

Optimization of Farming Systems in the Fakara (Sahel) with Regard to Soil Fertility Using a Dynamic Modelling Approach

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Environmental Protection and Agricultural Food Production

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Abstract

A simple dynamic model, based on the works of Bontkes (1999, 2005), was built to assess the impact of different management practises on important variables of soil fertility on field scale. Five farm types, grouped by their production factor endowment (Hiernaux and Turner 2002), were compared regarding sustainability of cropping systems. The dataset used in this work was collected by different organisations in the Fakara region (SW-Niger) over the last decade. It was found that only the high endowment group is able to achieve the objective of sustainable land use. Suggestions for improvement were made and tested using the mentioned model. The importance of mineral fertiliser use to increase yields and crop residues to maintain soil fertility was again affirmed.

Additionally two different climatic change scenarios were used in a simple CGM to estimate temperature and precipitation development in the objective area for the next three decades.

Results from these simulations give occasion to the hope that the West African Sahel is one of the few areas in the world actually benefiting from climatic change.

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1. Introduction

The Sahel, (from Arabic sahil, shore or coast of the Sahara desert) is a band of land between the 75th and 450th isohyet, running across the African continent from the Atlantic to the Horn of Africa. Because of this low precipitation, agriculture in this region is marginal.

Furthermore this region is highly susceptible to famine. In the last century alone, it suffered at least three major famines. In the summer of 2005 again pictures of starving children and malnourished people and livestock reached Europe and the rest of the world. This time from the country of Niger, a former part of the French West Africa colony, landlocked between Nigeria to the south and the Sahara desert of Algeria to the north.



Figure 1: Location of the Sahel

This crisis in the south of the country, where 3.6 million people faced severe food shortages, has been caused by a drought and a plague of locusts which destroyed much of last year's harvest (BBC 2005). But drought alone is not why Africa suffers regularly from famine and widespread malnutrition.

Other factors are at work, including: armed conflict, corruption and the mismanagement of food supplies, trade policies that harm African agriculture and the long-term economic effects of Aids. Malnutrition is widespread across Africa, even in famine-free years where food production or imports appear to meet a country's needs. Two problems may be singled out when looking at Food security, the population increase and along with it the environmental degradation. As in the rest of Africa population in the Sahelian countries is increasing steadily since the mid of the 20th century. During the last two decades the rate of population growth was still increasing together with the rate of urbanisation. Based on the age and gender composition of the population, levels and trends of fertility and mortality these rates of increase should persist over the next two decades. Demographers predict an increase of the population in sub-Saharan West Africa from 215 million in 1990 to 430-470 million in 2020 with 40 % and 63% urban respectively. (Snrech 1994).

But still half of the African population is rural, and directly dependent on locally grown crops or foods harvested from the immediate environment.

The Sudano-Sahelian zone of West Africa is the home of the world poorest people, 90% of who live in villages and gain their livelihood from subsistence agriculture (Bationo and Buerkert, 2001).

Per capita food production has declined significantly over the past three decades. According to FAO, total food production in Sahelian countries grew by an impressive 70% from 1961 to 1996, but it lagged behind the population growth, which doubled causing food production per capita to decline approximately by 30% in the same period.

The growth rate for cereals grain yield is about 1% while population growth is about 3%.

During the last 35 years, cereals production per capita in Africa has decreased from 150 to 130 kg/person, whereas in Asia and Latin America an increase from about 200 to 250 kg/person have been observed. Annual cereal deficit in sub-Saharan Africa amounts to 100 million tons and the food gap is widening. Food imports increased by about 185% between 1974 and 1990 while food aid increased by 295%. The average African consumes only about 87% of the calories needed for a healthy and productive life. (Bationo et al., 2004)

Increasing population pressure has decreased the availability of arable land and it is no longer feasible to use extended fallow periods to restore soil fertility. Continuous and intensive cropping without restoration of the soil fertility has depleted the nutrient base of most soils.

The fallow period which would have restored soil fertility and organic carbon is reduced to lengths that cannot regenerate soil productivity leading to system non-sustainability (Nandwa, 2001). Additionally high population densities have necessitated the cultivation of marginal lands that are prone to erosion hence further environmental degradation through soil erosion and nutrient mining. The Global assessment of soil degradation (GLASOD) project estimates that 65% of the African agricultural land, 31% of permanent pastureland, and 19% of forest and woodland has already been degraded (Sivakumar and Wills, 1995). The same authors recently reviewed the global extent of water and wind, chemical and physical land degradation. They stated that the main causes of human induced soil degradation are deforestation, overgrazing, agricultural activities, overexploitation of the vegetation for domestic use, and industrial activities. Areas of soil degradation are extensive in sub-Saharan Africa in the regions bordering the Sahara and Kalahari deserts. 70% of deforestation is caused by farmers, who in their quest for food, have no incentive to ponder long-term environmental consequences (Bationo et al., 2004).

