The importance of within-field soil and crop growth variability to improving food production in a changing Sahel

A summary in images based on five years of research outside and on ICRISAT Sahelian Center, Niamey, Niger funded by the Ministry for International Cooperation, The Hague, The Netherlands, through Wageningen Agricultural University

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IUCN Commission on Ecosystem Management

A1 *The Sahel turns a lush green each rainy season, but soils are generally poor and yields low. Changes with the seasons of a landscape near the Niger river, just south of Niamey. Top April-June 1991; centre July-September 1991; bottom October-December 1991.*

Imprint

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Contents

A | Food security in the Sahel, threatened by global change

The Sahel is of course not always brown and dusty. During the height of the rainy season it is even riotously green. But, while the millet is up to 3 meters tall in August (see centre image A1) and the fields look very lush, the millet harvest index is only 20%. In other words, of the above-ground dry matter only 20% is grain. The rest is straw, useful as cattle feed or for making fences, but much less valuable than grain. As a result of this low harvest index, and because of low soil fertility and poor rainfall reliability, average millet yields in Niger are of the order of 250-400 kg ha^{-1}. For wheat in NW Europe the harvest index is 50% and yields are of the order of 12.000 kg ha^{-1}.

Because conditions are unreliable, farmers in the Sahel look for a high minimum, allowing them each year to make it to the next harvest. They are less interested in high averages. A strategy aimed at a high average usually means more variability in annual yield, and a higher risk of falling below the minimum that they need to survive the next twelve months. This is because, unlike farmers in NW Europe, farmers in the Sahel have little control over the environment. They mostly cannot irrigate, they cannot drain excess water, they cannot control pests, they can improve fertility only to a limited extent, etc. So they reduce their risks by investing in different production strategies, at least one of which each year should help them produce enough to survive until the next harvest.

(A3a) The early millet is ready for harvest, the late millet still quite small. And in between the two millet varieties cowpeas have been sown. Which of the three will yield well depends on how the rains are distributed that year.

(A3b) Sorghum can produce more per hectare than millet, but is also more sensitive to water stress. So this farmer has put a bet each way.

(A4) The millet grows best on the little mounds where the Guiera bushes grew before they were cut. The bushes are still present in the uncleared background. The roots of the bushes hold together the topsoil and reduce fertility losses through wind and water erosion.

In South-West Niger, dust from the air brings in roughly enough nutrients in ten years to allow three reasonable millet harvests, followed by another seven years of fallow.

A2 *Yield stability, and risk reduction, are of paramount importance to this Fulani woman and her son.*

A3a *Spreading risks near Gaya (Niger) by sowing several varieties.*

A3b *Spreading risks near Birni N'Konni, Niger: millet-sorghum intercrop.*

A4 *A newly cleared field. The unevenness of the millet growth is related to the previous vegetation.*

A5 *Sheep and cattle graze fallow areas and millet fields by day, and deposit their manure and urine on selected millet fields by night.*

A6 *Nutrients are in short supply and used mostly close to the village. The resulting soil fertility gradient is clearly reflected in the millet growth around this village near Niamey.*

(A5) Another way to keep fields fertile is by manuring them. Livestock are allowed to graze fallow and grazing areas during the day and are camped on the fields by night, leaving behind their manure and urine.

(A6) There is not enough manure to go around all the fields. The fields fertilised by livestock are generally found near the village, to make it easier to watch over the livestock at night. Further from the village management is less intensive and yields are generally lower, as can be seen in this aerial overview.

➔ Our research results indicate that substantial leaching losses of nutrients occur following deposition of manure and urine in the fields, because many farmers leave the livestock in the same plot for too many nights in a row. It would be more efficient to move the livestock around more frequently, allowing fertilisation of a larger area and reducing leaching losses of nutrients.

The production system just described was sustainable for many centuries, with population levels not changing a great deal in the Sahel. However, present population growth in Niger, for instance, is estimated at 3.1–3.3% per year. This means a doubling of the population in just over 20 years, and a quadrupling in 45 years.

