The animals that are taken to be watered at the well during the dry season leave large amounts of manure and urine, which promote millet growth (Figs 11, 12) However, it is this same area around the well that gets manured every year How effective is this use of a scarce fertilizer resource? Some answers to this question have come from a manuring trial set up by the International Livestock Centre for Africa (ILCA) at ISC, which we monitored in part

This experiment tracked the movement of N, P, and organic C through the soil following application of manure Small plots were given sheep and cattle manure in two ways (1) the animals were coralled on the plots for 1 or 3 nights, (2) an equivalent amount of manure (without much of the urine) was carried to the plots

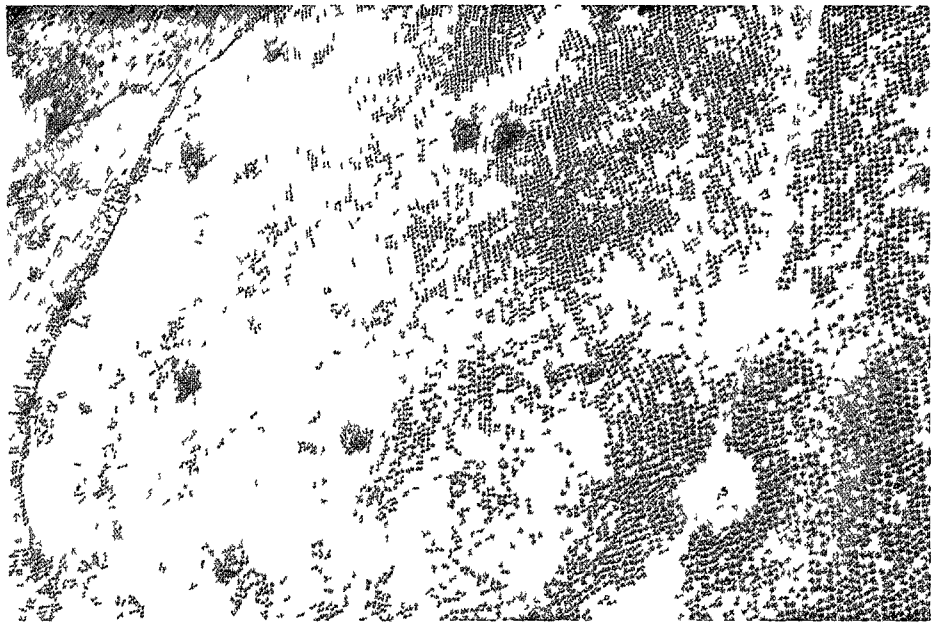

Figure 11 Crop growth variability in a farmer s field at Bellare near ISC Millet growth around the well (right foreground) where livestock are watered is markedly better than in other parts of the field

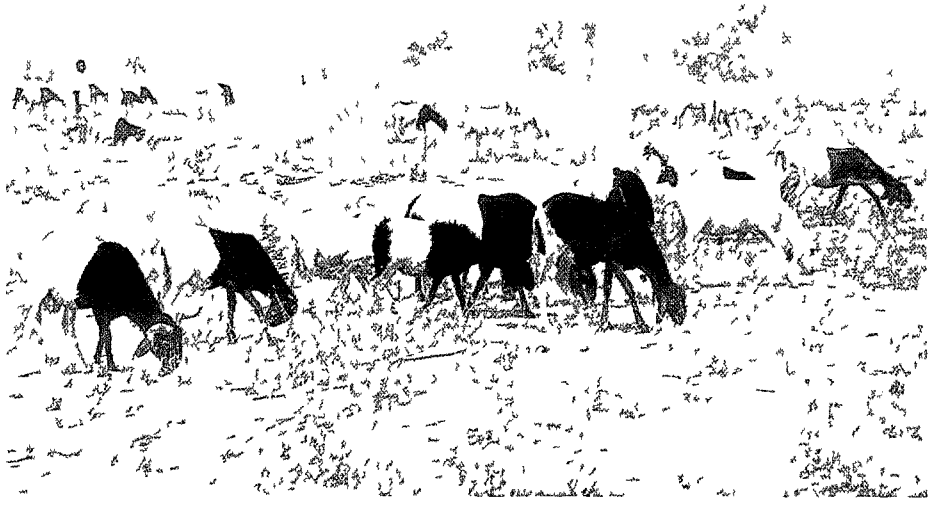

Figure 12 Animal manure is the chief source of soil nutrients in the Sahel Sheep and cattle graze fallow areas by day and deposit their manure and urine in millet fields where they are corralled by night

from stalls where similar animals were kept overnight Nutrient movement was tracked using soil samples taken from several plots to a depth of 1 9 m, five times over 1 year, Figure 13 shows the course of organic C movement

