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Risk management in crop production and fertilizer use with uncertain rainfall; how many eggs in which baskets*

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Abstract

The adagium 'Don't put all your eggs in one basket' does not specify how many and which baskets should be used and how the eggs should be distributed. Risk management can be based on controlling external sources of variability, on maintaining a meaningful diversity of activities and on delaying decisions. Quantitative analysis of risks in crop production and of the possibilities for these three ways of dealing with them is possible when dynamic crop growth models are combined with long-term weather records.

Model results are analyzed for risk management options for sorghum production with a range of N fertilizer rates on three soils of a toposequence in three climatic zones in Burkina Faso. The three levels of analysis are a) quantifying the probability distribution of physical and economic yield for a range of fertilizer levels and soil types, b) quantifying the possible variance reduction by soil heterogeneity or by a combination of soils and N rates, c) developing a procedure for selecting 'meaningful diversity' of soil and N fertilizer combinations.

Keywords: toposequence, risk avoiding, meaningful diversity, sorghum, Burkina Faso

Introduction

Agricultural production in many parts of the world takes place in an unpredictable and highly variable environment. In dealing with this uncertainty three principles are applied in many fields, ranging from agriculture to economics and politics: 1) controlling the external sources of variability, 2) maintaining meaningful diversity of ac-

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tivities, and 3) maintaining flexibility (keeping open as many options as possible) by delaying decisions as long as possible. In terms of the adagium 'Don't put all your eggs in one basket' the first principle is based on improving the quality of the baskets and the way in which they are transported, the second on the use of several baskets instead of the best single one, and the third on switching eggs to other baskets while underway. Agricultural development has been mainly characterized by the first approach, by improving control over physical growth conditions and by reducing farmer uncertainty about prices for his/her products. However, the other two ways of dealing with uncertainty are important as well, especially where, due to erratic rainfall regimes, water availability is uncertain and technical control over water supply (irrigation and drainage) is not economically feasible. In farming systems developed under uncertain conditions various examples of 'meaningful diversity' and 'delayed decision-making' exist. Quantitative analysis of these practices, however, is difficult: How many baskets are needed and how should the eggs be distributed over the baskets? How long can decisions be postponed in view of the necessary 'timeliness' of field operations?

Agricultural research tends to be confined to analyzing single commodities under relatively homogeneous conditions, with pre-defined experimental plans during a few experimental years. Research is usually aimed at identifying the best single solution, rather than optimizing a combination of activities. Conclusions based on such experiments, especially where they deviate from established farmers' practices, should not be directly extrapolated to farmers' conditions.

Crop growth models, as used here, allow analysis of spatial variability and of temporal interactions among various commodities in search of 'meaningful diversity'. They also permit analysis and optimization of schemes for flexible decision-making. On the basis of long-term weather records, the evaluation may be extended to longer periods, which may better reflect the probabilities for the coming years than the few years on which field research is normally based. If this is considered to be relevant, a correction for trends in annual rainfall can be made, or an artificial 'rainfall simulator' can be used. In this paper an outline is given of methods for such analysis, applied to the implications of fertilizer use in the Sahelian zone with uncertain rainfall.

Concepts

Decision-making in crop production and fertilizer use

Two levels of decision-making may be considered, with partly conflicting objectives, the government and the farming households. National governments aim at feeding their urban population and, if possible, earning foreign exchange from agricultural exports. Farming households aim at food security and cash income. Government decisions affect farmers' decisions primarily through prices of inputs and products. If an increase in production can be achieved without incurring increased risk, the interests of farmers and government coincide. Here we will focus on farmers' decisions, in the context of politically determined prices and environmentally induced risks.

Mokwunye & Hammond (1992) discussed the 'myth' that because of risks involved in the use of fertilizers under rainfed conditions, small farmers in dry areas will not adopt this practice. Although such risks may not prevent fertilizer use in all situations, the interaction between uncertain rainfall and fertilizer response should be studied (Van Keulen & Breman, 1990; Keating *et al.*, 1991).

The simplest approach to risk analysis is based on a yield response curve for an average year. Fertilizer recommendations are normally based on the point where the marginal response equals the price ratio of input (fertilizer) and output (yield). This price ratio can be multiplied with a factor that takes into account the climatic risks of crop failure (Van Noordwijk & Scholten, 1994). Higher rainfall variability or more uncertainty about prices thus leads to lower fertilizer use. Such an approach, however, neglects a number of possible interactions between the actual rainfall pattern in a given year and the associated N response. It is preferable therefore to calculate the N response before averaging over the years (De Wit & Van Keulen, 1987).

To stimulate farmers to use more inputs and aim at higher production levels, governments may reduce the risks of investment for farmers by implementing a type of 'rainfall insurance' that compensates farmers in case of low rainfall. A detailed analysis of the prospects of such a scheme in India showed, however, that inter-annual variability in grain yield was less and inter-plot variability more than expected initially; for the area investigated 'rainfall insurance' would not meet the targets of increasing productivity and reducing farmers' risks (Bakker, 1992).

Decisions in crop production can be broadly classified in *strategic* and *tactical* decisions, which are taken before and in the course of the growing season, respectively (Table 1). *Strategic* decisions are aimed at long-term targets and can only be based on estimated probability distributions of the sources of variation. *Tactical* decisions are aimed at short-term goals and can be based on the current state of the system as determined by recent values of the environmental variables and on conditional probability distributions for the near future. Flexibility in tactical decision-making is generally highest for decisions concerning labor use and other local resources; decisions on the use of external inputs may be constrained by economic conditions and accessibility of credit. Market conditions may restrict the scope for tactical decisions, e.g. when fertilizer for top dressing has to be bought in advance and cannot be

Table 1. Classification of decisions involved in crop production (modified after Van Keulen & Penning de Vries, 1993)

Strategic decisions **before** the growing season	Tactical decisions **at the start and in the course of** the growing season
Choice of land	Planting time
Drainage	Crop variety/-ies
Crop rotation	Plant density, weeding
Crop variety/-ies	Irrigation
Soil tillage	Topdressings of fertilizer
Basic dressings of fertilizer	Pest and disease control
	Harvesting

stored to a next year. The choice of crop varieties appears under both headings, as decisions on which seeds to use can be postponed to planting time, provided that sufficient stock is kept (by the farmer or by commercial suppliers) of different varieties. A conflict of interests may exist between government and trade planning which wants to know fertilizer use in the next cropping season well in advance and farmers who may want to postpone decision-making until the growing season has actually started. The choice for 'meaningful diversity' is mainly a strategic one.

The various tactical decisions each have their own critical periods in the course of the growing season. Fertilizer top dressings may, in the absence of rain, be unaccessible to the crop roots. Plant density cannot be increased halfway the growing season, but it can be reduced, so starting from a high initial plant density, above the optimum for an average year, may increase the scope for tactical decision-making (Wafula, 1993).

The degree of success of the decision-making process strongly depends on the reliability of information about the current situation and the probable course of events in the near future (Van Keulen & Penning de Vries, 1993). As reliable weather forecasts more than a few days in advance are not (yet) possible, statistical analysis using past weather records may be the best information to rely on.

