Rapports PSS Nº 3

Production Soudano-Sahélienne (PSS)
Exploitation optimale des éléments nutritifs en élevage

Projet de coopération scientifique

Agricultural production: ecological limits and possibilities

Contribution to the Sahel ecology, economy and demography study

Sonja van der Graaf and Henk Breman, CABO-DLO [1)]

Prepared for the Club du Sahel

1) Adresse: CABO-DLO, B.P. 14, 6700 AA Wageningen, les Pays-Bas

IER, Bamako
CABO-DLO, Wageningen
DAN-UAW, Wageningen
IB-DLO, Haren

PSS

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Résumé

Ce rapport sur "La production agricole: les contraintes et les potentiels écologiques" est une contribution à l'étude du nexus écologie, économie et démographie du Club du Sahel. Cette contribution ne sera pas publiée en extenso par le Club. Elle reflète cependant bien l'analyse de la situation des pays sahéliens qui a mené à l'élaboration du projet PSS. Ainsi, le projet a jugé utile de la publier, pour mieux faire comprendre l'accent mis sur l'intensification de l'agriculture comme moteur du développement rural au Sahel.

La Banque Mondiale estime que la production agricole des pays sahéliens devrait croître avec 4% par an pour parer à la croissance démographique et la dégradation de la situation économique. Ainsi il faut la peine de se demander si une telle croissance est au moins théoriquement possible.

Pour répondre à cette question, les facteurs qui déterminent la production primaire de la zone ont été analysés (sols et climats notamment). Une attention particulière à été donnée aux aspects écologiques de la production durable (chap. 2).

La production potentielle a été estimée, ceci aussi bien pour la production végétale qu'animale (chap. 3). Elle a été comparée avec la production actuelle. En plus la capacité de charge des ressources naturelles seules a été confrontée à la densité de la population (chap. 4).

Finalement une analyse a été faite du potentiel des options techniques pour une augmentation de la production agricole. Successivement sont traités le fumier, la fixation biologique d'azote, l'agroforesterie, les engrais chimiques et l'agriculture intégrée. L'agriculture intégrée est l'option élaborée et étudiée dans le cadre du projet PSS. Il s'agit de l'intégration des éléments de l'agriculture écologique et de l'agriculture intensive dite "moderne".

Le rapport conclut qu'au Sahel il est question en générale d'une surexploitation des ressources naturelles, due au surpeuplement et à la situation économique. Vu le fait que l'agriculture est encore le moteur principal du développement de la région, l'intensification agricole devrait être prioritaire. Ceci implique que la disponibilité des éléments nutritifs devra être augmentée. Les engrais chimiques se présentent comme les plus efficaces dans ce cadre. L'implication est que la production doit s'orienter plus sur le marché.

Le rapport PSS no. 1 (Wooning, 1992) montre clairement les difficultés d'une utilisation rentable des engrais chimiques pour l'agriculture des pays sahéliens. Ainsi, il n'existe pas une recette simple pour l'intensification de cette agriculture. Il faut l'élaboration des paquets des mesures techniques et socio-économiques, différentiés par zone agro-écologique en dépendance des conditions économiques. La subvention n'est qu'un des instruments éventuels.

Une planification compréhensive est indispensable, en se fixant des priorités. Le rapport souligne les

responsabilités des partenaires divers, la population, les gouvernements et les bailleurs de fonds. Le PSS espère de contribuer à leur établissements de priorités à travers ce rapport.

1. Introduction

Recent calculations of the World Bank made clear that growth of agricultural production in the Sahel should be 4% a year to counteract the growing population and the declining economic performance (World Bank, 1991). However, it is questioned whether there is a potential for this growth and how it should be realised. Especially while the natural resource base in Sahelian countries is diverse, one should indicate the limits and possibilities in order to avoid failures and disappointment.

This report will give estimates of the potential production. These figures will be compared with actual production, so that the actual exploitation intensity of the natural resources can be determined and the margin for increased production can be identified. Implications for rural development and possible technical options will be discussed.

Because of the special climatological conditions and soils prevailing in the Sahel, a brief introduction will describe the factors determining primary production. Also the consequences of the often expressed need to produce in an ecological sustainable manner are translated in terms related to the Sahelian context.

2. Primary production and ecological sustainable resource use

2.1. Factors determining primary production

> "For both arable farming and animal husbandry, production of plant material forms the basis of the production process. The level of primary production is determined by the interaction between the genetic properties of the plant and environmental conditions, especially climatic conditions and soil properties" (van Keulen & Breman, 1990).

Which part of the primary production will be converted in products useful for men, depends of the climate and variety or species. For cereals for example it is the fructification which counts. Varieties may differ in *e.g.* the relative production of seed and straw, or the length of growth cycle. For animal production, almost all parts of the primary production by herbaceous species can be used. Differences in production will occur according to difference in breeds and species (*e.g.* Zebu or N'dama, goat or sheep).

Climate and soils

"The prevailing climatic conditions in the Sahel are unique. Such an extreme combination of concentrated monomodal rainfall, high temperatures during the growing season and very high temperatures combined with very low atmospheric humidities in the off season, exists nowhere else. The consequences are very difficult conditions for perennials and a strong impact of the length of the growth cycle on the production of annuals.

Unconstrained production of plant materials requires the availability of sufficient water. Although rainfall is limited in the Sahelian region, and can be scarce in drought years, stating that the lack of water is the major constraint for primary production is jumping to conclusions. Careful examination of the soil water balance, *i.e.* a quantitative description of all incoming and outgoing water, shows that in the south Sahel only a small fraction (10-15%) of the annual precipitation is actually used by the vegetation and at a relatively low efficiency (Stroosnijder & Koné, 1982). A considerable part of the precipitation does not infiltrate at the site, but runs of, due to the low infiltration capacity of many of the soils. In addition, a large proportion of the water that infiltrates, is lost as direct evaporation from the soil surface because the low availability of nitrogen and phosphorus limits the rate of plant growth, so that soil cover is reached only after a prolonged period of time, if at all".

"In West-Africa, a strong gradient exists in precipitation which increases from the dry Sahara, via the semi-arid Sahel and the relatively humid savannah, to the tropical rain forest in the south. Over the whole transect, the supply of plant nutrients from natural resources is low, although it increases slightly with increasing rainfall as a result of direct and indirect effects (Breman & Krul, 1982). For example, average annual nitrogen supply to the above-ground plant parts in natural rangelands increases from 2.5 kg ha^{-1} at an annual precipitation of 100 mm to 12.5 kg ha^{-1} at 400 mm and a saturating level of +/- 20 kg ha^{-1} is reached at 1000 mm. Phosphorus availability fluctuates around one-tenth of nitrogen availability" (van Keulen & Breman, 1990).

Reports on nutrient cycles of 65 agro-ecosystems from all over the world, showed an average consumable output of nitrogen of 9 kg ha^{-1} per year for animal husbandry and 21 kg ha^{-1} for arable farming in those systems where no fertilisers and/or concentrates were used (Frissel & Kolenbrander, 1978, in Breman, 1991). In the West-African savannah, stable rangelands with a nitrogen availability for aboveground plant growth of 15 kg ha^{-1} produce animal protein equivalent to less than 0.5 kg ha^{-1} of nitrogen, whereas for arable farming, with a sustainable availability of 10 kg ha^{-1}, the consumable amount of nitrogen is less than 5 kg ha^{-1}, which underlines the unique, extreme conditions in the Sahel (Breman, 1991).

Primary production and vegetation composition

Besides the absolute availabilities of water and nutrients, their relative availability in view of the need for plant growth is important. Research indicated that at less than 200-250 mm of annual infiltration, like in the North Sahel, water is the most limiting factor for the primary production. Further South, the availability of nutrients is more limiting, except on those places where strong run-off and/or shallow soils decrease water availability to values found in the North (Penning de Vries & Djitèye, 1982).