A major conclusion from this manuring experiment was that, at least on the sandy soil at ISC, there can be considerable leaching of nutrients Calculations showed that within 1 year after the application of 10 t ha^{1} of cattle manure (a rate that does occur in farmers' fields), soil nutrient store at 1 5–2 0 m depth had increased by 91 kg ha^{1} of N, 19 kg ha^{1} of P, and 1070 kg ha^{1} of organic C Similar amounts had probably been leached to beyond the 2 0 m depth (Brouwer and Powell 1995, 1996)

These findings clearly show that such large amounts of manure need not be applied every year, although that does happen, for instance, around wells, as at the on-farm site To reduce leaching losses, it would be more efficient to apply smaller amounts of manure more frequently, rather than large amounts less frequently (Brouwer and Powell 1995, 1996) The appropriate smaller amount depends on the individual plot Yield and nutrient balance data for individual plots (Table 2) show that, although the average yield depends on the number of nights livestock were corralled in a plot, the maximum yield is scarcely influenced by this factor Within a treatment, the ratio between highest and lowest yield is much higher for the one-night than for the three-night treatment From this, we conclude that one night of manuring each year (manure and urine about 2 8 t ha^{1} from cattle or 3 0 t ha^{1} from sheep) is enough to attain maximum yields on some plots but not on others (Brouwer and Powell 1995, 1996) Similarly, three nights of manuring each year (10 t ha^{1} of cattle or sheep manure) is probably adequate on some plots but too much on others (Bouma et al 1995, 1996)

For the most efficient use of the manure available, we need to know which plots should receive one night's worth of manure and which three nights' worth The ILCA experiment gave a first indication For each plot, the relative wetness (amount of infiltration) was determined from water content of some of the soil samples Within each of the four treatments, the wettest plot (i e , the one with the deepest drainage and the most leaching) showed the highest net losses of N and P (Bouma et al 1995, 1996)

Subsequently, plot wetness was related to microtopographical position Wetness of individual plots correlated well with plot position on the slope, as inferred from the 0 05 m contours on a specially prepared topographic map plots on concave slopes or at the bottom of depressions were the wettest, followed by those on flat crests, and next by those on straight slopes, plots on convex slopes were the driest (Table 2)

As net nutrient balances were negatively correlated with plot wetness (Bouma et al 1995, 1996), which, in turn, was correlated with plot position on the slope, it

