Bio-economic capability of West-African drylands

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Contents

Executive summary

In this report, prepared by the DLO Centre for Agrobiological Research (CABO-DLO) in Wageningen, at the request of the United Nations Sudano-Sahelian Office (UNSO), a review is presented of methods to analyze production potentials of West-African drylands. These methods would have to be applied in a follow-up study to assess the bio-economic capability of West-African drylands. However, the extensive examples used throughout this study to illustrate the various methods, already provide a first approximation of the agro-technical options.

Any assessment of bio-economic capabilities should be based on estimates of the production potentials of arable crops, natural rangelands and the associated animal husbandry systems, and woody species, either in monoculture or in mixed systems with arable crops or rangelands, for various agro-ecological zones of the region. These production potentials are on one hand determined by environmental conditions, such as soil properties and weather (or climate), on the other hand by the means of production available, such as labour, irrigation water, fertilizers, biocides, etc. Hence, the estimated production potentials should be accompanied by estimates of the inputs required to realize them.

The quantitative description of production techniques in terms of outputs (production level) and the inputs required to realize those production levels, allows a cost/benefit analysis. Comparison of different production techniques, however, requires more than simple calculation of the net returns per unit area, as the production capacity of the systems should also be maintained in the long run. Hence, to secure sustainability, specific measures may be necessary, for instance to control erosion, to prevent nutrient exhaustion of the soil, etc., and suggestions are included in this study to take the associated costs into account.

Arable farming

For assessment of the production potential of arable crops, the use of dynamic crop growth simulation models is suggested, in which the available knowledge on crop characteristics and physiological processes and their interaction with the environment are combined (de Wit & van Keulen, 1987). To fully exploit the available insights, a hierarchical approach is followed, in which the number of factors affecting crop production at the highest hierarchical level is substantially reduced, by assuming that all constraints that can feasibly be removed, have indeed been eliminated. At subsequently lower hierarchical levels, the factors considered at the higher levels are fixed and an increasing number of possibly limiting factors is taken into account, leading to increasingly lower production potentials, and concurrently to higher input requirements to achieve potential production.

Schematically, three production levels are 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 macronutrients from natural sources, mainly determined by soil organic matter content and chemical soil properties, and the reaction of the crop to limited nutrient availability, are taken into consideration.

Yields under actual farming practice are at the moment generally lower than either of the yield levels calculated, as effects of lack of timeliness of the various agricultural operations and losses through competition from weeds and infestation by pests and diseases have not been taken into account. These 'actual' yield levels may be derived from the calculated yields at the lowest hierarchical level, by assuming an overall 'loss' percentage. The results of such a procedure for three staple crops in Burkina Faso are illustrated in Table 1.

Table 1. Estimated national average grain yields (kg/ha, 12% moisture) for major food crops in Burkina Faso; A: water-limited yield, B: nutrient-limited yield; C: estimated 'actual' yields, taking into account losses due to lack of timeliness, weeds, pests and diseases; D: ranges of yields from statistical data; E: mean yields from statistical data.

Crop	A	B	C	D	E
Maize	5800	1100	825	511 - 1066	700
Millet	2400	550	415	351 - 601	440
Sorghum	3900	875	655	460 - 678	570

These results, that appear representative for the majority of arable farming systems in the sahelian and sudanian zones in West-Africa (cf. van Keulen & Breman, 1990; van Wijngaarden *et al.*, 1988), indicate that optimum crop management in the 'natural' situation, might result in average yield increases for cereals of the order of 150 to 300 kg ha^{-1}. It is, however, doubtful, whether under the present socio-economic conditions the additional inputs, in labour and external means, required to arrive at such a situation, are best applied in this way: manual weed control is very time-consuming, and complete pest and disease control without pesticides is practically impossible. The next observation is, that availability of nutrients from natural sources is so low, that nutrient-limited yields are considerably lower than those dictated by water availability. The consequences are, that water, which is a scarce resource in these drylands, is used very inefficiently in crop production, and that average yields could be substantially increased by introduction of external nutrients into the system, either through application of organic manure (transport of fertility from natural rangeland to arable land) or chemical fertilizer. This conclusion, however, requires immediate cautioning: (i) the quantities of organic manure required are so high, that at the present ratio of arable land to rangeland, manure application at the required rate is only a theoretical possibility; (ii) fertilizer availability and its price ratio to products from arable cropping are major constraints for its application. Moreover, concurrently with average production, the variability increases, as in dry years water remains the major limiting factor. This variability imposes additional problems on the system, for which practical solutions must be found.

Animal husbandry

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 drylands (Breman *et al.*, 1990). For the region, three feed sources can be distinguished: biomass production from natural rangelands, consisting of herbaceous vegetation and browse from woody species, by-products from arable farming, such as millet stover and groundnut hay, and imported concentrates. To estimate the production potential for animal husbandry, the availability of feed from the various sources has to be estimated. Moreover, the quality of the available feed is a major determinant of intake and production, hence that also has to be taken into account.

Biomass production of the rangelands in the West-African drylands is either determined by moisture availability or by the availability of nutrient elements, especially nitrogen and phosphorus. Which of the two is the major limiting factor in a particular situation, depends on environmental conditions, notably rainfall and soil properties, that determine on one hand the partitioning of precipitation between infiltration and runoff and on the other the supply of nutrients from natural sources.

Where annual infiltration is less than 250 mm, such as in the northern part of the sahelian zone, or further south on soils susceptible to crust formation, where runoff is prominent, moisture availability is the major constraining factor for primary production. Going to the south, particularly in the sudanian zone, annual infiltration increases and availability of plant nutrients increasingly becomes the limiting factor for production.

For both situations, i.e. production determined by water availability or production determined by nutrient availability (based in this study on availability of nitrogen) semi-empirical relations have been developed to estimate biomass production of the herb layer on the basis of rainfall and soil properties. The results of application of these relations for some representative land units and climatic zones in Mali are illustrated in Table 2.

Although the classification criteria used are rather rough, and hence the results are only indicative, the data in Table 2 clearly illustrate the effects of both rainfall and soil properties on the production potential of natural pastures. At the lowest rainfall regime, production is fully dependent on water availability and decreases with increasing runoff and/or percolation (La > Os > Ps > Sq > Pl). Although the ranking is not much different at the highest rainfall regime, production is fully dependent on nitrogen availability. It should be realized that these differences have important consequences when considering improvements in the situation by removing constraints.

In addition to the herbaceous layer, natural pastures may contain woody species, that contribute to forage availability. The cover of woody species is dependent again on soil type and rainfall regime, which dictate the availability of water for these perennial species. However, the effects of exploitation pressure, by animals as well as man, may modify that situation. In the present study, the production of woody species has been based on estimated cover and estimated number of leaf layers, both as a function of water availability (precipitation and soil properties). From leaf production total browse production, including young twigs and

Table 2. Estimated annual biomass production (kg/ha) of the herb layer for a number of selected soil/climate combinations in Mali, for average (p.50) and dry (p.10) years.

Climate zone1)	North Sahel	South Sahel	North Sudan	South Sudan
Land unit2)				
Os p.50	750	2050	-	-
Os p.10	150	1550	-	-
Ps p.50	600	1750	-	-
Ps p.10	50	1100	-	-
Pl p.50	150	850	1600	1600
Pl p.10	-	200	1350	1400
La p.50	1250	3250	2300	4400
La p.10	200	2300	1900	4100
Sq p.50	550	1100	1600	1950
Sq p.10	50	6500	1350	1750

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

2) land units: Os: parallel dunes, coarse sand; Ps: flat dunes, fine sand; Pl: plains, sloping towards La, loam; La: depressions with runon, loam/clay; Sq: plains, shallow loam

fruits, has been estimated using empirical relationships derived in the sahelian zone. The resulting browse production for a selected number of agro-ecological zones in Mali is given in Table 3.

Again, the production of browse is directly related to rainfall and soil properties, dictating the relative availability of water and nutrients. It should be emphasized here, that these results serve as an illustration of the method and the type of information generated only, and that for a more accurate analysis of the contribution of browse to forage availability in the West-African drylands, more detailed information is necessary on the current state of woody species and herd composition in the various agro-ecological zones.

During exploitation of rangelands by grazing, only part of the production is available for intake by the animals, as unavoidable losses occur. These losses depend among others on grazing regime.

As explained earlier, animal production cannot be directly related to the quantity of forage available, but should be considered in relation to its quality. In the present study, quality is related to the nitrogen content of the material produced, as other quality characteristics, such as phosphorus content and digestibility appear te be strongly correlated with nitrogen content. The nitrogen content can be estimated on the basis of the relative availability of water and nitrogen for the various agro-ecological zones as illustrated in Table 4.

The data in Table 4 clearly illustrate the major effect of water availability on the nitrogen content of the material produced. In the northern sahelian zone quality is generally high, hence all biomass produced can be considered forage, while in the southern sudanian zone average nitrogen content is so low, that only a small proportion of the production can be utilized by the animals. The quality of browse in terms of nitrogen content, can also be estimated on the basis of moisture avail

Table 3. Estimated annual browse production (kg/ha) for a number of selected soil/climate combinations in Mali, for average (p.50) and dry (p.10) years (for definition of climate zones and soil types, see Table 2).

climate zone	North Sahel	South Sahel	North Sudan	South Sudan
Land unit				
Os p.50	70	130	-	-
Os p.10	40	80	-	-
Ps p.50	70	130	-	-
Ps p.10	40	80	-	-
Pl p.50	70	650	950	1750
Pl p.10	40	430	750	1550
La p.50	70	720	5400	5400
La p.10	40	480	4200	4200
Sq p.50	-	580	950	1450
Sq p.10	-	380	750	1300

ability. The values are generally higher than for the herbaceous vegetation, and the differences between the sahelian zone and the sudanian zone are limited.

Availability of forage can be derived now from the average quality and the amount produced, while for browse an additional criterion has been applied, related to sustained production capacity of the woody species. For the woody species a distinction must also be made between 'grazers', i.e. cattle and 'browsers' such as goats. Taking into account the relative proportion of the various land units in the four climatological zones distinguished, forage availability per zone can be calculated, again distinguishing between normal and dry years, as illustrated in Table 5.

Table 4. Estimated nitrogen content in the herb layer at the end of the rainy season for a number of selected soil/climate combinations in Mali, for average (p.50) and dry (p.10) years (for definition of climate zones and soil types, see Table 2).

climate zone	North Sahel	South Sahel	North Sudan	South Sudan
Land unit				
Os p.50	12.5	7.6	-	-
Os p.10	23.0	10.0	-	-
Ps p.50	14.7	8.0	-	-
Ps p.10	25.0	11.3	-	-
Pl p.50	21.3	12.9	7.0	5.5
Pl p.10	-	15.5	8.0	6.0
La p.50	9.5	6.1	5.4	5.0
La p.10	16.5	7.5	5.8	5.3
Sq p.50	14.6	8.0	7.0	5.6
Sq p.10	25.0	11.3	8.2	6.1

Table 5. 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 (for definition of climatic zones see Table 2).

climate zone	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

From forage availability and quality, carrying capacity can be estimated, although different assumptions can still be made, as explained in this study. For illustrative purposes, estimated carrying capacity based on feed availability in dry years is given in Table 6. This carrying capacity thus ensures sufficient feed for the animals in all but the 10 % driest years.

Table 6. Estimated carrying capacity (ha UBT^{-1}), based on feed availability in dry years (p.10) for various climatic zones in West-Africa for mixed herds of 'grazers' and 'browsers' (for definition of the climate zones see Table 2).

climate zone	North Sahel	South Sahel	North Sudan	South Sudan
carrying capacity	45.5	3.9	2.5	1.9

At the animal densities defined in Table 6, forage availability and quality are such, that in nine out of ten years animal production is sufficient to guarantee maintenance of a viable herd. However, if higher animal production is aimed at, in either meat or milk, better quality forage is required and the carrying capacity will consequently decrease.

The possibilities for such production increases can be estimated on the basis of the energy and protein requirements for specified production targets in terms of meat and milk. In Table 7 four such systems have been defined in quantitative terms.

The four systems defined in Table 7 from I to IV represent situations characterized by increasing forage quality, and the associated increase in animal production. 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 specialized dairy farming operations where abundant supplementation (concentrates or high-quality crop residues) is practiced.

The information in Table 7 shows that 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, i.e. the fraction of total gross energy intake 'harvested' in meat and milk, 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 utilized for production. Hence, the productivity of animal husbandry systems in the West-African drylands is very sensitive to small variations in feeding conditions (quantitatively and/or qualitatively). Herd and pasture management are important tools therefore to affect that productivity. Herd management includes such options as the production target (draught power, manure, milk or meat), degree of mobility and supplementation, pasture management may include fertilizer application, introduction of leguminous species or cultivation of forage crops. The effect of such measures on forage availability can be quantified, as well as the consequences for animal production.

Table 7. 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 composition:				
N concentration (g kg^{-1})	9	10	11	12
digestibility (%)	52	54	56	59
average liveweight (kg)	150	173	183	196
feed intake:				
% of liveweight per day	2.2	2.2	2.3	2.2
relative feed intake (%)	100	108	115	123
herd structure:				
% male animals	33	43	44	44
% female animals	67	57	56	56
percentage offtake	67	57	56	56
production (kg $animal^{-1}$)				
liveweight	22	39	52	59
milk	-	64	160	229
total protein	1.9	5.6	10.2	13.2
total energy (MJ $animal^{-1}$)	142	495	932	1226
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

Woody species

The production of woody species is in principle not very different from that of arable crops or rangelands, as it is determined by the same production factors, i.e. the availability of water and nutrient elements. Methods to estimate their productivity can thus be based on the same principles, as has been treated already for woody species as a component of natural pastures.

However, woody species, because of some special characteristics, such as their perennial nature, their morphology, etc., may provide added value, in terms of modifying the microclimate, improving the efficiency of utilization of limiting factors such as water and nutrients by reducing losses, etc. Methods to account for these special characteristics are being developed, but the quantitative aspects are still incompletely understood, so that especially in this area, further development is necessary (Kessler & Breman, 1991).

However, to assess the possibilities for introduction of species, not yet cultivated in the West-African drylands, the methods provide a first approximation.

Sustainability

For assessment of the long-term prospects of agricultural production systems in the West-African drylands, sustainability should be a major consideration. The production capacity can only be maintained in the long run, if at least the availability of water and nutrient elements is not unfavourably affected by increasing runoff, decreasing water holding capacity, chemical exhaustion of the soil, soil acidification, wind and water erosion. In a comparative analysis of production systems, the decrease in production capacity could be taken into account as costs. That, however, appears very difficult to quantify. Therefore, an alternative approach is followed in which only sustainable production techniques are defined. For arable farming techniques that implies for example adoption of certain cultivation practices and the use of sufficiently long fallow periods or application of manure and/or fertilizers (Table 9). The consequence is that the area that can be cultivated is limited or that the required inputs (labour and/or capital) are higher than under current practice. For animal husbandry systems herd size should be restricted to not exceed carrying capacity, while for woody species exploitation pressure should be restricted to guarantee sustained production capacity.

Assessment of bio-economic capability

In the first sections of the report technically feasible production techniques have been identified for the various agricultural sectors. To judge the socio-economic feasibility of these production techniques with different attainable yield levels under well-defined conditions, a further analysis is required.

An example of such an analysis is given in Table 8, referring to production techniques based on the use of well water in Mauretania (Breman, 1981).

The results in Table 8 led to the conclusion, that only animal husbandry systems allowed renumarative use of well water at the prices of inputs and outputs at that time.

A more detailed analysis can be made by using the interactive multiple goal linear programming (IMGLP) technique (de Wit *et al.*, 1988). For application of that technique, the inputs required to realize the various yield levels should be specified in quantitative terms, as illustrated in Table 9 for growth of millet on sandy soils in the 5th region of Mali (van Duivenbooden & Gosseye, 1990).

Table 8. Comparison of the economics of animal husbandry, vegetable production, forage production or date production systems, based on the use of well water in Mauretania. Numbers are expressed in 1000 UM, based on the use of 10 000 m^3 water at a price of 10 UM/m^3.

production system	livestock	vegetables	alfalfa	dates
exploitable area (ha)	36 500	1.1	0.7	2.0
production (t/yr)	49	18	9	7
labour (man-year)	26	23	21	21
market price	4 287	644	240	504
gross trade margin (15%)	643	97	36	75
transport (2.5 UM/kg/100km)	306	95	21	44
losses	364	64	9	49
capital (3 %)	129	19	7	17
sundries	487	97	9	74
producer price	2 358	277	158	245
water	100	100	100	100
seeds (seedlings)	-	41	4	32
tools, maintenance	5	42	31	68
manure, fertilizer pesticides	-	PM	PM	PM
producer gross margin	2 253	89	23	45
income per man-year	86.65	3.87	1.1	2.14

Similar input/output tables can be constructed also for animal husbandry systems, systems including woody species, fisheries, etc., on the basis of the methods described in the first chapters of this report. In the IMGLP-analysis these production systems are now confronted with the regional resources defined in quantitative terms: land, human resources, capital endowment, etc., and the prevailing economic conditions in terms of prices of inputs and outputs. By setting specific development goals, such as maximizing food security, or minimizing risks, or maximizing regional income, the possibilities for regional development can be examined. By changing the boundary conditions, such as prices of inputs and outputs, the effects of economic conditions can also be examined.

The result of such an analysis is definition of the bio-economic capabilities of the West-African drylands under present and alternative conditions. In this report the methods employed have been illustrated, using information at hand. For a more thorough analysis, however, a systematic definition of agro-ecological zones and their production potentials under well-defined conditions is necessary. That would have to be the subject of a follow-up study.

Table 9. Input/output table for different millet production techniques on sandy soils in the 5th region of Mali.

Technique nr.	1	2	3	4	5	6
Animal traction	-	-	+	+	+	+
Manure	-	+	-	+	+	+
Fertilizer N/P	-	-	-	-	+	+
Fallow	+	-	+	-	-	-
Inputs						
<u>Labour</u> (man-day, oxen-day)						
Field clearance	1	1	1	1	1	1
Fallow land clearance	3	-	3	-	-	-
Manure transport	-	5	-	5	5	5
Manure spreading	-	7	-	7	7	7
Ploughing	-	-	4 + 2 Ox	4 + 2 Ox	4 + 2 Ox	12 + 6 Ox
Sowing	4	4	4	4	4	2 + 1 Ox
Weeding	27	27	22 + 2 Ox	22 + 2 Ox	22 + 2 Ox	22 + 2 Ox
Fertilizer application	-	-	-	-	4	9
Biocide application	-	-	-	-	-	5
Harvesting	6	6	6	6	9	14.5
Transport	8	8	2	2	2	2.5
Threshing/winnowing	16	16	16	16	20	38
Labour total	65	74	58 + 4 Ox	67 + 4 Ox	78 + 4 Ox	118 + 9 Ox
Oxen pair	-	-	0.25	0.25	0.25	0.5
<u>Other inputs</u>						
Manure (kg dry matter)	-	3000	-	3500	2000	2000
Fertilizer N (inorg.,kg)	-	-	-	-	36	150
Fertilizer P.(inorg.,kg)	-	-	-	-	19	69
Biocide (1000 FCFA)	-	-	-	-	-	5
Investments (1000 FCFA)	1.3	1.3	5.2	5.2	6.2	17.1

References

Breman, H., 1981. Mise en place des perimetres irrigués autour des 36 forages. Mission de formulation UNSO en Mauretanie, du 17/10 au 2/11, 1981. CABO, P.O.Box 14, 6700 AA Wageningen, The Netherlands.

Breman, H., J.J.M.H. Ketelaars & N. Traoré, 1990. Un remède contre le manque de terre. Agriculture et élevage au Sahel. Secheresse 2, 109-117.

Duivenbooden, N. van & P. Gosseye (Eds.), 1990. Compétition pour des ressources limitées: le cas de la cinquième region du Mali. Rapport 2: Productions végétales, animales et halieutiques. CABO, Wageningen/ESPR, Mopti, P.O.Box 14, 6700 AA Wageningen, The Netherlands.

Kessler, J.J. & H. Breman, 1991. The potential of agroforestry to increase primary production in the Sahelian and Sudanian zones of West Africa. Agroforestry Systems (in press).

Keulen, H. van & H. Breman, 1990. Agricultural development in the West African Sahelian region: a cure against land hunger? Agric., Ecosyst., Env. 32, 177-197.

Wijngaarden, W. van, avec collaboration de H. Breman et H. van Keulen, 1988. Analyse des systèmes de production dans les départements Maradi-Zinder-Diffa. Rapport PIGRAR. 41 pp.

Wit, C.T. de & H. van Keulen, 1987. Modelling production of field crops and its requirements. Geoderma 40, 253-265.

Wit, C.T. de, H. van Keulen, N.G. Seligman & I. Spharim, 1988. Application of interactive multiple goal linear programming techniques for analysis and planning of regional agricultural development. Agric. Syst. 26, 211-230.

1. Introduction

The capability of African drylands can generally be considered low due to the low and erratic rainfall and the low fertility of the soils. This low capability limits the production potential which easily leads to overexploitation and degradation of the ecosystem. To identify possibilities and bottle-necks for developing the drylands, a complete picture is required of the farming systems, both the present systems and systems that might be introduced.

West-African drylands show large variations in climatic conditions, soil characteristics and topography. Precipitation increases from the dry Sahara in the North, via the semi-arid Sahelian zone and the relatively humid savannah to the tropical rain forest in the South. With increasing rainfall the length of the growing season increases, which results in different farming systems (Figure 1). For example, (semi)nomadic systems of animal husbandry are gradually replaced by sedentary systems, arable crops with a short growth cycle such as millet by crops with longer growth cycles, such as sorghum and maize. Concurrently, the cover by woody species increases.

To allow comparison of farming systems, they have to be described in quantitative terms. Hence, for each agro-ecological zone the production of various farming systems should be estimated. To cover the full range of possibilities, these should include current systems at the present input levels, more intensified ones at higher input levels and alternative ones, not yet introduced in the area but poten

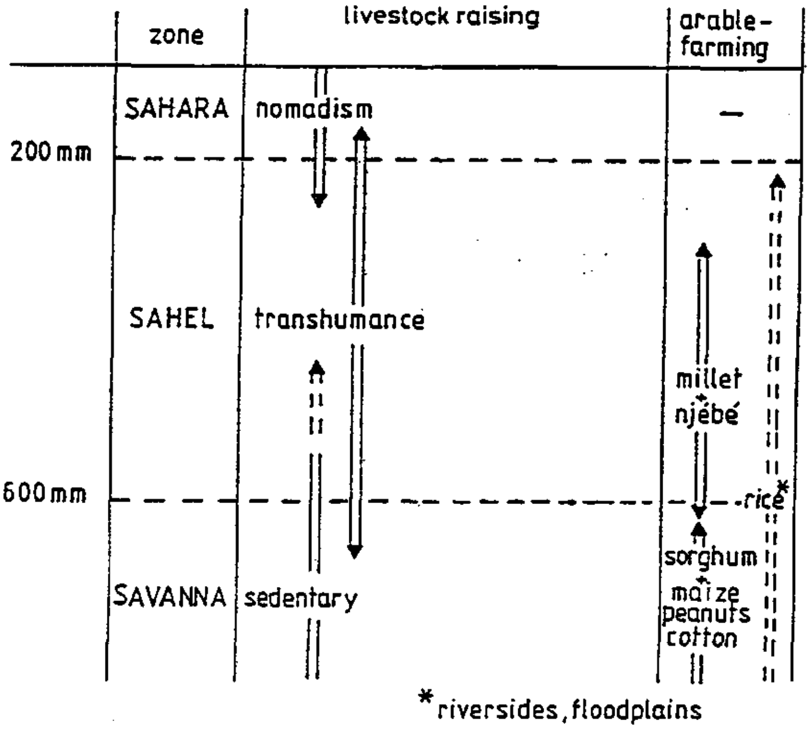

Figure 1. Schematic representation of various farming systems in the West African drylands in relation to the rainfall. (Source: Penning de Vries & Djitèye, 1982)

tially of great value. Farming systems comprise cropping activities, animal husbandry activities, including both pastures and animals, and forestry activities. In this report methods are presented for calculating the production of arable crops, rangelands and the associated animal husbandry, and woody species, respectively illustrated with some examples of their application.