Risks and meaningful diversity

The concept of risk reduction by diversity (or diversification if one starts at low diversity) of activities is widespread, but needs quantification. 'Risk' can be defined as the probability of not meeting one's targets (Schweigman, 1985). 'Risk' thus defined depends on the average yield, the yield target and on the variance of the yields. For results with a normal probability distribution, the risk can be read from tables of a standardized normal (z) distribution on the basis of:

$$q = P\,[z > |\frac{\mu - T}{\sigma}|] \qquad (1)$$

where T is the target result, μ is the average, and σ is the standard deviation. If the target is higher than the average ($T > \mu$), an increase in σ helps to reduce risk, but the risk will always exceed 50% and one may consider the target to be not realistic and look for other activities. If the target is lower then the average ($T < \mu$), the risk decreases for smaller standard deviations. Given T, a rational choice can be made between two activities once μ and σ are known for each activity. An activity with intermediate average μ and small standard deviation σ may be preferred over an activity with larger μ and σ, or *vice versa*, depending on T and thus on the q-value for each activity. The best solution can, however, in certain situations be formed by a combination of the two activities.

The average yield for a combination of two activities, say the use of two different crops, crop varieties or soils, equals the weighted sum of the average yield for each activity, unless a specific combination is chosen with a RYT (Relative Yield Total) above 1.0 (De Wit, 1960; Trenbath, 1986). RYT values above 1.0 are confined to intercropping practices with some degree of niche differentiation between the crops (i.e. for the two components different environmental factors limit yields). If RYT is 1.0, $\mu_{1,2}$ is at best equal to the maximum of the pair (μ_1, μ_2).

The variance of the total yield of a combination of activities is normally less then the weighted average of the variances of each activity, unless the two activities show exactly the same response to the source(s) of variation (Schweigman *et al.*, 1988). Consider two components with an (approximately) normal distribution. If a component 1 with standard deviation σ_1 on fraction f_1 of the area is combined with component 2 with standard deviation σ_2 on fraction 1 - f_1 of the area, the standard deviation, $\sigma_{1,2}$, of the total yield is:

$$\sigma_{1,2} = \sqrt{f_1^2\sigma_1^2 + (1-f_1)^2\sigma_2^2 + 2\rho_{1,2}f_1(1-f_1)\,\sigma_1\sigma_2} \qquad (2)$$

where $\rho_{1,2}$ is the correlation coefficient of the yields of components 1 and 2 in the various years. If $\rho_{1,2}$, which by definition is in the range −1 to +1, is less than 1 the standard deviation of the combination is lower than the weighted average of the two component standard deviations (Figure 1). If $\rho_{1,2} < h$, where h is the ratio of the smallest and largest σ, we can always find a value f_1 for which the standard deviation of the combination is even smaller than that of the most stable component. In mathematical notation: $\sigma_{1,2} < \min(\sigma_1, \sigma_2)$. This result can be verified (Schweigman *et al.*, 1988) by differentiating [2] with respect to f_1 to find an optimum value $f_{1,opt}$ which results in a local minimum for $\sigma_{1,2}$ and by requiring this optimum value to be in the domain ($0 < f_{1,opt} < 1$). Apparently a system based on component 1 with relatively small σ_1, can sometimes be stabilized (transformed to a system with even smaller $\sigma_{1,2}$) by adding a more variable component 2, with large σ_2. If $\sigma_{1,2} < \min(\sigma_1, \sigma_2)$, risks are reduced for some (extreme) values of q, for some combinations of compo-

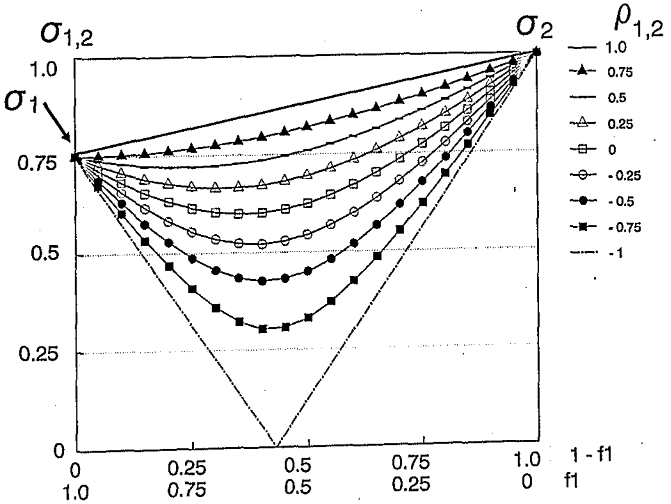

Figure 1. Standard deviation $\sigma_{1,2}$ of a sum of two components as a function of the fraction of component 1, f_1, and the correlation coefficient $\rho_{1,2}$. In this example σ_1 was taken as 0.75 and σ_1 as 1.0.

nent 1 and component 2, even when the most stable component has the largest average yield. Schweigman *et al.* (1988) gave equations for the optimum choice of f_1, depending on $\rho_{1,2}$, μ_1/μ_2 and the value of X (production is maximized for the worst X percent of years).

Winterhalder (1990) applied a similar reasoning to risk reduction by hunter-gatherer groups, sharing a common pot, and to the number of field plots per family in pre-industrial age farming systems in England. If components can be found with $\rho_{1,2} = -1$, risk is minimized by having only two components; if $\rho_{1,2}$ is around 0 there is scope for the highest diversity (or group size), but beyond 8 components (or group members) adding new components has little effect. Variance reduction by a combination of activities is well known in economics as 'portfolio theory' (Liliehom & Reeves, 1991). Babu & Rajasekaran (1991) and Lilieholm & Reeves (1991) applied 'portfolio' theory to planning of agroforestry systems. The key in all these studies is knowledge of the covariance matrix of all possible activities, or the correlation matrix. The correlation matrix can be estimated on the basis of long-term studies, as they did, or on the basis of crop growth models, as we will show here.

Schweigman *et al.* (1988) and Van Noordwijk & Van Andel (1988) showed, with the sorghum model of Van Loo *et al.* (1990), that a certain combination of early and late flowering sorghum varieties may meet the $\rho < h$ criterion for variance reduction. Such a combination, grown on neighboring fields with the same rainfall regime, will give a higher yield in the worst X% of the years than the best monoculture. Both the early and the late variety would probably be discarded in a selection programme aiming at the 'most stable' sorghum variety, without regarding the possibility of crop diversity.

Rainfall uncertainty and flexible management

In Sub-Saharan Africa rainfall uncertainty, expressed as coefficient of variation, generally decreases with increasing average rainfall; in the Sudan the standard deviation of annual rainfall increases only slightly from zones with 700 mm to zones with 1500 mm average rainfall and the coefficient of variation decreases from 100 to 10% (El Tom, 1975); similar effects are found elsewhere in Africa and in other semiarid zones (Le Houérou, 1989). Tactical decision-making would be easier if medium-term weather forecasts were available. McCown *et al.* (1991) and Franquin (1984) found, for Kenya and Burkina Faso, respectively, that total seasonal rainfall is correlated with rainfall in the first part of the cropping season. De Leeuw & Snijders (1987), however, analyzed long-term weather records for four stations in Burkina Faso (annual rainfall ranging from 600 to 1000 mm; partly the same stations as studied by Franquin (op. cit.)) and found that this conclusion was misleading: rainfall in the second part of the growing season (whatever date is chosen for separating 'first' and 'second' part of the season) is statistically independent of the amount of early rainfall; the correlation of early and total rainfall follows from the correlation of A with A + B.