All elements of the vegetation compete for these limited resources. The relative availability of water and nutrients and the characteristics of the different elements of the vegetation mainly determine the relative importance of the different elements in the natural vegetation. "There are two general clues to the competition between annual plant species on the one hand and perennials (grasses, shrubs, trees, etc.) on the other: competition for water determines the abundance, and competition for nutrients and light determines the success in producing biomass.

In the North Sahel the advantage of annuals is such, that perennial grasses and woody species are almost absent; the annuals leave no water for the perennials to survive the dry season. This advantage decreases with the increase of water storage outside the reach of annuals (Kessler & Breman, 1991): in the South Sahel, where light soils becomes less dominant and redistribution of rainwater becomes more general, deep water infiltration occurs in places with enough run-on. The increased abundance of perennials on such spots is often not accompanied by a visible decrease in productivity of the annuals, because the availability of nutrients increases as well as the availability of water.

The productivity of annuals decreases when the overall importance of woody perennials increases gradually, going further South, into the savannah. The increasing cover and the associated annual production from the woody species are associated with a decrease in the availability of nutrients for the herb layer. This is still masked in the sudanian savannah where perennial grasses are able to produce more biomass at the same nutrient availability, as long as they are not intensively exploited (Penning de Vries & Djitèye, 1982)" (Breman, 1991).

The consequences of the limitations related to the natural resources should be mentioned. Favouring one component of the vegetation above another component is not always without negative consequences for the latter, which might be undesirable. Stimulating the growth of trees will in certain conditions be accompanied with a decrease of the productivity of crops and the herb layer (Kessler & Breman, 1990). Secondly, it should always be kept in mind which factor is limiting primary production. *E.g.*, if nutrients are the most limiting factor, no sustainable increase of production may be expected from an improvement of the availability of water.

In the south, the use of perennials seems to be a must because of the risks of losing nutrients with run-off and leaching.

2.2. Ecological sustainability

The biosphere offers man flows of energy, materials and buffers against threats by human activities, which can be named, the "environmental utilisation space" (James *et al.*, 1989). This space differs all over the world, is limited but also dynamic. There is a resilience capacity; to a certain extent, an ecosystem has the ability to adapt to a changing environment and is able to absorb external shocks without major structural damage (Munn, 1989). The environmental utilisation space may increase with the further evolution of human knowledge and skills, with the discovery of new resources and the development of new ways of using existing resources (James *et al*., 1989).

When the exploitation of the environmental utilisation space exceeds the resilience capacity, degradation of the environment occurs, which decreases the environmental utilisation space of future generations. Over-exploitation of stocks, pollution, and break down of biotopes, ecological structures and processes are most commonly causes of the shrink of the environmental utilisation space (Opschoor, 1991).

Degradation in the Sahel

The main factor which threatens the environmental utilisation space in Sahelian countries is the break down of ecological structures and processes induced by exhaustion.

There are two mechanism involved with exhaustion. A direct threat of the biotic elements of the natural resources occurs when the rate of exploitation is bigger than the rate of reproduction. This occurs with hunting, fishing, exploitation of wood and specific gather activities. The indirect threat is mostly executed by agriculture and animal husbandry; with overexploitation, the water and nutrient balances and composition of species are negatively affected.

The water balance will be influenced negatively when the physical characteristics of the upper soil layer deteriorate in such a way (*e.g.* sealing) that the capacity to absorb water decreases. Run-off will increase and hence infiltration will decrease. Also the ability to store water can deteriorate due to a declining soil depth and decay of soil structure (*e.g.* porosity). The most crucial causes are the decline of the soil protecting biomass and the organic matter contents of the soil.

The nutrient balance will be influenced negatively when the output (as biomass in the form of crops and animal products) is bigger than the input (by natural or human supply). At the same time a deterioration of the capacity to hold nutrients will take place, which leads to more leaching. The acidity will increase which leads to worse rooting conditions and lower nutrient uptake by the roots. Nutrient availabilities will also decrease with soil losses by water and wind erosion, due to a decrease of the vegetation cover.

In general agriculture is more harmful than animal production while with agriculture there is a greater output of nutrients and a more important influence on the physical characteristics of the soil (Breman, 1991a).

Resilience

The resilience capacity and possibility for regeneration differ predominantly according to soils and climate. A major distinction is the susceptibility of soils to sealing.

Sandy soils, like in the Sahel can be characterised as having a low resistance to degradation but a high regeneration capacity. Overexploitation leads to disappearance of the vegetation cover and to wind-erosion and ultimately to moving sand dunes. Once the causes of degradation are removed, regeneration is quick, owing to the pioneer characteristics of the annual plant species and the infiltration capacity of the sandy soils.

Loamy soils, dominant in the Sudan zone, are susceptible to sealing. After sealing, biological soil activity will be annihilated which inhibits further regeneration. The intact ecosystem with its important perennial vegetation component which permits to bridge shorter fluctuations, is fairly resistant to degradation but has a low regeneration capacity. Hence, the degraded system is very stable and considerable efforts and inputs are needed to initiate regeneration, like *e.g.* lowering of actual exploitation pressure, labour and the use of fertiliser to counterbalance exhaustion of soil nutrients (Geerling & De Bie, 1990). Especially lateritic soils, which are generally shallow too, are difficult to regenerate.

The susceptibility to degradation is also influenced by the extreme length and aridity of the dry season. During this period the vegetation remains inactive and hence soils are badly protected. The intensity of rainfall, result of time and amount of water, is another factor which counts. A high intensity increases the chance of degradation (soil deformation and run-off).

Regarding the composition of a vegetation, it should be mentioned that perennials and woody species easily disappear but are difficult to regenerate. They are very sensitive to overexploitation and natural regeneration will hardly occur while the seed dispersion mechanism (the harmattan and migrating herds) is directed southwards. Hence, the habitat of these species will easily be pushed to the South.

Parameters for sustainable production in the Sahel

With degradation several processes are involved. There are negative balances of water, nutrients and organic matter, deformation of the soil morphology (structure and porosity), and deregulation of physical, chemical and biological systems (acidification, N-fixing capacity). These processes are not clearly visible (one cannot see if *e.g.* exploitation concerns annual production, or soil mining occurs) while their results are strongly masked by the year to year dynamics of the (agro-)ecosystems

To indicate whether techniques influence the sustainability of the production system, other parameters than annual output can be used, because they represent the basis of the degradation processes (Meerman *et al.*, 1991).

First there is the nutrient balance. Inputs and outputs of nutrients should be quantified at the farm level. If that is not possible, due to lack of information, it is worthwhile to construct the nutrient balance at a higher level, *e.g.* regional or national, to get at least some idea of the nutrient situations and its direction of change. Secondly the ratio between infiltration and run-off should be analysed. Generally, a decrease in this ratio is a first sign of physical land degradation (reduced infiltration capacity and crusting). A reduced infiltration will also result in a decrease of the nutrient availability for the vegetation (Breman & De Ridder, 1991).

The vegetation cover and species composition also function as an indicator for crusting and sealing. These processes result in a change of species composition (perennials replaced by annuals; annuals with shorter growth cycle) or a decrease in vegetation cover (Breman & De Ridder, 1991).

Extension of the environmental utilisation space

New techniques of using existing resources more efficiently are explored. However, possibilities are probably limited. In the past, misjudgement of the actual production systems led easily to overestimation of possibilities to increase production. Irrigation appeared to be little successful, as water is not always the most limiting factor. The semi-nomadic animal production systems in the Sahel were supposed to function rather inefficient while in fact they produced 1 to 10 times more animal protein per hectare per year than the production systems in comparable areas in Australia (Breman & De Wit, 1983). Evidently, a comparison should be made between potential production and actual production, as will be done in part 3.