The quantitative description of farming systems by their production level and the inputs required to realize those levels, allows an analysis of costs and benefits. Comparison of systems, however, requires more than a simple calculation of the net returns per unit area, as the production capacity of systems should also be maintained in the long run. Hence, to guarantee sustainability certain measures may be necessary to control erosion, to prevent nutrient exhaustion, etc. and indications are given how such additional costs could be taken into account.

This report has been prepared by the Centre for Agrobiological Research (CABO), at the request of the United Nations Sudano-Sahelian Office (UNSO) as a basis for a more comprehensive study of production systems including comparative cost-benefit analyses for West-African drylands.

2. Arable farming systems

2.1 General outline

In the last two decades methods have been developed for estimating the yield levels of crops growing under well-specified conditions. These methods are based on application of crop growth simulation models, combining knowledge about crop characteristics and their interactions with the environment. This approach allows identification of the principal constraints as a basis for estimating quatitatively the effects on yield of alleviating them. Its basic structure is schematically presented in Figure 2.

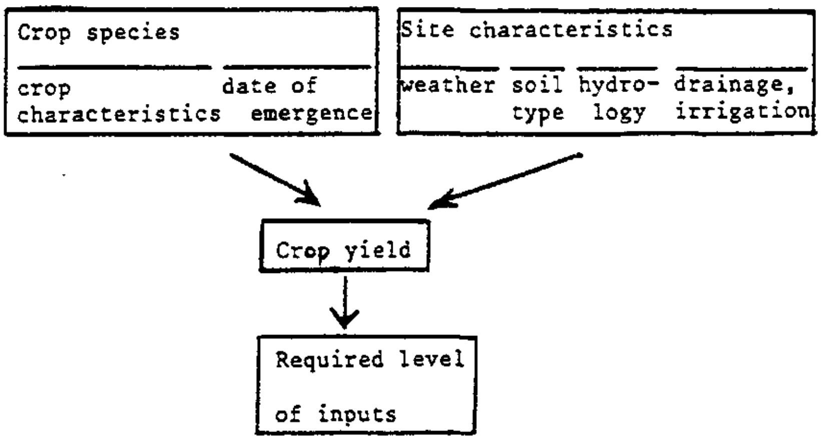

Figure 2. Basic structure of methodology.

For any selected emergence date the relevant phenological, physiological and physical crop characteristics, weather data (amount and distribution of rainfall, temperature, solar radiation, etc.) and soil and topographic characteristics (water holding capacity of the soil, inflliltration capacity, etc.) are combined to calculate crop yield (marketable product) and production (total dry matter) for specified situations. For actually attaining these yields, inputs are required such as human and animal labour, irrigation water, fertilizers, etc. The requied input levels are dictated by the yields aimed at and the specified production situation.

The various processes that are important in determining growth and yield of crops are interrelated, but the actual quantitative relationships are in many cases only partially understood. To use that partial knowledge as efficiently as possible the method of analysis follows a hierarchical approach. At the highest hierarchical level the number of factors considered is restricted, by assuming that the constrainst that can feasibly be removed, have indeed been eliminated. Going to lower hierarchical levels, the factors taken into account at the higher levels remain fixed, and effects of limiting factors supposed to have been eliminated at the higher levels, are successively taken into consideration.

The analysis reported here covers three levels of crop production and yield:

1. Potential: Yield level is determined by crop characteristics, temperature and solar radiation. Water and nutrient availability are assumed to be optimal, and effects of weeds, pests and diseases negligible. Realization of that situation requires adequate supply of water and nutrients, and optimum crop management.
2. Water-limited: Yield level is determined by crop characteristics, temperature, solar radiation and water availability, dictated by rainfall pattern and soil physical properties. Realization of that situation requires adequate supply of plant nutrients, and optimum crop management.
3. Nutrient-limited: Yield level is determined by crop characteristics, temperature, solar radiation, water availability, as dictated by rainfall pattern and soil physical properties, and soil chemical properties.

These calculated yield levels serve as the basis fot the assessment of yields at lower hierarchival levels, such as current yield levels with no external inputs, without control of pests and diseases and with limited weed control. The procedure used will be treated in Section 2.4.

An example of the results of the hierarchical approach is given in Table 1, based on a study of the Centre for World Food Studies (SOW, 1985). For sorghum in Burkina Faso, growing under 'average' conditions with respect to climatic conditions, soil fertility, etc., yields for the three hierarchical levels and for a low-input system are specified as well as the production limiting factors and the required inputs. These data clearly indicate that under the conditions in Burkina Faso nutrient availability rather than water availability is the major constraint for crop production, so that substantial production increases can be obtained from fertilizer application, and that irrigation will only result in increased production, if combined with fertilizer application.

2.2 Assessment of potential and water-limited yields

2.2.1 Methodology

The Centre for World Food Studies developed a dynamic crop growth simulation model, WOFOST, to calculate agricultural production potentials on the basis of physiological, physical and agronomic information. The principles underlying the model are treated in detail in van Keulen and Wolf (1986), and the implementation and structure are described by van Diepen *et al.* (1989).

In the model, the growth of a crop is simulated from emergence to maturity on the basis of physiological processes as determined by the crop's response to environmental conditions. The major processes considered are CO_2 assimilation, respiration, partitioning of assimilates to various plant organs, transpiration and phenological development. In calculating potential yield, solar radiation and temperature are the only environmental conditions considered. In calculating water-limited yield, moisture availability is introduced as a possible growth-limiting factor.

The basis for the calculation of dry matter production is the rate of gross CO_2 assimilation of the green canopy, determined by prevailing radiation level, the

Table 1. Hierarchical sequence with decreasing amounts of external inputs and corresponding increase in number of production limiting factors. Grain yields of sorghum are calculated for a situation being about the average in Burkina Faso with respect to weather and soil characteristics.

Level of production	Production limiting factors	Required inputs in agriculture	Sorghum grain yield[1]
1. Potential production	Solar radiation, crop characteristics, temperature	Irrigation, drainage, fertilizer appl., crop protection, weed control etc.	5300 kg/ha
2. Water-limited production	Idem + availability of soil moisture	Fertilizer appl., crop protection, weed control etc.	3900 kg/ha
3. Nutrient-limited production	Soil fertility, crop characteristics	Crop protection, weed control etc.	870 kg/ha
4. Low-input farming	Soil fertility, yield losses	Some control of weeds, tillage, sowing, harvesting	460 - 680 kg/ha[2]

[1] 12 percent moisture.

[2] Range of actual yields from agricultural statistics (FAO, 1985 etc.).

intercepting (leaf) surface of the crops and the assimilation characteristics of individual leaves. Part of the assimilates formed is used by the crop for respiratory processes to provide energy for maintenance, which is a function of crop dry weight and chemical composition, modified by ambient temperature. The remainder is used for increase in structural dry matter, which is partitioned over the plant organs, roots, leaves, stems and storage organs (Figure 3), as a function of phenological development stage. The fraction partioned to the leaves determines leaf area development and hence the dynamics of radiation interception. This procedure results in potential yield, assuming that water and nutrient supply are optimal throughout the crop's life cycle, and that weeds, pests and diseases are completely controlled.

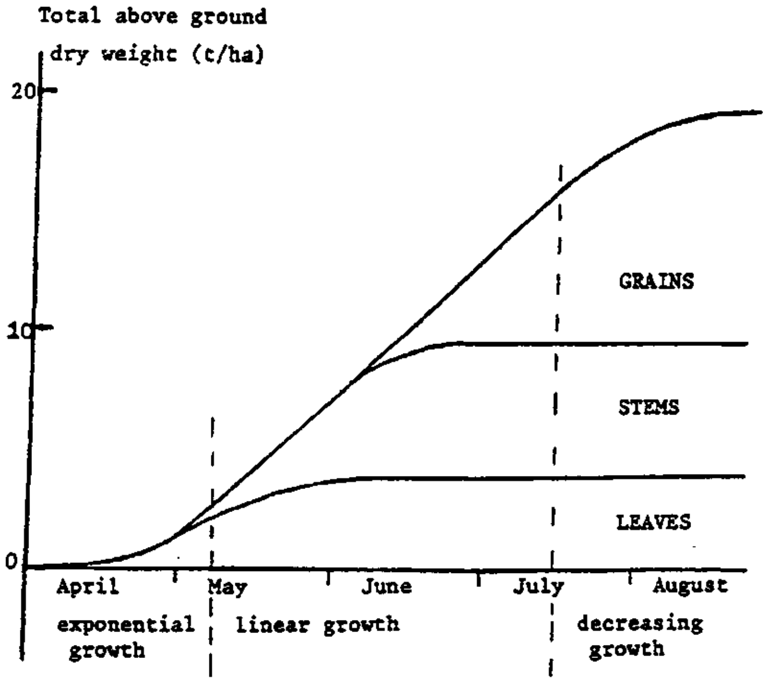

Figure 3. Simulated course of dry weights of the various plant parts for summer wheat growing in the Netherlands.

Transpiration refers to the loss of water from the crop to the atmosphere. The transpiration losses are replenished by water uptake from the soil. Within the optimum soil moisture range for plant growth the losses are fully compensated, and transpiration and hence assimilation proceed at their potential rates. Outside that range the soil can be either too dry or too wet. Both conditions lead to reduced water uptake by the roots, desiccation of plant tissue, closure of the stomata and hence reduced growth: in a dry soil due to water shortage, in a wet soil due to oxygen shortage (Figure 4). Soil moisture content in the root zone (SM) follows from quantification of the water balance (Figure 5) including rainfall (P), irrigation (I_e), surface runoff (SR), soil surface evaporation (E), crop transpiration (T), capillary rise from the groundwater (CR), and percolation beyond the root zone (D).

The degree of drought stress is quantified in this way, resulting in an estimate of the associated yield reduction.

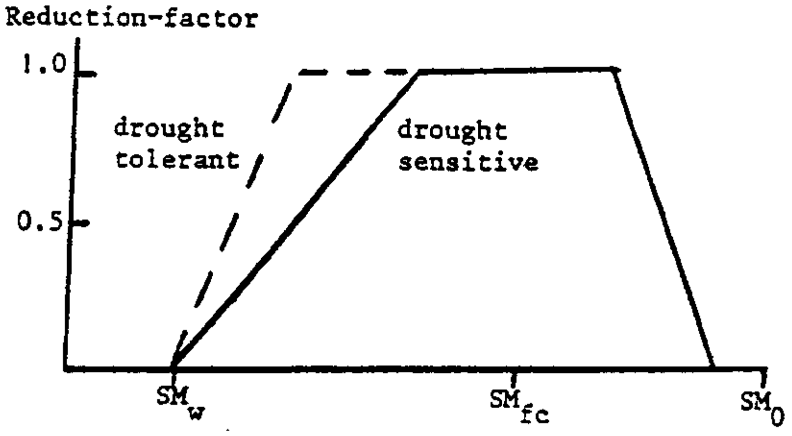

Figure 4. Schematic representation of the reduction in transpiration and assimilation rates of drought-tolerant and drought-sensitive crops as a function of soil moisture content. SM_w*,* SM_{fc} *and* SM_0 *are the soil moisture contents at wilting point, field capacity and saturation, respectively.*

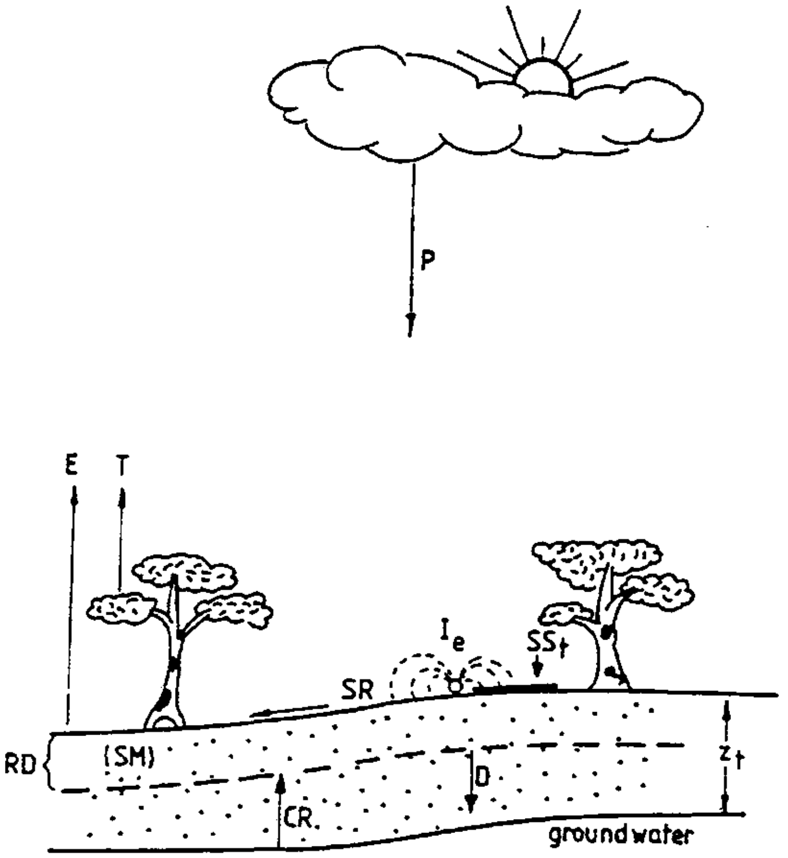

Figure 5. Schematic representation of the terms of the water balance. (Source: Driessen, 1986)

2.2.2 Data requirements

Crop-specific data

For the simulation model, each crop is characterized by its properties with respect to assimilation and respiration processes, response to moisture stress, and phenological development pattern. The minimum required site-specific information on crops includes data on seeding rate or planting density and a crop calendar defining, dates of emergence, anthesis and maturity. The yield potential is strongly dependent on growth duration, which for a given cultivar mainly depends on temperature, for photo-sensitive cultivars modified by effects of daylength. Cultivars having shorter than optimum growth cycles for a particular environment produce less, because they cannot develop sufficient green leaf area for fully intercepting solar radiation, while cultivars having a longer growth cycle develop so much vegetative material that a large part of the assimilates is necessary for respiration at the expense of grain, root or tuber production (van Keulen & Wolf, 1986).

Climatic data

For the calculation of gross CO_2 assimilation rates, average and minimum daily temperatures and solar radiation are required (Goudriaan & van Laar, 1978). For the water balance rainfall regime, and potential evaporation and evapotranspiration rates are required. These rates are calculated with the Penman formula, using data on radiation, average daily air temperature, vapour pressure and wind speed (Frère & Popov, 1979).

Soil physical data

For calculating the soil water balance, the soil's infiltration, retention and transport properties must be known. Soils are physically defined by:

- soil moisture characteristics, notably soil porosity and volumetric moisture contents at field capacity and wilting point, respectively;
- effective soil depth;
- maximum infiltration rate or other characteristics from which surface runoff can be derived;
- hydraulic conductivity of the subsoil.

2.2.3 Results from a study on staple food production in Burkina Faso

As an illustration, some results from a study on the potential for food production increases in three countries in Africa (SOW, 1985) are reproduced in Table 2. For three locations in Burkina Faso with different rainfall regimes water-limited yields of a medium-duration millet cultivar, growing on a loamy sand, having 0.07 cm^3 cm^{-3} of available soil water, are compared to potential yields. These results show that on relatively deep, well-drained soils water-limited yields equal potential yields, if precipitation during the growing cycle exceeds 500 mm, i.e. in the south of the Sahelian zone. 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. Serious yield reductions due to drought

Table 2. Calculated water-limited grain yields (10^3 kg ha^{-1}, 12 percent moisture) for millet for some selected soil-climate combinations in Burkina Faso. (Source: SOW, 1985)

Location	Soil type[1]	Rain-fall[2]	Potential yield	Water-limited yields		
				120[3]	70[3]	30[3]
Dori	loamy sand	420	2.8	2.4	1.6	1.3
Ouahigouya	loamy sand	510	2.9	2.9	2.8	2.0
Ouagadougou	loamy sand	530	2.9	2.9	2.9	2.8

[1] Volume fraction available soil moisture equal to 0.07 cm^3 cm^{-3}.
[2] Rainfall during growth cycle, mm.
[3] Effective rooting depth, cm.

occur, if both the soils are rather shallow and annual rainfall is relatively low. In this example reductions in yield due to drought are rather modest, because the crop cultivar used is suitable for the relatively short rainy season, and because the climatic data used in the calculations are averages for the period 1930 - 1960. As average rainfall for the period 1970 - 1985 was about 30 percent lower, the situation for Ouagadougou for that period would be about comparable to that for Dori as given in Table 2.

Such calculations have been performed for the whole of Burkina Faso, taking into account the various agro-climatic zones and different soil types, for millet, sorghum and maize. The results, summarized in Table 3, although based on rather broad generalizations, provide a reasonable first estimate of the average maximum production level of these cereals, if in addition to crop characteristics, availability of moisture, as determined mainly by soil physical properties and rainfall regime, would be the only limiting factor and crop management and nutrient supply would be optimum.

2.3 Assessment of nutrient-limited yields

Nutrients are needed in certain quantities for optimum functioning of the plant. If their supply is limited, nutrient concentrations in the plant tissues decrease till an absolute minimum value. Under such conditions, crop yield and production are determined by the ratio of nutrient supply and minimum nutrient concentration in plant tissue (van Keulen & van Heemst, 1982). Nutrient-limited yields refer to situations that no fertilizers are applied and thus nutrient supply depends only on natural sources. In such situations nutrient supply is generally much more limiting for crop production than water availability, and effects of drought on production can be neglected.

Table 3. Summary of results of calculations of water-limited grain yields (kg ha^{-1} 12 percent moisture) for maize, sorghum and millet on different soil types in Burkina Faso. (Source: SOW, 1985)

Crop	Yield range	Fraction of total arable area %
Maize	< 1000	36
	1000 - 4600	5
	> 4600	59
Sorghum	< 1900	2
	1900 - 2600	29
	2600 - 4000	29
	> 4000	40
Millet	< 600	4.5
	600 - 1250	6.5
	1250 - 1900	9
	1900 - 2850	27
	> 2850	53

2.3.1 Methodology

Soil fertility, in this analysis restricted to the macro-elements nitrogen (N), phosphorus (P) and potassium (K), has been evaluated according to the QUEFTS system (Janssen *et al.*, 1990), comprising a number of successive steps. First, the quantities of nitrogen, phosphorus and potassium that are potentially available for uptake by a 'standard' maize crop during one growth cycle, are estimated using empirical relationships between chemical properties of the topsoil and potential nutrient supply (Table 4). These relationships were developed in the course of two land evaluation projects in Kenya and one in Surinam. For other crops or cultivars, the values for potential uptake are derived from that of the 'standard' crop by taking into account differences in length of the growth cycle.

In the subsequent step, relationships between actual and potential uptake are used to calculate the actual nutrient uptake by the crop. Next, ranges of yields are established from the actual uptake of the three macro-elements using uptake-yield relationships. From these yield ranges the actual crop yield level without fertilizer application is calculated.

Actual uptake of a certain nutrient, for example nitrogen, is only equal to the potential uptake, if the supply of phosphorus and potassium is adequate. If phosphorus supply strongly limits crop yield, the nitrogen concentration in the crop will approach its maximum level, so that actual nitrogen uptake is limited by the P-limited crop yield multiplied by the maximum nitrogen concentration in plant tissue. The same applies for the other nutrients.

Table 4. Equations for calculating the potential supply of nitrogen (SN), phosphorus (SP) and potassium (SK) by a soil. Potential supply is expressed in kg/ha of N, P and K, respectively; organic carbon and organic nitrogen in g/kg, P-Olsen and total P in mg/kg, and exchangeable potassium in mmol/kg. Sample depth is 0-20 cm. (Source: Janssen *et al.*, 1990)

$$SN = fN \times 6.8 \times \text{org. C}^{1)}$$

$$SP = fP \times 0.35 \times \text{org. C} + 0.5 \times \text{P-Olsen}^{2)}$$

$$SK = \frac{fK \times 400 \times \text{exch. K}}{2 + 0.9 \times \text{org. C}}$$

f = correction factor related to pH (H_2O):

$$fN = 0.25\ (pH - 3)$$
$$fP = 1 - 0.5\ (pH - 6)^2$$
$$fK = 0.625\ (3.4 - 0.4\ pH)$$

---

1) Instead of organic carbon, organic nitrogen can be used:
$SN = fN \times 68 \times \text{org. N}$

2) If total P is known, it is preferred to calculate the phosphorus supply with:
$SP = fP \times 0.014 \times \text{total P} + 0.5\ \text{P-Olsen}$

For each of the nutrients, relationships between uptake and crop yield have been established, both for the situation that nutrients are fully diluted and for the situation that nutrient concentrations are at their maximum (Figure 6). If one nutrient is mainly limiting crop production, the concentration of that nutrient is at its minimum and its yield-uptake ratio is maximum. In that situation, the concentrations of the other nutrients are high and if actual uptake of these nutrients is high, the maximum nutrient concentrations may be attained and yield-uptake ratios are at their minimum. From the actual uptake of N, P and K and their yield-uptake ratios at minimum and maximum nutrient concentration, the ranges in yields are calculated. From these ranges in yield the actual yield is calculated by weighing according to the relative availability of the three nutrients. A more detailed description of the system is given by Janssen *et al.* (1990).