According to Williams and Balling (1994), 332 million hectares of African dry lands are

subjected to soil degradation. This represents one third of the entire area of dry land soil degradation in the world. African soils and particularly those of West Africa, are much weathered and fragile and mostly of low inherent fertility. Soil fertility depletion (mainly N, P and carbon) has been described as the single most important constraint to food security in West Africa.

For many cropping systems in the region, nutrient balances are negative indicating soil mining. Nutrient balances are quantified by subtracting the nutrients outputs from the nutrient inputs in the soil systems. Stoorvogel and Smaling (1990) showed that nutrient outputs generally exceed nutrient inputs. The study, commissioned by FAO on N, P, and K balances for 35 crops in 38 sub-Saharan African countries revealed that the mean annual losses per hectare were approximately 22 kg N, 2.5 kg P, and 15 kg K in the period 1982-1984.

Table 1 shows the aggregated nutrient budgets for some West African countries.

Table 1. Aggregated N, P and K budgets by Country (1983)

Countries	Arable ('000 ha)	Fallow (%)	N (kg ha ⁻¹)	P (kg ha ⁻¹)	K (kg ha ⁻¹)
Benin	2 972	62	-14	-1	-10
Burkina Faso	6 691	50	-14	-2	-10
Cameroon	7 681	50	-20	-2	-12
Gambia	326	29	-14	-3	-16
Ghana	4 505	24	-30	-3	-17
Côte d'Ivoire	6 946	31	-25	-2	-14
Mali	8 015	72	-8	-1	-6
Mauritania	846	79	-7	0	-5
Niger	10 985	47	-16	-2	-11
Nigeria	32 813	18	-34	-4	-24
Senegal	5 235	53	-12	-2	-10
Sierra Leone	1 842	43	-12	-1	-7
Togo	1 503	49	-18	-2	-12

Source: Stoorvogel and Smaling (1990).

Another important factor of soil fertility is the amount of organic matter in the soil (SOM). Organic matter acts as a source and sink for plant nutrients. Other important properties of soil organic matter in low-input agro systems apart from retention and storage of nutrients are increasing buffering capacity in low activity clay soils, and increasing water-holding capacity. (Bationo et al. 1998)

The same author reported (1994) that continuous cultivation in the Sahelian zone has led to drastic reduction in organic matter levels and a subsequent soil acidification. In many tropical cropping systems, few if any agricultural residues are returned to the soil. This leads to a

decline in soil organic matter, which frequently results in lower crop yields or soil productivity (Woomer and Ingram, 1990). In northern Nigeria, Jones (1971) found that during 18 years of continuous cropping, soil organic matter declined at the rate of 3–5% per year. By looking at these figures some scientists wonder how farmers in the Sahel are still able to harvest. Others like Fairhead and Leach (1996) or Leach and Mearns (1996) doubt these so-called doom studies or at least question their interpretations and assumptions. As mentioned above the growth rate for cereals grain yield is about 1% while in the last 50 years a downward rainfall trend can be observed in this region. The yield increase for Millet and Sorghum can hardly be attributed to increased use of external inputs, because these crops receive little fertiliser and are largely based on hand hoe cultivation. (Mazzucato and Niemeijer 2001).

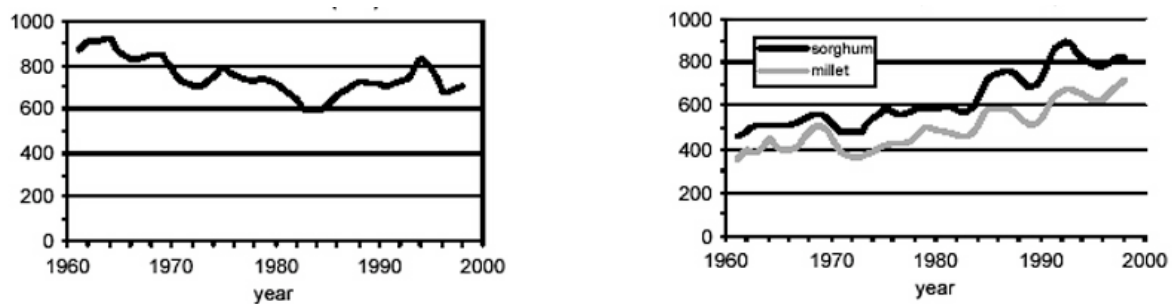


Figure 2: Trend in Rainfall and trend in yield of Sorghum and Millet in eastern Burkina Faso (1960-2000). Source: Mazzucato and Niemeijer (2000)

These authors state that, a major reason for the overestimation of land degradation has been the underestimation of the abilities of the local farmers. These Farmers have developed flexible, efficient, and effective land management strategies to deal with the limited availability of labour and external inputs, as well as the harsh environment in which they work.