Still, prospects for an extension of the environmental utilisation space in the Sahel exist; the use of external inputs is still very limited. For instance several phosphate deposits were discovered and new techniques to improve the efficiency of this phosphate are in the R & D pipeline.

Implementation of innovations to improve the production potential depend mainly on economical aspects. Discussion of some options will follow in part 5.

3. Potential and actual production

3.1. Methodologies

To know whether there are possibilities for an increase of agricultural production, a comparison should be made between actual production and potential production. Agricultural research has traditionally relied heavily on field experiments to evaluate management practices and indicate potential production increases. Statistical methods were used to detect and analyse relationships between crop performance and states of the environment. However, field experiments have high costs and labour requirements and they can be used to sample only a fraction of the alternatives available in only a fraction of the weather conditions a farmer may encounter. Simulation models have been developed to supplement field experiments and extrapolate, in time and space, the information provided by the field experiments (Jones, 1990).

Dynamic simulation models are 'reduced' representations of real systems in the form of mathematical calculation schemes. They describe systems in terms of differential equations which relate the state of a system to a number of rate variables, a limited number of inherent system properties, and relevant external conditions (ten Berge, 1991). Models have been developed for a number of agricultural processes, including weather, hydrology, soil erosion, nutrient transformations and losses, and plant phenology, growth and yield. Models of specific processes have been combined into comprehensive crop growth models, which predict effects of environment, crop genotype and management on yields and, in some cases, on the soil resource (Jones, 1990).

The use of simulation models doesn't attempt to replace experimentation, but it certainly does alter the role of experimentation into one of testing explicit hypotheses (models) in order to assess their applicability, and one of collecting new information. The latter concerns often basic processes that have a more general validity and therefore greater 'transferability' than empirical information about production technologies (ISNAR, 1984, in ten Berge, 1991).

There are several methods which describe potential production. Some are predominantly based on the analysis of individual environmental factors (as climate, land form, soils and vegetation) and others are based on analysis of the environment as a whole, as these developed by the FAO-agro-ecological zones project and the Wageningen CABO-DLO/TPE-LUW and related working groups. Both begin with a calculation of the effects of climate on crop yields, followed by consideration of soils. The Wageningen approach differs from the FAO one in the greater complexity of agro-climatic analysis, and a fundamental difference in treatment of the effects of soils (Young, 1986).

3.2. Potential arable production

The project Primary Productivity in the Sahel (PPS) in Mali at which the Wageningen group participated, used a method of analysis which makes a distinction between different production levels in order to indicate the environmental bottlenecks of plant growth. Dynamic simulation models were developed to describe primary production, which were later specified for arable and animal production.

"Schematically, three production levels were distinguished:
(i) potential production, determined by crop characteristics and the environmental conditions that can not easily be modified, *i.e.* solar radiation and temperature;
(ii) water-limited production, in which the availability of water for the crop, as determined by precipitation pattern and soil physical conditions, and the reaction of the crop to temporary water shortages, are also taken into account;
(iii) nutrient-limited production, in which in addition the availability of macro-nutrients from natural resources, mainly determined by soil organic content and chemical soil properties, and the reaction of the crop to limited nutrient availability are taken into consideration.
This approach allows identification of the principal constraints as a basis for estimating the effects on yield of alleviating them" (Wolf, 1991). This analysis has been carried out for sorghum, millet, and maize for Burkina Faso (SOW, 1985).

It appeared that on relatively deep, well-drained soils, water-limited yields are equal to the calculated maximum yields when annual precipitation exceeds 500 mm, so in the south of the Sahelian zone and in the savannah. Apparently, the water holding capacity of the deep soils is sufficient to overcome dry spells during the growing season and end-of-season drought by exploiting stored soil moisture. On shallower or more sandy soils with a lower water-holding capacity, the storage capacity is insufficient. Dry spells during the growing season and end-of-season droughts affect the crops, especially during the crucial grain-filling periods, resulting in serious yield reductions even at much higher annual rainfall. Table 1 gives the results of this study.

Table 1. Estimated yields (kg ha^{-1}, 12 percent moisture) of main food crops in Burkina Faso.

crop	A	B	C	D	E
maize	5800	5800	1100	511 -1066	700
millet	2600	2400	550	351 -601	440
sorghum	4700	3900	875	460 -678	570

A, maximum potential yield at specific locations; B, water-limited yields; C, nutrient-limited yields; D, ranges of yields from statistical data (FAO, 1985, etc.); E, mean yields from statistical data. B, C, D and E are national average yields. (Source; SOW, 1985; Wolf *et al*., 1991)

The comparison between the water and nutrient limited yield suggests that availability of nutrients is the most constraining factor. The calculated nutrient-limited yields are practically always higher than actual yields, because of inevitable yield losses at farm level. These losses vary strongly, depending on crop cultivar, yield level, growing conditions, and the level of crop protection. Harvest losses will also occur.

It may thus be concluded that in most years, if soils are not too shallow, in Burkina Faso higher crop yields are possible by increased nutrient supply. The determination of nutrient-limited yields based on the availability of the major nutrient elements, clearly illustrated that for these crop species, nitrogen is the major limiting factor. However, the difference with the phosphorus-limited yield is only marginal in most cases, hence increasing nitrogen availability alone through the application of fertiliser, will only have a limited effect (van Keulen & Breman, 1990).

Assuming that in general in Burkina Faso weed control is incomplete and that almost no pest and disease control is practised, the 'actual' yield of cereals (V, Table 2) is estimated at 75 percent of the nutrient-limited yield.

The reported average yields (E, Table 1) are in close agreement with the estimated value for millet, but are 15 percent lower for sorghum and maize. Because of their longer growth cycles, sorghum and maize were probably more affected by dry spells, particularly on shallow soils.

The Wageningen group also distinguished a "target" yield; the potential yield, to obtain with application of fertiliser and optimal management. They set this yield at 80 percent of the long-term average water-limited yield. In that way, even in dry years with short grain-filling periods due to end-of-season drought, grain yield-nutrient uptake ratios will not become so low that fertiliser application becomes less attractive with the prevailing economic situation. A higher nutrient supply increases the risk for losses (higher risks for pests and diseases, potentially higher nutrient losses by leaching and runoff, and more intensive weed competition), hence, yield losses for this intensified production situation are estimated at 20 percent, so that the attainable yield at the specified target level (W, Table 2) is (0.80 * 0.80) times the average water-limited yield (Wolf *et al.*).

The FAO in *e.g.* their Agro-ecological zones Project assessed the potential of land for rain-fed production by comparing attributes of land with requirements of crops. The assessment includes two classifications; one of agro-climatic suitability and one of agro-edaphic suitability.

Potential constraint-free yields were determined according to the length of growing period. Different levels of input were considered; *e.g.* low, intermediate and high levels of inputs and management, corresponding respectively to traditional farming, improved local practices and advanced technical methods. Yields were supposed to double with increase of production level.

The climatically determined potential crop yields were estimated by rating agro-climatic constraints like *e.g.* variability in water supply within and between years, variability in temperature, incidence of pests, weeds, insects, etc..

The land suitability classification, based on rating of soil and land form requirements of crops and the edaphic properties and land form features of prevailing soil units, indicated estimations of the potential yield (FAO, 1978).

In practice with this method, length of growing period is the predominant physical variable influencing the estimates of potential yield. It outweighs the effects of temperature and soils. The influence of levels of inputs is also much larger than that of temperature and soils, which accords with experience (Young, 1986).

The figures of FAO in Table 2 are derived from computations for agro-ecological zones prevailing in Africa. The high input level can be compared with the former mentioned 'target' yields whereas the low input yields can be compared with 'actual' yields.