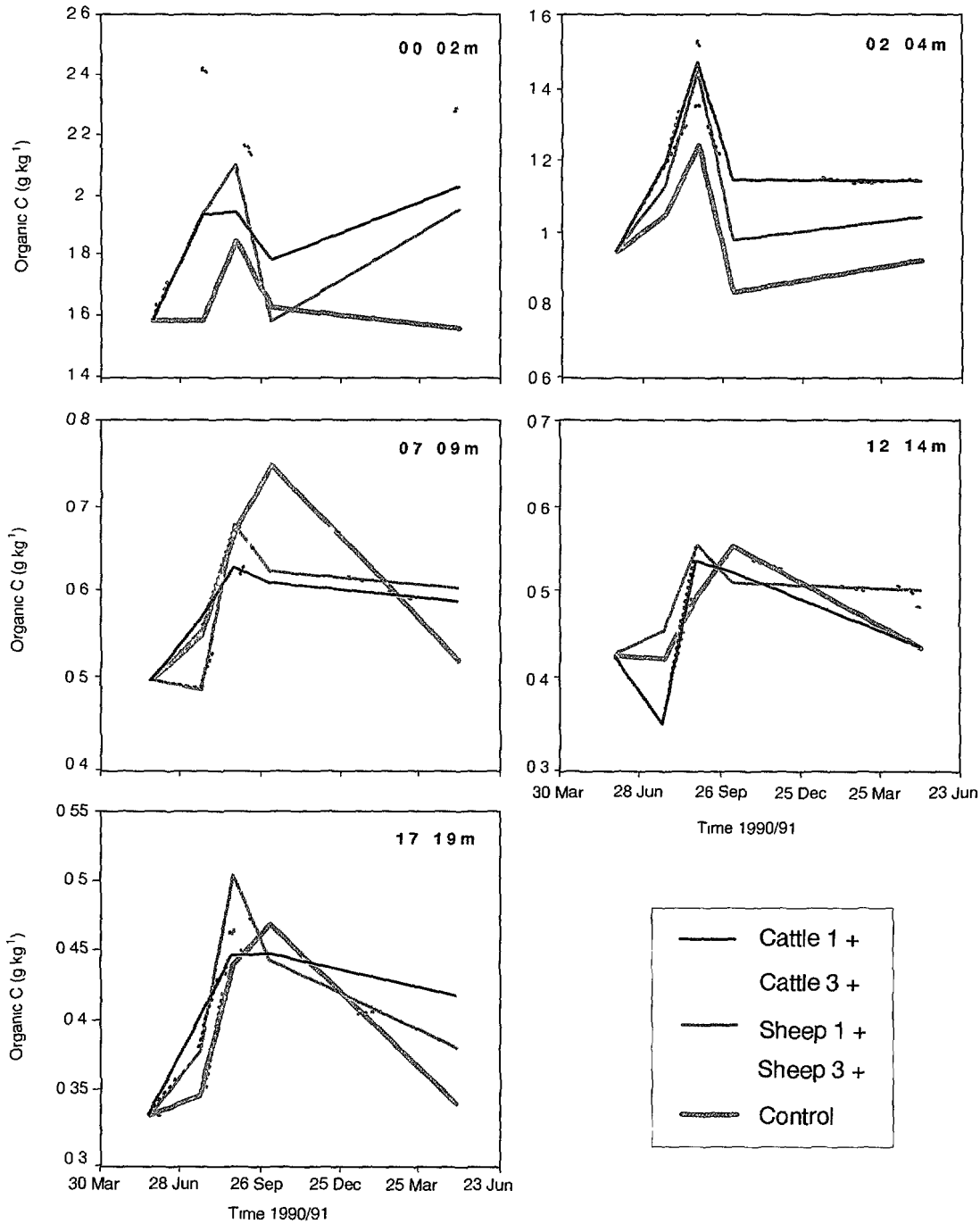

Figure 13 The movement of organic carbon through the soil during the year following application of manure

Table 2 Yields, N and P balances (in kg ha⁻¹ for the top 2 0 m of soil), May 1990–May 1991, using average background values for May 1990 Data from ILCA/ICRISAT/Agricultural University of Wageningen experiment on manure application, ICRISAT Sahelian Center, Niamey, Niger

Species	Nights[1]	Manure (kg ha⁻¹)	Wetness[2]	Position on slope	Yield (kg ha⁻¹) Grain	Stover	Dry matter	Ratio highest lowest yield Grain	Stover	Dry matter	Net balance N	Net balance P
Cattle	1	2970	3	Concave	356	1428	1783				177	-167
Cattle	1	4030	2–3	Straight	1288	4429	5717	3 6	3 1	3 2	454	-157
Cattle	1	1530	2	Crest	814	3970	4785				260	-241
Cattle	3	8460	3	Crest	974	3914	4888				-11	-67
Cattle	3	9830	2	Convex	751	3814	4566	1 4	1 3	1 3	251	-43
Cattle	3	9430	2	Convex	709	3078	3787				329	244
Sheep	1	2810	2	Concave	1154	3763	4917	1 6	1 7	1 7	314	-108
Sheep	1	3160	1	Convex	717	2181	2898				464	-18
Sheep	3	11940	3	Concave	875	3955	4830				-200	-108
Sheep	3	9100	2	Straight	626	3966	4593	1 4	1 1	1 1	236	-151
Sheep	3	9050	1	Convex	802	3480	4282				210	58
Control	0	0	2–3	Concave	243	855	1098				35	-25
Control	0	0	2–3	Crest	361	1575	1936	2 4	1 9	2 0	179	-163
Control	0	0	2	Straight	153	821	974				-80	-151
Control	0	0	1–2	Straight	357	1373	1730				321	-211

1 Number of nights livestock were corralled in plot
2 Wetness 1=low 2=average 3=high (estimated rainfall infiltration)

Source Bouma et al 1995

would appear that scarce nutrient resources are best applied where leaching would be lowest, that is, to plots on convex slopes, flat crests, and possibly straight slopes, in that order, but not in depressions

Such targeted application would reduce the losses of N, P, and C through leaching on these very sandy soils However, crop production is also limited by lack of water, and in dry years or years with a pronounced intraseason drought, low spots may be the only areas in the field where enough water is available when the crop most needs it (see Brouwer et al 1993a, 1993b, Gaze et al 1996) This aspect needs to be taken into account in applying manure and requires further investigation

Another aspect to consider in targeting manure application is the combined effect of topographic position of the plot and the type and rate of manure applied The ILCA manuring experiment indicated how this combined effect influences millet yields