For situations that the relative availability of the three macro-nutrients corresponds reasonably well with the relative needs of the crop, the nutrient uptake by the crop and the resulting crop yield can also be calculated by hand. Potential nutrient uptake is again calculated with the equations is in Table 4. In this 'equilibrium' situation, actual crop uptake of each macro-nutrient is estimated at 90 percent of the potential value, and their concentration in the crop at an 'average' level, between minimum and maximum. These estimates are used to calculate yield-nutrient uptake ratios (Table 5). Multiplication of crop uptake of each macro-nutrient with its yield-nutrient uptake ratio results in the crop yield as dictated by the supply of that nutrient from natural sources. Minimum and maximum concentrations of the three macro-nutrients have been collected for a large number of

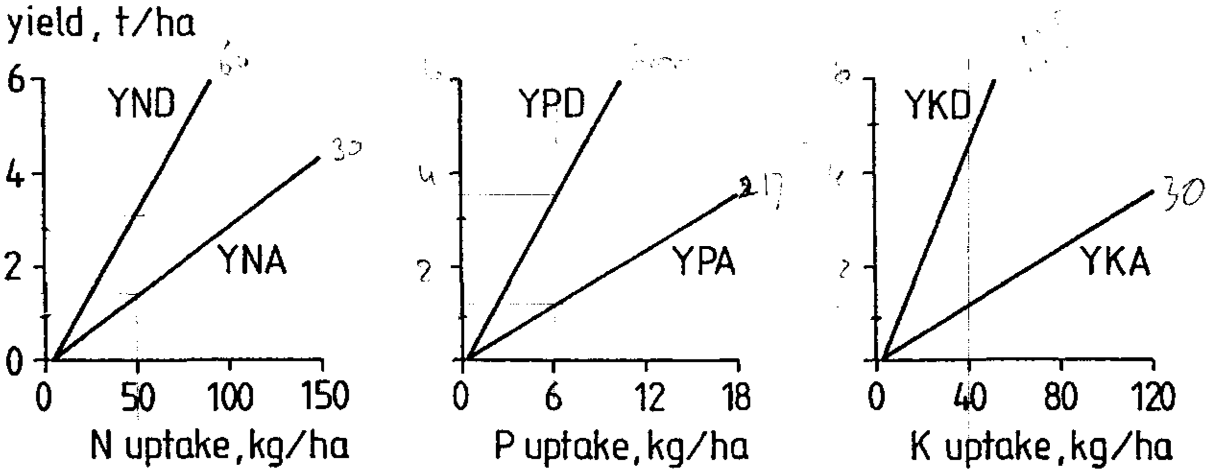

Figure 6. Relationships between grain yield of maize and uptake of nitrogen, phosphorus and potassium. The upper lines, YND, YPD and YKD, represent the yields at maximum dilution and the lower lines YNA, YPA and YKA those at maximum accumulation of the elements in the crop. (Source: Janssen et al., 1990)

Table 5. Grain/stover ratios (dry matter) nutrient concentrations (g kg^{-1}) in dry matter of stover and grains, and "average" yield (dry matter in grains) -nutrient uptake ratios for the three macronutrients for a number of grain crops.

Crop	Grain-stover ratio [1]	"Average" nutrient concentrations [2]		"Average" yield-nutrient uptake ratio [3]
		Grains	Stover	
Maize	0.7	N 14	7	42
local var.		P 3.6	1.3	183
		K 3	10	58
Maize	1.0	N 14	7	48
HYV		P 3.6	1.3	204
		K 3	10	77
Millet	0.35	N 17	6	29
		P 3.6	1.2	142
		K 5	14	22
Sorghum	0.45	N 17	6	33
		P 2.9	1.2	180
		K 4	14	28

[1] Ratios refer to situations without moisture stress.

[2] "Average" concentration is calculated as (2 * minimum conc. + maximum conc.)/3.

[3] Yield-nutrient uptake ratio is calculated as:
1 / (average nutrient conc. (grain) + (1/grain-stover ratio) * average nutrient conc. (stover)).

(sub)tropical annual field crops and some tropical perennials (Nijhof, 1987a; 1987b; 1987c), which allows calculation of the yield-nutrient uptake ratios and the nutrient-limited crop yields. This applies both to this simple method and to the QUEFTS method.

2.3.2 Data requirements

Soil chemical data showing best performance as diagnostic properties for calculating the potential uptake of nitrogen, phosphorus and potassium, appeared to be pH-H_2O, organic C, P-Olsen and exchangeable K (Table 4). If values for organic N and total P are available, they should also be used to increase the reliability of the results. Potential uptake of nitrogen equals net mineralisation from organic nitrogen and increases both with increasing organic matter content, either expressed in C or in N, and with increasing pH (Figure 7). Potential uptake of phosphorus depends on two characteristics: P-Olsen and organic C. Organic C is included because it is related to total P that is seldom determined. But if total P values are available, their use is preferable. Available phosphorus is estimated via P-Olsen. The effect of pH on potential uptake of phosphorus is described by a parabolic expression with an optimum at pH 6 and zero values at pH 4.6 and 7.4, respectively (Figure 7). Potential uptake of potassium increases with increasing

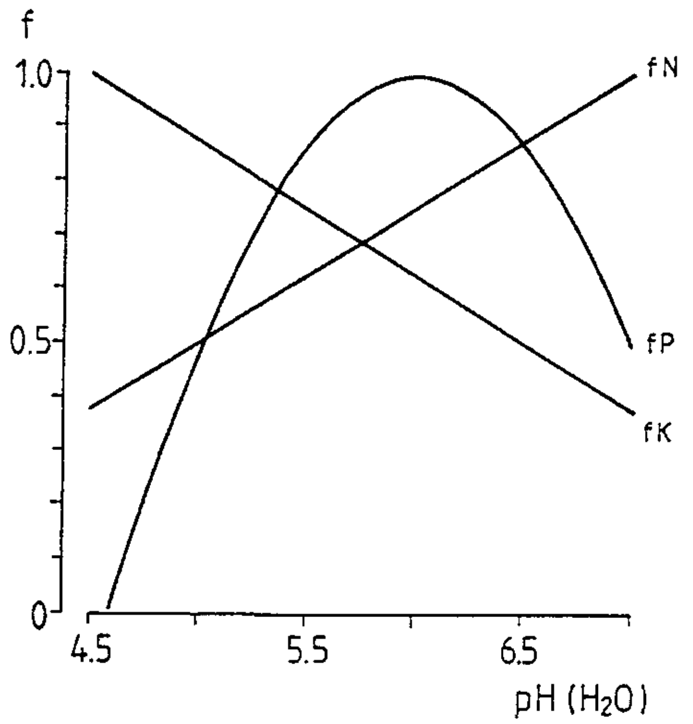

Figure 7. The effect of pH (H_2O) on the potential supply of nitrogen, phosphorus and potassium, expressed as the pH-correction factors fN, fP and fK, respectively. (Source: Janssen et al., 1990)

values of exchangeable K and decreases with increasing pH and increasing organic C. These negative effects of increasing pH and organic C can probably be explained by their positive effect on the effective CEC.

If the required soil chemical data are not available, the potential uptake of nutrients may be divered from nutrient uptake data from field trials without fertilizer application for soil representative types.

2.3.3 Crop response to fertilizer nutrients

The response of crops to fertilizer application can also be evaluated with the QUEFTS system. That requires, however, data on the fraction of the applied fertilizer nutrient taken up by the crop (recovery fraction), which may be derived from fertilizer trials. In the QUEFTS system the maximum value for the recovery fraction is applied, which only depends on the soil- and water regime-specific losses by leaching, precipitation etc., but is not affected by limited supply of other nutrients.

The additional uptake from the fertilizer nutrient obtained as the fertilizer rate times the recovery fraction is added to the potential uptake of the unfertilized soil. This yields the quantities of nitrogen, phosphorus and potassium that are potentially available for uptake by a fertilized crop. The successive steps are then the same as described for the non-fertilized situation.

2.3.4 Results from a study on maize production in Zambia

As the QUEFTS system has not been applied yet for analyzing soil fertility in the Sahelian region, some results from a study on the limitations to maize production in Zambia (Wolf *et al.*, 1987) are presented as illustration. For mapping units on the soil map of Zambia (Brammer, 1973), representative soil chemical data were collected (Table 6). The number of soil units distinguished is rather small, and consequently the variability in properties within each unit rather large, limiting the accuracy of the calculated results. In the high rainfall areas in the northern

Table 6. Representative soil chemical data for some of the soil types of Zambia, without and with liming to a pH value of 5.5. (Source: Wolf *et al.*, 1987)

Soil	pH-H_2O	Organic C g kg^{-1}	P-Olsen mg kg^{-1}	Exch. K mmol (+) kg^{-1}
Red clays	6.2	22.0	3	6.0
Leached red clays	4.5	15.0	2	3.0
Idem after liming	5.5	15.0	2	3.0
Sandveldt soils	5.6	7.0	1.5	3.0
Leached Sandveldt soils	4.3	7.0	1.0	1.5
Idem after liming	5.5	7.0	1.0	1.5

parts of Zambia leached soils occur. Their pH is so low that maize production is almost impossible. Yields have therefore been calculated both for the original pH and for a pH of 5.5, attained by liming.

For two main soil types in Zambia, the sandy (Sandveldt) and the clay soils, potential uptake of nitrogen, phosphorus and potassium and the corresponding nutrient-limited yields were calculated, following the QUEFTS system (Table 7). Grain yields range from about 1400 kg ha^{-1} (12% moisture content) on Sandveldt soils to about 3800 on Red clays, both situated mainly in the Central, Eastern and Southern provinces. On the leached soils in the Northern and Northwestern provinces, only after liming acceptable yields between 1200 and 2400 kg ha^{-1} can be attained. The main limiting nutrient appears to be phosphorus.

Values for recovery fractions of applied fertilizer nutrients were derived from results of local fertilizer experiments (Table 8). For three different levels of fertilizer application potential uptake of nitrogen, phosphorus and potassium was calculated and used to assess the grain yields and the increases in grain yield due to fertilizer application per soil type (Table 9).

Table 7. Soil supply of nitrogen, phosphorus, and potassium (kg ha^{-1}) to a maize crop, calculated from soil chemical data for a number of soils in Zambia, the corresponding grain yields[1)] of maize HYV (kg ha^{-1}), and the yield limiting nutrient. (Source: Wolf *et al.*, 1987)

Soil	Soil supply			Yield	Limiting nutrient
	N	P	K		
Red clays	119.7	9.1	63.3	3843	PK
Leached red clays	38.3	1.0	77.4	360	P
Idem after liming	63.8	5.6	58.1	2384	P
Sandveldt soils	30.9	3.0	104.8	1384	P
Leached Sandveldt soils	15.5	0.5	75.9	60	P
Idem after liming	29.8	2.6	54.2	1165	P

[1)] Grain yields at 12 % moisture and without correction for losses.

Recovery effic.

[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	26.8	4.1
32.9	354.6	26.1
[illegible]	465.0	11.6
3.4	105.6	0.7
[illegible]	[illegible]	18.9

Table 8. Indicative values for recovery fractions[1)] of applied fertilizer nitrogen, phosphorus and potassium for a number of soils in Zambia, without and with liming to a pH value of 5.5. (Source: Wolf *et al.*, 1987)

Soil	Recovery fraction, kg kg^{-1}		
	N	P	K
Red clays	0.40	0.15	0.40
Leached red clays	0.30	0.10	0.30
Idem after liming	0.40	0.15	0.40
Sandveldt soils	0.30	0.10	0.30
Leached Sandveldt soils	0.20	0.07	0.20
Idem after liming	0.30	0.10	0.30

[1)] These values apply to situations where the other nutrients in adequate supply sufficiently, and would be lower otherwise. They have been derived from results of demonstration plots of the FAO fertilizer programme (FAO, 1984; 1985) and results of fertilizer experiments (Pawson, 1953).

Table 9. Grain yields1) (kg ha^{-1}) of maize HYV for a number of soils in Zambia, without and with liming to a pH value of 5.5, for specified levels of fertilizer application and increases in grain yield (kg ha^{-1}). (Source: Wolf *et al.*, 1987)

Soil	Amounts of fertilizer nutrients2), kg ha^{-1}					
	N - P_2O_5 - K_2O 43 - 20 - 10		N - P_2O_5 - K_2O 86 - 40 - 20		N - P_2O_5 - K_2O 135 - 70 - 35	
	Yield	Increase	Yield	Increase	Yield	Increase
Red clays	4345	502	4833	990	5508	1665
Leached red clays	892	532	1398	1038	2096	1736
Idem after liming	2926	542	3453	1069	4166	1782
Sandveldt soils	1872	488	2315	931	2911	1527
Leached Sandveldt soils	426	366	780	720	1292	1232
Idem after liming	1582	417	1984	819	2524	1359

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1) Grain yields and increases in grain yield at 12 % moisture and without correction for losses.

2) Other nutrients and particularly sulphur are assumed to be included sufficiently in the compound fertilizers.

2.4 Actual yields and target yields

Actual yields in agricultural practice are the result of complex interactions among weather conditions, availability of water and nutrients, competition by weeds, pests and disease incidence and actual management practices. In the study on the potential for food production increases in three countries in Africa (SOW, 1985), both water-limited and nutrient-limited yields were calculated for the main food crops in the main agro-ecological zones per country. For Burkina Faso, national average yields were given for maize, millet and sorghum. In Table 10 statistical field data (C & D) are compared with both nutrient-limited (A & B) and water-limited yields (E & F). The comparison suggests that availability of nutrients is the most constraining factor, even in the North (except on shallow soils in dry years; Table 2). Actual yields will be mainly determined by nutrient supply from natural sources.

The reported yields for Burkina Faso were realized without any appreciable use of chemical fertilizers, i.e. less than 5 kg per planted hectare. The associated yield increase of less than 20 kg ha^{-1} is negligible in view of the measurement error, and nutrient extraction during continuous cropping will considerably exceed this average nutrient application.

The calculated nutrient-limited yields are practically always higher than actual yields, because of inevitable yield losses. These losses vary strongly, depending on crop cultivar, yield level, growing conditions, and the level of crop protection. Harvest losses will also occur. For Burkina Faso no local data on these yield losses were available. Hence, average values were estimated on the basis of information about average yield losses for various crops under a wide range of growing conditions (van Heemst, 1985). 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 (B, Table 10) is estimated at 75 percent of the nutrient-limited yield level.

Actual yields as reported in the FAO Production Year-books (e.g. FAO, 1985, etc.), show considerable variation from year to year due to variable weather conditions, degree of pest and disease infestation, etc. (Table 11). Ranges and means of these yields are given in Table 10. The reported average yields are in close agreement with the estimated value for millet, but are about 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.

It may thus be concluded that in most years, if soils are not too shallow, also in Burkina Faso higher crop yields are possible by increased nutrient supply through fertilizer application. A target yield may be set 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 fertilizer application becomes less attractive.

In such a more market-oriented system, farmers may intensify crop and soil management (improved weed, pest and disease control, runoff control and soil tillage), but the risk for losses in situations with a higher nutrient supply also increases. That is associated with higher risks for pests and diseases, potentially higher nutrient losses by leaching and runoff, and more intensive weed competi-

Table 10. Estimated national average grain yields (kg ha^{-1}, 12 percent moisture) of main food crops in Burkina Faso; A, nutrient-limited yields; B, nutrient-limited yields corrected for losses during harvest and by pests, diseases and weeds (= estimated "actual" yields); C, ranges of yields from statistical data; D, mean yields from statistical data; E, water-limited yields; F, target yields. (Source: SOW, 1985)

Crop	A	B1)	C2)	D	E	F3)
Maize	1100	825	511 - 1066	700	5800	3700
Millet	550	415	351 - 601	440	2400	1500
Sorghum	875	655	460 - 678	570	3900	2500

1) Yield losses are estimated at 25 percent.
2) Yields reported by FAO (1985, etc.).
3) 64 percent of water-limited yield, see text.

Table 11. Reported national average grain yields (kg ha^{-1}, 12 percent moisture) of main food crops in Burkina Faso. (Source: FAO, 1985 etc.)

Year	Maize	Millet	Sorghum
1966	752	438	530
1967	550	429	460
1968	600	601	638
1969	600	440	500
1970	645	444	541
1971	739	380	472
1972	702	390	490
1973	658	351	464
1974	683	435	588
1975	587	420	648
1976	511	406	630
1977	600	389	610
1978	667	446	592
1979	1066	478	678
1980	983	412	658
1981	830	492	608
1982	823	485	581
1983	557	432	558
Average	700	440	570

tion. Hence, yield losses for this intensified production situation are estimated at 20 percent, so that the attainable yield at the specified target level is (0.80 * 0.80) times the average water-limited yield. These target yields for maize, millet and sorghum in Burkina Faso are given in Table 10 (F). However, if such intensified systems cannot be properly managed due to lack of pesticides, adapted crop cultivars, human labour, animal traction, tools or machinery, or insufficient support from the extension services, actual yield losses can easily reach 50 percent, implying almost negligible yield increases due to fertilizer application.

Fertilizer application will not only affect nutrient uptake and crop production in the first year, but also in subsequent years. Hence, from an economic point of view the applied fertilizers should not only be considered as yield-increasing inputs in the year of application, but also as an investment for a longer period because of their residual effects. For full profit from fertilizer applications and improved soil management, land tenure systems are required that guarantee the farmer the use of the same plot for at least several years.

Production can exceed water-limited production, if irrigation can be applied, e.g. in areas along the rivers Niger and Senegal. Using average conditions in Burkina Faso as an example, this could result in yield increases from 3900 to 5300 kg ha^{-1} for sorghum (Table 1) and from 2400 to 2800 - 2900 kg ha^{-1} for millet (Tables 2 and 10). In the northern part of the country the yield of millet could increase from 1300 to 2800 kg ha^{-1} (SOW, 1985). These data have to be multiplied by 0.64 to obtain realistic target yields.

However, the high investments required for irrigation projects cast serious doubts on their economic feasibility. That could only be achieved through very intensive crop production systems (GEAU, 1984), that are market-oriented, using improved crop varieties, high fertilizer rates, and a high level of crop and soil management. That, however, would imply a very abrupt transition from the present low-input production systems, and as investments in soil fertility could lead to substantial production increases more gradually, irrigation development seems mainly of interest for the following two options: (i) production of crops such as rice and some vegetables for which drought stress during the growing season entails substantial production losses; (ii) production of crops in the northern part of the Sahelian zone, where low rainfall prevents crop production completely.

2.5 Input - output relations for millet production in Mali

After calculating the various yield levels attainable under well-defined constraints, as explained in the preceding sections, the proposed method of analysis continues with an evaluation of the inputs required to realize these yields. An example of such an evaluation is given in Table 12, referring to cultivation of millet in the fifth region of Mali on a sandy loam soil at an average annual rainfall of about 530 mm (van Duivenbooden & Gosseye, 1990).

Inputs have been specified for six different production techniques, all assumed to be sustainable (Table 12). Sustainability has many different aspects (TAC, 1989). In the study referred to here, it has been defined in terms of plant nutrients, i.e. export of nutrients from the system should be fully compensated by inputs either from natural sources (fallowing) or by application of organic or chemical fertilizer. Fallowing (techniques 1 and 3) to restore soil fertility can be practiced, as long as sufficient land is available, i.e. the fraction of cultivated land is small. In technique 1 (six years of fallow per year of cultivation) it should not exceed 15%, in technique 3, where more intensive soil tillage leads to accelerated organic matter decomposition, it should not exceed 10%. Under increasing population pressure and the associated expansion of the cultivated area, systems based on these techniques rapidly deteriorate.

In techniques 2, 4, 5 and 6 animal manure is used as an input, in the first two techniques as the sole external source of nutrients, in the latter two mainly to maintain organic matter content and favourable soil structure. For the production of manure, animals and sufficient grazing land is required. If arable farming expands, and consequently the grazing area decreases, systems based on techniques 2 and 4 rapidly become unsustainable, as the nutrient balance of the grazing land becomes negative.

In techniques 5 and 6 export of nutrients is compensated by the use of chemical fertilizer, which results in substantial yield increases from 400-500 kg ha^{-1} to 1000 (technique 5) or 1900 (technique 6) kg ha^{-1}.

Field work in techniques 1 and 2 is completely based on human labour, whereas in the other four techniques animal traction is incorporated. The total labour requirements in technique 2 are higher than in technique 1 as a consequence of the labour-intensive transport and application of manure. Human labour

Table 12. Different techniques of millet production in the fifth region of Mali, defined on a hectare basis. (Source: van Duivenbooden & Gosseye, 1990).

Ploughing, animal traction	-	-	+	+	+	+
Manure	-	+	-	+	+	+
Fertilizer N and P	-	-	-	-	+	+
Fallow [1]	+	-	+	-	-	-
	Low input	Low input	Low input	Low input	Semi-intensive	Intensive
Technique nr.	1	2	3	4	5	6
Inputs						
Labour in man-day, in oxen plough-day (OX).						
Field clearance	1	1	1	1	1	1
Fallow land clearance	3	-	3	-	-	-
Manure transport	-	5	-	5	5	5
Manure spreading	-	7	-	7	7	7
Ploughing	-	-	4 + 2 Ox	4 + 2 Ox	4 + 2 Ox	12 + 6 Ox
Sowing	4	4	4	4	4	2 + 1 Ox
Weeding	27	27	22 + 2 Ox	22 + 2 Ox	22 + 2 Ox	22 + 2 Ox
Fertilizer application	-	-	-	-	4	9
Biocide application	-	-	-	-	-	5
Harvesting	6	6	6	6	9	14.5
Transport harvest to farmstead	8	8	2	2	2	2.5
Threshing, winnowing	16	16	16	16	20	38
Labour total	65	74	58 + 4 Ox	67 + 4 Ox	78 + 4 Ox	118 + 9 Ox
Oxen pair per hectare	-	-				
Other inputs						
Manure (kg dry mat.)	-	3000	-	3500	2000	2000
Fertilizer (inorg., kg)	-	-	-	-	36 (N)	150 (N)
	-	-	-	-	19 (P)	69 (P)
Biocide	-	-	-	-	-	*

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[1] Ratio between fallow years and cultivated years is estimated at 6 for non-ploughed and 10 for ploughed land.

requirements in techniques 3 and 4 are lower than those in 1 and 2, as they are partly substituted by animal traction. In techniques 5 and 6 both human and animal labour requirements are higher, partly associated with application of chemical fertilizer and crop protection agents, partly with the higher yields, requiring more labour during harvest and post-harvest operations.

A cost/benefit analysis for these production techniques is elaborated in Table 13. The total costs of production are lowest in the extensive techniques (1-4) and increase with the level of intensification. The difference between comparable techniques with and without animal traction (1 and 2; 3 and 4) is negligible, as the additional costs of oxen and the associated implements are fully compensated by labour saving. However, labour saving is only profitable if alternative opportunities are available, either by cultivating a larger area, or through off-farm activities.

For techniques 5 and 6 the increase in total production costs, compared to technique 4 amounts to 37 000 and 166 000 FCFA, respectively, if the costs of additional human labor are taken into account, and to 26 000 and 155 000, respectively if the latter are neglected.

Apparently, in years with relatively low grain prices such as 1988/89, production increases by fertilizer application do not cover the additional costs, but with a much higher price level for grains, such as in 1987/88, application of technique 5 results in a considerably higher income, but in view of the variable grain prices, at a high risk. Only if grain prices are stabilized at a relatively high level, or fertilizer prices at a lower level, and the efficiency of fertilizer use reaches the theoretical maximum, intensification of agricultural production using chemical fertilizers, etc. may become a feasible option for increasing food production in the region (Veeneklaas *et al.*, 1990).

Table 13. (see next page)

1) Techniques are specified in Table 12.

2) Costs of human labour are estimated at 1000 FCFA per day. Total labour requirements are derived from Table 12.

3) Acquisition of a pair of oxen costs about 80.000 FCFA. After five years of use they can be sold at 40.000 FCFA. Depending on intensity of cultivation (see Table 12) 2 or 4 ha can be covered with one pair of oxen.

4) Animal manure has no real price, but herds that are allowed to graze the fields and to use water from the wells, produce manure in return. Hence, availability of manure depends on the total animal population in the region.

5) Nitrogen fertilizer is priced at 350 FCFA per kg N and phosphorus fertilizer at 630 FCFA per kg P, based on prices of urea and ammonium phosphate. Total amounts of fertilizer applied are given in Table 12.

6) Price of seed estimated at 60 FCFA per kg. Amount of 10 kg of seed applied per hectare.

7) Improved type of tools.

8) Price of millet in the fifth region of Mali was about 120 FCFA per kg in 1987/88 and about 50 FCFA in 1988/89.