Final yields are determined in a late stage of the growing season. This is illustrated by the results of an analysis of the prospects for 'early warning' (Figure 2;

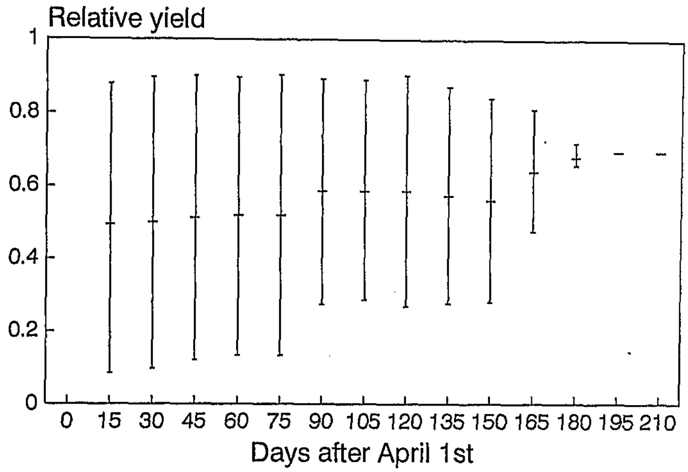

Figure 2. Expected sorghum yield and its 95% confidence interval relative to the average over a range of years, in Ouahigouya (Burkina Faso) based on actual rainfall data for 1979 up to the date on the X-axis, and the probability of subsequent rains (Snijders, 1988).

Snijders, 1988) based on sorghum yields for a station in Burkina Faso (Ouahigouya) in a given growing season. Crop development was calculated with a calibrated crop growth simulation model based on actual rainfall data up to the date on the X axis and based on the frequency distribution of subsequent rainfall for the remainder of the season to determine the expected yield and its 95% confidence interval. Large uncertainties remain until a few weeks before harvest time.

Rainfall in semi-arid regions has a high degree of spatial variability. Daily rainfall records for stations only 1 km apart may have a correlation coefficient which is as low as that between stations 200 km apart (Mellaart, pers. comm.; Stroosnijder & Van Heemst, 1982).

Delayed decision-making reflects tactical risk management, which is best illustrated by the 'response farming' technique described by Stewart (1991) and Wafula (1993) for maize production in the Machakos area in Kenya. In this approach, the decision on planting density and initial fertilizer rate is based on early rainfall, while the decision on topdressing of fertilizer and possibly reducing plant density by thinning is based on subsequent rainfall. Crop growth modelling may be used to adjust and optimize the decision criteria (how much biomass or cumulative rainfall at a certain date is needed for a proper decision, what are the risks involved).

A critical factor for the success of such methods, however, is the correlation between the best plant density and N rate, and the information available at the last moment that corrections can be made. The correlation between 'early' and 'late' rainfall may be site-specific. For the rainfall data (and the crop growth model) used for Figure 2, the scope for tactical decision-making seems to be small.

As the scope for tactical decision-making in fertilizer use seems small for both logistical and statistical reasons, the choice for 'meaningful diversity' as strategy may be more relevant. In this article a specific crop growth model is used to explore three levels of risk management: a) quantifying risk for physical and economic yield for a range of fertilizer levels and soil types, b) quantifying the variance reduction by soil heterogeneity or by a combination of soils and N rates, c) developing a procedure for selecting 'meaningful diversity' of soil and N fertilizer combinations. In the future, the model can also be used for evaluating possibilities for flexible management during the growing season.

Materials and methods

Crop growth model

Dynamic crop growth models can be used to predict the N response of a given crop (variety) on a given soil over a large number of years, provided that long-term weather data are available. As an example results are discussed here for a sorghum production model (Van Loo *et al.*, 1990) developed for Burkina Faso. The model contains a simplified N and water balance for a compartmentalized soil profile. Under high rainfall conditions N may be leached beyond the root zone, while N uptake may be restricted by low soil water contents. The model has not been rigorously validated, hence it should be used with caution for extrapolation, but as the yield levels calculated are in the right range and the predicted interactions between rainfall pattern and N response are plausible, it may be used to illustrate general trends.

Calculations were performed for three climatic zones in Burkina Faso, characterized by long-term (30 years: 1956–1985) rainfall data of Ouahigouya (13.6' N, 2.5' W, annual rainfall 600 mm), Ouagadougou (12.4' N, 1.4' W, annual rainfall 800 mm) and Bobo Dioulasso (11.2' N, 4.3' W, annual rainfall 1000 mm). A long-term average seasonal trend for Burkina Faso was used as value for daily potential evapotranspiration; other climatic input values were taken from Van Loo *et al.* (1990). In each climatic zone three soil types were considered, typical for the toposequences in this area (Figure 3; Tables 2, 3). For each site simulation runs were made with N fertilizer rates in the range 0–250 kg ha^{-1} (with intervals of 25 kg ha^{-1}).

Table 2. Parameter values used for three soils on a toposequence; available soil water storage capacity is the difference between field capacity and wilting point, integrated over soil depth

	A	B	C
Rooting depth (cm)	50	100	150
Run-off fraction	0.2	0.2	-0.2*
Texture	clayey-sand + gravel	clayey-sand	clay
Available soil water storage capacity (mm)	45	95	250

* negative run-off means run-on

Table 3. Crop parameters used for the three rainfall zones; other parameter values as in Van Loo *et al.* (1990)

	Location		
Parameters	Ouahigouya	Ouagadougou	Bobo-Dioulasso
Start simulation, DOY*	180	155	135
Day of flowering, DOY	235	235	235
Days between flowering and maturity	40	45	50

* DOY is Day Of Year (Julian calendar).

Calculations

On the basis of the predicted grain yield for each combination of location, soil, N-rate and year, a number of summaries were made:

1. diagrams of N response curves showing average as well as the standard deviation (for the 30 years) for each soil and location,
2. frequency distributions of the gross margin (grain yields minus fertilizer cost) on the basis of a price ratio of 6 kg grain per kg N,
3. correlation matrices of physical as well as economic yields for the various soils and N rates at a single location,
4. a matrix showing whether or not the $\rho_{1,2} < h$ criterion was met by each combination,
5. calculating effects of within-field spatial variability in N supply by applying 'filters' (weighted n-points moving averages) shown in Table 4,

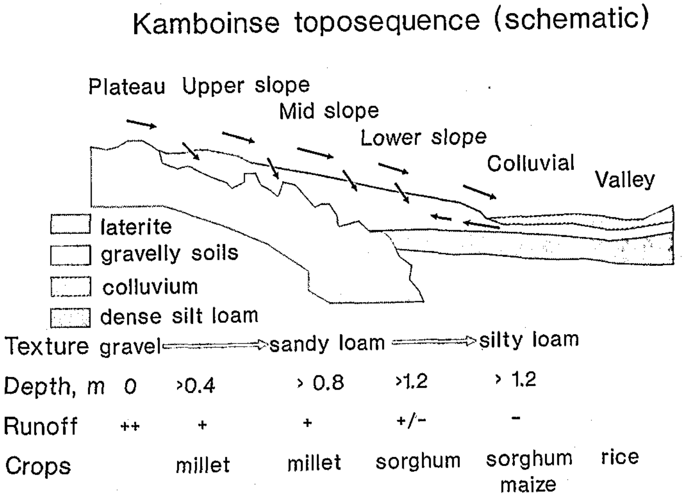

Figure 3. Schematic presentation of a toposequence common in Burkina Faso (simplified from Stoop, 1987).