Cattle manure

- On flat crests or convex slopes, 1 5 t ha^{1} yr^{1} of manure with urine, deposited by cattle corralled on-site for one night, seems adequate for obtaining good yields (800 kg ha^{1}, or two to four times the yields of the control plots) Thus, 9–10 t ha^{1} yr^{1} of manure appears excessive
- Where 5–10 t ha^{1} of cattle manure was applied even on a relatively dry, convex slope or a crest, large amounts of nutrients were leached to a 2-m depth Therefore, 1–2 t ha^{1} of cattle manure applied every year may be more efficient than 5 t ha^{1} every 2 or 3 years
- On a straight slope, 4 t ha^{1} yr^{1} of cattle manure and urine is more than enough for attaining good millet yields
- On a concave slope, 3 0 t ha^{1} yr^{1} of cattle manure and urine was not enough to obtain a good millet yield Whether larger amounts should be applied in such situations is discussed below

Sheep manure

The effect of sheep manure and urine appears to be independent of the topographic position of the plot On both concave and convex slopes, 2 8 t ha^{1} yr^{1} of manure and urine, deposited by sheep corralled on-site for one night, gave an excellent millet yield (800 kg ha^{1}) This may be because sheep urine increases soil pH

markedly, so that, even in leached areas, the low soil pH no longer limits millet growth Cattle urine does not have the same effect

Sheep manure is also broken down and leached more slowly than cattle manure (see Brouwer and Powell 1995) For the most effective use of nutrients, therefore, cattle manure and urine could perhaps best be applied in the higher, less leached areas, and sheep manure and urine in the lower, more acid areas This possibility needs to be confirmed through further investigation

We emphasize that the data on which we based our conclusions regarding millet yield and manure application rates were obtained during a year with good rainfall distribution, except during a 3-week dry period in August The results may be different in years with different rainfall distribution

This experiment raised one other question if at the outset some of the experimental plots were inherently wetter, some inherently drier, how were they distributed over the various treatments, and how might this have affected experimental results? Background soil values need to be measured for individual plots, rather than averaged fo. experimental blocks or whole experiments, this will be discussed later

Natural variability of soil parameters during the year

Soil nutrients show a natural variability over the year In the manure application experiment, control plots also showed changes in concentrations of N, P, and C with time The increases in nutrient concentration near the surface at the beginning of the growing season (May–July) and lower down somewhat later, are caused partly by natural background levels of leaching partly by the development of the millet root system At the end of the rainy season, when the millet is harvested, the soil is often still near field capacity Leaching and breakdown of organic matter can continue well into the dry season, as long as there is sufficient moisture in the ground Termites may also continue to incorporate organic matter, causing the increases in organic C at 0–0 2 m depth in the dry season While changes during the cropping season can be expected, our experiments showed that such changes continue to take place in the dry season as well

Because of such natural cyclical changes in soil parameters (including pH), comparing samples taken at different times of the year (for example, at the start of the cropping season and at harvest time) may give a false impression of treatment effects Therefore, soil samples to be compared should be taken at the same time of year, at the very least, differences in sampling time and their possible effects should be noted when reporting treatment results

Termites can raise soil fertility

Differences in soil fertility and crop growth stem chiefly from differences in water balance and in management, but other causes also contribute to them One cause is the activity of termites Although termites are usually considered pests because some species attack wooden structures or even crops, such as groundnut before harvest, other species can serve useful ecological functions In the Sahel, termites that build large mounds, such as *Macrotermes* sp, can increase soil fertility The material of which they make their mounds, and with which the underground tunnels are coated or backfilled, is often richer in clay and nutrients than the surrounding soil When the mounds are abandoned and break down, they create areas that are both chemically and physically more fertile than the unaffected soil This is evident from the glossy, dark green color and luxuriant growth of the millet, cowpea, groundnut, or sorghum growing on such microsites in farmers' fields (Fig 14) In our farmer's field at Bellare, Rotmans (1994) estimated that 20% of his experimental area of 20 x 200 m showed better growth that could be related to former termite mounds

Figure 14 Luxuriant growth of groundnut around an old termite mound at ICRISAT Sahelian Center Soil around such mounds is more fertile than the surrounding soil