Where bough camps of experts, the pessimists and the optimists, meet is in the common opinion that improving the food situation in West African, agricultural growth must depend on improved soil productivity rather than on expansion of area under cultivation. The soil fertility in intensified farming can only be maintained through integrated plant nutrient management with efficient recycling of organic materials such as crop residue, compost or manure in combinations with mineral fertilizers and using rotations with legumes (Bationo et al., 1994).

This work is intended to contribute to the project “Improved livelihoods in the Sahel through the development and implementation of household level bio-economic decision support

systems”, a cooperation of different organisations working on Integrated Natural Resource Management in the Sahel. Participants of this cooperation are: International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Université Catholique de Louvain, Institut National de Recherche Agronomique du Niger (INRAN), International Livestock Research Institute (ILRI), Université Abdou Moumouni and Centre Agrhymet to name but a few. This contribution tries to estimate how the most important factors of soil fertility, that is to say macro nutrients (nitrogen and phosphorus) and soil organic matter, will react on different management options of the local farmer in the long run. A dynamic model was build, based on the work of Bontkes (1999 and 2005) and adapted to the conditions in the Fakara, a region in the south west of Niger. It was tested with the help of the original model and run on different management options like livestock per hectare or input of mineral fertilizer.

2. Material and methods

2.5 Objective area

Fakara is a small natural region of Western Niger covering about 6000 km² between the confluent valleys of the Niger River to the West and the fossil valley of the Dallol Bosso to the East (see fig. 3). The road Niamey-Baleyara follows approximately the contact between the Zarmaganda to the North and the Fakara to the south. Fakara is part of the Zarmatarey (together with the Boboye and Zigui located further East), the country of the southern expansion of the Jerma speaking people coming from the Zarmaganda, the historical cradle of the Jerma people. Though a Jerma region, Fakara also harbours a strong minority of Fulani people who dominate in neighbouring regions to the West (Torodi, Ouro Gueladio), South (Say) and East (Boboye) (Beauvilain, 1977). There are also small minorities of Hausa (Maouri) and Kel Tamachek people established in the Fakara. The Fakara extends over all of two administrative districts: Fakara and Kouré cantons, and part of Hamdallaye, Kollo and Birni Ngaouré cantons. The cantons of Fakara, Kouré and Hamdallaye are all part of the arrondissement of Kollo, itself included within the Tillabery administrative region of Niger (see fig. 3). The study site covers 500 km² (included within latitude North 13° 20' - 13° 35'; longitude East 2° 35' - 2° 52') all falling within the Fakara canton which administrative head is the small town of Dantiandou (lat N 13° 24' 45", long E 2° 45' 23") located at 75 km to the east of the Niger state capital town Niamey. The study area encompasses 10 villages but also extend over the lands of surrounding villages. In 1998, about 6000 individuals are living in the study area all included in the canton of Fakara (Hiernaux and Ayantunde, 2004).