Table 4. Weights used in calculating field level yields as weighted n-point moving average from the simulated N response data for homogeneous units (with an interval of 25 kg N ha^{-1}). Four situations, with *no* to *strong* field level spatial variability in N supply were considered for figure 7

	x – 4	x – 3	x – 2	x – 1	x	x + 1	x + 2	x + 3	x + 4
No	–	–	–	–	1.0	–	–	–	–
Mild	–	–	0.10	0.20	0.50	0.20	0.10	–	–
Medium	–	0.05	0.12	0.18	0.30	0.18	0.12	0.05	–
Strong	0.05	0.08	0.12	0.15	0.20	0.15	0.12	0.08	0.05

6. hierarchical cluster analysis of the correlation matrix (rescaled from the interval $\{-1,1\}$ to $\{0,1\}$).

All these calculations were made with Genstat-V (Payne *et al.*, 1987).

Results

Variability of yields for each soil and N level

Figure 4 presents the results for the nine soil * climate combinations, for N fertilizer levels of 0–250 kg ha^{-1} derived from model runs for 30 years. At each N level maximum, minimum and average yield, μ, as well as the standard deviation, σ were determined. In the graphs $\mu - 1.64\ \sigma$ and $\mu - 2.33\ \sigma$ are indicated, which represent the expected yield in the worst 5 and 1% of the years, respectively, provided that yields are normally distributed.

For all climatic zones a considerable increase in average yield is predicted with increasing N fertilizer application rate on soils B and C. On soil A, with a very limited water holding capacity, only at the wettest location, Bobo Dioulasso, average yields are increased by N fertilization. At the drier sites maximum yields are higher with increasing fertilizer application, but this is associated with a higher risk of complete crop failure. Interannual yield variability increases in nearly all cases at higher N rates. At Ouagadougou and Bobo Dioulasso the minimum yield also increases with increasing N fertilizer rates on soil C. At Bobo Dioulasso on soil C the N response curve tends towards a sigmoid shape; according to the model the harvest index is reduced at low N availability in this situation. Total aboveground biomass does not show this sigmoid tendency. On soils C with the highest water holding capacity and with run-on instead of run-off, average yields, especially at higher N rates, are higher than on soils A and B. This effect is most pronounced in the driest zone, represented by the Ouahigouya rainfall records, as may be expected.

Frequency distributions of economic yields

Figure 5 shows the frequency distribution of gross margin (yield minus fertilizer costs, assuming a price ratio of 6 kg grain per kg N) based on the model calculations for Ouagadougou. For the three soils three different patterns emerge: on soil A all lines with N fertilizer application are to the left of the line without N fertilizer application. This

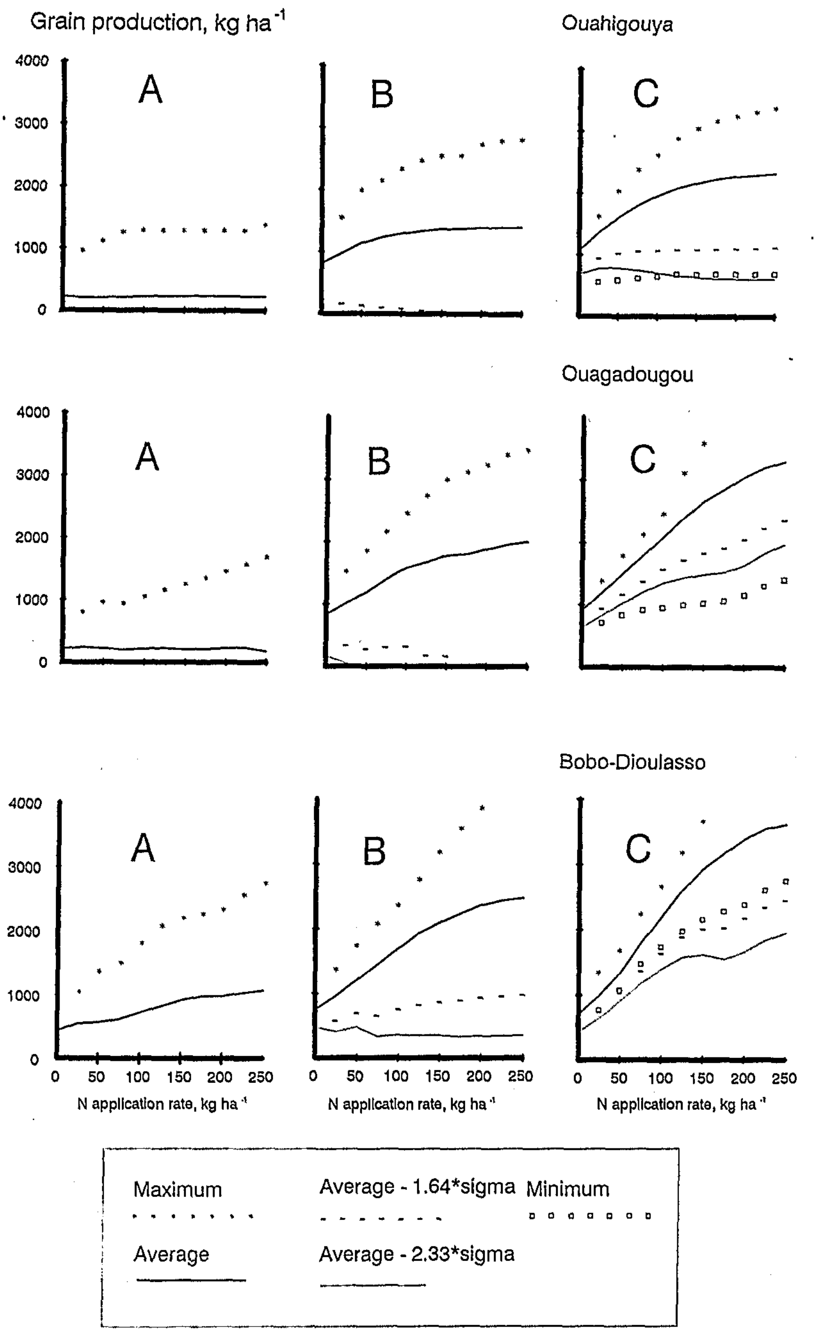

Figure 4. N response curves calculated with the model of Van Loo *et al.* (1990) for three soils (Table 3) in three climatic zones in Burkina Faso; for each N fertilizer rate the average, μ, and the observed maximum and minimum yields are given for a 30-year period, and the values of $\mu - 1.64\ \sigma$ and $\mu - 2.33\ \sigma$ (σ = calculated standard deviation), as they represent the expected yield in the worst 5 and 1% of years, respectively.