Table 2. Comparison of different estimates of potential yields (in t ha^{-1}).

	V	W	X	Y		Z	
				90-119 1)	120-149 1)	90-119 1)	120-149 1)
maize	0.8	3.7	2.5-3.5	1.9-2.7	3.7-5.4	0.4-0.5	0.7-1.0
millet	0.4	1.5	1.5-2.0	2.2-3.1	2.2-3.0	0.5-0.8	0.5-0.8
sorghum	0.7	2.5	2.0-2.5	1.8-2.6	2.7-3.8	0.3-0.5	0.5-0.7

[1)]length of growing period (in days).
V, actual yield SOW; W, target yield SOW; X, potential yield CILSS/INSAH; Y, high input yields FAO; Z, low input yields FAO. (Source; SOW, 1985; Charreau, 1986; FAO, 1978).

Research of the regional millet, sorghum, cowpea and maize improvement project run by CILSS and Institut du Sahel from 1981 to 1984 gave field indications of production potentials of this area (X, Table 2, Charreau & Rounet, 1986).

The figures compare reasonably well, except those for millet of the high input level of FAO which are considerable higher. It can be concluded that the potential yield, with application of fertiliser and optimal management, is far greater than the actual yields.

3.3. Potential animal production

The production potential for animal husbandry systems in a region depends on the quantity and quality of the available feed resources, provided that epidemic animal diseases are under control and that availability of drinking water is not a constraint, as is the situation for most of the West-African rangelands. Primary production of these rangelands are the most important source of fodder en hence forms the basis for animal production (Breman *et al.*, 1990).

Studies on the productivity of Sahelian rangelands in Mali determined the water-limited production of rangelands. Depending upon the amount of water that had infiltrated into the soil, aboveground biomass production of 6000-12000 kg ha^{-1} in the Southern Sahel was recorded, whereas actual production is much lower and lies in the order of 2000 kg ha^{-1}. Figure 1 gives a clear illustration of the relation between the water-limited and actual production.

Theoretical derived estimations of maximum potential production (nutrient nor water limited) indicated that production could even increase up to 75000 kg ha^{-1} $year^{-1}$ (Penning de Vries & Djitèye, 1982).

The present biomass production of the rangelands has been estimated using simple relations and calculation procedures (Breman & De Ridder, 1991). In the northern Sahelian zone quality is generally high, hence all biomass produced can be considered as forage, while in the southern sudanian zone average nitrogen content is so low, that only a small proportion of the production can be utilised by livestock. Taking into account the relative proportion of the various land units in the various climatological zones distinguished, forage availability per zone has been calculated, as illustrated in Table 3.

Figure 1. The relationship between annual rainfall (mm) and actual and water-limited biomass production. (Source: Penning de Vries & Djitèye, 1982)

Table 3. Total forage availability (kg ha^{-1}) and its distribution (%) among the herb layer and browse for the different climatological zones in West-Africa in normal (p.50) and dry (p.10) years.

climate zone[1)]	North Sahel		South Sahel		North Sudan		South Sudan	
	p.50	p.10	p.50	p.10	p.50	p.10	p.50	p.10
Total	250	50	800	500	1000	800	1200	1050
herb layer	92	80	80	80	59	62	60	61
browse	8	20	20	20	41	38	40	39

[1)] average annual precipitation 200, 450, 750 and 1050 mm, respectively.

(Source: Wolf *et al.*, 1991)

From forage availability and quality, carrying capacity can be estimated. The standard carrying capacity if defined as the maximum stocking rate that in a year with average rainfall guarantees the viability of a herd in sedentary animal husbandry systems with year-round grazing. This criterion implies that a heifer of 150 kg liveweight should attain an annual net liveweight gain of at least 25 kg, resulting in an average first age at calving of about five years, which just allows replacement of old animals that die or are sold (Breman & De Ridder, 1991). If higher animal production is aimed at, in either meat or milk, better quality forage is required and the carrying capacity will consequently decrease.

A "standard carrying capacity" is given in Table 4 based, on feed availability from natural rangelands and agricultural by-products in dry years. At the animal densities defined in Table 4, forage availability and quality are such that in nine out of ten years animal production is sufficient to guarantee maintenance of a viable herd. A difference have been made between mixed herds of 'grazers' and 'browsers' and present herd composition where cattle (in terms of TLU) constitute +/- 55% of the herd in the Northern Sahel, increasing to +/- 85% in the savannah.

The importance of woody species is clearly illustrated by the comparison of A and B in Table 4. Especially in the South Sahelian zone the carrying capacity increases when more browsers are supposed to profit from woody species.

Table 4. Estimated carrying capacity (ha TLU^{-1}), based on feed availability from natural rangelands and agricultural by-products in dry years (p.10) for various climatic zones in West-Africa.

climate zone	North Sahel	South Sahel	North Sudan	South Sudan
A	45.5	3.9	2.5	1.9
B	45	10 - 15	5 - 6	5 - 6
C	12 - 30	4 - 12	2	1.5 - 2.0

A: for mixed herds of 'grazers' and 'browsers'; B: the "present" (1987) herd composition; C: FAO figures.
(Source: Wolf *et al.*, 1991; van Keulen & Breman, 1990; FAO, 1986.)

The FAO also gave indications of livestock carrying capacity differentiated for agro-ecological zones in South Saharan Africa (arid, semi-arid, dry sub-humid and moist sub-humid).

The rather big difference between figures of FAO and those from the Wageningen group concerning the carrying capacity of the north Sahelian zone is most probably due to the fact that figures from FAO were not only derived from the situation in the Sahelian region. As already indicated (part 1) soil fertility in the Sahel and the contribution of perennials are particularly low.

Animal production can be estimated from feed intake which depends of feed availability and quality in the course of the growing season. This is shown in Figure 2 for three agroclimatic zones in West Africa.

Feed quality in the northern Sahel is such that even in the dry season, some liveweight gain is possible, resulting in an annual liveweight gain for a heifer of up to 100 kg. In the southern Sahel, annual liveweight gain for a similar animal is only +/- 5 kg as the liveweight gain during the green season is almost completely lost during the dry season. Further south, the situation improves because the length of the green period allowing more selective grazing due to a longer rainy season and a higher proportion of perennials with a longer growth cycle in the vegetation. In the Guinea savannah, average annual liveweight gain reaches values of +/-30 kg.

These theoretically derived data are confirmed by the scarce experimental data. Liveweight gains of 80 kg per head per year for young steers have been recorded in sedentary herds in the northern Sahel (Klein, 1981; Wylie *et al.*, 1983, in De Leeuw & Tothill, 1990) and liveweight losses of 10 kg per year per head in the southern Sahel (Diarra, 1983, in van Keulen & Breman, 1990). Cattle grazing rangelands receiving 700 to 800 mm rainfall, gained 60 to 90 kg during the rains, but net annual gains per head were much lower due to weight losses of 30 to 50 kg during the dry season (Hiernaux, unpublished data, in De Leeuw & Tothill, 1990).

Figure 2. The relationship between mean annual rainfall and, on the one hand, annual liveweight gain for a heifer of 150 kg and, on the other, mean annual herbage production. Herbage production is separated into three quality classes. The dotted line gives the theoretical relationship between rainfall and liveweight gain based on forage intake of average quality; the solid line refers to the situation where feed selection is practised to guarantee reproduction (Source: van Keulen & Breman, 1990)

The possibilities for production increases can be estimated on the basis of the energy and protein requirements for specified production targets in terms of meat and milk. Examples are given in Table 5.

"As feed intake increases by 23% when going from system I to system IV, production in terms of protein and energy increases by about a factor 8 and the overall production efficiency, by a factor 6. The main reason for this disproportionality is, that at the lowest nutritional level most of the ingested energy is used for maintenance of the herd, while the additional uptake can be fully utilised for production. Hence the productivity of animal husbandry systems in the West-African drylands is very sensitive to small variations in feeding conditions".