Table 13. Costs and benefits of different techniques of millet production in the fifth region of Mali, in 1000 FCFA per hectare. (Source: van Duivenbooden & Gosseye, 1990)

Technique nr. 1)	1	2	3	4	5	6
Costs of total human labour 2)	65	74	58	67	78	118
Costs of animal traction 3)	-	-	2	2	2	4
Costs of other inputs:						
Manure 4)	-	-	-	-	-	-
Fertilizer (inorg.) 5)	-	-	-	-	25	96
Biocide	-	-	-	-	-	5
Seed 5)	0.6	0.6	0.6	0.6	0.6	0.6
Small tools	0.7	0.7	0.7	0.7	1.0	1.5 7)
Plough	-	-	3.1	3.1	3.1	7.5 7)
Barrow	-	-	0.8	0.8	1.5	2.5 7)
Sowing-machine	-	-	-	-	-	5
Total costs	66	75	65	74	111	240
Yield, kg grain	400	400	480	480	1000	1900
Value of yield (1987/88) 8)	48	48	58	58	120	228
Value of yield (1988/89) 8)	20	20	24	24	50	95
Net profit (1987/88)	- 18	- 27	- 7	- 16	+ 9	- 12
Net profit (1988/89)	- 46	- 55	- 41	- 50	- 61	- 145

Comments 1) to 8): see previous page.

3. Animal production systems

3.1 General outline

The potential of a region for animal production depends mainly on the amount and quality of forage that the natural pastures in the region can produce, provided that imported concentrates, residues from arable farming and fodder crops are of minor importance, epidemic animal diseases are under control and that availability of drinking water is not a constraint. This is the situation for most of the West-African drylands. Hence, primary production of the rangelands forms the basis for animal production and is therefore assessed first. In addition to the amount of forage available, its quality is a major determinant of the productivity of animal husbandry, hence, its variation over the year and its effect on animal production are treated. From this information, animal production and carrying capacity of rangelands can be derived for the various climatic zones of West-Africa.

The procedure applied is largely based on the results of elaborate studies on the productivity of Sahelian rangelands in Mali (Penning de Vries & Djitèye, 1982). From these results simple, mainly empirical, relations and calculation procedures have been derived, that are used to estimate the production of rangelands and the associated animal production. The procedures have been elaborated in a manual for evaluation of rangelands in Sahelian countries (Breman & de Ridder, in prep.), to which is referred for more detailed information.

3.2 Rangeland production

In West-Africa a strong gradient exists in precipitation, which decreases from the tropical rain forest in the south, via the relatively humid savannah and the semi-arid Sahel to the dry Sahara. Over the whole transect the supply of plant nutrients from natural sources is low, although it increases slightly with increasing rainfall, as a result of direct and indirect effects (Breman & Krul, 1982). For example, the average annual nitrogen supply to the above ground plant parts in rangelands increases from 2.5 kg ha^{-1} at an annual precipitation of 100 mm to 12.5 kg ha^{-1} at an annual precipitation of 400 mm and a saturation value of almost 20 kg ha^{-1} is reached at 1000 mm annual precipitation (Figure 8). Hence, water is relatively abundant in the rain forest, the savannah and the southern part of the Sahelian zone, and in those regions plant growth strongly responds to increased availability of nutrients, particularly nitrogen and phosphorus, through, for instance, fertilizer application. The response decreases towards the north, as moisture availability gradually decreases. Where annual infiltration is below 250 mm (northern part of the Sahelian zone and further south if runoff is significant), water is the main growth-limiting factor.

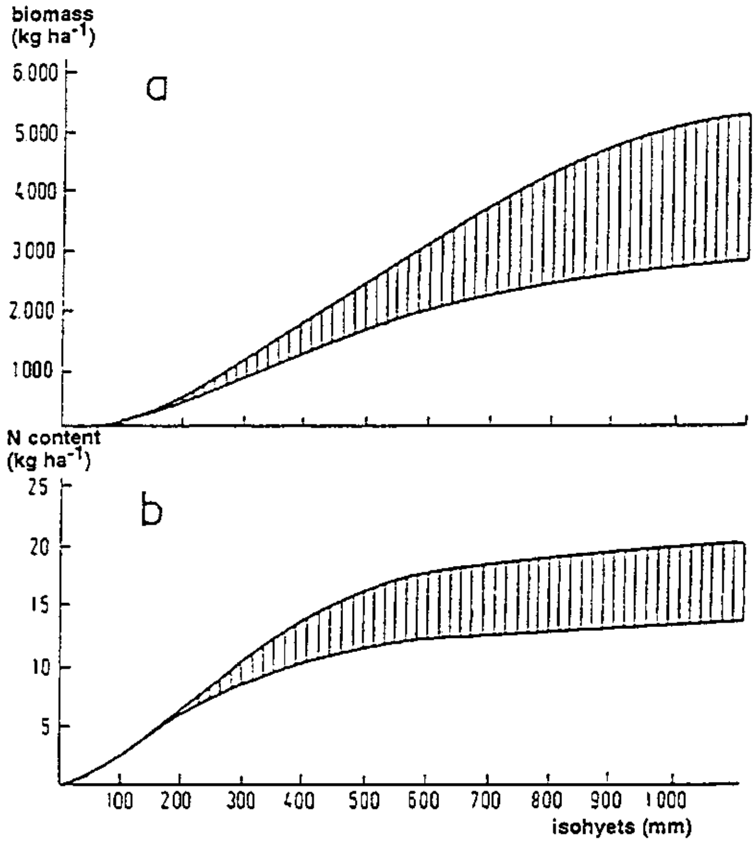

Figure 8. Theoretical relations between (a) biomass production and (b) nitrogen content in the biomass, and the average annual precipitation for a hypothetical transect representing the average situation in Sahelian countries. (hatched band). (Source: Penning de Vries & Djitèye, 1982)

3.2.1 Water-limited production

Primary production of rangelands is mainly limited by water availability, if annual infiltration is less than 250 mm. The basis for calculating infiltration is rainfall. Average rainfall data can for example be derived from a handbook with agroclimatological data for Africa (FAO, 1984). However, the year to year variability in rainfall is high in the Sahelian zone of West-Africa and consequently in production of plant material. To characterize that variability, plant production is calculated both for years with average rainfall, a value that is exceeded in five out of ten years (probability 50%) and for dry years, defined as those with rainfall exceeded in nine out of ten years (p. 10%). From an analysis of historical rainfall data for a number of weather stations in Mali, a relation between average rainfall and rainfall in dry years has been derived (Figure 9). This relation can be used to derive rainfall data for dry years from average rainfall data, but if actual rainfall data are available for a sufficiently long paeriod of time, it is advised to test whether the relation also applies to the location studied.

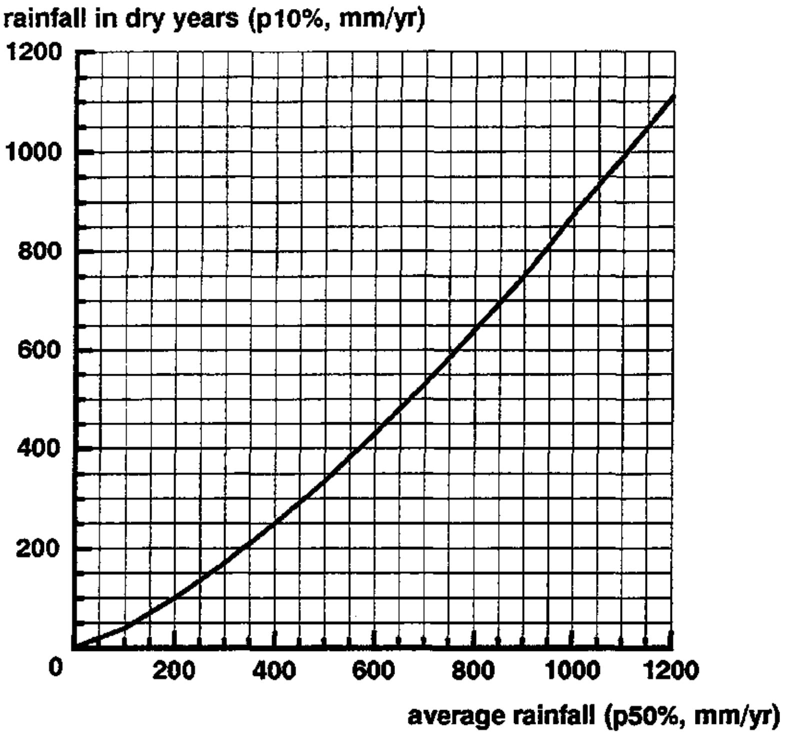

Figure 9. Relation between average rainfall and rainfall in dry years. (Source: Penning de Vries & Djitèye, 1982)

Infiltration (I, mm yr^{-1}) is derived from annual precipitation (P) via $I= P * (1 - R)$, where R is the fraction lost by runoff. The fraction lost increases with increasing amount and intensity of rainfall, decreasing infiltration capacity of the soil, decreasing soil roughness and soil cover by vegetation, and with an increase in slope. Consequently, R shows a strong spatial and temporal variability. In a global study such degree of detail can not be handled and therefore average annual values have been defined per soil type and per rainfall zone (Table 14). These values apply to the relatively high parts of a landscape, but in relatively low-lying areas runon may occur, implying negative values for R.

From total infiltration biomass production can be calculated. If total annual infiltration is less than 250 mm, the equations of Table 15 can be used. They have been derived from results of a simulation model that describes the soil water balance and the relation between growth and water availability. To derive the equations, biomass production was calculated for series of historical rainfall data from two locations in Mali and for six different soil types. These soil types varied from a coarse sand with low water-holding capacity and high infiltration capacity, to a clay with high water-holding capacity and low infiltration capacity.

Before the rains start, the soil is almost completely dry. For plant growth to start the moisture content in the top soil (over a depth of about 30 cm) has to be above wilting point. This requires an infiltration of only 3 mm on coarse sand, of about 9 mm on loamy soil, and of 54 mm on clay soil (Table 16). In addition, the

Table 14. Estimated runoff coefficients as a function of soil type and annual rainfall. (Sg = coarse sand; Sf = fine sand; Sl/Ls = loamy sand/sandy loam; L = loam; A = clay). (Source: Breman & de Ridder, in prep.)

	Soil type				
	Sg	Sf	Sl/Ls	L	A
rainfall ($mm\ yr^{-1}$)					
< 200	0.05	0.15	0.40	0.45	0.40
200 - 400	0.10	0.20	0.45	0.50	0.45
> 400	0.10	0.20	0.45	0.50	0.50

Table 15. Regression equations describing the relation between infiltration (I, mm) and biomass production (B, kg ha^{-1}) per soil type derived from results of model calculations. Symbols of soil types are explained in Table 14. Biomass production is given for I = 100 and 200 mm, respectively. (Source: Breman & de Ridder, in prep.)

Soil type	Regression line	Biomass production	
		I = 100	I = 200
Sg	B = 9.53 I - 691.5	262	1215
Sf	B = 8.72 I - 724.0	148	1020
Sl	B = 8.49 I - 675.6	173	1022
Ls	B = 9.20 I - 763.3	157	1077
L	B = 7.74 I - 611.1	163	937
A	B = 5.33 I - 609.9	0	456

higher soil moisture contents in loamy and clay soils result in higher water losses by soil surface evaporation. Therefore, the highest production levels are reached on coarse sand, intermediate levels on loamy soils and the lowest values on clay soils, ranging from 262 to 0 kg ha^{-1} at an infiltration of 100 mm and from 1215 to 456 kg ha^{-1} at an infiltration of 200 mm (Table 15). On coarse sand, runoff is very small (Table 14), hence infiltration is about equal to annual rainfall. On loamy and clay soils, however, the runoff fraction is about 0.40 and consequently the biomass

Table 16. Values for soil moisture content at field capacity and at wilting point for different soil types. (Sg = coarse sand; Sf = fine sand; Sl = loamy sand; Ls = sandy loam; L = loam; A = clay). (Source: Breman and de Ridder, in prep.)

	Sg	Sf	Sl	Ls	L	A
Field capacity m^3m^{-3} (pF 2,5)	0.055	0.068	0.088	0.095	0.103	0.325
Wilting point m^3m^{-3} (pF 4,2)	0.011	0.019	0.032	0.028	0.030	0.180

values presented in Table 15 for 100 and 200 mm infiltration, apply to an annual rainfall of about 165 and 300 mm, respectively.

The quality as a forage of the biomass produced appears to be well-described by its nitrogen content. The nitrogen concentration at the end of the growing season in relation to annual infiltration is given for four groups of herbaceous species in natural rangelands: annual species with C_3 type of photosynthetic pathway, annual species with C_4 type of photosynthetic pathway, C_4 type perennial grasses and legumes (Figure 10). These concentrations have been derived from the ratio of nitrogen uptake and biomass production in relation to annual infiltration. With increasing moisture availability the relative nitrogen shortage increases, resulting in decreasing nitrogen concentrations with increasing rainfall.

For the herbaceous layer of natural rangeland in Mali it was found that on average 73 percent of the total biomass consists of C_4 grasses, 22 percent of C_3 grasses and 5 percent of legumes. If annual infiltration exceeds 800 mm, the vegetation consists mainly of C_4 grasses. From this composition of the biomass and the nitrogen concentration in the various species groups (Figure 10), the relation between annual rainfall (or infiltration) and the average nitrogen concentration in the herbaceous layer at the end of the growing season has been derived (Figure 11).

Lower nitrogen concentrations associated with increasing infiltration appear to be strongly related with lower overall forage quality. Empirical relations have been established between nitrogen content, phosphorus content and digestibility. In the proposed method these relationships are used to characterize qualitatively the rangeland production. (Breman & de Ridder, in prep.).

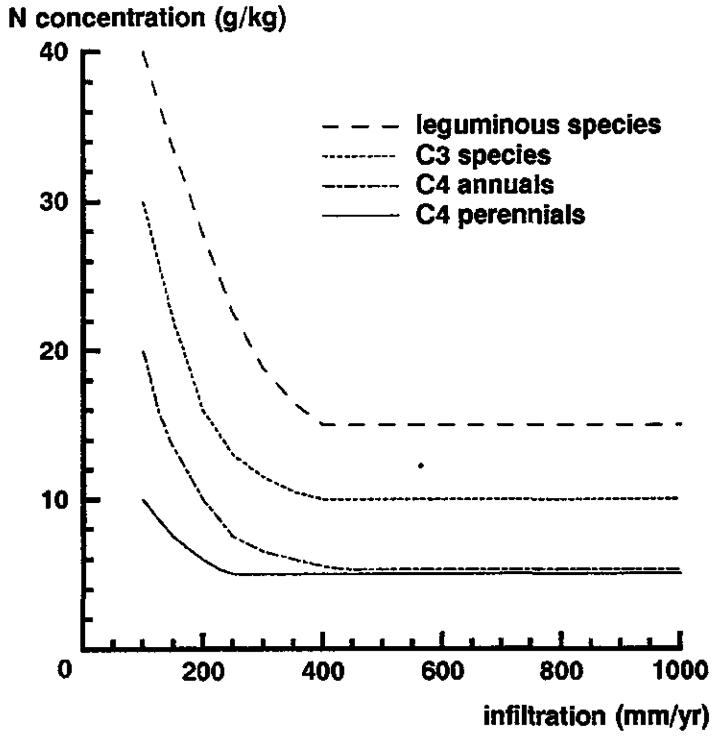

Figure 10. Average nitrogen concentration at the end of the growing season for various groups of plant species as a function of annual infiltration. (Source: Penning de Vries & Djitèye, 1982)

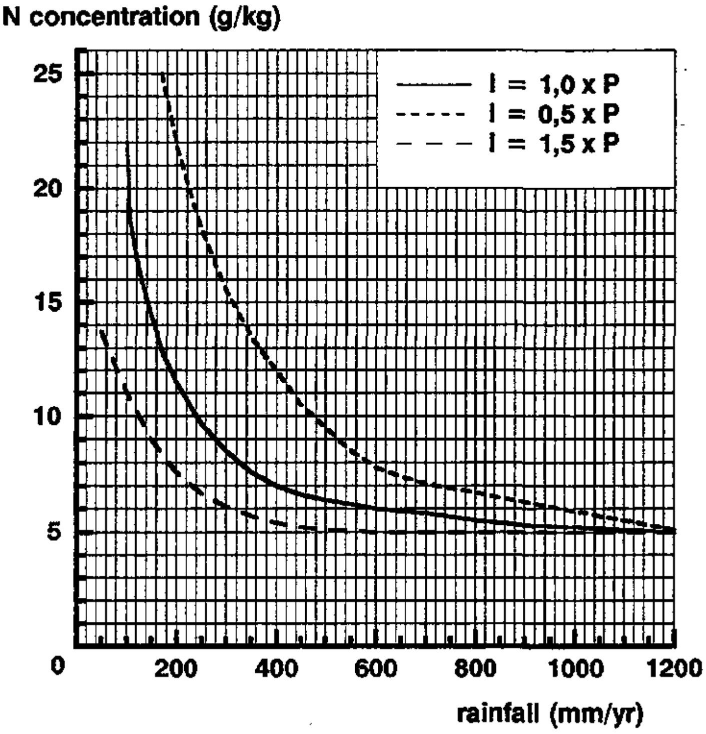

*Figure 11. Nitrogen concentration in the dry matter (g kg^{-1} dry mat.) of the herbaceous layer in relation to rainfall in average years (p.50%), for three situations: homogeneous infiltration (I= 1.0*P), with runoff (R= 0.5, I= 0.5*P) and with runon (R= -0.5, I= 1.5*P). (Source: Breman & de Ridder, in prep.)*

3.2.2 Nutrient-limited production

Components of equations for calculating production

Biomass production of the herbaceous layer is increasingly limited by nitrogen availability, as rainfall increases. The transition from water-limited to nutrient-limited conditions is schematically situated at an infiltration of 250 mm yr^{-1}. At the average annual maximum amount of nitrogen in the above-ground biomass (Nb) is calculated with:

$Nb= 0.0083\ (I - D)/(f - 0.13)$,

in which I is annual infiltration (mm yr^{-1}), D annual percolation (mm yr^{-1}) and f is the average fraction of Nb lost from the system annually.

The calculation of infiltration has been treated in Section 3.2.1. A simulation model has been used to calculate for various combinations of soil types and rainfall series from different locations in Mali, percolation losses from a potential rooting zone of 200 cm (Figure 12). The losses increase linearly with increasing infiltration and decrease with increasing soil moisture content at field capacity (WFC, i.e. the soil moisture content resulting after complete wetting against the gravity force). Percolation losses can be calculated with the following equation:

$D= 0.69\ I - 16.09 * WFC - 118.4$

For shallow soils the effect of soil depth (d) is included via:

$D= 0.69\ I - 0.446 * WFC - 0.22\ d - 0.0782 * WFC * d - 74.4$

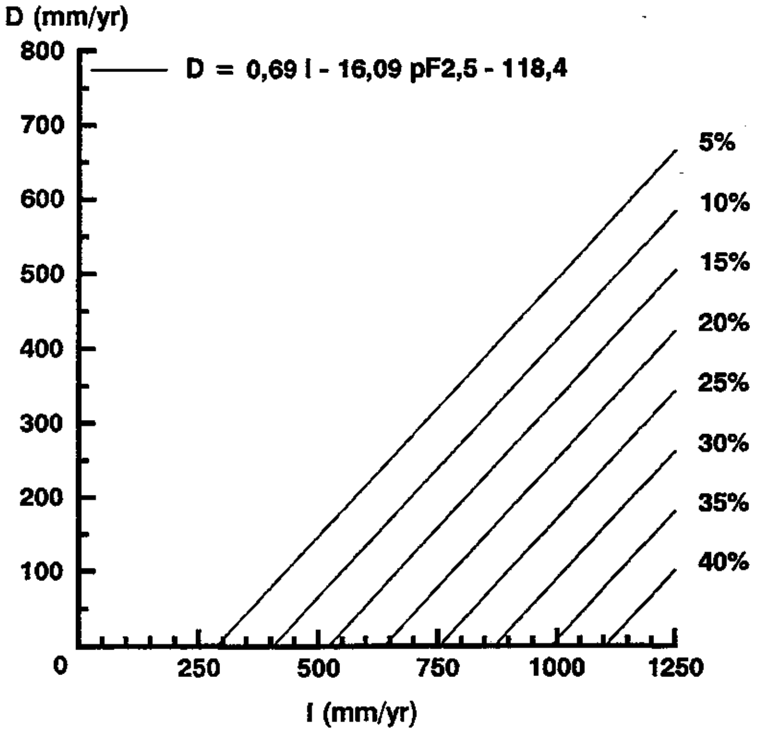

Figure 12. Calculated amounts of water lost out of the profile (D) as a function of annual infiltration (I) for soil types varying in moisture content at moisture content at field capacity (pF 2.5), assuming a soil depth of 2m. (Source: Breman & de Ridder, in prep.)

The fraction (f) of Nb that disappears from the system annually is the overall result of various processes such as volatilization from the biomass, burning, trampling and other grazing damage, etc. The losses through the various processes are interdependent, for example at a high grazing pressure, losses through burning will be limited. As a first approximation, an average value for the total fraction lost has been defined as a function of annual rainfall, on the basis of observations on a North - South transect in Mali over a period of 4 years (Figure 13). The graph shows that the loss fraction increases with increasing rainfall (range from 150 to 1000 mm) from 0.3 to 0.5, mainly as a result of burning. If each year the complete biomass of annuals or perennials is burned at the start of the dry season, f may be as high as 0.8 for annuals and about 0.4 for perennials. By haying, i.e. complete removal of the harvested biomass, f may be even higher than 0.8, particularly if the hay is fed to the animals and the manure produced is not returned to the field. However, that practice is still rare in the region today.

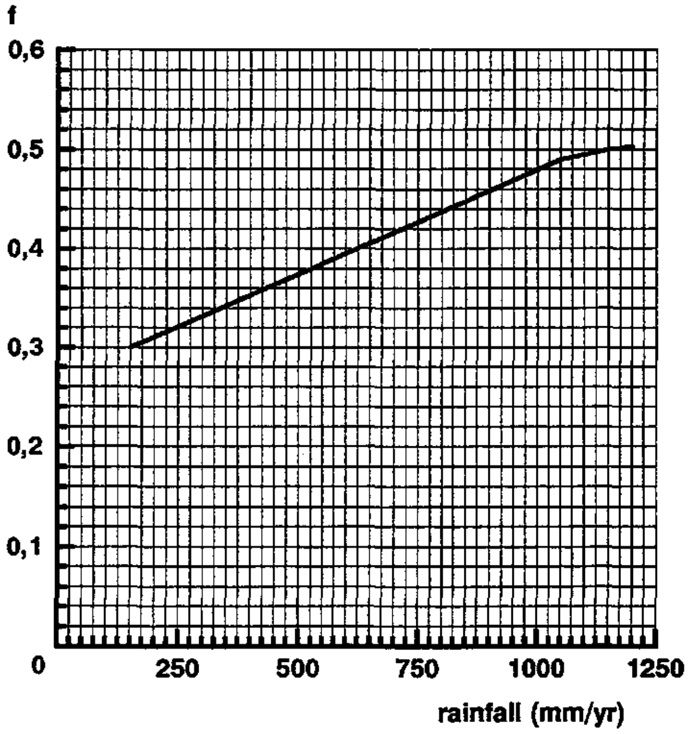

Figure 13. Relation between the average fraction annual losses of nitrogen (f) and rainfall, based on observations on a North-South transect in Mali during four subsequent years. (Source: Breman & de Ridder, in prep.)