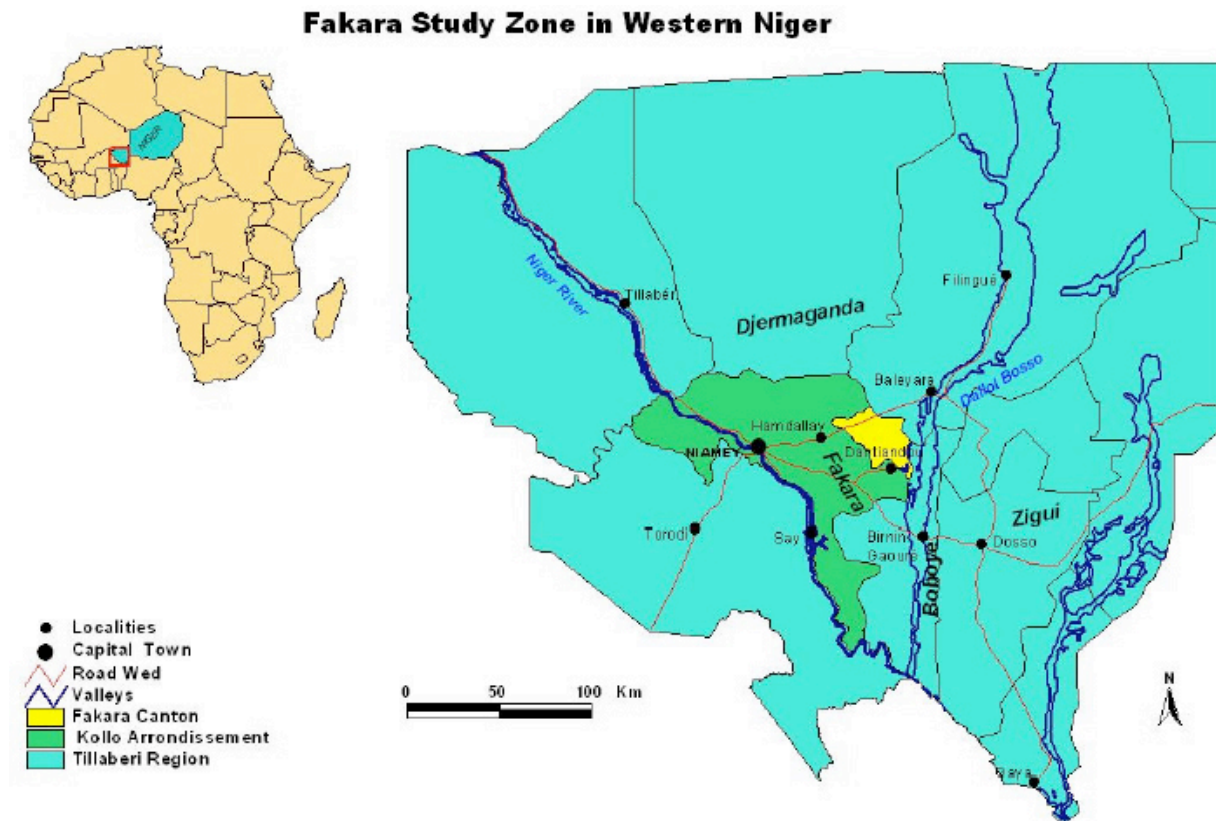


Figure 3: Objective area taken from Hiernaux and Ayantunde, 2004

2.5.1 Climate

The climate in Niger ranges from a Sudanian savannah climate in the south through Sahelian savannah to semi-desert and desert climate in the north (Sivakumar et al. 1993), with the length of the rainy season declining correspondingly from five months to one month.

The Fakara is situated in the Sudano-Sahelian zone with annual rainfall average (1921-1990) of 575 mm in Niamey and of 495 mm from 1968 to 1989 (Lebel et al. 1997). Rainfall takes place in summer when days are long, ambient temperatures are elevated, and potential evapotranspiration is high. Rainfall distribution is strictly monomodal, centred in August, with rainy seasons lasting 4 to 5 months. The rainfall distribution in the Sahel is often described as erratic. Meaning, although the seasonal pattern of this monsoonal system is quite regular, the spatial and temporal distribution of rains during the rainy season is highly irregular and unpredictable. Annual rainfall at a given site varies from year to year with a coefficient of variation between 25 and 30% (Le Barbé and Lebel 1997). Most of the rains fall during the passage of squall lines or convective storms of high intensity. The high prevalence of intense rainfall events contributes to higher rates of soil crusting and runoff than would be expected from the sandy soils and limited relief that are typical for the Sahel (Casenave and Valentin 1989). The long dry season is also characterised by extremely low air humidity (daily minima

< 5%) for 2 to 3 months, along with high temperature and aerosol density.

While the mean annual temperature is 29°C, the mean monthly temperatures range from 33°C in April to 24°C in January (FAO 1994), and their amplitudes increase towards the north.

There are two warm seasons, one after the rainy season and the other, more distinct, one between March and June. The monthly mean maximum temperatures are above 41°C in the hot season and the mean monthly minimum temperatures can reach 16°C in winter (Sivakumar et al. 1993). The averages of the maximum and minimum daily temperatures recorded during 1960-1996 were 46°C and 8°C (DMN 1997).

Over large areas in Niger, especially in the northern Saharan landscapes, the most crucial problem is water availability. The negative effect of erratic rainfall on crop yields has been shown on a nation-wide scale (Ministere de l'Agriculture et de l'Elevage 1997) as well as in field trials (Pichot et al. 1974). Therefore, reliable crop production is limited to regions in the south where average annual rainfall exceeds 300-400 mm. So agriculture is concentrated in the less arid south. Crops are planted and cultivated during the rainy season. Irregular rainfall and inadequate soil and crop management techniques contribute to poor yields and high annual variation in production (Sivakumar et al. 1993). These, variable and erratic climate conditions are said to be the most limiting factors for agriculture in the region. But some studies have indicated that phosphorus and nitrogen rather than water (Bley 1990, Payne et al. 1991) are the most limiting factors on the poor sandy soils of semi-arid Niger.

2.5.2 Soils

Western Niger is situated on various formations of the Precambrian West African shield (Liptako-Gourma region in the west, Aïr in the north-east) and on Palaeozoic, Mesozoic and Tertiary formations of the Iullemeden basin, which extends over most west Niger and southeast Mali.