"In actual practice at the moment, sedentary animal husbandry systems in the sudanian zone operate between level I and II, those in the northern Sahelian zone at level II, occasionally reaching level III. Mobile animal husbandry systems, migrating between rainfed wet season pastures in the Sahelian zone and dry season pastures on flood plains or in the sudanian zone, achieve at least level II and probably level III. Level IV refers to situations on experimental stations, or occasionally specialised dairy farming operations where abundant supplementation is practised" (Wolf *et al.*, 1991).

Table 5. Animal productivity of animal husbandry systems with emphasis on meat production, in the Sahelian zone at different levels of nutrition.

system identification	**I**	**II**	**III**	**IV**
forage N concentration (g kg $^{-1}$)	9	10	11	12
relative feed intake (%)	100	108	115	123
production (kg animal^{-1}):				
liveweight	22	39	52	59
milk	-	64	160	229
total protein	1.9	5.6	10.2	13.2
conversion efficiency (%)of forage energy in:				
meat and milk energy	0.7	2.0	3.5	4.2
meat and milk production as function of total energy:				
in animal biomass(%)	8	23	39	47

(Source; Wolf *et al.*, 1991)

4. Exploitation intensity of natural resources

4.1. Relation between potential and actual production

Planning of rural development should consider the actual state of an area; whether there exists a situation of over-exploitation, under-exploitation or optimal exploitation of the natural resource base. One should analyse to what extent production potentials determined by its natural resources are realised under present land-use systems. In other words how actual yields compare with the maximum yield respecting carrying capacity of the natural resources at current level of input use. The maximum yield respecting carrying capacity of the natural resources is the highest yield at which the quantity and quality of the factors that are limiting production don't decrease.

Arable farming is mostly executed in those areas where nutrients are the main limiting factor and the production potential depends on nutrient availability from natural resources. Quantitative evaluation of mineral balances for the most common production systems (cereals, groundnut and cereals-cotton) clearly indicated that for the actual average production levels, each year 60 to 100 kg ha^{-1} of nutrients are lost (N, P_2O_5 , K_2O, CaO, MgO) with the output of crops and erosion (Pieri, 1990). It is assumed that maintenance of soil fertility by fallowing, requires at least a ratio of 1:4 between the length of the cultivation period and that of the fallow period, which means that at most 20% of the cultivable area should be cultivated at any moment (Pieri, 1989, in van Keulen & Breman, 1990). However, at the moment in many parts of the southern Sahel and the northern Sudan savannah, and even in the southern Sudan savannah, this value is exceeded (Breman & Traoré, 1986, 1986, 1987).

This shortening of the fallow period is far from being compensated for by the use of chemical fertiliser, which has increased since the beginning of the 1960s, but at the moment amounts only +/- 1 kg N and 0.5 kg P annually per ha of cultivated land. The major part of this fertiliser is applied to cotton and hardly any to the cereals cultivated in subsistence farming (van Keulen & Breman, 1990). Even in the cotton area in the South of Mali average nutrient losses of 25 kg ha^{-1} and 20 kg ha^{-1} for N and K were estimated and it was calculated that 40% of the farmers income is derived by soil mining (van der Pol, 1990). The decreasing productivity is clearly illustrated with the reduction of sorghum productivity per unit area. During the period of 1960-83 in 13 countries of West-Africa, yield per hectare decreased with an average annual rate of 1.5% (Matlon, 1990).

For animal husbandry a comparison should be made between the calculated carrying capacity (based on the factors limiting primary production) and the animal densities present in the various agro-ecological zones.

Due to the favourable weather conditions in the 1960's, animal densities had reached such high values that the natural pastures were overexploited in the northern Sahel, in large parts of the Sudan savannah, and particularly in the southern Sahel. The decimation of the herds during the drought period at the beginning of the 1970s supports this conclusion (Breman, 1975; Breman & Cissé, 1977; Penning de Vries & Djitèye, 1982, in van Keulen & Breman, 1990).

"At the beginning of the 1980s, animal densities in the region had been restored to levels comparable to those just prior to the severe drought period, although the relative proportion of small ruminants was somewhat higher. The drought of 1983/84 therefore again had comparable effects" (van Keulen & Breman, 1990).

"The conclusion from the analysis of arable farming and animal husbandry systems in relation to the production capacity of the natural resources in the West African Sahel is evident: in large parts of the region the natural resources are at present overexploited" (van Keulen & Breman, 1990).

4.2. Carrying capacity and population density

The conclusion that there exists a situation of overexploitation of the natural resources is not enough to develop a strategy for an increase of agricultural production. The reason why there is an overexploitation should be analysed. Is it because people are ignorant or traditional and thus extension should try to change people's behaviour. Is it out of obstinacy (doomsday mentality) or caused by social inequality and more structural innovations may be necessary like a reform of tenure regulations. Or is it out of necessity because there are to many people in relation to the potential of the natural resources and the economic situation and an increase of the production potential of the natural resources should be realised.

A comparison of the population supporting capacity with actual population densities may indicate whether there is a situation of relative overpopulation or whether it is a question of the first two reasons. Social and economic analysis may indicate in the last case, which of the two reasons dominates.

The population supporting capacity should be estimated based on sustainable production figures of the animal husbandry and arable production systems. In fact, it is easy to translate "consumable nutrients" into animal or crop production, but the translation into the carrying capacity for man becomes difficult as soon as the consumption is not direct, in other words when markets and prices are involved (Breman, 1991). The production of a certain quantity of milk in the vicinity of a city might be able to support more people than the same quantity produced for self subsistence in a pastoral area.

In the analysis of Breman (1991; see Table 6), as far as crop production concerns, only production for local subsistence has been taken into account. For animal production, the exchange rate between milk and cereals and the producer prices for animals from the seventies were used, when the EC and Argentine had not taken over yet the coastal markets of West-Africa.

Stocking rates of 22 TLU km^{-2} for the transhumance systems and the sedentary systems in the Guinea savannah and 20 TLU km^{-2} for sedentary systems elsewhere, were supposed. The sustainable cereal yield of arable land was set at 190 kg ha^{-1} for the South Sahel and 300 kg ha^{-1} in the Sudanian and Guinea savannah. The population supporting capacity under integrated land-use is not simply the sum of the values for exclusive use by pastoral systems or arable farming because, it is supposed that arable farming will occupy the best soils. The fraction of land suitable for permanent cropping is estimated to be 25, 35 and 50% for the South Sahel, the Sudanian and the Guinea savannah respectively.

The need of wood is estimated to be 8 ha $head^{-1}$ in the Sahel, 1.6 for the Sudanian and 0.6 for the Guinea savannah.

Table 6. Carrying capacity of the agro-ecosystems (persons km $^{-2}$) in relation to land use, in comparison with the population density.

zone	**carrying capacity:**			**population density**
	animal husbandry	**arable farming**	**integrated land use**	**actual land use**
North Sahel	1 (nomadic)	-	1	1(0-7)
South Sahel	7 (transhumance)	10	11	13(7-27)
Sudanian savannah	7 (transhumance)	34	36	33(7-66)
Guinea savannah	3 (sedentary)	48	51	25

(Source: Breman, 1991)

A comparison between the actual population density and the carrying capacity for integrated land use suggests a saturated North Sahel, a seriously overpopulated South Sahel and an almost saturated sudanian savannah, locally heavily overpopulated. Less alarming appears to be the situation in the Guinea zone" (Breman, 1991).

"The comparison of the acreage per person related to the carrying capacity for integrated land use, representing the maximum sustainable population density, with the acreage of rangeland needed to satisfy the wood production, shows that in the Sahel the production of wood is almost as limiting as the agricultural potential. If 25% of the zone is occupied by fields, the rest produces enough wood for about 10 persons km^{-2}.