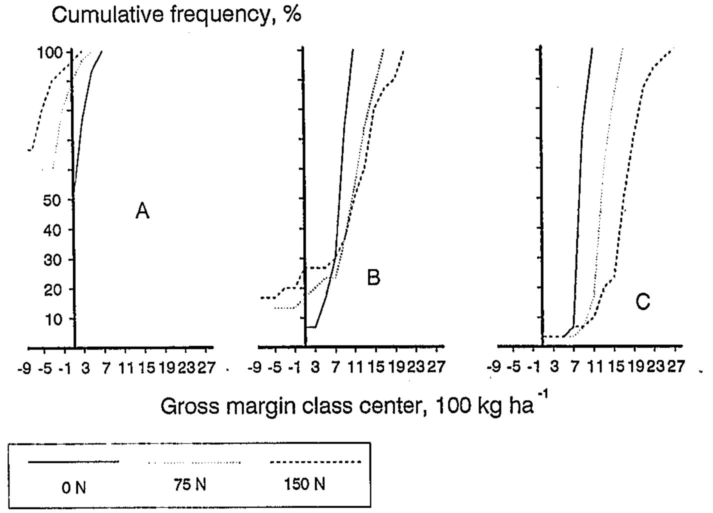

Figure 5. Calculated frequency distribution of gross margin (grain yield minus fertilizer costs, for a price ratio of 6 kg grain per kg N in fertilizer) at N rates of 0, 75 and 150 kg ha^{-1}, for three soils in Ouagadougou.

means that fertilization always has a negative effect on income when the costs of fertilizer are considered. For soil B the lines cross and here the farmer is better off in about 1 out of 4 years without N fertilizer. For soil C the lines for 75 and 150 kg ha^{-1} N are to the right of that for 0 N application and fertilizer increases financial yield throughout.

The calculations show large differences in N response and yields among soils, which are entirely due to differences in water balance, as N mineralization was kept unchanged in the simulations. The total available soil water storage capacity and its two components, the available water storage capacity per unit volume of soil, which depends on texture and soil organic matter content, and the rooting depth are important parameters, as the intervals between rain events in the growing season can be long, even when total rainfall seems to be sufficient. N fertilizer application, or increased N supply from organic sources, on soils with a low available water storage capacity such as soil A and, because of more dry spells soil B in Ouahigouya, is not advisable, even though in years with favorable rainfall it may lead to a substantial yield increase. On soils with high available water storage capacity and run-on, such as soil C, increased N supply to the crop will lead to substantially higher yields on average, without increasing the risk of crop failure. For intermediate soils, such as soil B, in a climate such as in Bobo Dioulasso efforts to increase N supply will be rewarded with higher average yields, although the increased variability, not only absolute (variance) but also relative (coefficient of variation), has consequences which can not be neglected. One way to reduce the variability for the farming household might be based on maintaining a ‘meaningful diversity’ of activities.

$p_{1,2} < h$ *criterion for physical yields*

The combinations of soil types and N fertilizer rate that meet the $\rho_{1,2}/h$ criterion for variance reduction are indicated in Table 5 for each climatic zone. At the driest site, Ouahigouya, combinations of the three soils nearly always lead to variance reduction, irrespective of the N rate, while combinations of different N rates on the same soil meet the criterion only once (on soil A for 0 and 50 kg ha^{-1} of N). At Ouagadougou combinations of soil A with either B or C generally meet the criterion, but combinations of B and C do not. In Bobo-Dioulasso again most combinations among soils meet the criterion, but different N rates on the same soil meet the $\rho_{1,2} < h$ criterion only rarely (notably on soil C).

Figure 6 presents an example for the expected yields of a combination of fields on soils B and C in Bobo Dioulasso, both at an N rate of 75 kg ha^{-1}. For this combination $\rho_{1,2}$ was −0.006. Although the average yield on soil C is 24% higher than that on soil type B, the expected production in the worst 10% of the years is higher for almost any combination of B and C, instead of soil C alone. The optimum f_1 depends on the target yield, or on the extremity of the years for which production is maximized.

Effects of spatial heterogeneity

Spatial heterogeneity in N supply in a field could lead to some degree of variance reduction. On the basis of Table 5 we expect that such variance reductions will be the

Table 5. Combinations of soil and N fertilizer rate, within each climatic zone, where the $\rho_{1,2} < h$ criterion is met and where a combination has a smaller standard deviation than the most stable single component(+); A. Ouahigouya, B. Ouagadougou, C. Bobo Dioulasso.

Table 5A. Ouahigouya

		TOPOSEQUENCE														
		A					B					C				
		0	50	75	150	250	0	50	75	150	250	0	50	75	150	250
A	0		+	.	.	.	+	+	+	+	+	+	+	+	+	+
	50	+		.	.	.	+	+	+	+	+	+	+	+	+	+
	75	.	.		.	.	+	+	+	+	+	+	+	+	+	+
	150	.	.	.		.	+	+	+	+	+	+	+	+	+	+
	250	.	.	.	.		+	+	+	+	+	+	+	+	+	+
B	0	+	+	+	+	+		.	.	.	.	+	+	+	+	+
	50	+	+	+	+	+	.		.	.	.	.	+	+	+	+
	75	+	+	+	+	+	.	.		.	.	.	+	+	+	+
	150	+	+	+	+	+	.	.	.		.	.	.	+	+	+
	250	+	+	+	+	+	.	.	.	.		.	.	+	+	+
C	0	+	+	+	+	+	+	.	.	.	.		.	.	.	.
	50	+	+	+	+	+	+	+	+	.	.	.		.	.	.
	75	+	+	+	+	+	+	+	+	+	+	.	.		.	.
	150	+	+	+	+	+	+	+	+	+	+	.	.	.		.
	250		+	+	+	+	+	+	+	+	+	+	.	.	.	

Table 5B. Ouagadougou

		TOPOSEQUENCE														
		A					B					C				
	N	0	50	75	150	250	0	50	75	150	250	0	50	75	150	250
A	0		.	+	+	+	+	+	.	.	.	.	+	+	+	+
	50	.		+	+	+	+	+	+	.	.	.	+	+	+	+
	75	+	+		.	+	+	+	+	.	.	.	+	+	+	+
	150	+	+	.		+	+	+	+	.	.	.	+	+	+	+
	250	+	+	+	+		+	+	+	+	+	+	+	+	+	+
B	0	+	+	+	+	+		.	.	.	.	.	.	+	.	.
	50	+	+	+	+	+	.		.	.	.	.	.	.	+	+
	75	.	+	+	+	+	.	.		.	.	.	.	.	+	+
	150	.	.	.	.	+	.	.	.		.	.	.	.	.	+
	250		.	.	.	.	+	.	.	.	.		.	.	.	.
C	0	.	.	.	.	+	.	.	.	.	.		.	.	.	.
	50	+	+	+	+	+	.	.	.	.	.	.		.	.	.
	75	+	+	+	+	+	+	.	.	.	.	.	.		.	.
	150	+	+	+	+	+	.	+	+	.	.	.	.	.		.
	250	+	+	+	+	+	.	+	+	+	+	.	.	.	.	