In the Palaeozoic a gulf open to the north filled the southern limits of the Aïr and Adrar with deposits overlapping towards the south (Greigert 1963). During the Mesozoic and Tertiary the West African shield receded and was periodically invaded by marine transgressions diminishing in thickness to the south and passing laterally into continental series. Uplift movements beginning in the Middle Eocene gave the basin its present aspect. It was subsequently filled with continental, fluvial and lacustrine oolitic iron-containing series (Greigert and Pougnet 1967). Further uplift movements caused these sediments to form an extended land surface undergoing ferralitic weathering and residual iron-oxide accumulation in a humid tropical climate (Leprun 1979). Subsequent dry periods caused the indurations and

sealing of the iron-rich surface, which induced the formation of the ironstone-capped plateau and terraces, found in the southern part of the country. These plateau were carved during the Pleistocene humid periods by river systems originating locally and from the Aïr (Gavaud 1966).

The Iullemeden Basin can be divided into four different sedimentary covers

- A series of Infracambrian age,
- The Perm to Cretaceous “Continental intercalaire”,
- The Upper Cretaceous to lower Eocene “Continental hamadien”,
- The Eocene to Pliocene “Continental terminal”, and
- Quaternary alluvial deposits, dunes and sand deposits

The “Continental terminal” deposits cover the central part of the Basin. At the edge of the Birrimian they have only few decimetres depth but they attain 450 m depth in the centre. (Graef and Vennemann 1999)

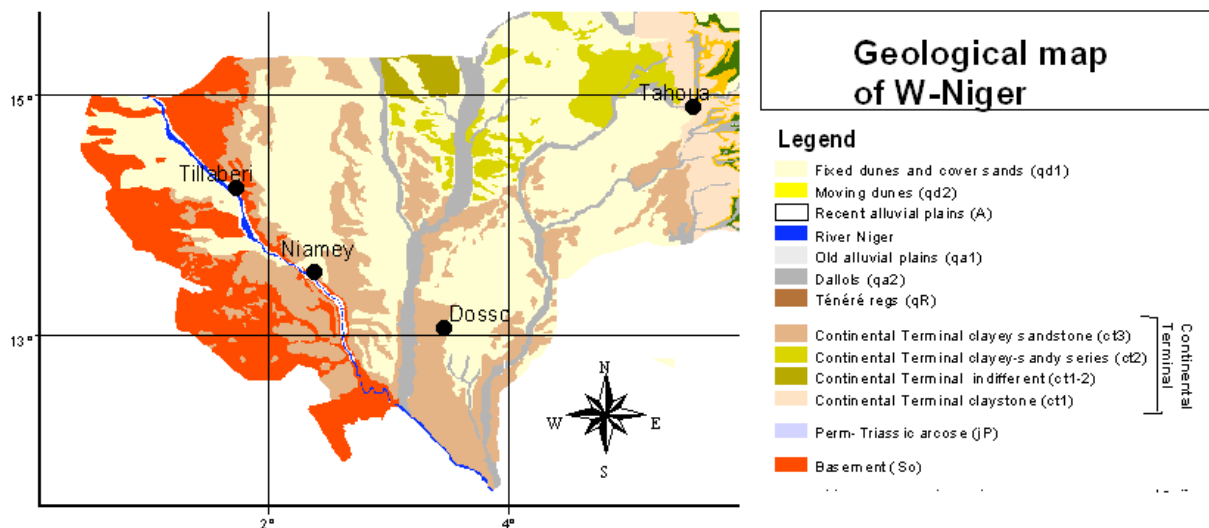


Figure 4: Geological setting of South Western Niger.

Source: Friedrich Graef and Karsten Vennemann, Institute of Soil Science and Land Evaluation University of Hohenheim, 1999.

The Fakara is located in the bottom part of this basin, dominated by more or less loamy sandstones of thick deposits of the tertiary (Greigert, 1966). The geology explains the sandiness of the derived soils and their poor chemical fertility. Topography, geomorphology and soils are inherited from a long history of climate fluctuation during the quaternary: from hyper-arid to sub-humid. The landscape topography is dominated by the horizontal surface of the low sandstone plateau (actually the floor of the sedimentary basin), capped and protected

from further erosion by a 5-20 m thick iron-pan ('cuirasse latéritique'). This iron-pan formed in the B-horizon of a deep ferric soil that developed in the late Pliocene under sub-humid tropical climate. This low plateau was dissected by the River Niger to the West and by the Dallol Bosso, a fossil affluent of the River Niger, to the East and by their tributaries. The Dallol Bosso used to drain waters from a large watershed centred on the Azawak basin extending to the Adrar of Ifoghas, Ahaggar and Aïr mountains. The Dallol Bosso carved in the continental terminal sandstones a 12-18 km wide valley bordered by cliffs (Beauvillain, 1977). This valley oriented North-South limits the Fakara to the east. As in all the Sahel, arid and sub-humid climates alternated during the quaternary shaping landscapes and soils. Wind erosion during the arid periods of the quaternary triggered the selective export of clays and loams deposited as loess further south as in the Kano area in northern Nigeria (Mortimore, 1989) and the deposition of sand on the slopes and in the valley, sometimes extending over the low plateaus. Sand deposits and dunes established during the more arid periods were then reshaped by water erosion and covered by savannas during the more humid periods of the quaternary. In spite of low altitude and quite homogeneous geological background, alternating arid and sub-humid climates during the quaternary resulted in a large diversity of edaphic situations, organised along the slopes in loose hierarchy (Fig 3). The chemical properties of the top soils, texture, acidity, organic and nutrient content depends on the age of the deposit, and the number, duration and extent of the dry and wet periods that occurred since they were put in place (Gavaud and Boulet 1967).