The equation for Nb describes an equilibrium situation, i.e. inputs of nitrogen and losses are identical. That applies if only nitrogen and not another factor limits the productivity of the system. Nitrogen is supplied via rainfall and via biological fixation by algae and associative, free living and symbiotic bacteria. All input terms increase with increasing rainfall. If excess water (D) percolates from the system, nitrogen will be lost, mainly at the start of the growing season when annual grasses still have a small root system and mineralisation of nitrogen from soil organic matter may occur at a higher rate than nitrogen uptake by the plants. For perennials, with permanent deep root systems, these percolation losses will be limited and therefore, D is set to zero.

Calculation of production, an example

For a location with a rainfall of 600 mm yr^{-1}, the average loss fraction (f) is about 0.40 (Figure 13). On a fine sandy soil, the runoff coefficient (R) is 0.2 (Table 14), hence infiltration is 480 mm, of which about 100 mm is lost by percolation (Table 16 and Figure 12). Hence,

Nb= 0.0083 (480 - 100)/(0.40 - 0.13)= 11.7 kg N ha^{-1}.

From total nitrogen in the above-ground biomass (Nb) and its nitrogen concentration, biomass production is calculated. At an infiltration of 480 mm nitrogen concentration in the biomass is 6.5 g kg^{-1} (Figure 11). Hence, biomass production then is: (11.7/0.0065=) 1800 kg ha^{-1}. The nitrogen concentration of 6.5 g kg^{-1} has to be used also to characterize the quality of this biomass (3.2.1).

Calculation of production in dry years

The total amount of soil organic matter and its distribution with depth depend on climatic conditions (mainly rainfall), preceding land use and soil type. Although these factors cause spatial variability, an average relation between depth of wetting and relative nitrogen uptake by the vegetation has been derived that represents the general observation that organic matter content decreases with soil depth (Figure 14). The rooting depth of a vegetation, mainly consisting of annuals, does not exceed 2 m, hence the relative nitrogen uptake does not increase with greater depth of wetting.

The relation in Figure 14 can be used to calculate the amount of nitrogen in the above-ground biomass in dry years from the Nb value for average years, on the basis of the difference in depth of wetting. For the example described earlier, i.e. a

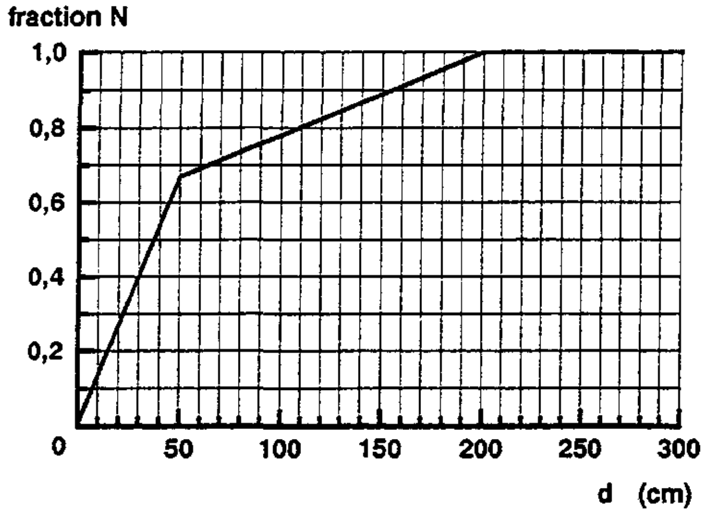

Figure 14. Fraction of nitrogen in the soil available for plant uptake in relation to the depth of wetting of the profile (d). (Source: Breman & de Ridder, in prep.)

site with average rainfall (p. 50%) of 600 mm yr^{-1}, 20 percent runoff and Nb equal to 11.7 kg N ha^{-1}, annual rainfall in a dry year, (p. 10%), can be derived from Figure 9, i.e. 450 mm. The depth of wetting (d) is a function of total infiltration (I) and variable A, which depends on the moisture content at field capacity: d= A(I - 69)/1.163. This equation is based on the results from model calculations of the soil water balance for different soil types and 50 different rainfall years from 10 weather stations on a North-South transect in Mali (Figure 15). On a fine sandy soil with a moisture content at field capacity of about 10 percent, the depth of wetting is 200 cm for I= 480 mm in an average year, and 160 cm for I= 360 mm (20 percent runoff) in a dry year (Figure 15). The fractions of nitrogen uptake in an average and a dry year are 1.0 and 0.9, respectively (Figure 14), so nitrogen uptake in a dry year is: (0.9/1.0 * 11.7)= 10.5 kg ha^{-1}.

Total infiltration of 360 mm in a dry year results in a nitrogen concentration in the biomass of 7.5 g kg^{-1} (Figure 11) and total biomass production in the dry year is then 1400 kg ha^{-1}. In this way, variations in nitrogen uptake around the calculated value of Nb or a measured nitrogen uptake value, can be related to variations in rainfall from year to year. Note that the increase in nitrogen content, and thus in quality, with decreasing average annual rainfall (Figure 10) resembles the relation between nitrogen content and rainfall on a given location: 7.5 g kg^{-1} for a dry year in the example, against 6.5 g kg^{-1} in a normal year.

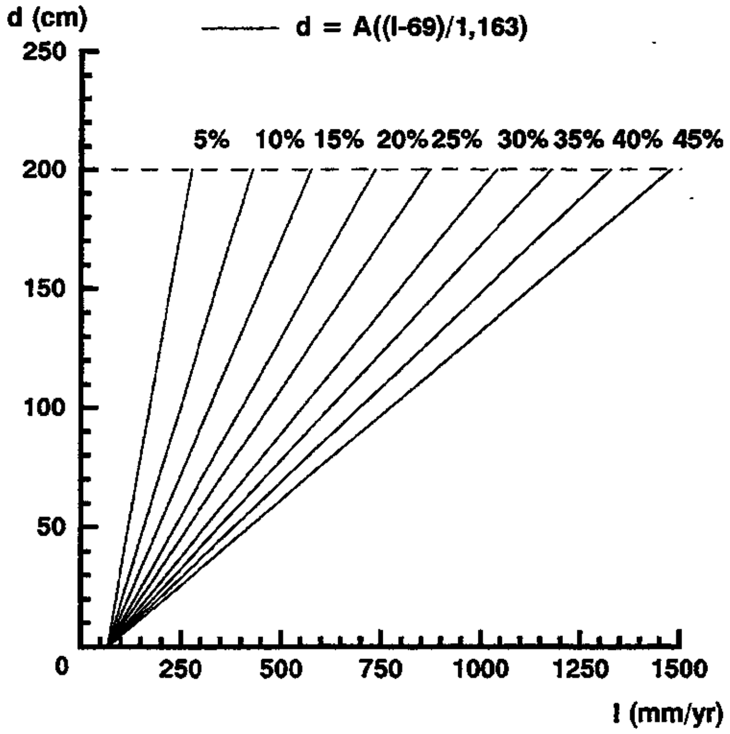

Figure 15. Relation between annual infiltration (I) and depth of wetting of the profile (d), for soil types with different moisture contents at field capacity. (Source: Breman & de Ridder, in prep.)

3.2.3 Production of rangelands in the West African drylands

As an illustration, biomass production of rangelands has been calculated for representative land units and climatic zones of West African drylands (Table 17) for both average years and dry years. Also the available browse of woody species is presented here, but the calculation procedure will be treated in Section 4.

The land units in Table 17 are: Os, dunes; Ps, sandy plains; Pl, loamy plains; La, loam or clay soils in valleys and depressions with runon; Sq, shallow loam soils on laterite or sandstone. For each of the land units, biomass production has been calculated on the basis of land characteristics such as runoff coefficients, moisture content at field capacity, etc. For the northern part of the Sahelian zone (annual rainfall between 100 and 300 mm) the procedure for water-limited production (3.2.1) was applied, elsewhere the procedure for nutrient-limited production (3.2.2).

Not all biomass produced can be regarded as available forage. To arrive at that value, different losses as well as accessibility (browse!) have to be taken into account. Under rainy season grazing, about half the biomass of the herbaceous layer is available to the animals and under dry season and year-round grazing, about 35 percent. If rangelands are burned regularly, the available fraction is smaller. In the rainy season, grazers (cattle, sheep) depend for food on the herbaceous layer only, but for browsers (goats, dromedaries) leaves, twigs and fruits from woody species, further referred to as browse, also contribute. The maximum available browse is estimated at 30 percent of the annual production, the remainder being lost by leaf fall and wilting. In the Sahelian zone, 35 percent of this available fraction can be used by cattle and in the Sudanian zone 25 percent. Browsers consume browse year-round and consequently can use all available material (30%). However, on average not more than 15 percent of the browse production should be used in total, to guarantee sustainable production.

The result is forage availability for the various climatic zones of the West African drylands, as presented in Table 18. These values are averages of the land units in Table 17, weighted according to their relative surface area per climatic zone. Table 18 shows a strong increase in available forage with increasing rainfall, especially in the Sahelian zone. The difference between normal and dry years is also substantial there.

The nitrogen concentration in the forage at the end of the rainy season for the various agro-ecological zones has been calculated for average and dry years (Table 19). In the northern part of the Sahelian zone water availability is low, so that the nitrogen concentration is relatively high already in average years and even higher in dry years. Going to the south the relative nitrogen deficiency increases and consequently, its concentration in the biomass decreases. Different land units within

Table 17. Estimated production kg ha^{-1}) distributed over herb layer and browse of woody species in average (p. 50 %) and dry (p. 10 %) years per agro-ecological zone; northern Sahelian zone (annual rainfall of 200 mm), southern Sahelian zone (450 mm), northern Sudanian zone (750 mm) and southern Sudanian zone (1050 mm); Os - sand dunes, Ps - sandy plains, PL- loamy plains, La - loam and clay soils in depressions, Sq - shallow loam soils on laterite or sandstone. (Source: Breman & de Ridder, in prep.)

		northern Sahel		southern Sahel		northern sudan		southern sudan	
		herb layer	"browse"	herb layer	"browse"	herb layer	"browse"	herb layer	"browse"
Landunit									
Os	p50%	750	70	2050	130	-	-	-	-
	p10%	150	40	1550	80	-	-	-	-
Ps	p50%	600	70	1750	130	-	-	-	-
	p10%	50	40	1100	80	-	-	-	-
Pl	p50%	150	70	850	650	1600	950	1600	1750
	p10%	-	40	200	430	1350	750	1400	1550
La	p50%	1250	70	3250	720	2300	5400	4400	5400
	p10%	200	40	2300	480	1900	4200	4100	4200
Sq	p50%	550	-	1100	580	1600	950	1950	1450
	p10%	50	-	650	380	1350	750	1750	1300

Table 18. Total available forage (kg ha^{-1} yr^{-1} dry matter) and the contribution of herblayer and browse, per climatic zone in normal (p. 50 %) and in dry (p. 10 %) years.

	northern-Sahel		southern-Sahel		northern-sudan		southern-sudan	
	p50%	p10%	p50%	p10%	p50%	p10%	p50%	p10%
total	250	50	800	500	1000	800	1200	1050
herb layer	0.92	0.80	0.80	0.80	0.59	0.62	0.60	0.61
"browse"	0.08	0.20	0.20	0.20	0.41	0.38	0.40	0.39

Table 19. Nitrogen concentration (g kg^{-1}) in the herb layer in average (p. 50 %) and dry (p. 10 %) years per agro-ecological zone:
northern Sahelian zone (annual rainfall of 200 mm), southern Sahelian zone (450 mm), northern Sudanian zone (750 mm) and southern Sudanian zone (1050 mm). For explanation of agro-ecological zones see Table 17. (Source: Breman & de Ridder, in prep.)

Landunit		northern Sahel	southern Sahel	northern sudan	southern sudan
Os	p50%	12.5	7.6	-	-
	p10%	23.0	10.0	-	-
Ps	p50%	14.7	8.0	-	-
	p10%	25.0	11.3	-	-
Pl	p50%	21.3	12.9	7.0	5.5
	p10%	-	15.5	8.0	6.0
La	p50%	9.5	6.1	5.4	5.0
	p10%	16.5	7.5	5.8	5.3
Sq	p50%	14.6	8.0	7.0	5.6
	p10%	25.0	11.3	8.2	6.1

one climatic zone may have different soil characteristics, affecting water availability and thus nitrogen concentration and overall quality of the forage produced.

The estimated forage availability and nitrogen concentration represent the average situation at the end of the rainy season. In the subsequent dry period, particularly at the beginning, biomass losses occur and nitrogen concentrations in the standing biomass decrease due to fires, decay of plant material by late rainfall, seed fall, seed harvesting by insects, etc. These biomass losses have been taken into account in estimating forage availability. From field data collected on a North-South transect in Mali over a period of four years (Penning de Vries & Djitèye, 1982), a relation between the nitrogen concentration at the end of the rainy season and that at the end of the dry season has been derived (Figure 16). That relation has been applied to derive the average nitrogen concentrations during the dry season and the concentrations at the end of the dry season. For browse a similar estimate has been made (Table 20).

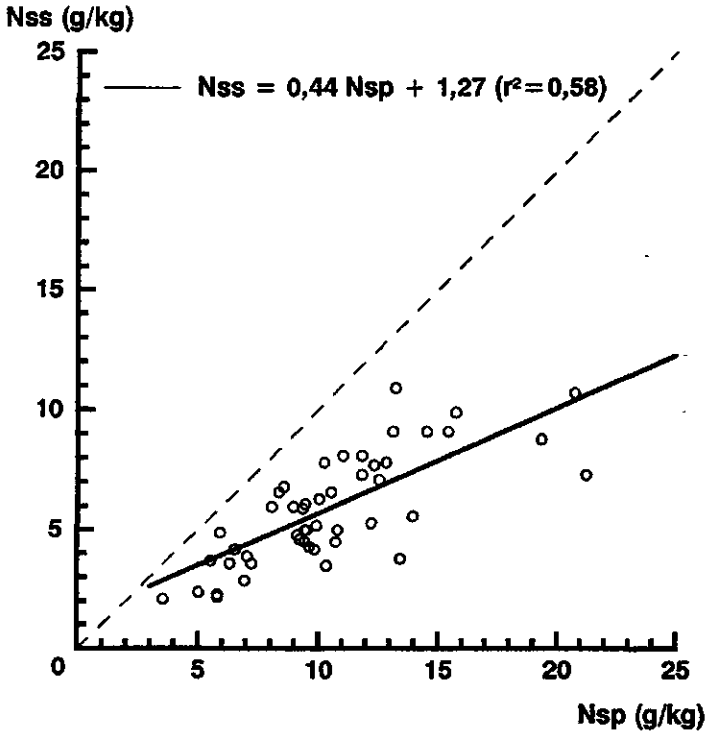

Figure 16. Relation between the nitrogen concentration in standing biomass at the end of the dry season (Nss) and that at the end of the rainy season (Nsp), based on field data collected on a North-South transect in Mali during four subsequent years. (Source: Breman & de Ridder, in prep.)

Table 20. Nitrogen concentration (g kg^{-1}) of the total forage on rangelands and of the herb layer, and browse separately in the course of the dry season in normal (p. 50%) and dry (p. 10%) years per climatic zone. (Source: Breman & de Ridder, in prep.)

	northern Sahel		southern Sahel		northern Sudan		southern Sudan	
	p50%	p10%	p50%	p10%	p50%	p10%	p50%	p10%
End of the growing season:								
Total	14.9	21.8	11.0	12.1	10.3	10.7	9.5	9.7
Herb layer	14.6	22.7	9.4	10.7	6.8	7.8	5.5	6.0
Brouwse	18.2	18.2	17.5	17.5	15.4	15.4	15.4	15.4
End of dry season:								
Total	8.0	11.4	6.6	7.1	6.7	6.8	6.3	6.4
Herb layer	7.7	11.3	5.4	6.0	4.3	4.7	3.7	3.9
Browse	12.0	12.0	11.6	11.6	10.2	10.2	10.2	10.2
Weighted average dry season:								
Total	10.3	14.9	7.6	8.1	7.9	8.0	7.5	7.7
Herb layer	9.9	14.9	5.9	6.5	4.5	5.0	4.0	4.5
Browse	15.1	15.1	14.6	14.6	12.8	12.8	12.8	12.8

3.3 Animal production

The North-South gradient in relative availability of water and nutrients in the West-African drylands has important consequences for quantity and quality of rangeland production and hence for the carrying capacity of rangelands. In the north Sahelian zone and on sites with high runoff losses, water availability is relatively low, so that the nutrient concentration and the feeding value of biomass are relatively high. In such situations all plant material can be considered as forage and the carrying capacity is directly related to primary production as determined by water availability. The high quality of the forage results in large increases in liveweight of cattle in two ways: directly, by a high conversion efficiency from plant material to liveweight, and indirectly through a positive influence on intake.

Further south, total biomass production increases with increasing water availability, resulting in increasing nutrient stress, and thus decreasing nutrient concentrations and quality of the biomass, with the consequence of almost no liveweight increases for cattle on an annual basis. In such situations, carrying capacity cannot be derived directly from total plant biomass at the end of the rainy season, but biomass production and quality in the course of the seasons have to be considered. These characteristics form the basis for estimating feed intake and the associated animal performance. Figure 17 illustrates these relations between rangeland production and quality and animal production for West African drylands, using performance of a heifer as an example.

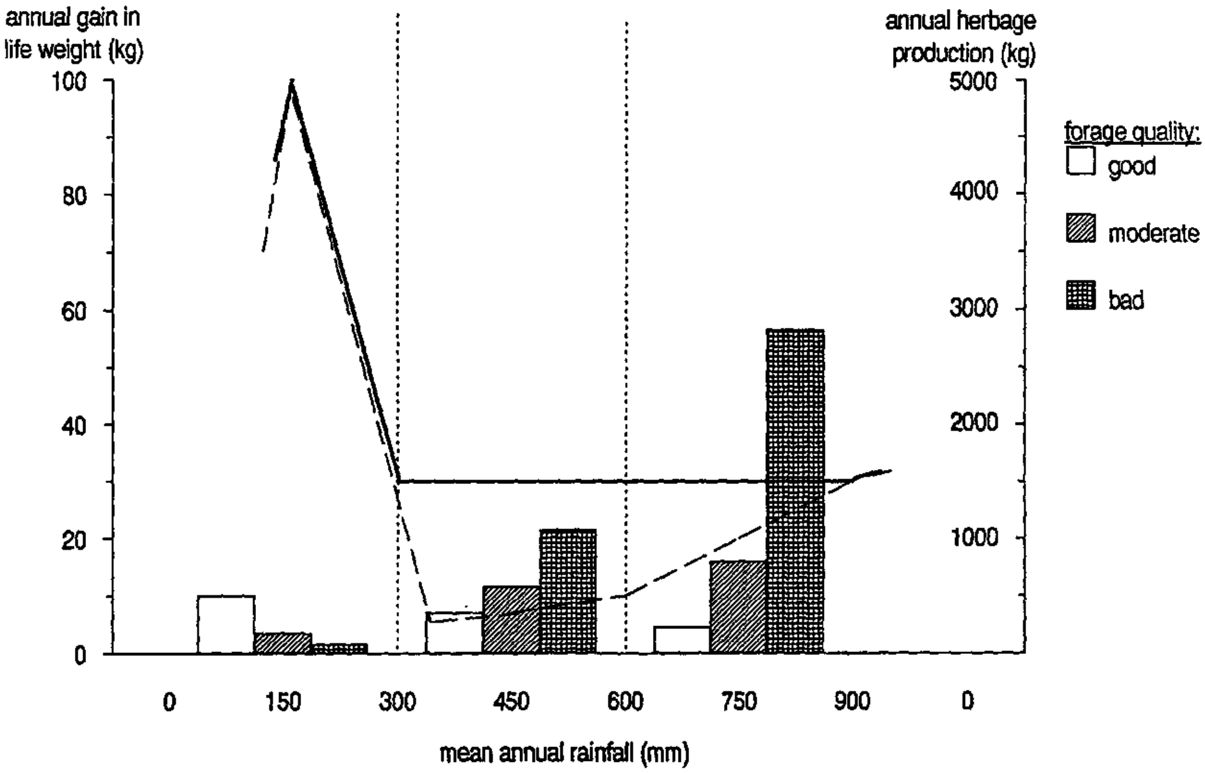

Figure 17. Relation between mean annual rainfall and on the one hand annual liveweight gain for a heifer of 150 kg and, on the other, mean annual herbage production. Herbage production is separated into three quality classes. The dotted line gives the theoretical relationship between rainfall and liveweight 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)

To allow comparison of animal husbandry and plant production systems, animal production can be described as the product of average production per animal and maximum number of animals per unit area that can sustain that production. Methods for estimating both parameters are proposed.

3.3.1 Carrying capacity

To compare rangelands in terms of animal production potential, the concept of "standard carrying capacity" is introduced, defined as the maximum stocking rate that in a year with average rainfall guarantees the viability of 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.

An annual liveweight gain of 25 kg requires a certain diet in terms of quantity and quality. From the quality criterion, expressed as the lower limit to nitrogen concentration, the fraction of the available forage that can be used by the animals, i.e. that part of the biomass that meet that criterion, can be derived. For a global evaluation, the criterion is set at a nitrogen concentration of 7.5 g kg^{-1}. The fraction of the biomass with a higher concentration can be read from Table 21 as a function of its average nitrogen concentration.

Table 21. Fraction of biomass with specified average nitrogen concentration (g kg^{-1}) that meets minimum nitrogen concentration levels of 7 and 8 g kg^{-1}, respectively. (Source: Breman & de Ridder, in prep.)

	N concentration "top" fraction (g kg^{-1})	
	7	8
Average N concentration		
3	0	0
4	0.25	0.20
5	0.50	0.40
6	0.75	0.60
7	1.00	0.80
8		1.00

As an example, the situation is considered on a ranch in Niono, Mali where total biomass of the herbaceous layer at the end of the rainy season was 2600 kg ha^{-1}, with an average nitrogen concentration of 5.9 g kg^{-1}. Under year-round grazing, (0.35 * 2600=) 910 kg ha^{-1} can be grazed (3.2.3). The nitrogen concentration decreases in the course of the dry season to 3.9 g kg^{-1} (Figure 16), so the average nitrogen concentration during that period is 4.9 g kg^{-1}. In that situation, 43 percent of the biomass of the herbaceous layer has a nitrogen concentration of at least 7.5 g kg^{-1} (linear interpolation in Table 21), the criterion for an annual net liveweight increase of 25 kg. For the year as a whole, assuming a rainy season of 3 months, the weighted available fraction is equal to (3/12 * 1 + 9/12 * 0.43=) 0.57. Hence, available forage of sufficient quality amounts to 520 kg ha^{-1}.

From that available forage the standard carrying capacity is calculated by dividing by the annual feed requirement of a Tropical Livestock Unit (TLU, 250 kg liveweight) of (365 d yr^{-1} * 5.5 kg d^{-1} =) 2000 kg yr^{-1} dry matter (3.3.2). The result represents the number of cattle that can be maintained per hectare, i.e. 0.26 TLU, or, the minimum area required to feed one TLU is 3.8 ha.