Table 5C. Bobo-Dioulasso

		TOPOSEQUENCE														
		A					B					C				
	N	0	50	75	150	250	0	50	75	150	250	0	50	75	150	250
A	0		.	.	.	.	+	+	+	.	.	+	+	+	+	+
	50	.		+	.	.	.	+	+	+	+	+	+	+	+	+
	75	.	+		.	.	.	+	+	+	+	+	+	+	+	+
	150	.	.	.		.	.	.	+	+	+	+	+	+	+	+
	250	.	.	.	.		.	.	.	+	+	+	.	+	+	+
B	0	+	.	.	.	.		.	.	.	.	+	+	+	+	+
	50	+	+	+	.	.	.		.	.	.	.	+	+	+	+
	75	+	+	+	+	.	..	.		.	.	.	+	+	+	+
	150	.	+	+	+	+	.	.	.		.	+	+	+	+	+
	250	.	+	+	+	+	.	.	.	.		+	.	+	+	+
C	0	+	+	+	+	+	+	.	.	+	+		+	+	+	+
	50	+	+	+	+	.	+	+	+	+	.	+		+	+	+
	75	+	+	+	+	+	+	+	+	+	+	+	+		.	.
	150	+	+	+	+	+	+	+	+	+	+	+	+	.		.
	250	+	+	+	+	+	+	+	+	+	+	+	+	.	.	

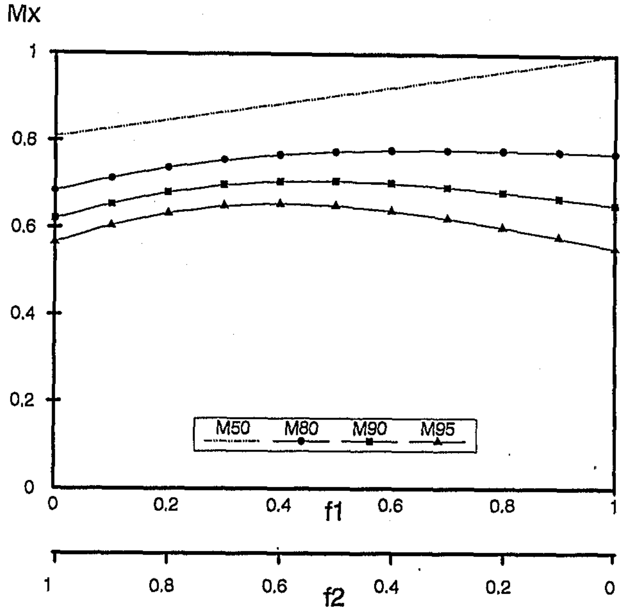

Figure 6. Expected relative (physical) yield in the worst 50 (M50), 20 (M80), 10 (M90) or 5 (M95) % of the years for a combination of soil types B and C (with fractions $(1 - f_1)$ and f_1, respectively), at 75 kg ha^{-1} of N each in Bobo Dioulasso. Yield is expressed relative to the average yield on soil type C (1790 kg ha^{-1}).

exception rather than the rule. Still, such exceptions may be interesting as they possibly contradict the conventional wisdom that N should be applied uniformly and that spatial heterogeneity has a negative effect on yields (Van Noordwijk & Wadman, 1992). Figure 7 shows results for a model run for Bobo Dioulasso with run-on and rooting depth as for soil C, but with a 25% higher water holding capacity of the soil; at low N rates spatial heterogeneity has a yield-stabilizing effect. The points for the various degrees of heterogeneity are above the line for the homogeneous case, for μ (Figure 7A) but especially for $\mu - \sigma$ (Figure 7B); the effect on μ is due to the sigmoid shape of the yield response curve in this situation, but additionally σ is reduced in this case by spatial variability in N supply. At higher N rates heterogeneity has a negative effect on average yield, as one may expect, and does not reduce σ. For the current model runs, effects of spatial variability in N supply on variance reduction are small; the possibility of such effects, however, cannot be excluded for other situations.

Procedure for selecting meaningful diversity

The $\rho_{1,2} < h$ criterion allows decisions whether or not a specific combination of activities will reduce the variance, but does not by itself allow decisions when more than two possibilities exist. A decision tree can be constructed, however, on the basis of similarity dendrograms as used in numerical taxonomy and ecological classification studies. Instead of the usual 'similarity' measures, we based the cluster analysis on the matric of correlation coefficients (of gross margin). Figure 8 shows the results for three locations. A stepwise decision-making process can now be followed, starting with the least similar pairs and evaluating the $\rho_{1,2} < h$ criterion for the two representatives of each group with the highest average yield. If $\rho_{1,2} < h$, then a comparison is made on the next split in the dendrogram. If $\rho_{1,2} > h$ on a particular split, then the best member of that group should be chosen, rather than a combination.

The dendrogram for the driest site, Ouahigouya, only reflects the three soils (A, B and C) and no grouping on the basis of N rate. Combinations of the best (average) N rates for the three soils (0 kg ha^{-1} on soil A, 50 kg ha^{-1} on soil B and 100 kg ha^{-1} on soil C) will be the best choice for minimizing risk. In Ouagadougou N rates lead to slightly more differentiation, but the $\rho_{1,2} < h$ criterion is again only met by combinations of the best N rates for each soil (in this case: 0 kg ha^{-1} on A, 100 kg ha^{-1} on B and 200 kg ha^{-1} on C). In Bobo-Dioulasso the pattern is slightly more complex and now there may be scope for including soil C with only 50 kg ha^{-1} on N, in combination with the best treatment of each soil (in this case: 0 kg ha^{-1} on A, 150 kg ha^{-1} on B and 200 kg ha^{-1} on C).

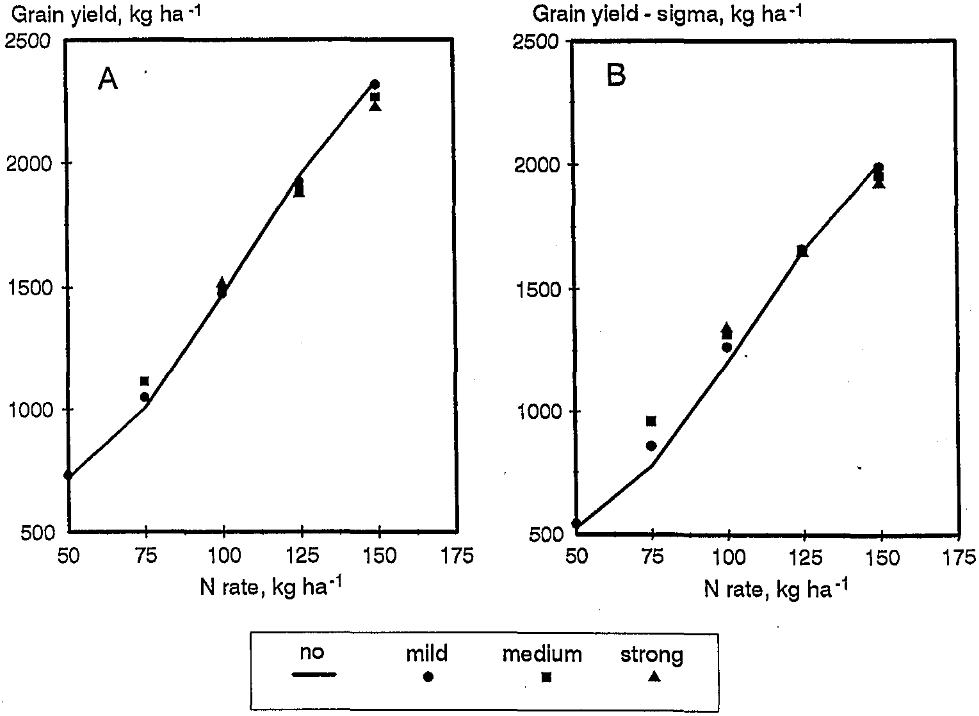

Figure 7. Effects of spatial variability in N supply on the average yield, μ, and on $\mu - \sigma$; to simulate spatial variability in N supply, 'filters' described in Table 4 were used as n-point moving average; rainfall data for Bobo-Dioulasso, soil C with modified (higher) water storage capacity. Four situations with no to strong field level variability in N supply.