As a result of alternating humid and arid periods, landforms and soils are all polygenic. Despite their polygenic nature, the land form and soils vary along the slope, the material found in the soils of the plateau or up-slope is closer to the Eocene kaolinic weathering mantle and ferralitic soils, while down-slope material, when it is not recent colluvium, are highly leached of clay and iron. Except for the content in organic matter more linked to management, the main soil characteristics can be related to land form and topographic position. Thus, the depth of the loose soil above either weathered sandstone or iron pan, the texture and colour of the loose material are major characteristics of the soil types.

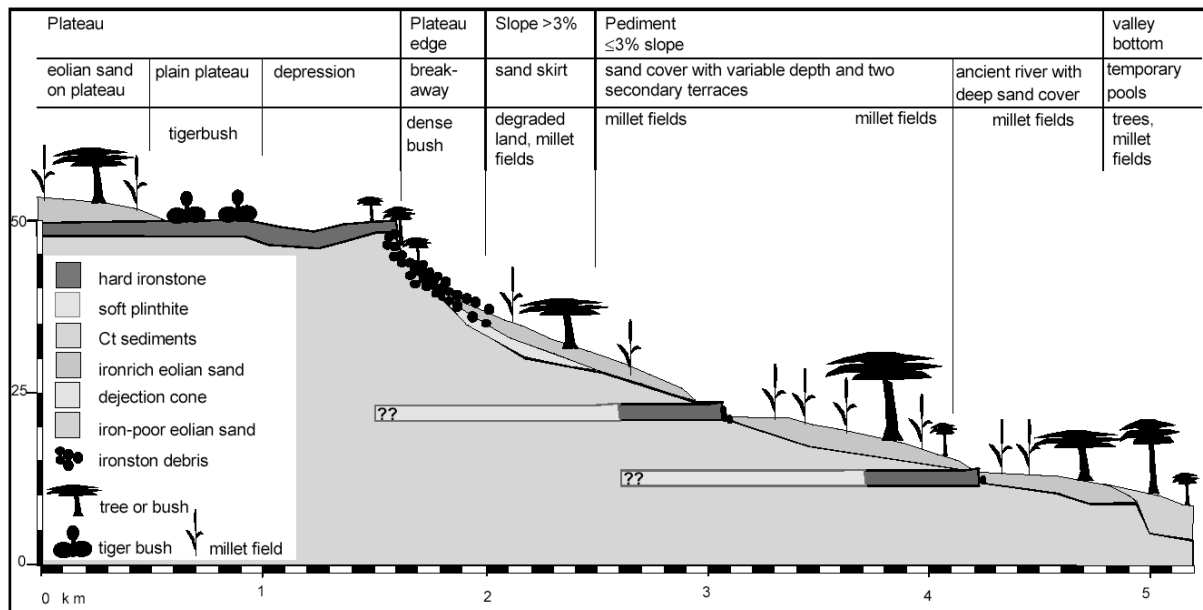


Figure 5: Generalised Continental terminal (CT) landscape patterns, taken from: Frieder Graef and Karl Stahr 2000

In their survey in 2000 Graef and Stahr found that in terms of texture, pedogenesis and depth, the main soil groups in the study area are Arenosols and Cumulic Anthrosols (39%), Arenic soils, which have a sandy superficial stratum thicker than 20 cm overlying stony or heavy-textured soils (22%), Acrisols, Alisols and Luvisols (7%), Cambisols (6%), Leptosols (20%), Vertisols, Gleysols and Fluvisols (5%) and others (1%). This corresponds to 38% sandy soils, 22% sand-covered stony or loamy-clayey soils, 20% shallow stony soils and 18% loamy-clayey soils.