If browse is also taken into account, 1500 kg ha^{-1} on the ranch in Niono, of which (0.3 * 0.35 * 1500=) 160 kg ha^{-1} can be used by cattle in the dry season (3.2.3), the total amount of available forage is (520 + 160=) 680 kg ha^{-1}. The carrying capacity of the ranch then increases and the minimum area per TLU is maximally (2000/680=) 2.9 ha. Probably it is somewhat lower because the average nitrogen content of the diet increases by the relatively high proportion of browse

(Table 20). If this compensates for the low nitrogen content of the herb layer, more than 520 kg ha^{-1} will be consumable. For a mixed herd with browsers, the carrying capacity increases further, as the available browse can also be used in the rainy season.

The quality criterion in terms of nitrogen content in the diet of at least 7.5 g kg^{-1} is used to guarantee a net liveweight increase per animal of at least 25 kg yr^{-1} necessary for maintaining a viable herd. Results of application of such a criterion are shown in Table 22, giving the average nitrogen concentration in the biomass of rangelands, the nitrogen concentration in the diet (at least 7 g kg^{-1} via selection, instead of 7.5), and the monthly change in liveweight of a heifer in the course of the year for four different climatic zones. On an annual basis the liveweight gains in the north Sahelian zone (annual rainfall between 100 and 300 mm), the south Sahelian zone (300-600 mm), the Sudanian zone (600-1200 mm) and further south (>1200 mm) are 98, 5, 15 and 31 kg, respectively, and thus partly lower than the minimum of 25 kg. That has been the reason to select 7.5 g kg^{-1} as criterion in this study, rather than 7 as applied in Table 22.

Table 22 indicates that a more accurate estimate of the carrying capacity would be possible, by a sepcidic different criterion per zone. For example, in the southern Sahel a liveweight gain of 25-30 kg could be attained, if in 6 out of 9 months of the dry season the minimum nitrogen concentration in the diet would be 8 g kg^{-1} instead of 7.5.

If higher increases in liveweight are aimed at than required to maintain the herd, the quality criterion, i.e. the minimum nitrogen concentration in the selected diet, has to increase. In sedentary animal husbandry systems this implies that the consumable fraction of the biomass decreases and hence the carrying capacity. Increased production is thus associated with a decrease in carrying capacity. Using Table 21, the methodology proposed allows to estimate the carrying capacity in relation to the production per head, defined for any production system.

The attainable degree of selection, dictated by the stocking rate, which determines the nitrogen content in the diet, is one variable by which the production per head can be influenced. However, the nitrogen concentration in the diet can only be increased to a limited extent by selection. An alternative way to attain high liveweight gains is mobility. Table 22 enables determination of the diet of for example animals in the transhumance system, that migrate between the Sahelian and the Sudanian zones, resulting in net liveweight gains as high as 50 kg yr^{-1} per animal (Diallo, 1978).

After fixation in relation to a selected level of animal production of a minumum nitrogen concentration of fodder to select for each individual month with $\leq$ 8 g kg^{-1} nitrogen as average in the available forage, the use of Table 22 permits also in this case to calculate the related carrying capacity for each of the visited regions.

A third variable influencing animal production, that can be used to define and to evaluate production systems, is the availability and quality of feed supplements (crop by-products or agro-industrial products). If the nitrogen content of these products is high (e.g. cotton seed cake), it compensates for the low quality of the available herbage. On the basis of the nitrogen content of the supplements and that of the available forage from the rangeland, the increase of the fraction of low quality forage that can be used, can be calculated for a given minimum nitrogen crite

Table 22. Estimates of the monthly change in liveweight (kg) of a heifer with an initial weight of 150 kg in relation to the nitrogen concentration (g kg^{-1}) in the biomass of rangelands and the availability of green forage in the different climatic zones. (Source: Breman & de Ridder, in prep.)

Growing season of rangelands (weeks)	Average rainfall (mm)	Month	J	F	M	A	M	J	J	A	S	O	N	D	Year total
9	< 300	Green forage	-	-	-	-	-	-	+	+	-	-	-	-	
		N conc. biomass	9.0	9.0	9.0	9.0	9.0	8.0	32.0	25.0	13.0	12.0	11.0	10.0	
		N conc. diet	9.0	9.0	9.0	9.0	9.0	8.0	32.0	25.0	13.0	12.0	11.0	10.0	
		Change in liveweight	2	2	2	2	2	0	23	23	14	12	9	7	98
11	300-600	Green forage	-	-	-	-	-	-	+	+		-	-	-	
		N conc. biomass	5.5	5.5	5.5	5.5	5.5	4.5	27.0	14.0	9.0	7.0	5.5	5.5	
		N conc. diet	7.0	7.0	7.0	7.0	7.0	7.0	27.0	14.0	10.0	7.0	7.0	7.0	
		Change in liveweight	-4	-4	-4	-4	-4	-4	23	12	6	-4	-4	-4	5
17	600-1200	Green forage	-	-	-	-	-	+	+	+	+	-	-	-	
		N conc. biomass	3.5	3.5	3.5	3.5	3.5	24.0	14.0	10.0	8.0	6.0	3.5	3.5	
		N conc. diet	7.0	7.0	7.0	7.0	7.0	24.0	14.0	10.0	10.0	7.0	7.0	7.0	
		Change in liveweight	-4	-4	-4	-4	-4	23	12	6	6	-4	-4	-4	15
24	>1200	Green forage	-	-	-	-	+	+	+	+	+		-	-	
		N conc. biomass	3.5	3.5	3.5	3.5	24.5	14.0	10.0	8.0	6.0	5.0	3.5	3.5	
		N conc. diet	7.0	7.0	7.0	7.0	24.0	14.0	10.0	10.0	10.0	9.0	7.0	7.0	
		Change in liveweight	-4	-4	-4	-4	23	12	6	6	6	2	-4	-4	31

rion and a fixed amount of available supplements per head. The carrying capacity will increase almost proportionally.

For the comparison of animal and plant production systems not only the current cost/benefit ratio has to be considered. The sustainability of systems has also to be taken into account. The carrying capacity as defined earlier does not guarantee sustainable use of the rangelands. Only for browse such a criterion has been introduced (exploitation should not exceed 15% of the average annual production; 3.2.3).

Both the rangelands and the herds run a high risk in dry years. To reduce that risk, the stocking rate for grazers in the Sahelian zone should be based on the carrying capacity in dry years. For browsers this also applies to the Sudanian zone, where for grazers this only holds for production systems using considerable amounts of high quality supplements. Without such supplements the low quality of the biomass from the rangelands in the Sudanian zone forms a protection against overgrazing by grazers.

Table 23 shows how much less forage is available in a dry year. In the North Sahel biomass availability and also carrying capacity is only one fifth of that calculated for an average year. In the South Sahel it is about 65 percent, but the carrying capacity will not decrease to the same extent, if in such years the quality criterion is left out, i.e. it is accepted that cattle will decrease in weight.

Table 23. Availability of forage in a dry year (p. 10 %) as a fraction of the availability in an average year (p. 50 %) for different climatic zones. (Source: Breman and de Ridder, in prep.)

	northern Sahel	southern Sahel	northern Sudan	southern Sudan
Total	0.18	0.65	0.79	0.89
Herb layer	0.15	0.65	0.80	0.89
Browse	0.47	0.66	0.77	0.88

In view of the average herd composition (cattle, sheep, goats and camels) per climatic zone, the maximum number of animals for which reproduction (herd maintenance) is just guaranteed, can be calculated on the basis of 45 ha TLU^{-1} for the northern part of the Sahelian zone, 10 ha TLU^{-1} for the southern part, and 5 ha TLU^{-1} for the Sudanian zone (Breman *et al.*, 1990). Cost/benefit analyses for systems with a higher production of meat and milk than at maximum stocking rate, should be based on the procedures indicated above to estimate the related lower stocking rate.

Taking into account quality and the consequences of dry years is not a sufficient condition for guaranteeing sustainability. For rangelands on soils susceptible to crust formation, or rangelands with perennial grasses additional criteria have to be formulated (Breman & de Ridder, in prep.).

3.3.2 *Assessment of animal production*

In the approach suggested (Ketelaars, in prep.), feed intake and its nitrogen content and digestibility are the main determinants of animal production. If only nitrogen content has been measured or estimated (3.2.1 and 3.2.2), digestibility may be derived, using empirical relations for different groups of plant species as illustrated in Table 24 for natural vegetations dominated by annual grasses. If perennials or leguminous species are dominant, if browse is an important component, or if fertilizers are applied, special procedures have to be applied (Breman & de Ridder, in prep.).

Table 24. Digestibility in relation to the nitrogen concentration of roughage from the Sahel: an average relation. (Source: Breman & de Ridder, in prep.)

N concentration (g kg^{-1})	Digestibility (g g^{-1})		
	organic matter	dry matter	
	1)	2)	3)
3	0.29	0.275	0.32
4	0.33	0.315	0.36
5	0.37	0.355	0.39
6	0.40	0.385	0.42
7	0.44	0.425	0.45
8	0.47	0.455	0.48
9	0.51	0.495	0.52
10	0.54	0.525	0.54
11	0.56	0.545	0.56
12	0.59	0.575	0.59
13	0.61	0.595	0.60
14	0.63	0.615	0.62
15	0.65	0.635	0.64
16	0.66	0.645	0.65
17	0.68	0.665	0.67
18	0.69	0.675	0.67
19	0.70	0.685	0.68
20	0.71	0.695	0.69
21	0.72	0.705	0.70
22	0.72	0.705	0.70
23	0.73	0.715	0.71
40	0.73	0.715	0.71

1) Estimated in vivo digestibility of organic matter for sheep based on in vitro measurements.

2) Digestibility of dry matter for sheep calculated from that of organic matter.

3) Digestibility of dry matter for cattle calculated from that of dry matter for sheep.

Feed intake of ruminants is positively related to both nitrogen concentration and digestibility of the forage and it is suggested therefore to use these parameters to estimate feed intake. The approach followed is based on one hand on knowledge about the protein and energy requirements of cattle for different production targets, and on the other on interpretation of the results of published feed intake trials with cattle and sheep. Some results, referring to heifers, are specified for different combinations of nitrogen concentration and digestibility of the forage (Table 25).

For a Tropical Livestock Unit (TLU), feed intake is often estimated at 2.5% of its liveweight, i.e. 6.25 kg dry matter per day. Assuming for Sahelian cattle an average diet with a nitrogen concentration of 10 g kg^{-1} and a digestibility of 0.54 g g^{-1}, daily feed intake will be 80 g $kg^{-0.75}$ d^{-1} or 5.0 kg dry matter (Table 25), i.e. appreciably lower. Under Sahelian conditions liveweight of an average animal is about 175 kg, which implies a feed intake of 2.2% of the liveweight, hence per TLU 5.5 kg dry matter per day.

Liveweight changes are directly related to the daily feed intake and its quality (Figure 18). Under optimum feeding conditions animal continuously weight gain until mature liveweight is attained, but under the sub-optimum conditions typical for extensive animal husbandry systems in the Sahel, periods of weight gain alternate with periods of weight losses. From the body composition of the animal, protein and energy requirements for growth can be derived, or alternatively, the rate of growth can be calculated for a specified intake of protein and energy.

Liveweight increases if the intake of digestible dry matter (Md) exceeds 36 g $kg^{-0.75}$ d^{-1}, the amount needed for maintenance of the animal. An empirical relation has been derived to calculate the rate of liveweight gain (LWG, in kg d^{-1}):

$LWG = 0.00049\,(Md - 36) * (W^{0.75})$

W = liveweight of the animal (kg).

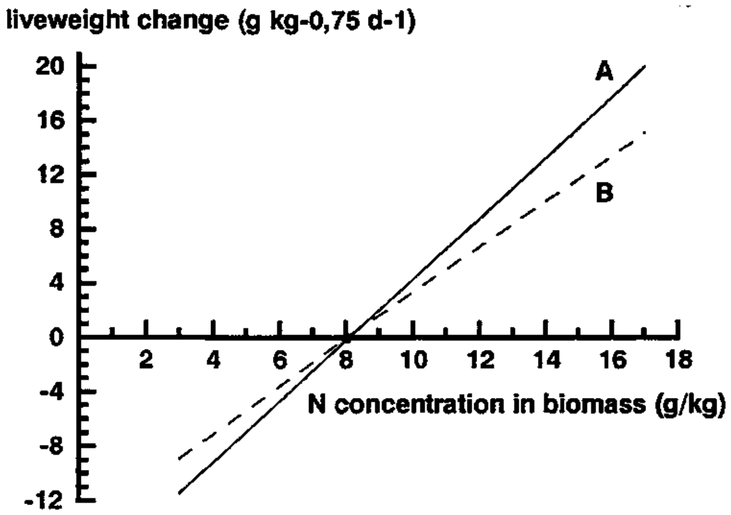

Figure 18. Comparison of the measured relation (A) between nitrogen concentration in forage and liveweight change and for cattle grazing on natural rangelands in Australia (Hendricksen et al., 1982) and a similar relation (B) derived for cattle grazing on natural rangelands in the Sahelian region. (Source: Ketelaars, in prep.)

Table 25. Estimated intake of dry matter by heifers (g $kg^{-0.75}$ d^{-1}), as a function of nitrogen concentration and digestibility of the diet. (Source: Ketelaars, in prep.)

	N concentration (g kg^{-1})															
dry matter digestibility (%)	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	36
36	64	68	73	78	85	-	-	-	-	-	-	-	-	-	-	-
38	64	68	72	78	83	90	-	-	-	-	-	-	-	-	-	-
40	65	68	72	77	83	89	96	-	-	-	-	-	-	-	-	-
42	60	68	72	77	82	88	94	-	-	-	-	-	-	-	-	-
44	56	68	72	76	81	87	93	100	-	-	-	-	-	-	-	-
46	52	69	72	76	81	86	92	98	-	-	-	-	-	-	-	-
48	48	66	73	77	81	86	91	97	104	-	-	-	-	-	-	-
50	46	61	75	78	82	87	92	98	104	-	-	-	-	-	-	-
52	43	56	75	79	83	87	92	97	103	110	-	-	-	-	-	-
54	41	52	73	80	83	88	92	97	103	109	-	-	-	-	-	-
56	39	49	67	80	84	88	93	97	103	109	116	-	-	-	-	-
58	37	46	62	81	85	89	93	98	103	109	115	-	-	-	-	-
60	35	43	57	83	86	90	94	98	103	109	115	121	-	-	-	-
62	34	41	53	75	87	91	95	99	104	109	115	121	-	-	-	-
64	32	39	50	68	89	92	96	100	105	110	115	121	128	-	-	-
66	31	37	46	62	92	96	100	104	108	113	119	125	131	-	-	-
68	30	35	44	58	84	98	101	105	110	115	120	125	132	139	146	165
70	28	34	41	54	76	100	103	107	112	116	121	127	133	140	147	164
72	27	32	39	50	69	102	105	109	113	118	123	128	134	140	148	164

This equation is valid after weaning for animals with a liveweight of at least 100 kg. The genetically determined maximum growth rate for Sahelian cattle is estimated at 0.75 kg d^{-1}. For an animal of 100 kg liveweight this requires an energy intake of 2.4 times the maintenance requirement of 36 g $kg^{-0.75}$ d^{-1}. Liveweight losses (LWL) occur if Md is less than 36, and can be estimated with:

$$LWL = 0.00058\ (36 - Md) * (W^{0.75})$$

Growth of male and female animals under comparable conditions is practically identical until female animals become pregnant. From then on, energy intake in female animals is distributed over maintenance and growth of the own body, growth of the foetus and later milk production (Figure 19).

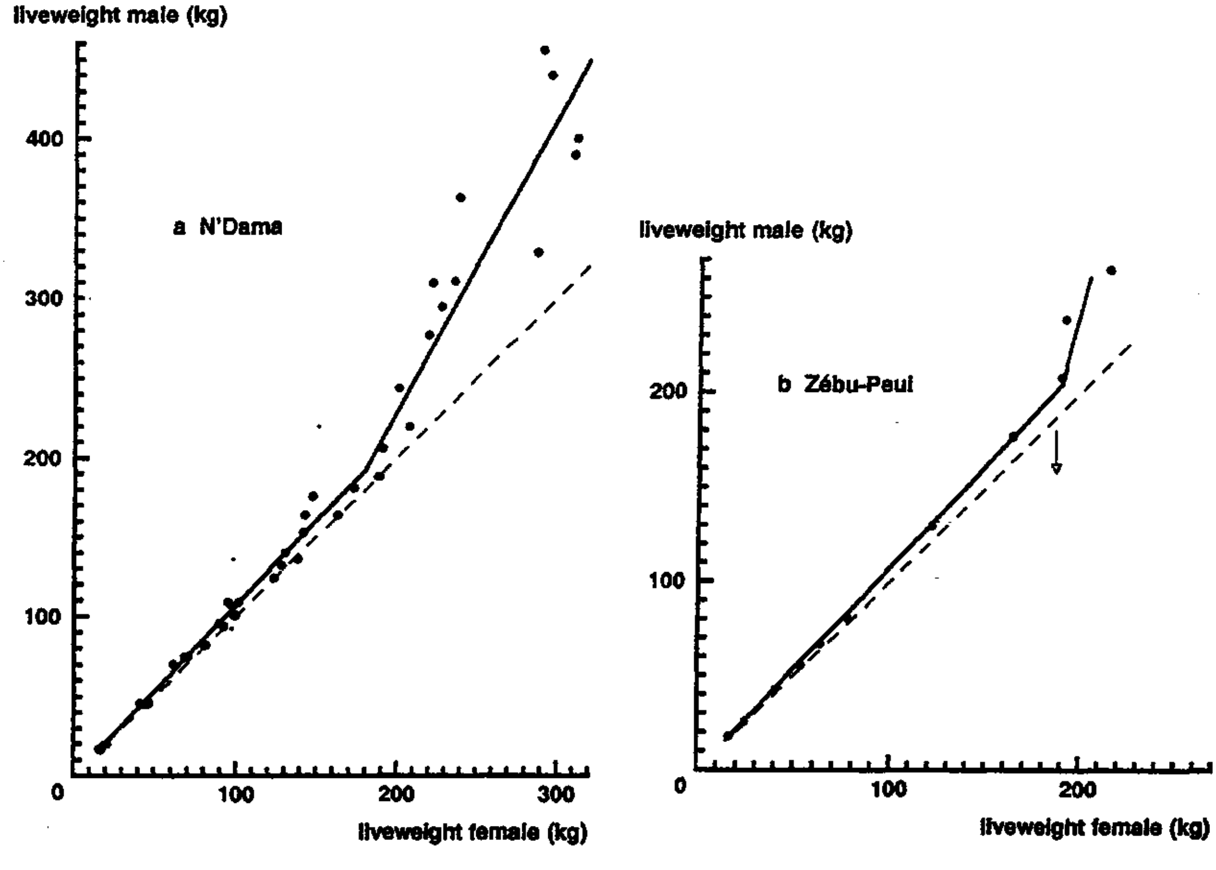

Figure 19. Relation between liveweight of male and female N'Dama (a) and Zebu-Peul (b) cattle at identical age and nutrition. (Source: Ketelaars, in prep.)

The reproductive process can be described by three parameters: age at first calving, interval between successive pregnancies and average life-time. The first two parameters are clearly influenced by feeding conditions. Under unfavourable feeding conditions, a mother animal will use its reserves for producing a calf, with the risk that its liveweight decreases below the critical level required for conception. Under favourable feeding conditions, hardly any reserves are used to produce the calf. Consequently, the interval between successive pregnancies decreases if feeding conditions improve.

As indicator for differences in feeding conditions, the annual weight gain of heifers during their second year of life is suggested (Figure 17). After weaning they depend completely on roughage, and are not yet pregnant. At an annual weight gain of 70 kg or more, the interval between two successive prgenancies is about 14 months (Figure 20). The interval increases to about 2 years at an annual weight gain of 25 kg, the minimum level of growth and reproduction, required for maintenance of the herd.

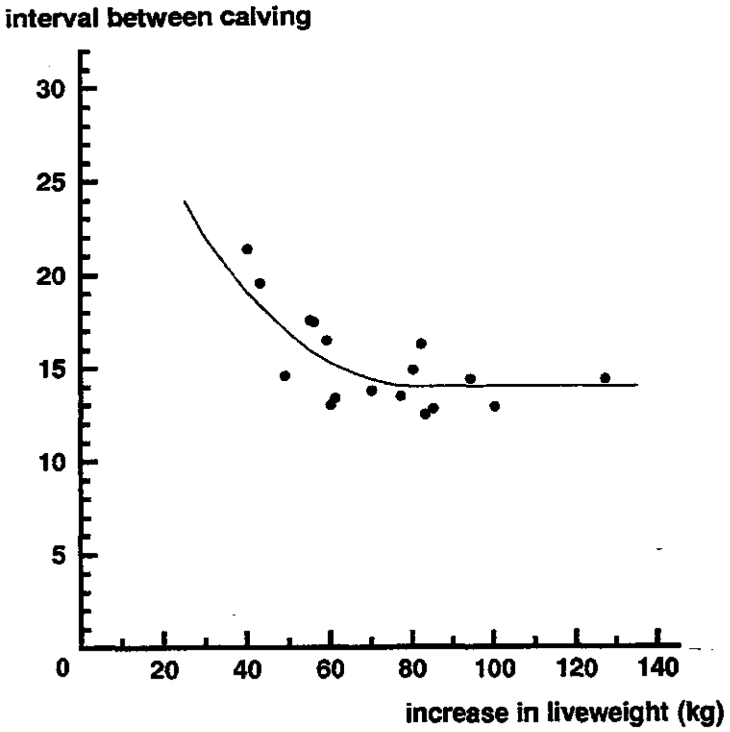

Figure 20. Relation between liveweight gain of heifers during the second year of life and the interval between calving from the same population. (Source: Ketelaars, in prep.)

Rough estimates of milk production during a lactation period can be made on the basis of feed intake, using the following assumptions:

- feed intake is 20 percent higher than that given in Table 25 for growing animals;
- lactation continues for one year;
- all energy from ingested forage in excess of maintenance requirements is used for milk production;
- energy content of 1 kg of milk is 3.5 MJ and energy use efficiency for production of milk is 0.5.

The results are shown in Figure 21, again in relation to the weight increase of heifers in their second year of life, as overall indication of the feeding conditions.

Sexual maturity in cattle is more closely correlated with weight than with age. For Sahelian cows, the required weight is about 200 kg and the age at first calving can thus be derived from the rate of weight gain. Assuming a weight of 100 kg at

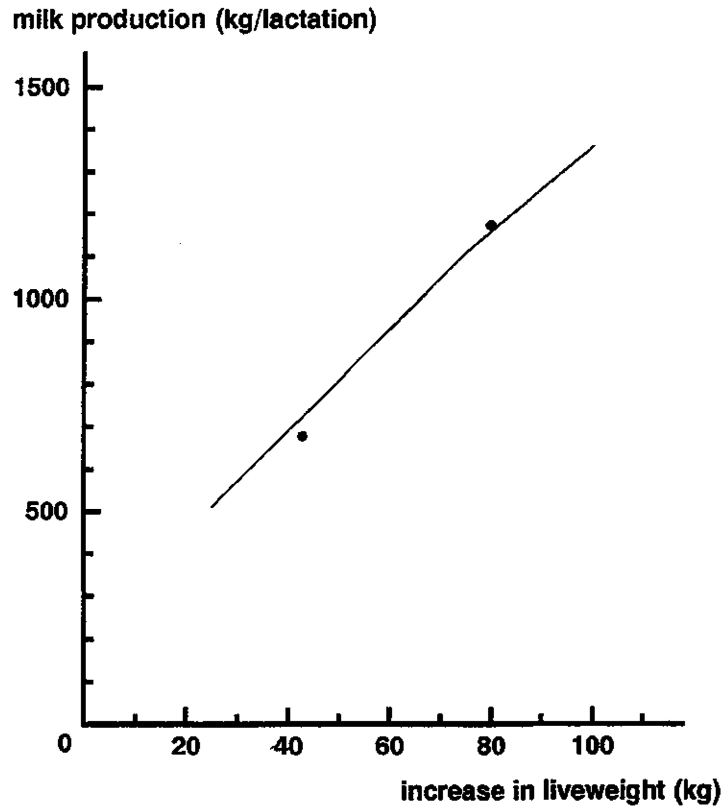

Figure 21. Relation between liveweight gain of heifers during the second year of life and milk production of cows from the same population. (Source: Ketelaars, in prep.)

one year of age and an annual weight increase of 25 or 50 kg, maturity will be attained at the age of 5 and 3 years, respectively.