These results for gross margins depend on the fertilizer:grain price ratio used for the calculations. With lower price ratios the gross margins are more similar to the physical yields and there may be slightly more scope for risk reduction by combinations of N rates and soils.

Discussion

Risk analysis as presented here requires a crop growth model sensitive to the yield-determining variables (in this case: rainfall) and the major management factors (in this case N supply) with the expected probability distribution of the environmental variables (in this case long-term actual climatic records). The model should be validated for a few well-chosen crop experiments; the current model has not been sufficiently tested, so it can only be used to illustrate the method for further analysis.
From such a model the three management options for uncertain environments can be evaluated:

1. Choosing the best single component, not only on the performance in an average year but on the expected frequency distribution of yields.
2. Criteria for maintaining meaningful diversity in cropping systems and land units: risk reduction is based on a combination of components with a low correlation coefficient, i.e. components which respond differently to environmental conditions.
3. Options for maintaining flexibility: N fertilizer application may be based on tactical rather than strategic decision-making, but this requires predictability of environmental conditions in the second part of the growing season. We have not yet attempted this approach, as a better knowledge of actual farmer's options is needed to do so.

Even under (semi-)arid conditions nutrient deficiency appears a major determinant for crop yield (Van Keulen, 1975; Penning de Vries & Djitéye, 1982; Keating *et al.*, 1991). This implies that use of additional (external) nutrients may, on average, lead to increased crop yields. Van Keulen & Seligman (1992) and the model results presented here showed, however, that risks of complete crop failure are high at low available-water holding capacity of the soil, and may be increased by fertilizer use. Fertilizer use is most effective on soils with the most reliable water supply and for crops that are most drought-tolerant. This implies high demands on management to cope with the uncertainty and the risks involved. The risk of not meeting one's target generally increases when the production target is closer to the maximum.

In the analysis given here a number of important points could not be taken into account. These include:

- Risks strongly depend on the level of aggregation of the study: for a farm household risks may be substantially reduced if it makes use of fields with different characteristics vis-a-vis the main limiting factor (Brouwer *et al.*, 1993); even to have fields on two sides of the village rather than a single field, may reduce risks, as these fields will have a different rainfall pattern, as rainfall is poorly correlated at a scale of a few km; for production at the village level, however, this aspect of

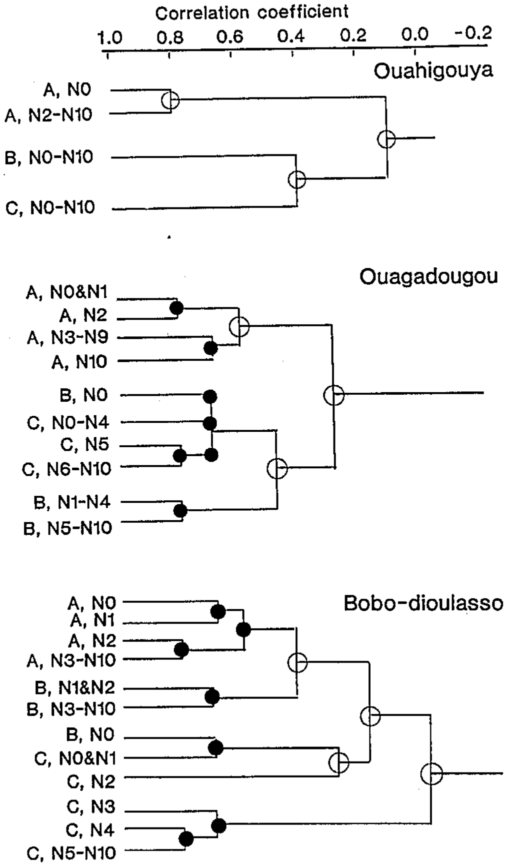

Figure 8. Hierarchical cluster diagram of gross margins for three soil types; open circles on an intersection indicate that the best (average) yielding member of the two groups meet the $\rho_{1,2} < h$ criterion; for closed circles this criterion is not met and no variance reduction can be expected. Cluster analysis was based on average-links.

land distribution is not relevant.

- Risks are much more pronounced for grain production than for total biomass (Seligman *et al.*, 1992), (in pastures consisting of mixed species stands risks are even lower); specific periods, such as pollination in maize, may be particularly drought-sensitive and need further attention in model formulation.
- Carry-over effects on soil nutrient and organic matter status in the next cropping season. For the current model, the same initial conditions were used each year, regardless of previous N rates and production in the previous years. Depending on climatic conditions part of the N fertilizer applied in one season may be used by a crop in a subsequent year, especially if the first crop failed; residual effects of N are most likely when there are no small rain events in the dry season between the cropping season. N transformations can already occur after small rain events. Carry-over effects are not restricted to fertilizer N. In the analysis of

Mediterranean natural vegetation systems by Seligman *et al.* (1992), it became clear that a wet year after a dry year always gave higher yields than a wet year after a wet year.

- Interactions between different nutrients; in the simulation model we assumed that the supply of P and other nutrients was not limiting; the practical consequences of this assumption depend on N input and water availability.
- Long-term effects of accelerated soil mining should be considered if short-term management decisions lead to the use of insufficient and unbalanced nutrient sources. Data on soil mining due to the prevalence of short-term interests over long-term interests for the 'Soudanian' zone in Mali were given by Breman (1990) and Van der Pol (1992).
- Risks primarily depend on the targets formulated. As various actors in society will formulate different targets, e.g. for food crop production, risks will be evaluated differently even if the average yield and its variability are the same. A further integration of socio-economic and agro-ecological aspects of risk management is needed and should be based on proper quantification.

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References

Babu, S.C. & B. Rajasekaran, 1991. Agroforestry, attitude towards risk and nutrient availability: a case study of south Indian farming systems. *Agroforestry Systems* 15: 1–15.

Bakker, E.J., 1992. Rainfall and risk in India's agriculture: an ex-ante evaluation of rainfall insurance. Ph.D thesis, Univ. of Groningen, Wolters Noordhof, Groningen, 180 pp.

Breman, H., 1990. Integrating crops and livestock in southern Mali: rural development or environmental degradation? In: R. Rabbinge, J. Goudriaan, H. van Keulen, F.W.T. Penning de Vries & H.H. van Laar (Eds.), Theoretical production ecology: reflections and prospects. Simulation Monographs no. 34, Pudoc, Wageningen, pp. 277–294.

Brouwer, J., L.K. Fussell & L. Hermann, 1993. Soil and crop growth micro-variability in the West African semi-arid tropics: a possible risk-reducing factor for subsistence farmers. *Agriculture, Ecosystems and Environment* 45: 229–238.