(A7) As a result of increased population pressure fallow periods are becoming shorter. The ratio of grazing land to millet fields is also becoming smaller. Less land can be manured. Mineral fertiliser is often not available or too expensive, or its application too risky. So yields per hectare are dropping.

Yields in the Sahel are also under threat from climate change. The prediction is that the number of rainfall events will decrease, even if total rainfall amounts don't. Fewer rainfall events means longer periods between events, and a greater chance of intra-season droughts, with associated yield declines.

A7 *Global changes, including demographic changes and climate change, threaten food security in the Sahel.*

B | Within-field variability can reduce production risks and increase efficiency – knowledge exchange with farmers is needed

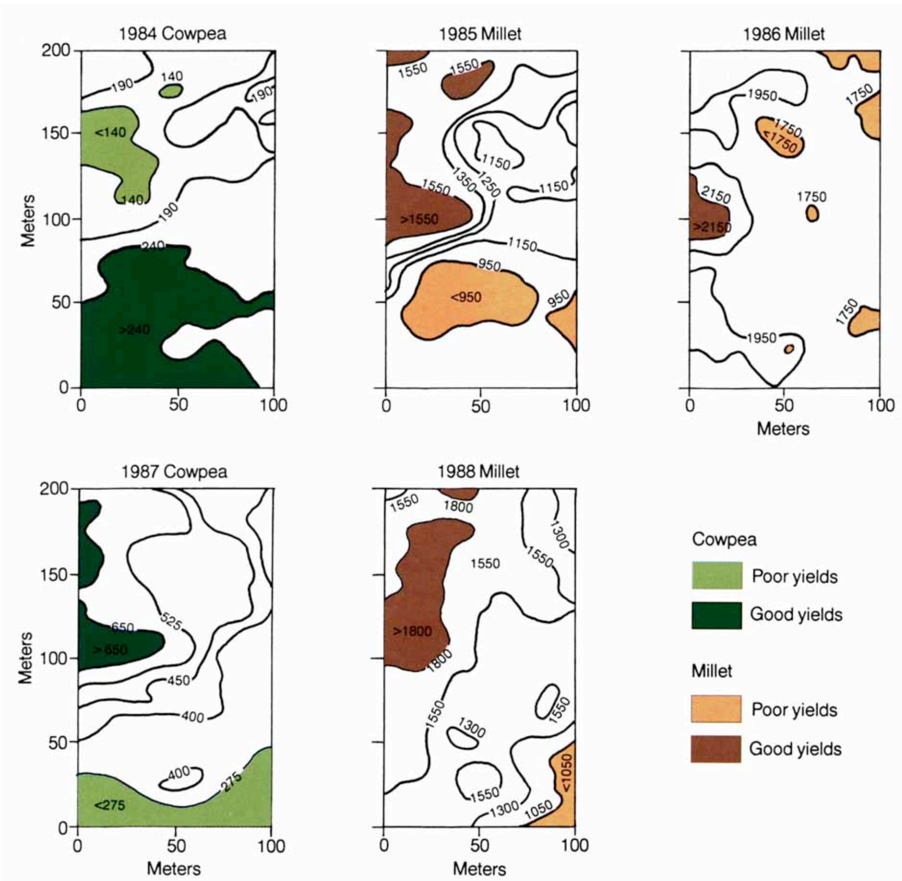
(B8) Different parts of a field may give the best yield in different years, because of uneven and unequal availability of water and nutrients in a field. Some parts of a field may be relatively fertile, but also relatively dry; other parts may be less fertile but wetter. Depending on the rainfall during a particular year, either nutrients or water may be most limiting, and either the most fertile or the wettest parts of a field may produce best.
Crops may also benefit from the amount of water stored in the soil at the end of one cropping season and carried over to the beginning of the next cropping season: where less water was used (and less dry matter was produced) one year, more water may be left in the soil for use the following year.