Animal production cannot only be considered at the level of an individual animal, but also at that of an average animal in a population. A herd represents a specific unit both in an economic and a biological sense. From a biological point of view, the question is what the performance of an individual animal should be to prevent extinction of the population. If this minimum requirement is met, the next question is how the production of an average animal varies under variable feeding conditions. At a low productivity level, improved feed supply may increase the average production per animal in the herd substantially through its parallel effect on various parameters, such as the rate of weight gain, age at first calving, interval between successive calvings and milk production. Conversely, under deteriorating feeding conditions herd productivity may decrease sharply.

Herd models are available to study the effects of differences in feeding conditions on their functioning and productivity. In such models, in addition to the above relationships, information is required on:

- number of year classes for male and female animals;
- mortality fractions per year class;
- expulsion fractions;
- prolificacy per year class.

These data can be derived from field studies or from the literature. To calculate herd productivity, the number of animals per class can be assumed constant, or the increase in number of animals can be fixed in advance, or the increase can be variable. The regulating principle is in all cases the number of heifers that enters the prolific year classes. In the first case, their number is identical to that of mature cows that has to be replaced because of sale or death, in both other cases that number may deviate in positive or negative sense, resulting in increase or decrease in herd size.

3.3.3 Productivity of animal husbandry at different levels of nutrition on West African drylands

The effect of differences in forage quality, resulting from variable environmental conditions, on the productivity of cattle in the Sahelian countries has been studied. For four climatic zones, the average annual course of forage quality has been established (Table 22), from which the liveweight changes for a heifer of 150 kg have been calculated per zone (Figure 22). Field observations have confirmed these theoretically derived levels of production (Breman *et al.*, 1990).

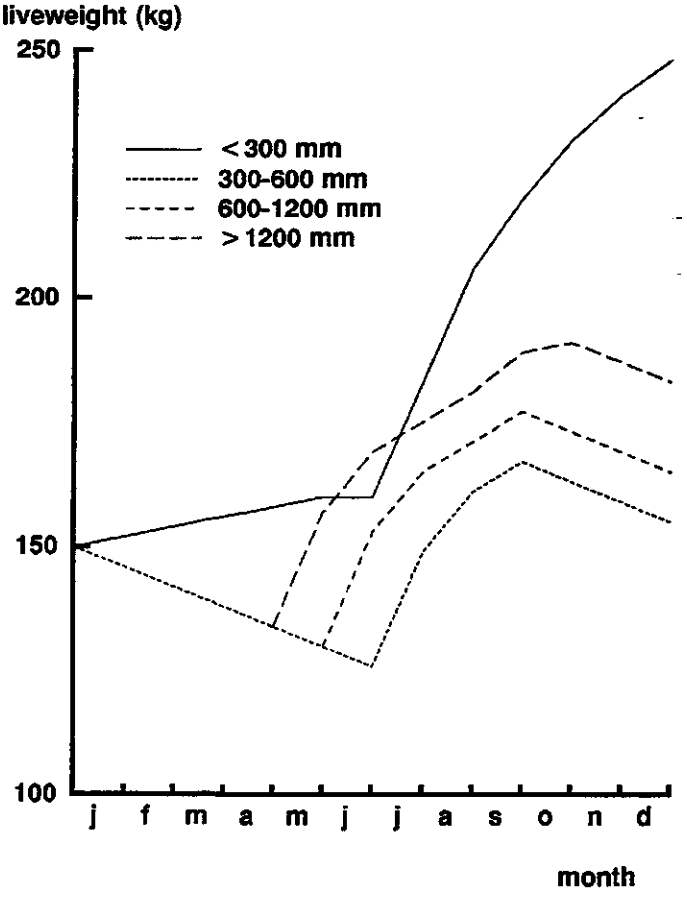

Figure 22. Computed liveweight of female Zebu cattle of 150 kg in the course of a year. Calculations are based on the annual course of forage quantity and quality of the herbaceous layer in the different rainfall zones. (Source: Ketelaars, in prep.)

The results clearly illustrate that the productivity is highest in the northern part of the Sahelian zone, rapidly decreases going South, but increases again in the more humid zones. This is the net result of two contrasting effects. On the one hand, liveweight gains in the rainy season increase, as the length of the rainy season and the period with green forage increase. On the other hand, liveweight losses in the dry season are negligible in the northern part of the Sahelian zone with its high-quality forage, but are considerable in the more southern zones with their low-quality forage.

Using the procedures proposed (3.3.2), the other relevant productivity parameters for cattle have been estimated also, for the different nutritional situations, covering the range of production situations in West-Africa (Table 26). Liveweights at birth and at an age of one year have been set to identical values, assuming nutrition with identical amounts of milk, and mortality parameters have also been assumed identical, because specific information was lacking.

Table 26. Productivity paramters for cattle at different levels of nutrition. (Source: Ketelaars, in prep.)

	Nutrition level			
	I	II	III	IV
weight (kg)				
at birth (m/f)	20	20	20	20
1 year old (m/f)	100	100	100	100
2 year old (m/f)	125	150	175	200
mature cow	200	250	300	300
age at first calving (year)	5.5	3.5	2.5	2.5
calving percentage	50	71	86	86
total milk production (kg)	511	810	1114	1361
milk use for human consumption (kg)	0	300	600	850
mortality (%)				
< 1 year	20	20	20	20
1-2 year	5	5	5	5
> 2 year	2	2	2	2

Differences in food quality can schematically be classified in a number of levels. The lowest level applies to a situation where no net annual liveweight gain is possible, i.e. not suitable for animal husbandry without fodder supplements. At the next level, annual weight gain is limited, as the level of nutrition is still so low that successful reproduction of the population is impossible. At the next level, corresponding to level I in Table 26, net annual liveweight gain is 25 kg for heifers. Animal husbandry becomes attractive for production of meat and manure, but milk production is still so low that it has to be reserved completely for the calf. Taking into account the advanced age at first calving and the low calving percentage, production is just sufficient to replace the cows that die or are sold at an age of eleven years. So natural increase in herd size is impossible. This is the situation of most sedentary animal husbandry systems in the region, between the 300 and 900 mm isohyets, if no supplements of sufficient quality are available (Figure 17, solid line).

At nutrition level II (Table 26), one third of the total milk production is available for human consumption without endangering life chances for the calf, and net annual liveweight gain of heifers is 50 kg. At nutrition level III it is 75 kg, associated with further improvements in the productivity parameters.

Mobile systems like the semi-nomadic transhumance, alternatively using the northern part of the Sahelian zone in the rainy season and the Sudanian zone or flood plains in the dry season, reach at least level II and sometimes level III, provided that the potential advantages of the dry season rangelands are not endangered by overgrazing. The same is possible for nomadic animal husbandry in the northern part of the Sahelian zone, again if animal density is not too high (Figure 17).

Level IV is only attained at experimental stations or incidentally on farms where large amounts of high-quality residues from arable farming are available. The net annual liveweight gain of heifers in that situation is 100 kg, and the production of milk for human consumption, for example, reaches 850 kg per animal per year (Table 26).

For comparison of animal and plant production systems, the productivity of the herd has to be calculated, the herd being the most common production unit. Such calculations have been carried out for the four levels of nutrition defined in Table 26. For nutrition levels II, III and IV, two alternatives can be distinguished, i.e. emphasizing the production of meat (a), or the production of milk (b). The latter represents a dairy cattle farm on which all superfluous calves are sold at the age of one year. The first system corresponds more with most current forms of extensive animal husbandry in West Africa.

In addition to herd productivity Table 27 presents at four levels of nutrition, also forage quality and intake, herd structure, characteristics of sales and the efficiency of forage conversion. The average forage quality required to realize the various production levels is indicated and the associated feed intake is given in relation to the average liveweight. Intake appears not to vary too much among the levels of nutrition, that at level IV being only 23 percent higher than at level I.

However, large differences exist in animal production, expressed in total protein and total energy to make milk and meat comparable: production at level II is 3 to 4 times that at level I, and at level III about two times that at level II. Hence, small differences in forage quality hardly affecting feed intake, result in large differences in production. This is typical for situations with very low production, where almost all energy and protein taken up in the feed is used to maintain individual animals and the herd. That is clearly reflected in the conversion efficiency of only 0.7 percent for gross energy intake in meat and milk at level I. At level II the efficiency is three times higher, but the absolute value is still very low (Table 27).

Table 27. Productivity of animal husbandry on the West African drylands at different levels of nutrition. For explanation see text. (Source: Ketelaars, in prep.)

	I	II		III		IV	
		a	b	a	b	a	b
forage composition:							
N concentration (g kg^{-1})	9	10		11		12	
digestibility (%)	52	54		56		59	
feed intake:							
% of liveweight per day	2.2	2.2	2.3	2.3	2.4	2.2	2.4
relative feed intake (%)	100	108		115		123	
average liveweight (kg)	150	173	162	183	173	196	177
herd structure:							
% male animals	33	43	18	44	22	44	22
% female animals	67	57	82	56	78	56	78
age at sale:							
male animals (year)	5	5	1	4	1	4	1
female animals (year)	5	3	1	2	1	2	1
expulsion percentage of total	11	15	27	19	33	19	33
composition of sale:							
% male animals	54	51	53	51	52	51	52
% heifers	0	26	26	33	33	33	33
% cows of 11 year	46	23	21	16	15	16	15
production (kg $animal^{-1}$)							
liveweight	22	39	35	52	43	59	43
milk	-	64	107	160	260	229	368
meat protein	1.9	3.3	3.0	4.4	3.7	5.0	3.7
milk protein	-	2.3	3.9	5.8	9.3	8.2	13.2
total protein	1.9	5.6	6.9	10.2	13.0	13.2	16.9
meat energy	142	272	178	367	214	426	214
milk energy	-	223	374	565	909	800	1288
total energy	142	495	552	932	1123	1226	1504
conversion efficiency of forage energy in milk and meat energy (%)	0.7	2.0	2.3	3.5	4.2	4.2	5.5
production milk and meat energy as a function of total amount of energy in animal biomass (%)	8	23	27	39	49	47	64

As shown in Table 27, conversion efficiency is highest when emphasizing milk production (alternative b). This does not imply automatically that milk production is the most attractive activity. In practice, problems with storage and transport of milk will negatively influence the cost-benefit ratio. The difference in meat and milk prices will therefore be a decisive factor.

3.4 Intensification of rangeland and animal production

Land use planning for rural development should be based on existing as well as on alternative production systems. The criteria for choice should incude, in addition to socio-economic feasibility, the degree of sustainability. As for crop production, increased nutrient availability is an option to stop over-exploitation of natural resources and the related soil exhaustion. Considerable increases in forage production can be obtained by fertilizer application at an annual rainfall of at least 300 mm, particularly if both nitrogen and phosphorus are applied (Table 28; Penning de Vries & Djitèye, 1982). It is estimated that 0.03 kg of nitrogen has to be applied to produce 1 kg of forage (dry matter) with a nitrogen concentration of 15 g kg^{-1}, or, in other words, 0.75 kg of nitrogen is required to produce 1 kg of meat. In actual animal husbandry systems in West Africa the situation is less favourable and about 1.33 kg of nitrogen is required to produce 1 kg of meat. Taking into account the costs for other nutrients (mainly phosphorus), total costs will be about 1.5 times those for nitrogen alone.

Introduction of leguminous species in the natural vegetation is an alternative for nitrogen fertilizer application. For the Sahelian zone this alternative hardly shows perspectives. The indigenous leguminous species have a sufficiently high capacity to fix nitrogen, but the potential for increasing production and quality of the rangelands through legumes is strongly limited by the low soil phosphorus availability and the climate. Fast germinating annual grasses instead of slowly germinating legumes are favored, while perennial legumes can not be introduced effectively (Penning de Vries & Djitèye, 1982).

Table 28. Biomass production of the herb layer (kg dry matter ha^{-1}) without and with application of fertilizer P, N and N+P at different annual precipitation levels. (Source: Breman & de Ridder, in prep.)

Rainfall (mm)	Soil type	Control	P*	N*	P + N*
450	clay	1800	3200	4000	9500
380	coarse/fine sand	2250	2600	2800	6000
260	fine sand	1020	1130	1580	1270
200	coarse/fine sand	780	540	630	750

* The applied amounts (in kg ha^{-1}) are at 450 en 380 mm of rainfall 90 P, 300 N and 90 P + 300 N and at 260 and 200 mm of rainfall 30 P, 75 N and 30 P + 75 N.

For the Sudanian zone, the potential for improving the situation by introducing leguminous species is indicated in Table 29, in analogy with the situation in northern Australia, because of lack of quantitative information from West Africa. The North of Australia closely resembles the Sudanian zone with respect to the concentrated monomodal rainfall, paucity of the soils, and carrying capacity of the rangelands. The data in Table 29 show, that introduction of leguminous species combined with phosphorus application leads to increased rangeland production and that the associated increase in animal production attains values of 35 kg ha^{-1} yr^{-1} of liveweight. This implies 0.3 to 1.4 kg of animal liveweight gain per kg of superphosphate (8% P). In practice, 0.5 kg of liveweight gain per kg superphosphate applied, i.e. 6.25 kg of liveweight or about 2.5 kg of meat per kg of phosphorus applied, appears to be a good result in Australia. Probably, that could also be realized in the Sudanian zone, but the socio-economic viability has to be compared to that of other production systems.

Another option for forage production for which the input/output relationship can be quantified, is cultivation of leguminous fodder crops combined with phosphorus application. Such a production systems is more labour-intensive, but the proportion of the applied phosphorus fertilizer taken up by the plants (recovery) will be higher and the chance for efficient fodder use is better than on rangelands. In that case about 1 kg of forage (dry matter) with a nitrogen concentration of 3 g kg^{-1} can be produced with 0.01 kg of phosphorus applied. Hence, 1 kg of meat could be produced by applying 0.25 kg of phosphorus. To take into account application of other nutrients, the costs of phosphorus application should be multiplied by about 1.5. In addition to the increase in meat production, also milk production will increase with 5 to 10 kg per additional kg of meat (Breman & Traoré, 1987).

Table 29. Effect of improving rangelands through introduction of leguminous species fertilized with phosphorus on cattle production in the extreme North of Australia. (Source: Breman & Traoré, 1987)

	Carrying capacity	Animal production in liveweight	
	ha/TLU	kg/TLU	kg/ha
Natural rangelands	15-20	30	1-2
+ leguminous spec.	3-5	30	5-10
+ leguminous spec. + P*	1-2	60	35-40

* Initially 50 to 200 kg ha^{-1} of superphosphate was applied; subsequently 25 to 100 kg ha^{-1} is applied each year.

4. Role of woody species

4.1 General outline

Total exploitable annual biomass production of woody species will not be very different from that of arable crops or rangelands in the same agro-climatic zone, as identical factors determine that production level (Kessler & Breman, 1991). However, woody species differ from herbaceous species as elements from agro-ecosystems:

- the total amount of live and dead organic matter in the system is higher, resulting in a more intensive circulation of nutrients in the overall soil-plant system;
- under certain conditions, availability of water and/or nutrients may be somewhat higher, especially due to lower losses, which contributes to the stability of the environment;
- a large proportion of the annual production originates from recirculation of the own nutrient reserves, so only a limited part of that production can be exploited without risks for the sustainability of the system.

Studies of indigenous woody species in their natural environment, combined with data from plantations, enables a first estimate of the consequences of such differences for total annual production, the possibilities for exploitation and environmental conditions.

To estimate the production of land planted with woody species, the partitioning of total production over the various plant parts should be known. Main products and by-products have to be distinguished and quantified, as for arable farming and animal husbandry. For the indigenous woody vegetation as a whole, the average partitioning of production among wood, leaves and fruits has been estimated and, for several individual species, data are available (Breman *et al.*, 1984; Kessler & Breman, 1991). For woody species not yet cultivated in the region, with products of great value, a method is proposed for estimating their expected yield levels.

In addition, suggestions are presented for estimating the positive role of woody species on the environment, growing in pure stands (plantations, forests), in combination with crops (agro-forestry) or as a component of rangelands. This indirect influence (via soil fertility, microclimate, etc.) has to be taken into account in land use planning, in addition to the direct economic benefits from woody species. However, in that situation the negative influence on crop and rangeland production due to competition for water, nutrient and light should also be considered.

4.2 Production of woody species

Estimation of biomass production

Annual production of leaves, the plant parts that through the photosynthetic process determine biomass production, is used as the basis for estimating the total production of woody species. For woody vegetation in the Sahelian region, annual production of leaves can be calculated from their estimated cover and the average number of leaf layers of trees and shrubs. The degree of cover can be derived from annual rainfall for various land units (Table 30). The number of leaf layers increases from about 2 in the Sahel to about 6 at the southern border of the Sudan zone (annual rainfall exceeding 1300 mm), at least for trees growing on relatively deep soils (Table 31). In valleys and depressions such as on land unit La, runon occurs, resulting in higher infiltration and thus in more leaf layers than on the other land units, where between 10 and 50 percent of the rainfall is lost by runoff.

Table 30. Estimated degree of cover by woody species during the second half of the seventies, on different land units in three rainfall zones. (Source: Breman & de Ridder, in prep.)

	Land unit*				
	De	S_d	S_a	$F_{éc}$	F_{sh}
northern Sahel (200 mm yr^{-1})	-	0.02	0.02	0.02	0.02
southern Sahel (450 mm yr^{-1})	0.16	0.035	0.035	0.18	0.10
northern Sudan (750 mm yr^{-1})	0.27	-	-	0.27	0.40

Tabel 31. Average number of leaf layers of woody species for increasing amounts of average rainfall (P) and infiltrated water (I). (Source: Breman & de Ridder, in prep.)

P (mm yr^{-1})	I (mm yr^{-1})	number of leaf layers
< 500	< 400	2
500-750	400-550	3
750-1000	550-700	4
1000-1300	700-900	5
≥ 1300	≥ 900	6

A leaf layer is a theoretical unit, comprising the leaf area required to cover the soil surface without gap or overlap. For Sahelian conditions, the weight of a leaf layer is about 1200 kg per hectare. Total leaf production of woody species is thus obtained by multiplying the number of leaf layers by 1200 kg ha^{-1} and by cover (Table 29). The resulting leaf production per land unit and rainfall zone is specified in Table 32.

Table 32. Estimated leaf production (kg ha^{-1} yr^{-1}) for various land units in three rainfall zones in years with average rainfall (p. 50%). (Source: Breman & de Ridder, in prep.)

	Land unit				
	De	S_d	S_a	$F_{éc}$	F_{sh}
northern Sahel (200 mm yr^{-1})	-	48	48	48	48
southern Sahel (450 mm yr^{-1})	384	84	84	432	480
northern Sudan (750 mm yr^{-1})	648	-	-	648	2880

Average fruit production is estimated at 15 percent of total leaf production. Total production of leaves, young twigs and fruits (for 'forage trees' all considered as browse) is estimated at 1.5 times the annual production of leaves. Wood production finally, is about 80 percent of the production of leaves in the Sahelian zone, but going south into the Sudanian zone it decreases to 40 percent.

Because of the strong influences of weather and man on the cover of woody species, and the rapid changes in conditions, it is advisable to use recent estimates of this cover if available rather than the averages presented in Table 30. To give, however, an indication of the level of browse production of rangelands, the calculated production for different land units and rainfall zones is presented in Table 33, based on the cover of woody species determined during the second half of the seventies.

It is assumed that production of woody species is directly proportional to rainfall. Hence, the ratio of rainfall in a dry year (p.10%) and that in an average year (p.50%), as derived from Figure 9, has been used to derive the production in a dry year (Table 33).

To estimate the value of the browse produced, its quality as forage has to be taken into account. Average nitrogen concentration in leaves of woody species is at the end of the rainy season 26, 25 and 22 g kg^{-1} in the northern and southern part of the Sahelian zone and in the Sudanian zone, respectively. For browse as a whole, the nitrogen concentration is estimated at 0.7 times that in the leaves. These concentrations are high in comparison with those of the components of the herbaceous layer (Figure 10), suggesting a high quality. However, this is a rather flattery picture because the presence of tannins in the leaves of woody species negatively influences digestibility. Particularly for cattle and sheep the usefulness of browse is limited and the relation between nitrogen concentration and digestibility is different from that for herbaceous species (Table 23).

Total production of woody species will become somewhat higher if the competition from the herbaceous layer is suppressed by men, by grazing, or by the woody species themselves, on places where they become strong competitors. The

Table 33. Estimated browse production (kg ha^{-1}) for land units in three rainfall zones in average (p. 50%) and dry (p. 10%) years. (Source: Breman & de Ridder, in prep.)

	Land unit				
	De	S_d	S_a	$F_{éc}$	F_{sh}
northern Sahel					
p50%	-	72	72	72	72
p10%	-	36	36	36	36
southern Sahel					
p50%	576	126	126	648	720
p10%	384	84	84	432	480
northern sudan					
p50%	972	-	-	972	4320
p10%	752	-	-	752	3341

latter happens on places where water availability is continuous, to assure survival during the extremely dry season of the region. The increased production can be estimated from data on forestry production (Clement, 1982) or by 'translation' of herbaceous production into production of woody species. The amounts of water and nutrients used by crops or rangelands (Sections 2 and 3) may serve as intermediate parameters for this 'translation'. However, complete replacement of herbaceous production by that of woody species will remain an utopia for most of the agro-climatic zones of the West-African drylands; the length of the dry season, its extreme aridity and the frequency of droughts make that impossible. Therefore, in the absence of continuous clearing by men, the cover by woody species before the droughts of the seventies (Table 30) is considered as the maximum for the region.

Introduction of plant species

Introduction of cash crops in agricultural systems can be beneficial, if the economic value of their products more than compensates the associated losses in food production. Such revenues could be used for rural development and improved resource management. Cotton, for example, plays such a role in Mali. The revenues from this cash crop allows some fertilizer use on grain crops too, resulting in increased food production.

Several perennial species with products of economic value have been identified. New opportunities are expected, for example, from gum from *Acacia senegal*, fine oil from *Jojoba* and diesel oil from *Jatropha*. In most cases, however, insufficient information is available about the region where they can be grown and on the production level that can be attained under different conditions. Even if in limited parts of the region (some) experience has been gained with a certain species, it is impossible to use the input and output data of these locations directly. Date palms in Mauritania for example yield only 15-18 kg yr^{-1} of dates at a density of 200 trees ha^{-1}. However, management is not optimum, considering the high percentage of male trees in the stand, the use of unimproved varieties and the occurrence of water and/or nutrients shortage. An average production of 120 kg. tree^{-1}.yr^{-1} is possible under optimum management, using irrigation and fertilizers (RAMS, 1988).