De Leeuw, J. & T.A.B. Snijders, 1987. Est-il possible de prédire la pluviometrie à venir à partir de la lame pluviale relevée en début de saison? Bulletin de Liaison du Comité Interafricain d'Etudes Hydrauliques, No. 69, pp. 37–41.

De Wit, C.T., 1960. On competition. *Verslagen Landbouwkundige Onderzoekingen* 66(8): 1–82.

De Wit, C.T. & H. van Keulen, 1987. Modelling production of field crops and its requirements. *Geoderma* 40: 253–265.

El-Tom, M.A., 1975. The rains of the Sudan. Khartoum University Press, Khartoum, 140 pp.

Franquin, P., 1984. Agroclimatologie et agrometeorologie en zone tropicale seche d'Afrique. *Agronomie Tropicale* 39: 301–307.

Keating, B.A., D.C. Godwin & J.M. Watiki, 1991. Optimising nitrogen inputs in response to climatic risk. In: R.C. Muchow and J.A. Bellamy (Eds.), Climatic risk in crop production: Models and management for the semiarid Tropics and Subtropics. CAB International, Wallingford, pp. 383–409.

Le Houérou, H.N., 1989. La variabilité de la pluviosité annuelle dans quelques régions arides du monde; ses consequences ecologiques. In: B. Bret (Ed.), Les hommes face aux secheresse. Collection Travaux et Memoires no. 42. Institut Hautes Etudes de l'Amerique Latin, Paris, pp. 127–137.

Lilieholm, R.J. & L.H. Reeves, 1991. Incorporating economic risk aversion in agroforestry planning. *Agroforestry Systems* 13: 63–71.

McCown, R.L., B.M. Wafula, L. Muhammed, J.G. Ryan & J.N.G. Hargreaves, 1991. Assessing the value of seasonal rainfall predictor to agronomic decisions: the case of response farming in Kenya. In: R.C. Muchow and J.A. Bellamy (Eds.), Climatic risk in crop production: Models and management for the semiarid Tropics and Subtropics. CAB International, Wallingford, pp. 383–409.

Mokwunye, A.U. & L.L. Hammond, 1992. Myths and science of fertilizer use in the tropics. In: R. Lal and P.A. Sanchez (Eds.), Myths and science of soils in the Tropics. SSSA Spec. publ. No. 29. Soil Science Society of America, Madison WI, pp. 121–134.

Payne, R.W., P.W. Lane, A.E. Ainsley, K.E. Bicknell, P.G.N. Digby, S.A. Harding, P.J. Verrier & R.P. White, 1987. Genstat 5 Reference Manual. Clarendon Press, Oxford, 749 pp.

Penning de Vries, F.W.T. & M.A. Djitéye (Eds.), 1982. La productivité des pâturages sahéliens. Une étude des sols, des végétations et d'exploitation de cette ressource naturelle. Pudoc, Wageningen, 525 pp.

Schweigman, C.; 1985. Operations research problems in agriculture in developing countries. Khartoum Univ. Press., Khartoum, 361 pp.

Schweigman, C., T. Snijders, J. van Andel & M. van Noordwijk, 1988. Observations quantitatives sur les risques dans l'approvisionnement alimentaire du plateau Mossi, Burkina Faso. Rijksuniversiteit Groningen, AGRISK report, 70 pp.

Seligman, N.G., H. van Keulen & C.J.T. Spitters, 1992. Weather, soil conditions and the interannual variability of herbage production and nutrient uptake on annual Mediterranean grasslands. *Agriculture and Forest Meteorology*, 57: 265–279.

Snijders, T.A.B., 1988. A method for early warning. CEDRES/AGRISK report, University of Groningen/Universite de Ouagadougou, 25 pp.

Stewart, J.J., 1991. Principles and performance of response farming. In: R.C. Muchow and J.A. Bellamy (Eds.), Climatic risk in crop production: Models and management for the semiarid Tropics and Subtropics. CAB International, Wallingford, pp. 361–382.

Stoop, W.A., 1987. Variations in soil properties along three toposequences in Burkina Faso and implications for the development of improved cropping systems. *Agriculture Ecosystems and Environment* 19: 241–264.

Stroosnijder, L. & H.D.J. van Heemst, 1982. La météorologie du Sahel et du terrain d'étude. In: F.W.T. Penning de Vries and M.A. Djitéye (Eds.), La productivité des pâturages Sahéliens. Pudoc, Wageningen, pp. 36–49.

Trenbath, B.R., 1986. Resource use by intercrops. In: C.A. Francis (Ed.), Multiple cropping systems. Macmillan, New York, pp. 57–81.

Van der Pol, F., 1992. Soil Mining: an unseen contributor to farm income in Southern Mali. Bull. 325, Royal Tropical Institute Amsterdam, 47 pp.

Van Keulen, H., 1975. Simulation of water use and herbage growth in arid regions. Simulation Monographs. Pudoc, Wageningen, 176 pp.

Van Keulen, H. & H. Breman, 1990. Agricultural development in the West African Sahelien region: a cure against land hunger? *Agriculture Ecosystems and Environment* 32: 177–197.

Van Keulen, H. & F.W.T. Penning de Vries, 1993. Farming under uncertainty: terminology and techniques. In: D.R. Buxton *et al.* (Eds.), International crop science I. Crop Science Society of America, Madison, WI (*in press*).

Van Keulen, H. & N.G. Seligman, 1992. Moisture, nutrient availability and plant production in the semi-arid region. In: Th. Alberda, H. van Keulen, N.G. Seligman and C.T. de Wit (Eds.), Food from dry lands. An integrated approach to planning of agricultural development. Systems Approaches for Sustainable Agricultural Development, Vol. I. Kluwer, Dordrecht, pp. 25–81.

Van Loo, E.N., M.C. Hanegraaf & E.A.R. Mellaart, 1990. The effect of variation in water and nitrogen availability on the yield of small grain sorghum (*Sorghum bicolor*) and millet (*Pennisetum typhoides*) in Burkina Faso: a simulation model. CEDRES/AGRISK report, University of Groningen/Universite de Ouagadougou, 33 pp.

Van Noordwijk, M. & J. van Andel, 1988. Reduction of risk by diversity, a theoretical basis for age-old farming systems. *ILEIA-newsletter* 4(4): 8–9.

Van Noordwijk, M. & J.H.M. Scholten, 1994 Effects of fertilizer price on feasibility of efficiency improvement: case study for an urea injector for lowland rice. Fertilizer Research. [in press]

Van Noordwijk, M. & W.P. Wadman, 1992. Effects of spatial variability of nitrogen supply on environmentally acceptable nitrogen fertilizer application rates to arable crops. *Netherlands Journal of Agricultural Science* 40: 51–72.

Wafula, B.M., 1993. Response farming for maize production in the dry tropics. In: D.R. Buxton *et al.* (Eds.), International crop science I. Crop Science Society of America, Madison, WI (*in press.*)

Winterhalder, B., 1990. Open field, common pot: harvest variability and risk avoidance in agricultural and foraging societies. In: E. Cashdan (Ed.), Risk and uncertainty in tribal and peasant economies. Westview Press, Boulder, pp. 67–87.