Crop growth variability reduces susceptibility to pests and diseases as well.

(B9) Infiltration around the neutron probe access tubes, in the mini catchment pictured here, varied from 30 to 340% of rainfall! It will be clear that such differences in infiltration of water also cause big differences in nutrient availability and nutrient use efficiency.

B9 *Not all rain infiltrates where it falls, even on very sandy soils as found near ICRISAT Sahelian Center. Effects on local water and nutrient availability can be very large.*

Farmers in Niger already can, and do, vary their management accordingly, over quite short distances within the same field. Researchers must take that into account when developing e.g. manure and fertiliser application strategies.



B8 *Soil and crop growth micro-variability may contribute to risk-reduction and yield stability in the Sahel. The Fussell yield maps illustrate this for a field at ICRISAT Sahelian Center: the pale-coloured areas of relatively poor yield during most years (lower end of field, 1985-1988) were dark-coloured areas of relatively good yield during a drought year (1984, top left).*

B10 *Variable soils, and variable management, in a farmer's field at Bellaré, near ISC.* Photo: Mark Smith.

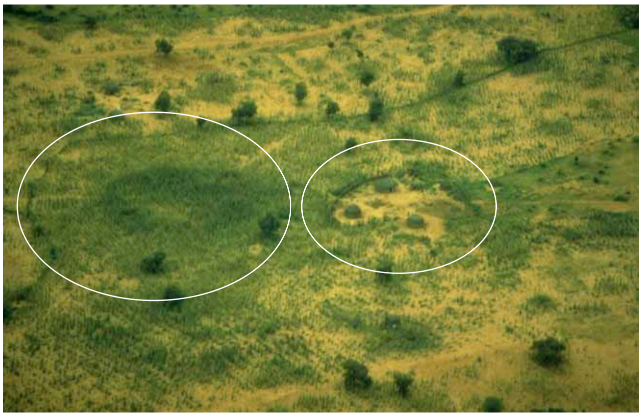
(B10) The four corners of the one-hectare area studied are marked by a small white square. Very noticeable is the very good millet growth around the well in the left foreground, caused by livestock dropping manure and urine as they wait to be watered.

Also noticeable is the generally poor growth in the upper half of the picture. The area in the upper half is actually on a different sand deposit, which seals more easily. It is therefore more drought-sensitive and reacts differently to management from the area in the foreground. The farmer knows this by experience, and manages the area in the background less intensively. He sows all the land in the foreground immediately after the first suitable rainfallevent. He sows the land in the background after the next event, and with greater spacing between millet pockets. Application of lime or gypsum may reduce sealing, increase water infiltration and reduce drought-sensitivity of the sand deposit in the upper half of this image.

(B11) Farmers do try to improve infertile areas, if they know how to and have the means to do so. They know that applying cattle manure on degraded areas is a

B11 *An eroded area, actively reclaimed by the application of sheep manure (Ouallam, 100 km north of Niamey).*

B13a *Luxurious growth of groundnut around an old termite mound on-station at ICRISAT Sahelian Center.*



B12 *Very good millet growth at a site where the village huts used to be.*

B13b *Improved growth of millet around an abondoned termite mound in a farmer's field.*

waste, even if they do not know why. Cattle manure in fact decomposes relatively quickly, and is then washed and leached away. Sheep manure, on the other hand, decomposes more slowly, resulting in lower leaching losses of nutrients. In addition, sheep urine has a higher pH than cattle manure, causing a favourable increase in the pH of the usually quite acidic eroded areas.

(B12) Farmers manage soil fertility not only through the application of manure and urine. Poor growth areas are improved by the household refuse left behind around the huts. Huts may be relocated periodically to improve new areas.

(B13a-b) On the sandy soils of south-western Niger, the activities of this species of termite called *Macrotermes*, include bringing up more fertile clay from below and concentrating organic matter from the surrounding fields. This increases soil fertility as well as water holding capacity on these poor sandy soils. Newly abandoned *Macrotermes* mounds have a high chemical fertility, but are physically too hard for roots to penetrate. In some regions farmers put branches etc. on abandoned mounds to attract other species of termites that help loosen the soil on the mound site.