This compares with the estimations of the World Bank (1985) and the FAO study of the population supporting capacity (1986). World Bank observed a heavily overpopulated Sahelo-Sudanian zone (350-600 mm), and a severely overpopulated Sahelian zone (limit of rainfed agriculture - 350 mm). The Sudanian zone (600-800 mm) was indicated to be saturated.

The FAO determined that in 1975 with low input farming techniques, the population supporting capacities in Mauritania, Niger, Senegal and Burkina Faso were to low for the prevailing population density. Mali just produced sufficient. Prospects for the year 2000 showed a deterioration of the situation. At this time Mali would also belong to the food-deficit countries and differences between supporting capacity and population density had grown for all countries.

These results clearly indicate that the overexploitation of the natural resources is mainly due to an overpopulation in view of the quantity and the quality of the natural resources, given the actual economic situation. It is not denied that locally there may exist a situation of underexploitation or overexploitation caused by lack of knowledge or social inequality. However, for the development of a strategy to break out of the vicious circle in the region, one should indicate the main causes whereas for the formulation of concrete projects the local situation should be taken into account.

No decline of the population density is expected as prospects of annual population growth figures of 3% are mentioned. In order to decrease the pressure on the natural resources, other options should be developed. Mainly there are three possibilities: migration, alternative employment or intensifying agricultural production.

A reallocation of rural populations through interzonal migration, as is actually taking place, alleviates overexploited areas and could bring about a production increase. Socio-political and economic considerations impose strict limits to the volume of migration. Moreover, the production increases once achieved, would be once-and-for-all, unless farming systems in higher potential areas were radically improved to assure a process of sustainable intensification (Matlon, 1990). These higher potential areas with higher rainfall, demands perennial cultures to avoid leaching of nutrients. People who migrated from more northern areas are very often not aware of the risks of their agricultural practices and degradation easily occurs.

Prospects for a rapid increase of alternative employment are also limited, so no relief of the exploitation pressure may be expected from this option. Hence intensifying agricultural production, increase the production per area, seems to be a necessity.

5. Options for increasing production

A sustainable increase of production is only possible when the growth-limiting factors are alleviated. As mentioned before, agricultural production is limited by the water availability in the north and in some areas characterised by a high percentage run-off. Although irrigation may be important from a micro-economic point of view, no sustainable increases of the production potential will be achieved. Nutrients will soon becoming limitative, because the absolute availability of nutrients at these areas is low.

The key for an increase of agricultural production is the increase of the nutrient availability. Possible solutions to the problem of nutrients shortage are the application of manure, biological nitrogen fixation, agro-forestry and chemical fertilisers.

One should realise that, to assure maximum efficiency of these options, proper soil and water conservation methods are a "conditio sine qua non"; for instance without contour lines, manure will easily be lost with run off water. With any economic assessment of options to improve production, the associated costs of these water and soil conservation methods should be taken into account .

For each of the options the potential effect on production and the possible effect on the long-term production potential will be discussed. Also the factors constraining adoption will be treated. A distinction will be made between application of these adoptions in animal husbandry or arable farming systems and application in different agro-ecological zones.

5.1. Manure

To maintain a constant production level after bush clearing, annual applications of at least 5 t ha^{-1} compost or animal manure are necessary (de Ridder & Van Keulen, 1990). To maintain soil structure and hence compensate for the loss of organic matter by mineralisation, 2 t ha^{-1} are advised (Berger, 1991). Production increases of 580 kg ha^{-1} of millet with application of 10 t ha^{-1} of animal manure were recorded (Sedogo, 1981, in de Ridder & Van Keulen, 1990), whereas experiments in Senegal with maize showed considerable production increases up to 560 kg ha^{-1} and 1060 kg ha^{-1} with manure applications of 2 and 4 t ha^{-1}. Most literature mentions an average production increase of 100 kg grain per ton manure per hectare (Landais *et al.*, 1990). The large differences in effects are presumably due to the differences in the quality of the applied organic matter. The C/N and P/N ratio of the soil organic matter, determining the efficiency of the organic matter gift, will have differed also substantially.

Berger (1990) indicated that it should be possible to maintain the organic matter content in the savannah (application of 2 t ha^{-1}) provided that 20 to 25% of the total area is cultivated with millet or sorghum and the availability of cattle represents a minimum of 1.6 per hectare in culture. Sorghum and millet are needed because they produce large amounts of crop residues. Animals are, besides their production of manure, needed to transform the crop residues into compost (cows mash the residues, melange their manure with it and the mixture will decompose during the rainy season).

An important restriction of the possibility to use manure as a viable option to increase soil fertility is the considerable number of animals needed to produce the required amount of manure, and the forage to feed these animals. Estimations of the fodder availability in Mali indicated that, to maintain soil fertility with manure and without use of fertilisers while respecting carrying capacity of rangelands, for each hectare in culture in the South Sahel zone and the Savannah, there should be respectively 40 and 15 hectares of grazing area. Only in the south savannah and in parts of the north savannah the actual area in culture did not exceed the 7% (Breman & Traoré, 1987). In other parts the maintenance of the soil fertility of the fields will go together with an overexploitation of the grazing areas.

In general it seems that only in the Guinea savannah and underpopulated areas of the Sudanian savannah, manure may act as a possible solution to shortage of nutrients (Breman, 1991).

A problem which hampers the use of manure is the availability of labour. As Landais *et al*. (1990) reported from a study by Schleich, the manual application of manure will not be remunerative, even when the distance to the field is only 500 m. The transportation over a distance of 2 km. and spreading of 5 ton manure at 1 hectare asks 120 days whereas 19 days are needed when traction is used. A distance of 0.5 km reduces the work to 37 days without and to 14 days with animal traction.

Attention should be given to the actual performers of the task. Normally women will be responsible to do the manual job whereas man are allowed to use animal traction. It is not clear whether this has any further consequences for the position of women (Landais *et al.*, 1990). An additional problem might be the price of the means of transportation, which is still to high for the majority of farmers (Berger, 1990).

An interesting aspect, is the fact that in situations of over-exploitation, manure quickly becomes as scarce as chemical fertilisers. Promotion of its use encourages growing social inequality just as rapidly as the introduction of fertilisers (Breman, 1990).

5.2. Biological nitrogen fixation

Leguminous species can be used to increase animal production; either via the direct production of fodder or the improvement of natural rangelands.

Production increases of natural rangelands in the Sahel were estimated at 3000 kg ha^{-1} $year^{-1}$ (Penning de Vries & Djitèye, 1982). In Australia, at research stations, the carrying capacity increased from 15-20 ha TLU^{-1} at natural rangelands to 3-5 ha TLU^{-1} at natural rangelands enriched with leguminous species. When an additional gift of P was applied carrying capacity increased to 1-2 ha TLU^{-1} (Breman & Traoré, 1987).

Experiments with fodder production have been recorded in Nigeria. In fenced areas with *Stylosanthes* up to 5 t ha^{-1} of high quality forage were produced with the supply of superphosphate at seeding. In the dry season animals were allowed to graze these parcels during two or three hours a day. A 50% decrease of animal mortality occurred and emergency sales of weak animals could be avoided (Bayer & Waters-Bayer, 1989).

In the Sahel the possibilities to increase rangeland production with leguminous species are limited. Leguminous species appear to be bad competitors under Sahelian conditions; expensive introductions are easily lost, even if the availability of P is satisfactory.