This beneficial effect of certain termite species on soil fertility and plant growth has been documented in agronomic experiments For example, in an experiment at ISC, various soil amendments, such as fertilizer and water-holding gel, were tested, to improve establishment of outplanted seedlings of *F albida* Two years of testing showed no effect of any amendment However, within the experiment, there were clear areas of good growth and poor growth that showed no correlation with treatment boundaries (Geiger et al 1992) Subsequent investigation showed that the higher soil fertility responsible for the areas of good growth was well correlated with the macroscopic evidence of prior termite activity (Brouwer et al 1992) Even where the macroscopically visible tunnels had been destroyed by other smaller termites turning over the soil, trees grew markedly better in these areas than in others (Miedema et al 1994) Termite activity may therefore be an important component of longterm sustainable agriculture in the Sahel This knowledge could be put to practical use, for instance, to increase the establishment of *F albida* seedlings by planting mostly in areas around termite mounds We are investigating this option further

However, there is now a trend towards replacing traditional spot tillage of millet and sorghum fields with whole-field tillage, using animal traction Frequent tillage often leads to changes in the composition of the termite population, its effect on the activity of beneficial termites such as *Macrotermes* sp therefore needs to be examined

We would like to add here that the effects of old termite mounds on crop growth are influenced by rainfall distribution The higher fertility may lead to excessive early growth of the crop, which could be a disadvantage if water is lacking For instance, during a prolonged intraseason drought one year, the site of an old termite mound in a groundnut experiment was marked by an area of large, wilting groundnut plants in the midst of smaller, healthy-looking plants

Faidherbia albida and microvariability

Another important component of sustainable agriculture in the Sahel is the tree, *F albida* The superior growth of crops under the canopy of these trees is well known in the region (Fig 15) Factors that may contribute to the "albida effect" include a more favorable microclimate under the mature trees, deposition of manure and urine there by livestock seeking shade or food, nitrogen fixation by the trees, and recycling by their deep roots of nutrients from lower soil levels Besides its traditional uses, this tree also has excellent potential for agroforestry, and planting out of its seedlings in farmers' fields forms part of many recent development projects

Figure 15 Millet grows markedly better under a Faidherbia (Acacia) albida *tree than elsewhere in the farmer s field*

Here again, we emphasize that the beneficial effects of *F albida* may depend on rainfall distribution One year, the high fertility under the trees caused such rapid early growth of the millet there that, during a subsequent 3-week drought in June, these plants wilted and died, the smaller millet plants in the open field survived and yielded normally (Brouwer et al 1993b)

Managing tigerbush vegetation

So far, we have mostly discussed the variability found in cultivated fields But what happens away from the fields, in the fallow and bush areas, is also important, especially in relation to the transfer of nutrients from there to the fields via livestock Farming families in the Sahel also use these noncultivated areas for other purposes such as collecting wood for fuel and for construction, as well as medicinal and other useful plants When these noncultivated areas change or degrade, life will also change or become more difficult for farmer families

Part of our research effort was spent on areas of tigerbush, a natural pattern of vegetation found on lateritic plateaus with very shallow, stony soils Tigerbush

consists of strips of bush vegetation, aligned along the contour, alternating with bare areas (Fig 16)—an extreme example of spatial variability! Our research confirmed that the bare areas, which are heavily crusted, are essential for delivering water and nutrients to the vegetated strips Without this redistribution of resources, the tigerbush would not survive in drier years (Bromley et al 1997a) The microclimate found in the middle of the vegetated strips is very different from that found in the open areas Clearly, this type of vegetation is in delicate balance with its environment Tampering with the ecological system—through overgrazing, excessive cutting of wood, or even clearing for cropping—will quickly lead to environmental damage that is difficult to redress Indeed, many plateaus around Niamey have become bare over the last few decades

Although there have been attempts to replant these denuded areas, many revegetation projects take no account of the ecology of the original tigerbush vegetation New trees are often planted in shallow basins spaced 3–4 m apart, constructed along the contours in rows spaced 4–5 m apart This regular spacing is completely different from that of the natural tigerbush Moreover, replanting is often done with trees and shrubs that are not native to the area It would be worth