- **Farmers in the Sahel already practise 'precision farming', 'site-specific agriculture', 'farming by soil', or whatever one may call it.**
- **But there is room for improvement, including large increases in resource use efficiency, for local as well as external inputs.**
- **To achieve these improvements it is necessary to combine farmer and researcher knowledge**

C | Researchers also need to know about spatial variability, so that they can improve research impact

Within-field variability complicates management not only for farmers, but also for agricultural researchers. The tendency has been for researchers to either ignore this variability, or to reduce it by artificial means. When variability is ignored, conclusions from research are usually rather less specific than they might have been.

The experimental area on the right in C14 became more homogeneous through a blanket phosphorus application, and experimental results were easier to analyse statistically. But as farmers never apply such a high level of phosphorus in their own fields, the results of the experiment were not very useful to them. At left in C14 the pre-existing soil variability was not altered. This complicated the interpretation of experimental results. But by finding the causes of that variability the results of the experiment could be interpreted well, and provided a lot of information valuable to farmers (Buerkert et al. 1995).

(C15) Agricultural reseachers must take within-field differences into account when developing and assessing new management options for farmers. Analysing our

C14 *Two experiments on a research station. On the right the effects of pre-existing soil variability on experimental results were reduced by an unrealistic blanket application of phophorus fertiliser.* Photo: Mark Smith.

C15 *ILCA manure application experiments show that manure is often wasted by farmers.*

experimental results at an individual plot level, rather than at the treatment level, we found that the application of cattle manure and urine in local depressions was a waste because of leaching problems. But even on higher ground, farmers apparently often over-manured by a factor of 4 to 6, leading to great and avoidable wastage of scarce nutrients.

In addition, is what is shown in C16 a case of a clear urine effect, or a case of a natural fertility gradient, with fertility gradually increasing from left to right, related to the presence of an old termite mound just off-picture on the right? Researchers should investigate both alternatives!

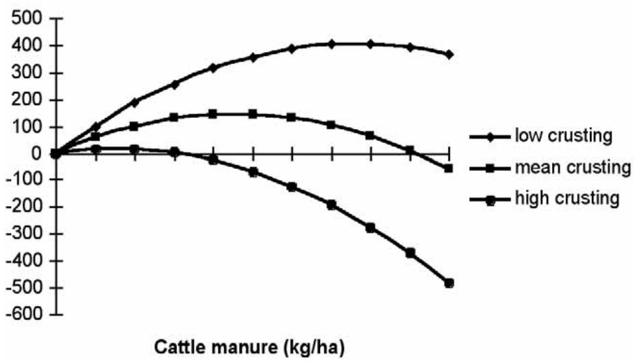
➔ Insufficient attention to soil and crop growth variability is without any doubt one of the factors contributing to the lack of adoption of a number of newly developed, technically promising agricultural production options for the Sahel.

C16 *Two millet plots that have both received one night's worth of cattle manure, either without urine (left hand plot) or including the urine (right hand plot). Does this image show a treatment effect, a case of pre-existing soil variability, or a combination of the two?*

D | Further practical results from an earlier variability project, for extension to farmers and researchers

While we try to relate variability in crop growth to things we can see at the surface, the actual causes of that variability are of course mostly underground (see Table 1 for information on spatial variability in root growth).

In the experimental hectare in a farmer's field shown in B10, soil samples were also taken, at depths of 0-20, 20-40 and 70-90 cm. Before chemical analysis, the samples were bulked in fours to give representative values per 10 x 10 m plot for each depth. Soil crusting condition, microtographical position, and amounts of cattle manure and of small ruminant manure were also measured. The resulting data are equivalent to the outcome of an



D17 *Contribution of cattle manure to millet grain yield at different soil crusting levels, in the one hectare area of a farmer's field at Bellaré, SW Niger* (from Voortman & Brouwer 2003).

experiment with 100 10 x 10m plots, some 40 variables (soil properties at various depths, surface conditions, manure application etc.), and no repetitions.