It is worthwhile to elaborate and to test whether the use of leguminous species is economically attractive in the savannah zone, where the prospects are better. However, biological fixation of nitrogen only solves the problem of nitrogen shortage if enough phosphorus is available. Today's prices of phosphates and animal products make it impossible to make full use of biological nitrogen fixation, at least where annual species dominate the herb layer. But even if the price situation improves, tenure of rangelands will have to be changed to give rangeland improvement a chance; without strict management the investments made in phosphates and leguminous species will be quickly lost (Breman, 1991). Leguminous fodder crops or fodder banks will have a better chance to become economically feasible.

Most arable farming production systems have a negative nitrogen balance; on average 25 kg ha^{-1} $year^{-1}$ is lost (Pieri, 1989). Biological nitrogen fixation *e.g.* via the cultivation of groundnuts and cowpea, which is a very common practice, can diminish this loss. Most legumes are cultivated in association with non-legumes like millet which increases the N fixing activity. The millet will use the available N which stimulates the legume to fix nitrogen.

The maximum profit of the capability to fix nitrogen will be gained when the plants are used as mulching or are ploughed into the ground to serve the crop of next year. This means that the maximum availability of crop residues should be returned to the field (Dommergues & Ganry, 1990).

Two major problems exist. Again P availability will be limitative. Unfertilised groundnut crops are notorious for their soil exhaustion in Sahelian countries. Secondly, the legumes are not primarily used because of their high ability to serve as a green fertiliser. Their products are in great demand for human and animal consumption. Therefore, the possibility to increase the availability of nitrogen is limited. Especially in those areas where there is already an overexploitation of the natural resources caused by overpopulation.

An other restriction may be the demand of labour during crucial phases of the cropping season, coinciding with those of the main crops. Only when subsistence levels are assured, farmers will probably be willing to devote more time to these crops.

5.3. Agro-forestry

Trees already play an important role in arable farming and animal production systems. They have a positive influence on the quality, quantity and stability of fodder availability, and on the stability of ecosystems. Also, a relatively high fertility of the soil is found under tree canopies. The question is whether trees are able to increase the overall food production, which basically means if they are able to increase the availability of nutrients and water for crops and the herb layer. Kessler & Breman (1990) analysed the characteristics of trees in relation to the Sahelian ecosystems and the ultimate result for grasslands and crops. The following is derived from this analysis.

Woody species may influence the water balance via rainfall interception, and changes of evapotranspiration and infiltration. Under certain conditions the positive influences can be more important than the negative ones, but it is difficult to identify conditions under which this is beneficial to the herb layer or adjacent crops.

The nutrient availability is influenced by reduction of nutrient losses and by redistribution and enrichment processes. The reduction of nutrient losses is only of importance in the (sub-)humid zone. In this area the risk of nutrient losses through water erosion and leaching is highest.

The redistribution of the available nutrients seem to be linked with the presence of trees. Different processes are involved; *e.g.* trees attract animals who deposit their manure and trees have lateral roots concentrated in the upper layer of the soil. The consequence of these processes is a fertilisation of the topsoil under shrubs and trees at the expense of the open field and the grazed areas.

Enrichment processes have serious potential limitations. The most interesting process could be pumping of minerals through deep rooting, but the subsoil is very poor. Besides in the savannah most soils are relatively shallow, while in the Sahel dryness of deep soil layers limit the advantage of deep rooting. The other interesting process, bacterial N-fixation, is limited by P shortage.

In addition to the redistribution, it seems to be the internal nutrient cycling and the related enlarged plant-litter-soil nutrient cycle which is responsible for the surplus value of woody species, mainly acting by suppressing the losses of water and nutrients. However, taking advantage of this leads to short term benefits but risks loss or decrease of the surplus value.

Besides these positive influences on the availability of water and nutrients, there is a negative influence: by winning the competition for light, woody species compete heavily with surrounding herbaceous species for water and nutrients. Breman & De Ridder (1991) suppose that for rangelands the negative influence depasses the positive one at a cover of woody species of 15%.

Consequently, there are limited possibilities to use woody species for an increase of agricultural production. Advantage should be taken of the niche differentiation, in run-on areas in the Sahel and on deep soils in the savannah: agro-forestry might be able to increase production here with about 25%, in view of nutrient losses by leaching and run-off on cultivated land.

Woody fodder species can be used to improve the dry season pastures where herbs have very low quality, if the 15% cover is respected. Zero-grazing systems could take profit out of much denser stands on very erodable elements of the landscape, like slopes with shallow loamy soils.

Further it seems to be profitable to aim at those processes that diminish nutrient losses by leaching or run-off. However, the more effective these processes are, the stronger will be the competition of the woody species with crops. The higher the rainfall, the more it is advisable to take direct advantage of the properties concerned by using tree crops (*e.g.* fruit orchards).

Also due to the risks of competition with crops, it will be difficult to take advantage of shelter belts outside irrigation areas or valleys with favourable conditions such as the Majjia valley in Niger (high ground water level), although the usefulness of shelter belts increases from South to North when water is becoming more limitative and sandy soils (prone to wind erosion) and hot dry winds are more common.

Besides these ecological limits to the use of trees, there are sociological and economical constraints. In many systems it will take some years before the planted trees are established and can be used and generally the initial labour input is rather high, as young trees require care and protection. Further on there exist many obstacles for farmers to plant trees; insecurity of land tenure, poor crop security (fires, animals), user and owner rights of trees which are not always clear, etc. (Barning *et al.*, 1990).

5.4. Chemical fertiliser

Chemical fertilisers have a high technical potential in the region, where in most areas nutrients are limiting plant growth. Indications are already given in part 4.

However, in the long term problems may arise, especially in the drier areas because the use of chemical fertiliser leads to decreasing base saturation and acidification of the soil. These phenomena, associated with the use of N fertilisers, are characterised by increasing K-deficiency, decreasing pH and occurrence of Al-toxicity. Application of supplementary organic materials, such as green manure, crop residues, compost or animal manure, can counteract the negative effects of chemical fertilisers, but in most areas, the availability of organic material will not be sufficient. Liming and the use of K and possibly Mg fertiliser, or the use of rock phosphates in combination with nitrate fertiliser, may prevent acidification of the soil (de Ridder & Van Keulen, 1990).

Besides these technical problems, which influences the production potential in the long term, there are some major economic problems which hampers application of chemical fertilisers at the moment. Cotton, and possibly cowpea and maize, seems to be the only important crops on which its use is economically attractive, particularly in the southern part of the Sudanian savannah. But, even then soil mining may occur. In Southern Mali, through the use of chemical fertilisers, high deficits of N and K are caused. The export, out of the region, of cotton cake, and the burning of cotton residues are the main causes for increased nutrient losses (van der Pol, 1991).

The cost/benefit relations depend on the prices of inputs and outputs, and the efficiency of the use of inputs.

A study in the cotton area in Mali clearly illustrated the relation between the use of inputs and their prices. In the seventies, with the expansion of cotton, fertilisation per hectare increased. From 1982 onwards, the situation changed. With the suppression of subsidies on fertiliser it became more profitable, at least on a short term, to direct investments towards expansion of the cultivated area rather than towards improvement of productivity of the existing area (Berckmoes *et al.*, 1988).

The bad cost/benefit-relations are certainly partly caused by the low population density at which overpopulation is already reached, in view of the limited and poor natural resources: the costs per capita of the creation of an effective infrastructure and distribution system are very high, which makes the occurrence of a green revolution actually unlikely (van Keulen & Breman, 1990).

Regarding the profitability of the use of chemical fertiliser, much depends also of the prices of outputs. For instance, use of P fertiliser to increase fodder production with legumes, will probably be economically attractive when milk is produced in the vicinity of cities. However, when dumping practices of the EC will continue, a comparative advantage will be difficult to gain (Wooning, 1991).

The efficiency of the use of chemical fertiliser depends of the production goal and the production system. Some comparisons are given in Table 7.