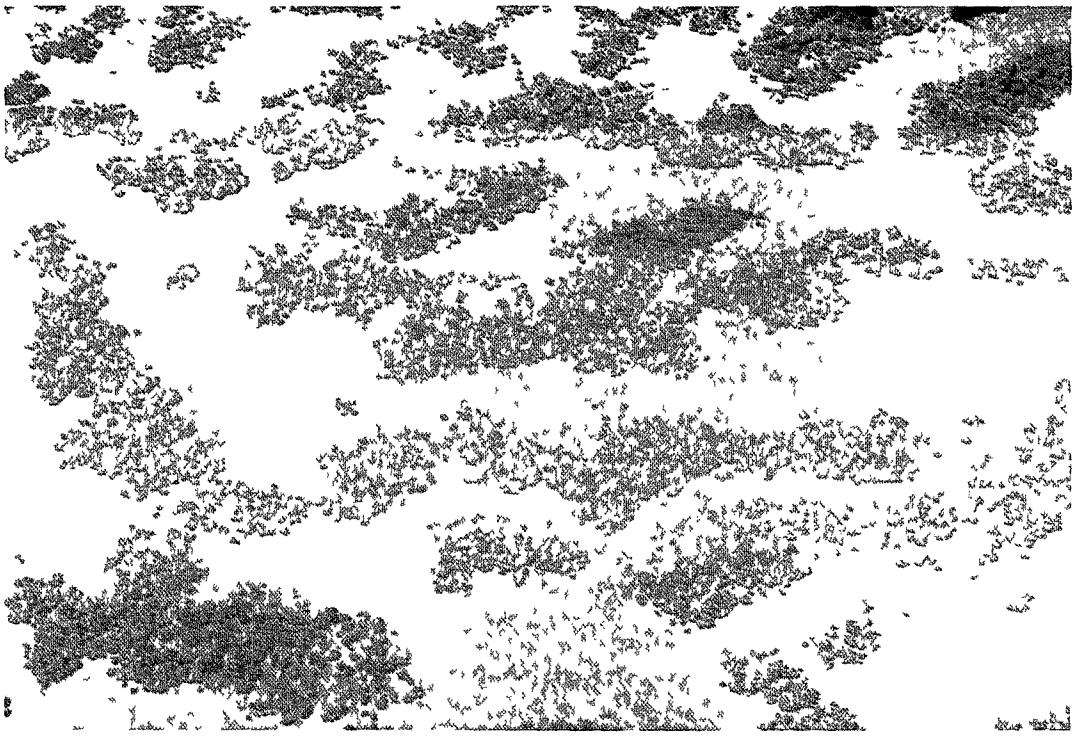

Figure 16 Tigerbush vegetation shows strips of bush areas alternating with bare areas, the drier the climate, the further apart are the vegetated strips

experimenting with a more natural method of revegetation, using local species planted in strips, preferably in the same places where the vegetated strips were last located and where the soil is more fertile Efforts should also be made to attract termites to the strips to be replanted, where they can help break up the hard crusts (Torrekens et al in press) This could be done by depositing dead branches or straw on the ground for the termites

Landscapewide processes groundwater recharge and climate change

Groundwater recharge

Away from the rivers and other wetlands, most people depend on groundwater for their domestic use, farming, and livestock for the major part of the year (Fig 17) Recharge of groundwater is therefore crucial (Bromley et al 1995) Groundwater recharge under millet fields is about 200–300 mm yr^{1} (Gaze et al 1996), under tigerbush and fallow areas, it is 10-20 mm yr^{1} (Bromley et al 1997b, L R Gaze 1995, personal communication) Gaze and colleagues (1996) calculated that surface redistribution of rainfall in a millet field caused a regular fieldwide increase in groundwater recharge of 15–20 mm every year Although relatively small during wet years, such an increase becomes significant during dry years Similarly, surface redistribution of rainfall in fallow areas, where there is little recharge during most years probably has an important effect on groundwater recharge This effect of surface redistribution on groundwater recharge is

Figure 17 A well under construction Groundwater is precious in the Sahel and land use profoundly affects its availability

independent of whether there is net runoff (as from many fallow areas) or not (as in many millet fields) While the increased clearing of bush and fallow land for cultivation reduces nutrient availability, it probably increases the availability of groundwater

Climate change

The increase in cultivated area and decrease in fallow and bush areas—through changes in the exchange processes between the lower atmosphere and the earth's surface—may also affect the climate of the region Because of this, we participated in, and contributed to, the International Hydrology Atmosphere Pilot Experiment, HAPEX-Sahel This experiment, one of a series in different parts of the world, was set up to study the interaction between the earth's surface and the lower atmosphere, in order to provide information relevant to the upscaling of hydrological, energy exchange and other models from the 1 x 1 to 200 x 200 km scale The latter scale is equivalent to the size of the grid cells in global circulation models, used to simulate climate changes Basic data for input into such global circulation models were also collected

For details, see Cuenca et al 1996, Goutorbe et al 1994, Prince et al 1995, and Wallace et al 1994

Using variability to improve crop production

The aspects of soil and crop growth variability discussed so far can also be put to practical use to improve crop production In outlining how, we must distinguish three types of agriculture, based on the external inputs used