➔ Powerful software developed for spatial econometrics allows the results of this experiment to be analysed statistically and produce graphs like the one in D17.

The graphs in D17 show that at high crusting levels there is no point in applying cattle manure and urine. And even at low crusting levels applying more than about 1,500 kg ha^{-1} is a waste. In farmers' fields, however, application rates of more than 10,000 kg ha^{-1} are often encountered. Thus this analysis of straight forward field data, using modern software, confirms the results of the very large on-station ILCA manure application experiment mentioned under C15.

(D18) As explained in B13, on these sandy soils *Macrotermes* termites increase local soil fertility, through incorporating nutrients and adding clay to support their tunnels and mounds. For young trees increased fertility is important, so that they can grow fast and there is less chance that they are eaten by livestock. Or that they wither during a drought. *Faidherbia albida* seedlings planted near old *Macrotermes* mounds were shown to grow faster than seedlings in the open field. Thus they apparently have a better chance of survival if planted near old mounds. This is important knowledge for

Dry matter class 16 Sep (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
No. 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
Growth score 24 June	1.9	3.9	4.9	5.7	6.1	6.3	6.8	6.8	6.7	6.7	6.5
Dry matter averages (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
Tiller Surface Area Index (m^2 m^{-1}) based on:											
above-ground d.m.	0.25	0.46	0.63	0.77	0.89	1.01	1.13	1.23	1.32	1.41	1.58
straw d.m.	0.20	0.37	0.49	0.61	0.70	0.80	0.89	1.00	1.08	1.13	1.29
Root length density (cm cm^{-3}); from 19 plots, showing only the averages per millet shoot growth class											
0-15 cm depth	0.30	0.80	1.15	1.20	1.00	0.80	0.70	0.55	0.50	0.40	0.40
15-30 cm depth	0.20	0.45	0.75	0.90	0.75	0.55	0.35	0.35	0.35	0.35	0.35
30-45 cm depth	0.10	0.25	0.40	0.50	0.45	0.35	0.30	0.25	0.20	0.20	0.20
60-75 cm depth	0.05	0.12	0.18	0.25	0.30	0.32	0.28	0.22	0.18	0.14	0.12
90-105 cm depth	0.01	0.03	0.05	0.07	0.09	0.11	0.13	0.15	0.17	0.19	0.21
120-135 cm depth	0.01	0.02	0.04	0.06	0.07	0.09	0.07	0.05	0.03	0.01	0.01
150-165 cm depth	0.01	0.02	0.03	0.03	0.04	0.05	0.06	0.04	0.02	0.01	0.01
180-195 cm depth	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

Table 1 *Average shoot and root characteristics of various millet growth classes, Bellaré, August-September 1992*

This information comes from the 400 5x5 m plots of the one hectare area in a farmer's field at Bellaré shown in figure B10. The eleven columns show millet growth data for different millet shoot growth classes, from < 1.000 to > 10.000 kg ha^{-1}. The harvest index was quite constant for all classes > 1.000 kg ha^{-1}, at 0.20-0.21. Root mass showed a maximum of about 935 kg ha^{-1} for the 3.000–5.000 kg ha^{-1} dry matter classes. At lower shoot production the soil was too poor for good root growth. At higher shoot production the soil was apparently better and better, so that less and less root mass was needed, at least in 1992. The best correlation between shoot growth and root growth was for root growth at 90-105 cm depth.

➔ Root growth conditions at about 1.0 m depth may be most important for determining millet shoot growth potential in SW Niger.