Topsoil tends to be rather acidic. The mean pH (H₂O) is usually between 5 and 7. Annual pH alterations of 0.1-0.4 units due to seasonal dynamics are common (Hebel 1995). Alluvial and granite soils have higher pH values of 6-7, compared to soils on the CT, schist or sandy soils with a pH of 5-6. Sandy soils overlying basement material tend to have topsoil with a higher pH (pH 5.9), which remains or even increases with depth whereas sandy soils on the CT have a lower pH (pH 5.5), which decreases with depth (pH 5.2). Higher topsoil pH may be an effect of buffering substrates (e.g. calcite) imported by dust (Herrmann 1996) or base renewal through the plant-soil bio cycling (Manu et al. 1996). Most soil profiles show a slight CEC increase with depth due to the higher clay contents. The CEC increases in the topsoil significantly with OM content. Cation exchange capacity, varying in relation to clay content, often very low, is usually unsaturated. Average CECs range from 1.3-4.4 (sandy soils) to 4.5-7.3 (loamy CT soils) and to 6.6-22.5 (loamy alluvial and basement soils) (Graef and Stahr 2000).

All soils tend to have low organic matter content and weak structure (Trop Soils, 1991; West et al. 1984). The average Corg for this sandy soils ranges from only 2.5 ‰ in the epipedon to 1.3 ‰ in the subsoil. Whereas corresponding values for Corg contents of heavy-textured soils are 6.7 ‰ and 4.1 ‰ respectively. The higher contents in heavy-textured soils can be attributed to stabilising organo-mineral complexes and the external influx of organic matter and stagnant water in alluvial sites. Corg decreases significantly with depth but the overall high soil densities of profile sets indicate a considerable disorder caused by soil erosion, redistribution and burial.

The averaged total nitrogen for sandy soils ranges between 0.3 ‰ in the epipedon and 0.2 ‰ in the subsoil, while heavy-textured soils show average Ntot contents of 0.7 ‰ and 0.4 ‰ respectively. Throughout the soil depth Ntot is correlated with the Corg ($r = 0.64$ and 0.57 at $p < 0.5$), but the Ntot - soil depth correlation itself is only weak (Graef and Stahr 2000). This is probably due to the mobile mineral N components (NO_3 and NH_4), which constitute 5- 20 % of the total N in those soils (Hebel 1995). Considering the water to nitrogen balance, Breman and de Ridder (1991) postulated that range production would become N-limited above 250 mm yr^{-1} of available soil moisture per year and established relationships to predict primary production from infiltrated rainfall and N availability, along with estimated N losses through grazing, volatilisation and leaching. In other Sahelian sites, P was recognised as the first limiting factor of primary production (Buerkert 1995). The available phosphorus (Pava) contents of the topsoils are distinctly higher than those of the subsoils. This is attributable to the integration and release of P within the superficial biocycle (Hammer 1994, Geiger et al. 1992).

Table 2: Soils types and main characteristics of the Fakara

	Arenic Gleysol	Gleyic Arenosol	Leptic lixisol	Arenic Cambisol	Arenic lixisol	Ferralic arenosol	Skeletal leptosol
Topography	valley	valley	down- slope	flats	mid- slope	up-slope	plateau
Land form	river bed	alluvial deposit	erosion surface	colluvial fan	sand deposit	eroded deposit	plateau cliff
Depth (cm)	> 300	> 300	20 to 80	> 300	> 300	10 to 50	0 to 10
Color (0-20)	10YR5/ 6	5YR 5/8	7.5YR3/ 4	10YR6/4	7.5YR4/ 6	5YR5/6	7.5YR 5/6
Texture at 0-30 cm depth							
gravels (% total)	0	0	0	0 to 5	0	0 to 20	20 to 90
sand coarse%	2-5	45-48	40-50	45-50	40-50	34-36	32-35
sand fine%	35-40	40-45	35-40	38-42	40-50	50-53	32-38
silt %	30-35	2-3	5-8	3-5	2-3	4-7	5-8
clay %	15-25	6-12	7-12	5-10	2-5	4-8	12-17
pH (water)	5.5-6.3	5.0-5.3	5.0-5.5	4.5- 5.5	5.2-6.2	5.0-5.9	5.0-6.0
CEC (meq/100g)	5.0-7.0	1.5-2.0	2.0-2.5	1.0-2.0	0.8-1.2	1-1.6	2.0-2.5
Total N (ppm)	250-350	60-120	150-200	200-250	100-250	150-250	200-300
Total P (ppm)	2.5-5.0	1.5-2.0	1.2-2.5	1.5-2.0	1.5-3.5	0.7-1.5	2.5-5.5
K (meq/100g)	0.20- 0.40	0.02-0.03	0.02- 0.03	0.03-0.05	0.03- 0.06	0.04- 0.09	0.20-0.30
OM (%)	0.40- 0.80	0.08-0.25	0.25- 0.35	0.20-0.70	0.12- 0.17	0.15- 0.30	0.1-0.5

Sources: Desconnet, 1994; Gavaud and Boulet, 1967; Rockstöm and Valentin, 1996;
Tropsoil, 1991

2.5.3 Land use and crop production

The agricultural system is characterised by the cohabitation of two agrarian cultures, the Jerma crop-farmer culture, and the Fulani pastoralist culture. For a century, both agrarian cultures have co-evolved towards sedentary crop-livestock systems (Bonfiglioli, 1990).