A procedure is proposed therefore that provides an indication of the potential of individual species. Whether a new species can be grown in a region, depends on the agro-ecological characteristics and on species requirements. For each perennial species, for which introduction is considered, information should be collected about the requirements for successful planting and production. Comparison of these requirements with the climatic and soil characteristics of a region should result in an estimate of the suitable area for that species. Important soil characteristics are soil depth and structure, soil acidity and toxicity, risk of soil moisture shortage or anaerobiosis, etc. Relevant climatic factors determining plant survival and production, are temperature, rainfall and daylength in the course of the year, and the degree of aridity of the dry season. Crucial plant characteristics are the operational mechanism for induction of flowering (temperature, daylength or water availability) and the synchronization of the growth cycle with the rainy season.

Nutrient limitation

It has been shown that under natural conditions in West-Africa woody species grow almost exclusively on places where nutrient availability is the main limiting factor. Hence, the yield of marketable products from woody species can be estimated in a way comparable to that for annual crops. Potential nutrient uptake may be calculated with the QUEFTS method (Table 4), indicating the nutrient supply to a 'standard' maize crop, or with the equation given in Section 3.2.2 for calculating nitrogen availability to natural rangelands. Which method yields better results for woody species, has yet to be examined by comparing both, for reference species for which data are available (dates, oil-palm, gum-tree, etc.). A correction will have to be made for the longer growth cycle, as perennials generally have access to water in deeper soil layers.

Important differences may be expected with respect to the characteristics of the marketable product. Yields of a product rich in proteins, like leaves and fruits of leguminous species, will be limited more often by nutrient availability than those of a product rich in energy, like the seeds of Jatropha or wood.

For a number of perennial species, nutrient concentrations in plant tissue have been collected (Nijhof, 1987c) and if necessary, they should be collected from the literature for other species of interest. The yield of marketable products can be estimated now for a perennial species by dividing its annual nutrient uptake by the nutrient concentrations in marketable products and in by-products. This method is identical to that presented for annual crops (Table 5). During the first years of production of woody species this approach cannot be applied, as production is then very low and the nutrients taken up are mainly used for tree development.

To what extent yields of perennials could increase through the use of improved plant material, better crop management, etc., can only be judged on the basis of information from relevant field experiments. To describe the effect of fertilizer application, the same procedure described for annual crops in Section 2.3.3 can be applied, i.e. the amount of fertilizer nutrients applied is multiplied by the recovery fraction, as derived from field experiments, and the resulting additional uptake is divided by the nutrient concentrations in the marketable and by-products. This yields an estimate of the increase in production that may be expected.

4.3 Woody species in arable and rangeland production systems

In the preceding section a monoculture of woody species has been considered, occupying as much as possible of a certain area. There are, however, arguments to include mixed cropping in this analysis. Annuals, with their short growth cycle followed by harvest or grazing, form a fragile component in the ecosystems in the region. Interest in the possibilities of agro-forestry, i.e. integrating woody species into arable farming systems, and sylvo-pastoralism, i.e. integrating woody species into rangeland and animal production systems, originates also from observations of relatively high soil fertility and high crop production under Acacia albida trees, and from experimental results of alley-cropping systems in the humid tropics. To what extent the availability of water and/or nutrients is higher in agro-forestry and sylvo-pastoral systems, thus providing added value, has been elaborated out in an evaluation of the potential for agro-forestry in the Sahelian and Sudanian zones (Kessler & Breman, 1991).

The approach proposed for the present study, is based on the fact that production of crops, rangelands and woody species is determined by the same factors, i.e. water, nutrients and light in the northern Sahelian zone, and nutrients in the zones further South. It has been shown for herbaceous species (3.2; Penning de Vries & Djitèye, 1982) that in general the availability of water is the limiting factor in the northern Sahelian zone, while the availability of nutrients is the limiting factor elsewhere in the region.

For proper evaluation, the following questions should be answered:

- to what extent can specific properties of woody species contribute to improved availability of water and nutrients in different agro-ecological zones;
- does such an improvement have an effect on the relative availability of water and nutrients;
- to what extent can herbaceous species profit from such an improvement.

The last question is related to the complicating factor light: Light plays a role in the competition between herbaceous species, without notable influence on total biomass production (Penning de Vries & Djitèye, 1982), hence it determines mainly the share of species with different properties, growth form included, in a vegetation (Spitters & Aerts, 1983; Gillard & Elberse, 1982). Woody species will win the competition for light with herbaceous species during most of their lifetime, constituting an important advantage in the competition for water and nutrients. The relative advantage of woody species in the competition for light is the result of their higher biomass production at a given level of availability of water and nutrients. So, coppicing of woody species, to diminish the competition with herbaceous species, hits them in the property by which they improve the environment (4.1). In other words, for production systems comprising woody species the question has to be answered for each individual agro-ecosystem, whether the added value is sufficient to compensate for the negative effects of competition between the woody species and crops or rangelands for water or nutrients. If that is the case, integration is advantageous. In other situations, it is better to cultivate woody species independently.

Improvement of the environment

It becomes increasingly clear that the possible positive contribution of woody species to the sustainability of agro-ecosystems, should not be judged simply by the improvement of the absolute availability of nutrients; increased environmental heterogeneity is another important aspect related to the presence of shrubs and trees (Kessler & Breman, 1991). Belsky *et al.* (1989) have shown that the physical and chemical properties of the soil in the vicinity of *Acacia tortilis*, a deep rooting leguminous species (with "nutrient pump", fixing nitrogen) are not different from those around *Adansonia digitata*, with very shallow roots and no N-fixation.

In the proposed approach it will be attempted to quantify the environmental value of woody species by quantifying the effect of increased organic matter content of the soil on its physical and chemical properties (4.1): on the one hand it increases the infiltration capacity and the water holding capacity, on the other hand it contributes to the cation exchange capacity (Budelman & Zander, 1990). The consequences are lower surface run-off losses (with the related losses of nutrient-rich top soil), less percolation and leaching of nutrients, and counteraction of soil acidification. The slow, but continuous build-up of organic matter, signifies that these contributions to environmental stability will be found to decrease from forests, by plantations and shifting cultivation to agro-forestry systems.

The improvements in microclimate will also have to be taken into account, but agro-ecosystems in which these effects counterbalance those of the competition for water with herbaceous species will be rare in the region (Breman, 1987).

Effects on production of the herbaceous vegetation

Improved environmental conditions due to the presence of woody species not automatically implies increased production from the herbaceous vegetation. The herb layer and the woody species compete for the different growth factors (4.2), and the woody species themselves are the first to profit from their influence on the environment (start of this paragraph). The consequence of this competition for the contribution of the two components to the overall production of rangeland is presented as an illustration.

In judging the value of woody species in rangelands not only the positive effects of browser production should be taken into account, as above a threshold of 15 percent tree cover, the production of the herbaceous vegetation is negatively influenced by the presence of woody species through competition for nutrients, induced by the competition for light. This may imply a negative influence on animal production, because a much smaller fraction of the annual production of woody species can be used by livestock than of the production of the herbaceous vegetation (3.3.1).

Breman and de Ridder (in prep.) present a method to estimate the effect of competition. The equation from Section 3.2.2, $Nb= 0.0083(I - D)/(f - 0.13)$, forms the basis. In this situation, however, for the loss fraction f a weighted average is used of the mean nitrogen losses from the above-ground biomass of the herbaceous vegetation and of the woody species. For the latter, the losses are supposed to be 0.4 times those from the herbaceous biomass, with a minimum of 0.2.

The amount of nitrogen in the annual production of browse can be estimated from the level of production and its nitrogen concentration. Only 40 percent of this nitrogen is taken up from the soil, the remainder originating from the internal reserve of the woody species. However, the 40 percent origination from the soil is not completely taken up in competition with the herbaceous vegetation. It is estimated that about 4 kg ha^{-1} is exclusively available to the woody species, due to niche differentiation (4 kg ha^{-1} is the amount of nitrogen that the woody species absorb from the soil at 15% canopy cover). Subtracting the resulting nitrogen uptake by woody species from Nb, yields the reduced nitrogen availability for the herbaceous vegetation.

The negative influence of more than 15% tree cover on the production of the herbaceous vegetation, and thus on animal production, does not imply that the excess trees should be eradicated, as is frequently done for example in semi-arid tropical Australia. This choice will have to be made, taking into account the need for and the prices of wood and meat and the contribution of the tree cover above 15% to environmental stability.

5. Comparison of production systems

In the preceding chapters it has been illustrated that it is possible to estimate the production potential of arable crops, natural rangelands and woody species on the basis of agro-ecological characteristics of the environment. Quantitative description of cropping systems by physical input and output parameters, allows in principle an analysis of costs and benefits. However, analysis of development possibilities requires more than a simple comparison of the net benefits per unit area. Decisions have to be made with respect to the required and attainable degree of accuracy, and the way in which sustainability and diversity of production systems have to be taken into account.

5.1 Accuracy

It is evident from the methods described that the production estimates for arable crops, natural rangelands and woody species don't have the same accuracy. For arable crops the most detailed calculations can be executed for the relevant climate and soil combinations. However, only limited experience exists in the use of the method for West-African drylands. The methods to estimate animal production have specifically been developed for that region, and therefore, the accuracy of these estimates is presumably relatively high, though the agro-ecological zonation is rather rough. For the woody species, the classification is even less detailed and in addition, the reliability of the production estimates is limited.

For a comparison of different production systems a more detailed classification of agro-ecological zones than appropriate for the estimation of production of woody species is not useful. Hence, we suggest to distinguish four climatic zones (northern and southern part of the Sahelian zone and northern and southern part of the Sudanian zone) and four soil types (deep sandy, loamy, and clay soils and shallow soils).

It will not be enough to simply perform the calculations according to the suggested procedures, for 4 * 4= 16 soil - climate combinations. Tests for reliability have to be executed too, using as much field data as possible, which may lead to adaptation of the calculation procedures, until, in an iterative way satisfactory results have been achieved.

5.2 Sustainability

A major goal of the comparison of production systems for the West-African drylands is to increase insight in their long-term prospects. Therefore, sustainability of the production systems should be a major consideration. Productivity of agricultural systems can be maintained in the long run only, if at least the availability of water and nutrients is not unfavourably affected (ecological sustainability). In other words, increasing runoff, decreasing water-holding capacity of the soil, a negative nutrient balance, soil acidification and wind and water erosion should be avoided.

Most of the current production systems do probably not meet this condition anymore. The comparison between those systems and more sustainable ones, could be made by taking into account the losses of production potential of the natural resources as costs. We prefer however the alternative: to describe the existing systems as they should be to avoid resource degradation (van Duivenbooden & Gosseye, 1990).

For arable farming that implies the adoption of certain cultivation practices and the use of sufficiently long fallows or of manure and fertilizers. As a consequence, there are limits on the area that can be cultivated and/or the required inputs (labour and capital) are higher than under current practice. For animal husbandry upper limits have been set to the number of animals per unit area. Trees, used for browse production, are allowed to be exploited only to a limited extent, for other tree crops a method is proposed identical to the one described for arable farming.

If woody species are used in agro-forestry systems, the lower requirement for organic manure and fertilizer, as well as the increased labour requirements are taken into account.

5.3 Production systems

In addition to the products that will be considered, the way in which they are produced, must be carefully chosen. For animal husbandry it is proposed to distinguish sedentary and mobile systems. Moreover, systems with low and high levels of external inputs should be defined, and with different production targets. Certain combinations, however, such as mobile systems with a high level of external inputs, are not appropriate.

It will be difficult to treat mixed systems in the comparison. A possibility might be to attach values to by-products, which can be derived from the benefits of their use as input in other systems (crop residues used as fodder, manure used as alternative for chemical fertilizer, effect of woody species in mixed systems on soil structure and fertility, etc.).

5.4 Examples

During the last decade (parts of) the suggested approach has (have) been applied for the region by CABO at several occasions. In the course of that the methods have continuously been improved on the basis of observations from the field and increased insights in the relevant processes and systems. In this section some of these studies are briefly described.

At the request of UNSO a comparative study has been carried out on the profitability of the use of deep wells for livestock, vegetable, fodder and date production (Breman, 1981). Livestock appeared to be the only activity for remunerative use of well water at the prices for inputs and outputs at that time.

Technical options for intensifying animal husbandry have been broadly compared for the region as a whole (Penning de Vries & Djitèye, 1982), and at country level, for Niger, Burkina Faso and Mali (Breman & Traoré, 1986a; 1986b; 1987). In the latter studies it was concluded that intensification of arable farming is a prerequisite for the intensification of animal husbandry.

By far the most detailed study is an analysis of existing and potential agricultural production systems as a basis for land use planning for the Mopti region in Mali (Cissé & Gosseye, 1990; van Duivenbooden & Gosseye, 1990; Veeneklaas, 1990; Veeneklaas *et al.*, 1990). This study goes beyond the goal of UNSO for the present study: it is not a neutral comparison of production systems, based on economic and ecological criteria, but a comparison of development possibilities in relation to (partly) conflicting development goals. Two development scenarios have been compared, the "high-revenu, high-risk or R-scenario" and the "high security and self-sufficiency or S-scenario". The choice for the R-scenario appears to imply promotion of animal husbandry and vegetable production, with a minimum level of external inputs. The S-scenario on the other hand can only be realized by increased production of cereals, using fertilizers and irrigation (Veeneklaas *et al.*, 1990).

This last study may serve as a guideline for UNSO to formulate the subsequent phases of the present project, and to make the necessary choices as formulated in 5.1, 5.2 and 5.3.

References

Belsky, A.J., R.G. Amundson, J.M. Duxbury, S.J. Riha, A.R. Ali & S.M. Mwonga, 1989. The effects of trees on their physical, chemical, and biological environments in a semi-arid savanna in Kenya. Journal of Applied Ecology 26: 1005-1024.

Brammer, H., 1973. Soils of Zambia. Ministry of Rural Development. Lusaka, Zambia.

Breman, H., 1981. Mise en place des périmètres irrigués autour des 36 forages. Mission de formulation UNSO en Mauretanie, du 17/10 au 2/11-1981. CABO, Wageningen.

Breman, H., 1987. The struggle of the green against the yellow dragon. The Chinese approach to desertification control and its usefulness for the Sahel. CABO, Wageningen. 62 pp.

Breman, H., C. Geerling, J.J. Kessler & F.W.T. Penning de Vries, 1984. Le rôle agro-sylvo-pastoral de la strate ligneuse au Sahel. Colloque Lutte contre la désertification, CILSS/Club du Sahel, Nouakchott.

Breman, H., J.J.M.H. Ketelaars & N'Golo Traoré, 1990. Un remède contre le manque du terre? Bilan des éléments nutritifs, production primaire et élevage au Sahel. Sécheresse 2: 109-117.

Breman, H. & J.M. Krul, 1982. Rainfall and forage production on natural rangelands. In: Penning de Vries, F.W.T. & M.A. Djitèye (Eds.). The productivity of Sahelian rangelands. Agric. Res. Rep. 918, Pudoc, Wageningen, the Netherlands. pp. 304-322.

Breman, H. & N. de Ridder (Eds.), Manuel sur les pâturages des pays sahéliens. Karthala, Paris. (in prep.)

Breman, H. & N. Traoré (Eds.), 1986a, 1986b, 1987. Analyse des conditions de l'élevage et propositions de politiques et de programmes. République du Niger; Burkina Faso; République du Mali, OECD, Paris, SAHEL D(86)284; D(86)300; D(87)302. 202 pp.; 194 pp.; 243 pp.

Budelman, A. & P.M. Zander, 1990. Land-use by immigrant Baoulé farmers in the Taï region, South-west Côte d'Ivoire (Ivory Coast). Agroforestry Systems 11: 101-123.

Cissé, S. & P.A. Gosseye (eds), 1990. Compétition pour des ressources limitées: le cas de la cinquième région du Mali. Rapport 1. Ressources naturelles et population. CABO, Wageningen & ESPR, Mopti. 106 pp. + annexes.

Clément, J., 1982. Estimation des volumes de la productivité des formations mixtes forestières et graminéennes tropicales (Afrique Francophones au nord de l'Equateur). CTFT, France. 68 pp.

Diallo, A., 1978. Transhumance: comportement, nutrition, et productivité d'un troupeau zébus de Diafarabé. Thèse de 3ème cycle. Centre Pédagogique Supérieure, Bamako, Mali. 75 pp.

Diepen, C.A. van, J. Wolf, H. van Keulen & C. Rappoldt, 1989. WOFOST: a simulation model of crop production. Soil Use and Management 5: 16-24.

Driessen, P.M., 1986. The water balance of the soil. In: Keulen, H. van, and J. Wolf (Eds.). Modelling of agricultural production: weather, soils and crops. Simulation Monographs, Pudoc, Wageningen, the Netherlands. pp. 76-116.

Duivenbooden, N. van & P.A. Gosseye (Eds.), 1990. Compétition pour des ressources limitées: le cas de la cinquième région du Mali. Rapport 2. Productions végétales, animales et halieutiques. CABO, Wageningen & ESPR, Mopti. 266 pp. + annexes.

FAO, 1984. Agroclimatological data for Africa. Vol. 1 and 2. FAO Plant production and protection series 22. Rome, Italy.

FAO, 1984. FAO fertilizer programme in Zambia; annual technical report for 1983-84.

FAO, 1985. FAO fertilizer programme in Zambia; annual technical report for 1984-85.

FAO, 1985 etc. Production yearbooks 1967-1984. Vol. 21-38. Rome, Italy.

Frère, M. & G.F. Popov, 1979. Agrometeorological crop monitoring and forecasting. FAO plant production and protection series 17. Rome, Italy.

GEAU, 1984. Gestion de l'eau. Tome I: Rapport principal sur la gestion de l'eau et l'expérimentation agricole dans le périmètre irrigué de l'Office du Niger, Mali. Vakgroep Weg- en waterbouwkunde en irrigatie, Université Agronomique, Wageningen. 83 pp.

Gillard, P. & W.Th. Elberse, 1982. The effect of nitrogen and phosphorus supply on the competition between Cenchrus biflorus and Alysicarpus ovalifolius. Neth. J. agric. Sci. 30, 161-171.

Goudriaan, J. & H.H. van Laar, 1978. Calculation of daily totals of the gross CO_2 assimilation of leaf canopies. Neth. J. Agric. Sci. 26: 373-382.

Heemst, H.D.J. van, 1985. The influence of weed competition on crop yield. Agric. Systems 18: 81-93.

Hendricksen, R., K.G. Rickert, A.J., Ash & G.M. McKeon, 1982. Beef production model. In: Animal production in Australia. Proc. of the Australian Soc. of Animal Production 14, 204-208. Pergamon Press, Sydney, Australia.

Janssen, B.H., F.C.T. Guiking, D. van der Eijk, E.M.A. Smaling, J. Wolf & H. van Reuler, 1990. A system for quantitative evaluation of the fertility of tropical soils (QUEFTS). Geoderma 46: 299-318.

Kessler, J.J. & H. Breman, 1991. Agroforestry potential in the Sahel and Sudan zone of West Africa in view of rainfall and soil fertility. Agroforestry Systems. (in press).

Kessler, J.J. & H. Breman (Eds.), Le rôle agro-sylvo-pastoral de la strate ligneuse au Sahel. (in prep.)

Ketelaars, J.J.M.H., in prep. The animal production. In: Breman, H. & N. de Ridder (Eds.). Manual for evaluation of rangelands in Sahelian countries.

Keulen, H. van & H. Breman, 1990. Agricultural development in the Sahelian region: a cure against land hunger? Agriculture, Ecosystems and Environment 32: 177-197.

Keulen, H. van & H.D.J. van Heemst, 1982. Crop response to the supply of macronutrients. Agric. Res. Rep. 916, Pudoc, Wageningen, the Netherlands.

Keulen, H. van & J. Wolf (Eds.), 1986. Modelling of agricultural production: weather, soils and crops. Simulation Monographs. Pudoc, Wageningen, the Netherlands. 479 pp.

Nijhof, K., 1987a. The concentrations of macro-elements in economic products and residues of (sub)tropical field crops. SOW working paper 87-08, Centre for World Food Studies, c/o CABO, P.O. Box 14, 6700 AA Wageningen, the Netherlands.

Nijhof, K., 1987b. The concentration of macro-nutrients in (sub)tropical crops of minor importance. SOW working paper 87-17, Centre for World Food Studies, c/o CABO, P.O.Box 14, Wageningen, the Netherlands.

Nijhof, K., 1987c. The concentration of macro-nutrients in plant parts of tropical perennials. SOW working paper 87-16, Centre for World Food Studies, c/o CABO, P.O.Box 14, Wageningen, the Netherlands.

Pawson, E., 1953. Maize fertilizer experiments in Northern Rhodesia 1950-1953. Agric. Bulletin no. 7. Dep. of Agric., Lusaka, Zambia.

Penning de Vries, F.W.T. & M.A. Djitèye (Eds.), 1982. La productivité des pâturages Saheliens. Agric. Res. Rep. 918, Pudoc, Wageningen, the Netherlands. 525 pp.

RAMS, 1980. Oasis Agriculture. RAMS project, Rural Assessment and Manpower Surveys SS4. USAID/ Min. of Economy & Finance, Mauritania. Nouakchott. 167 pp.

SOW, 1985. Potential food production increases from fertilizer aid: a case study of Burkina Faso, Ghana and Kenya. Centre for World Food Studies, c/o CABO, P.O.Box 14, Wageningen, the Netherlands.

Spitters, C.J.T. & R. Aerts, 1983. Simulation of competition for light and water in crop-weed associations. Aspects of Applied Biology 4: 467-483.

Technical Advisory Committee on the Consultative Group on International Agricultural Research, 1989. Sustainable agricultural production: implications for international agricultual research. FAO Research and Technology Paper No. 4, FAO, Rome. 131 pp.

Veeneklaas, F.R., 1990. Compétition pour des ressources limitées: le cas de la cinquième région du Mali. Rapport 3. Description formelle du modèle d'optimisation MALI5. CABO, Wageningen & ESPR, Mopti. 57 pp. + annexes.

Veeneklaas, F.R., 1990. Dovetailing technical and economic analysis. Ph.D. thesis, Univ. of Rotterdam. 160 pp.

Veeneklaas, F.R., S. Cissé, P.A. Gosseye, N. van Duivenbooden & H. van Keulen, 1990. Compétition pour des ressources limitées: le cas de la cinquième région du Mali. Rapport 4. Scénarios de développement. CABO, Wageningen & ESPR, Mopti. 182 pp. + annexes.

de Wit, C.T. & J.M. Krul, 1982. La production actuelle dans une situation d'équilibre. In: Penning de Vries, F.W.T. & M.A. Djitèye (Eds.). La productivité des pâturages sahéliens. Une étude des sols, des végétations et de l'exploitation de cette ressource naturelle. Agric. Res. Rep. 918, Pudoc, Wageningen, the Netherlands. pp. 275-283.

Wolf, J., C.A. van Diepen & C.H. van Immerzeel., 1987. Monitoring agro-ecological resources using remote sensing and simulation: a study on the limitations to maize production in Zambia using simulation models and a geographic information system. Centre for World Food Studies, c/o CABO, P.O.Box 14, Wageningen, the Netherlands.