D18 *Root systems of 3-year old* Faidherbia (Acacia) albida *trees growing where there had previously been little (left) and much (right) activity of* Macrotermes *termites.*

D19 *Superior growth of millet under a* Faidherbia (Acacia) albida *tree, as compared to elsewhere in the farmer's field.*

D20 *A so-called 'tiger bush' area near ISC: tiger bush can only exist because of spatial variability.*

agroforestry activities initiated by farmers or development organisations.

(D19) Related to this, better millet growth under older *Faidherbia* trees may be caused by:
- pre-existing locally higher soil fertility where the *Faidherbia* trees grow, due to a high level of activity of mound-building termites;
- a more favourable micro-climate under the mature albidas;
- the deposition of manure and urine under the trees, as mentioned above;
- recycling of nutrients by the deep-rooted trees;
- and nitrogen fixation by the *Faidherbia* trees themselves.

(D20) Short distance spatial variability is an essential part of ecosystem functioning in (semi-)arid regions, and not limited to millet fields. In so-called 'tiger bush', the bare areas deliver water (and nutrients) to the vegetated strips, essential for their survival. The vegetated strips are aligned parallel to the topographic contours, on almost flat plateaux with very shallow soils over an almost continuous laterite or ironstone layer. The drier the climate, the further apart the vegetated strips because a larger area is need to generate the necessary amount of run-off. In the north, close to the Sahara, the strips are therefore quite far apart. As you go south, you find the vegetated strips closer and closer together, until there is enough rain for continuous perennial woody vegetation. Ignorance of how tiger bush functions ecologically has led to the failure of many tiger bush restoration projects.

(D21) At an even larger scale, wetlands are areas of high potential productivity and relatively low production risk. Wetlands also allow more efficient utilisation of associated dryland areas. Wetland areas can provide a safety net for extra food production during times of drought. On the other hand, livestock grazing in dryland areas bring nutrients to the wetlands when they go there to drink. This can have a marked effect on primary and secondary production in the wetlands. Our research indicates that fish production per hectare, and waterbird densities, are indeed greater where the nutrient loading through watering livestock is greater.
Wetlands and associated dryland areas cannot really exist without each other. The two need to be managed in a participative and integrated manner, using an ecosystem approach such as e.g. described in SYSTANAL (Brouwer 2001).

➔ The following practical results from our variability research can be extended to farmers and/or researchers:
- **recognition of the yield stabilising role that with-in field variability can play;**
- **suggestions for reduction of over-manuring by farmers**
- **recognition of the need to apply different management to different aeolian sand deposits, often found side by side in a single field;**
- **suggestions for improving nutrient use efficiency by farmers, through microtopography-related site-specific management (this is important for the management of local fertility resources [manure, urine, compost, crop residues, domestic refuse], as well as for the management of mineral fertiliser);**
- **suggestions for improving with-in field rainfall infiltration by applying lime or gypsum;**
- **recognition of the important role that *Macrotermes* termites play in local increases in soil fertility on sandy soils;**
- **recognition of the fact that *Faidherbia albida* seedlings in agro-forestry projects are much more likely to grow well near an old *Macrotermes* mound;**
- **suggestions for better incorporation of short-distance soil- and crop growth variability in agricultural research;**
- **a checklist called SYSTANAL for the analysis of (agro)ecosystems, that can help in increasing the sustainability of (agro-) ecosystem use, including the use of wetlands and the drylands surrounding them.**

D21 *Essential variability at even larger scales: a wetland in the Sahelian zone (north-east of Zinder).*

E22 *Millet being stored.*

E | Conclusion

➔ A better knowledge of the causes and effects of soil and crop growth variability may help in increasing yields, yield stability, and resource use efficiency for farmers in the Sahel. Combining farmer and researcher knowledge on this subject is essential.

F | List of publications

(from the earlier soil and crop growth variability research project at and around ICRISAT Sahelian Centre, SW Niger)

Most important publications

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- Brouwer, J. 2003. Wetlands, biodiversity and poverty alleviation in semi-arid regions: a case study from Niger (see also: www.iucn.org/themes/cem/cem/region/niger.htm)