Table 7. Comparison of technical options to increase animal or arable production, in relation to the required nutrients.

product		**requirement per kg product**		**remarks**
type	**kg ha^{-1}**	**N**	**P**	
improvement of pasture with leguminous species:				
meat	35	-	0.36	
rainfed agriculture:				
grain	7500	0.03	+	
meat	170	1.33	+	plus milk
legumes	6000	+	0.01	
meat	200	+	0.25	plus milk
grain	4500	0.07	0.03	plus high quality crop residues
cowpea/groundnut	1750	+	0.03	plus leaves

(Source: Breman & Traoré, 1987.)

The production of cowpea with P fertiliser, and the use of its foliage for animal production, seems to be the most favourable option in terms of efficiency of input use. Such an intensification of arable production supports the intensification of animal production at the same time (Breman & Traoré, 1987).

However, one should be cautious with these conclusion while the efficiency of the use of external inputs doesn't say anything about the efficiency of the labour input, another scarce resource, or the efficiency to solve the problems of the Sahel. From a farmers point of view it might be more profitable to concentrate on cereals, in view of the relatively complicated production of leguminous species, causing a low labour efficiency. From a macro-economic point of view it might be profitable if farmers concentrate on cereals because it assures food self-sufficiency.

Even if the average cost/benefit relation of the application of fertiliser is positive, the acceptance of this innovation can still be limited due to the risks involved. Climatic variations have considerable influence on the output produced. These variations tend to increase with decreasing average rainfall, causing a parallel increase of risks for farmers using external inputs (Forest *et al.*, 1990). Such risks can be partly obviated by the choice of varieties with shorter growing cycles and by changing the cropping calendar. But it implies the necessity of adoption of a package of changes, instead a step-wise adaptation, a risky action as such.

5.5. Mixed low external and high external input agriculture

The preceding paragraphs clearly showed that simple solutions do not exist. It will be difficult to make the general use of external inputs economically feasible, in spite of the potential to increase agricultural production 5-fold (Tables 1 and 2; Figure 1). The potential of their biological alternatives, like manure, legumes and agro-forestry is however not high enough in view of the degree of overpopulation (Table 6) and the demographic growth. Besides, the ecological and the low external inputs agriculture (LEIA), making intensively use of such biological alternatives, are very labour intensive, while lack of labour during crucial periods of the year is already a bottleneck for agriculture (Brossier & Jager, 1984: Veeneklaas *et al.* , 1990). Lack of labour will be one of the reasons why farmers abandon agricultural systems based on ecological principals, systems which appeared to be unable to prevent the disaster of drought and overexploitation. Maximum efficiency should be searched for, concerning external as well as internal input.

Where neither high external input agriculture (HEIA) or LEIA can provide the solution, a mixture of both might be a logical idea. Mixtures of LEIA and HEIA might result in a higher efficiency for external inputs than in case of HEIA, an advantage in the competition for markets. Besides this efficiency decreases relatively slowly at decreasing production potential of the environment, in comparison with HEIA. In this way, the profitable use of external inputs can be extended to a larger area and more crops (Breman, 1990). The use of legumes and P-fertiliser is an example. The yield of 1000 kg ha^{-1} of cowpea fodder (Mali-South) is unacceptable given the labour requirement. Application of P-fertiliser might increase production 5-fold and thereby making it more attractive (Breman, 1990a).

Figure 3 gives a schematical view of the relationship between the efficiency of innovations and the production potential of land determined by the natural environment and its socio-economic context. The direction of change that the combination of LEIA and HEIA techniques might bring is indicated with the number 2.

This figure can also be used as a framework for the formulation of strategies to break out of the vicious circle in the Sahel. Strategies should differentiate between agro-ecological zones and prevailing economic conditions as is done in Figure 3.

Figure 3. The most probable relationship between the efficiency of innovations from private efforts in a liberal environment (1) and the production potential of land determined by the natural environment and its socio-economic context and the direction to be given to agro-ecological research (2) and socio-economic policies (3) (Source; Breman, 1990a).

The efficiency of innovations increases super proportionately with increasing production potential of land, determined by the natural environment and its socio-economic context.

A is the area where the use of external inputs on cash crops is feasible. To avoid pollution, as occurred in most high external input agriculture systems, research should indicate the most optimal levels of input use.

B is the area where the use of external inputs should be made feasible by agro-ecological research and socio-economic policies. Agro-ecological research should aim at developing innovations having curves less concave than the one in Figure 3 (flashes 2), like the former mentioned mixture of HEIA and LEIA.

Socio-economic policies should push the break-even line in Figure 3, where the costs equals the benefits, to the left as indicated with the flashes 3. This directly by national policies or international agreements and support, or indirectly by influencing the input/output ratio through proper incentives in areas such as tenure systems.

C is the area where the use of external inputs won't be feasible. The LEIA techniques should be promoted but alternative employment, migration and social welfare programs to assure a sufficient means of livelihood can not be avoided, given the state of overexploitation and low potential of this area. The costs and efficiency of such programs have to be weighed against the costs and efficiency of subsidised HEIA in area C.

An already mentioned example of the agro-ecological and socio-economic changes which might promote the use of external inputs is related to the risks attached to the use of chemical fertiliser. A reduction of this risk or a reduction of the farmers sensibility to risk could result in an increasing adoption of fertiliser. Such a reduction of risk could be obtained by the use of varieties with a shorter growing-cycle than normally used in the extensive production systems.

The risk-sensibility might be reduced through the implementation of long-term flexible credit facilities; reimbursements related to the production conditions of that year. Good storage facilities can have the same effect by reducing price fluctuations (Schweigman *et al.*, 1989).

Concerning the use of chemical fertiliser some remarks should be made.

A main issue which should be analysed is the effect of the subsidisation of chemical fertilisers. It is questioned before (Mokwunye *et al.* , 1986; Davis, 1986) why subsidisation of chemical fertiliser could not be treated in the same way as the infrastructure of an irrigation system or check dams. These latter received enormous financial support whereas the former is generally out of the question. In fact, part of the fertiliser could be perceived as a regeneration or a build-up of the production capacity. On poor soils, it takes several years of intensive fertiliser use before the maximum efficiency is reached; the soil organic matter will have to be adapted to the new situation. At least during this period fertiliser use is a real investment.

It should also be analysed whether the costs of subsidisation may outweigh the costs of a further degradation of the environment and the associated expected marginalisation of the people (Breman, 1987).

Considering the prices of external inputs it is interesting to look at the possible positive effects of a growing population. Higher population densities decreases the costs per capita of the development of an infrastructure. The probable growing urbanisation might also generate alternative employment which may release the exploitation pressure of the rural areas. It is only the question whether the rural area and the natural resources have enough resilience to carry this burden long enough.

Considering the rentability of the different options, the micro and macro effects should be taken into account. The use of rock phosphate in stead of chemical fertiliser may be attractive from a macro-economic point of view; use of foreign-exchange can be limited. From a farmers point of view it might be less attractive because of the slow effect and short term credits.

5.6. Concluding remarks

The main conclusion of this report is that there exists a situation of overexploitation of the natural resources, due to an overpopulation in relation to the production potential and existing economic situation. As agriculture is still the most important motor of development, priority should be given to the intensification of agriculture, which means that the availability of nutrients should be increased. The most effective way to do this, is the use of chemical fertiliser, which demands an increasing production for a market.

There are no simple technical solutions to increase the agricultural production. There should be packages of socio-economic and technical measures differentiated for agro-ecological zones and economic conditions. Subsidisation is but one of the instruments of incentives, disincentives and prohibitions.

Comprehensive development plans should be developed, which clearly describe which priorities will be given. In view of the existing political situation, it seems also necessary to equally pronounce the responsibilities of the different *partenaires*; the population, the Sahelian governments and the donor countries. Hopefully this report will contribute to indicate the priorities and actions to be taken.

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