- Zero external input agriculture aims largely at self-sufficiency and thus at reduction of risk This allows little margin for purchasing inputs not produced locally In much of the Sahel, this situation will prevail for the foreseeable future Pertinent research should therefore be aimed at reducing risk, offering farmers an array of possibilities for wet and dry years, rather than the one solution that does best overall but may do poorly during dry years Increasing the choice of suitable crop species and varieties can play a key role here Pertinent research should also aim at fostering more efficient use of the limited resources available locally, rather than at using external inputs
- Low external input agriculture produces some material for the market, using small amounts of purchased inputs, either because risk of crop failure is relatively low (as on farms along margins of water bodies and where rainfall is

more assured) or because farmers have sufficient financial reserves to absorb the losses of occasional crop failure However, risk reduction may still be a secondary goal Research should be aimed at making the most of locally produced and imported inputs, with some thought of reducing risk through diversification

- High external input agriculture aims almost solely at production for the market Such high-input agriculture is relatively uncommon in the Sahel Longterm management of soil fertility is a major concern here, to avoid exhausting the soil As the production environment can be controlled to a greater degree than in other types of agriculture, diversification to reduce risk is not a direct objective

The spatial and temporal variability we have discussed is an advantage in the first type of subsistence agriculture, contributing to yield security At the other end of the scale, cash cropping aims at high average yields rather than yield security, because this requires a controlled environment in which the whole crop matures at the same time, soil and crop growth variability is a disadvantage here

However, improved knowledge of such variability can help the farmer use all local and external resources more efficiently, managing different parts of a field differently if necessary If, for example, infiltration of water into the soil can range from 30 to 340% of rainfall, knowing precisely where water is available can help the farmer decide which variety of a particular crop to sow where Knowing where nutrients will get leached out of the soil will indicate how to match the kind and amount of manure to the terrain

In both subsistence agriculture and cash cropping, efficient use of nutrients is essential in the first, because fertilizer resources are limited, in the second, because of production economics and the need to protect the environment The benefits for agricultural production in the Sahel of "farming by soil," or "precision agriculture" should be explored and exploited further

Handling variability in agronomic research

For agronomic researchers, variability can cause problems in the interpreting of experimental data However, because it is so widespread in farmers' fields, eliminating such variability in experimental areas by such means as tillage and blanket applications of fertilizer may distort the results of agronomic research In the field, variability may affect water- and nutrient-use efficiency, reduce production risks, and increase yield stability Therefore, it is essential that researchers take into account—especially for transfer of technology or assessment of

risk and yield stability—the soil and crop growth variability so characteristic of the Sahel

To handle the problems of spatial variability in experiments, researchers can

1 *Sow a cover crop the year before the actual experiment starts* the cover crop will help identify areas with different growth potential, which is a function of soil fertility and the rainfall in that year If the cover crop is harvested and its biomass or grain production determined separately for each future plot area, the production in each plot can be used as a covariable in the statistical analysis of the subsequent experimental results Alternatively, the cover crop production can be used to delineate within the experimental area blocks of similar production potential These blocks may be of irregular shape and can then be used to distribute treatments and replications over the experimental area in such a way that all treatments have the same number of replications in poor, average, and good growth potential areas Of course, differences in weather can also affect yield patterns, for example, if the rainfall distribution in the cover crop year differs markedly from subsequent years, there may be a negative rather than a positive correlation between cover crop yields and experimental yields

   If such a preliminary cover crop cannot be sown, it may be possible to evaluate the inherent production potential of individual plots by (a) estimating or measuring early crop growth in each plot about 3 weeks after sowing and using this estimate as a covariable in analyzing treatment effects (see Buerkert et al 1995) or (b) classifying the experimental plots according to their microtopographical position and using that to estimate crop production potential (cf the interpretation of results from the ILCA manuring trial discussed above)

2 *Identify the factors most responsible for the crop growth variability* these factors can then be quantified per plot (not per block or experiment!) and the measured values used as covariables in the statistical analysis Factors to be measured will differ between sites They may include soil depth, soil physical, chemical, and biological parameters, surface topography, and previous land use (former locations of huts, trees, termite mounds, refuse mounds, animal corrals, etc) They may also include above-ground physical, chemical, and biological parameters during the growing season, such as sand blasting, runoff-runon, removal or deposition of sand by wind or water, and incidence of pests and diseases The measurement of above-ground parameters will be especially useful for comparing treatments or microsites in a field in relation to yield stability

   In measuring soil parameters before, during, and after an experiment, it should be recognized that soil properties change cyclically with the seasons Therefore,

it is best to compare only soil samples taken at the same time of year, to eliminate effects of season on treatments When one compares, e g , organic matter content under treatments A and B at harvest time with background values at sowing time, it is not possible to say to what extent the differences over time for the two treatments are due to the treatments themselves, and to what extent due to seasonal effects

Buerkert et al (1995) tried some of these methods in an experiment on millet variety x fertilizer interaction The surface soil parameters they measured on a plot-by-plot basis did not explain much of the yield variability they observed However, by using an estimate of early crop growth (4 weeks after sowing) as a covariable, they were able to reduce the residual variation by 32% for straw yield and by 51% for grain yield Buerkert and colleagues also used early crop growth estimates to classify plots into low and high fertility groups (a procedure they called post stratification) Application of 2000 kg ha^{-1} of crop residues greatly improved yields on low-fertility but not on high-fertility plots Broadcast application of 13 kg ha^{-1} P, however, was equally effective on both (Buerkert et al 1995)

In the context of variability and yield security, it is also important not to look for the single solution the "best" variety, rotation, or management package for a particular set of environmental circumstances Rather, farmers should be given a range of options from which they can choose what they need, to suit the different conditions and management of different fields, their expectations regarding the weather (a long season or a short one), and their wishes regarding risk reduction and efficiency of resource use (higher or lower levels of inputs)

Because of the potential beneficial effects of soil and crop growth variability in the Sahel, we feel that, until its effect on yield stability and sustainable crop production is determined more clearly, we should not try to eliminate it, either on-farm or on-station For the management of research stations in the Sahel this means avoiding the blanket applications of fertilizer that cause an unnatural buildup of soil fertility in experimental fields There should also be an active effort to reduce excessive fertility in experimental fields on-station, for instance through cut-and-carry of cover crops

Summing up

The population increases and climatic change forecast for the Sahel make the wide use of external inputs in Sahelian agriculture unlikely Large-scale use of fertilizer is a long way off Efficient use of local resources is therefore more important than ever A better knowledge of soil and crop growth variability in the Sahel can help farmers improve resource use and stabilize yields

Although more insight has been gained and some questions have been answered, applying these to farmers' needs requires further investigation This is being addressed by two projects "Increasing resource use efficiency in spatially variable fields of subsistence farmers in Niger," and "Exploiting multi-scale variability of land-use systems to improve natural resource management in the Sudano-Sahelian zone of West Africa"

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Acronyms and abbreviations

DFPV	Departement de formation en protection des vegetaux (Niger)
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics (India)
IER	Institut d'économie rurale (Mali)
IFDC	International Fertilizer Development Center (USA)
IH	Institute of Hydrology (UK)
ILRI	International Livestock Research Institute (Ethiopia and Kenya) (formerly ILCA, International Livestock Centre for Africa)
INERA	Institut d'études et de recherche agronomique (Burkina Faso)
INRAN	Institut national de recherche agronomique du Niger (Niger)
ISC	ICRISAT Sahelian Center (Niger)
IUCN	World Conservation Union (Switzerland)
ORSTOM	Institut francais de recherche scientifique pour le developpement en cooperation
PDAAT	Projet de developpement agroforestier et amenagement de terroirs villageois (Niger)
TropSoils	Soil Management Collaborative Research Program (USA)
UNDP	United Nations Development Programme (USA)
USAID	United States Agency for International Development (USA)

About ICRISAT

The semi-arid tropics (SAT) encompasses parts of 48 developing countries including most of India, parts of southeast Asia, a swathe across sub-Saharan Africa, much of southern and eastern Africa, and parts of Latin America Many of these countries are among the poorest in the world Approximately one-sixth of the world's population lives in the SAT, which is typified by unpredictable weather, limited and erratic rainfall, and nutrient-poor soils

ICRISAT's mandate crops are sorghum, pearl millet, finger millet, chickpea, pigeonpea, and groundnut, these six crops are vital to life for the ever-increasing populations of the semi-arid tropics ICRISAT's mission is to conduct research which can lead to enhanced sustainable production of these crops and to improved management of the limited natural resources of the SAT ICRISAT communicates information on technologies as they are developed through workshops, networks, training, library services, and publishing

ICRISAT was established in 1972 It is one of 16 nonprofit, research and training centers funded through the Consultative Group on International Agricultural Research (CGIAR) The CGIAR is an informal association of approximately 50 public and private sector donors, it is co-sponsored by the Food and Agriculture Organization of the United Nations (FAO), the United Nations Development Programme (UNDP), the United Nations Environment Programme (UNEP), and the World Bank