The present farming system is largely subsistence oriented, based on millet (*Pennisetum glaucum L.*) and sorghum (*Sorghum bicolor L.*) associated with a range of secondary crops, either dual-purpose legumes like cowpea (*Vigna unguiculata L.*) and groundnut (*Arachis hypogaeae L.*) or pure cash crops like sesame (*Sesamum indicumL.*) and sorrel (*Rumex acetosa L.*).

Most families possess some livestock, particularly small ruminants, but many also own some cattle for meat, sale and draft power. Animal husbandry is a major source of income and the stock often represents the farmer's savings. Animals are either kept in or around the villages or given to contract herders of the Fulani (Peulh) ethnic group, who guard the animals on village pasture land or go on transhumance to far off pastures, especially in the rainy season, when animals are not allowed to enter the millet fields. Rangelands and fallowed lands, however, are common ground and grazed year round (Schlecht and Huelsebusch 2000). After harvest, trough most of the dry season, cattle are corralled at the best fields to feed on crop residues and improve soil fertility by manure deposition.

The most important production unit is the nuclear family consisting of about 8-14 members. The farm is managed by the family head (farm-household chief) who has the overall responsibility for the family members and for all collective activities such as the production of adequate food on the family fields. The farm chief and his wives (up to four according to the Islamic law) form separate economic households with their own capital resources and a certain freedom of decision-making (Heidhues et al. 1996).

The over all family labour capacity determines the area cultivated. In western Niger, average land cropped per household is less than 5 ha and less than 1 ha per adult equivalent in the densely populated Dallol Bosso (Beauvilain, 1977), while in less densely populated villages of Fakara, lying immediately to the west, these values increase to 13.2 ha per household and 2.3 ha per adult equivalent (Hiernaux and Ayantunde 2004)

The predominant staple crop millet is either cultivated as a single crop (58%) or as an intercrop with cowpea (23%). Minor important crops are sorghum (9%) or groundnut (6%) cultivated at more remote fields or restricted to small areas and plots within the fields (Laouali and Rockström 1993). The legume crops produce both, valuable hay for the

livestock and protein-rich grains that are usually sold on the local market (Enger 1979, Heidhues et al. 1996). In intercropping systems the crops sown later are usually of minor importance with only small amounts harvested.

The best cropland is considered the level and lightly sloping terrain with deep sand cover, as the valley bottom is highly prone to flooding in the rainy season and the shallow and hard loamy soils of the plateaux are too poor to crop. There the so-called Tiger bush is located earning its name from the regular banded patterns of vegetation bands or dots, alternated by bare soil. It is usually degraded due to overgrazing and removal of fuel wood. The proportion of crop land to fallow land and tiger bush was once 2 : 2 : 1. (Kusserow 1994, IGN 1965-1996) but is now shifting to cropland.

As already mentioned in the introduction, the increasing population pressure on available lands, leads to shorter fallow periods, increased soil degradation and declining yields. Lands unsuitable for cropping because of slope, erosion hazard or shallow soils with marginal potential are being taken into cultivation (Enger 1979, Laoualy and Rockström 1993). This extension leads to diminishing grazing land and fodder for livestock and consequently to land conflicts between farmers and herders (Neef 1998). Level terrain with deep sands cover is left fallow for shorter periods than sloping land and plains with or without thin sand cover.

On land, formally considered marginal, the cropped area is rapidly increasing on account of pasture or fallow land. Presently, half of the sloping or lightly sand-covered land (40%) is cultivated. The Tiger bush on plateaux is also degraded due to overgrazing and removal of wood for fuel (Graef and Stahr 2000).

Production technique

Starting with the first substantial rains (approximately 50 mm of rain within the interval of a few days) in early June to early July the farmers start to seed millet with the aid of all family members. Customary pocket densities are 5.000 - 8.000 Pock.ha⁻¹. Reseeding is commonly necessary during the first weeks due to droughts or damage to young seedlings by water- or wind-erosion. The first weeding takes place about 10 days after planting. The first weeding leaves about 2-3 plants per pocket. Two to three weedings are carried out, depending on weed development and labour availability. In intercropping systems cowpea is sown 2-3 m apart between every second or third millet row after 3-4 weeks. Crop rotation is considered beneficial to the land, but it is not done regularly or on large areas (Graef and Stahr 2000). Fallowing is the principle management practice used to restore soil fertility, but these practices have changed over the years because of uncertain yields and increasing pressure on

the land. The traditional long bush fallow of over 10 years is breaking down to be replaced by 3-5 year fallow periods (Taylor-Powell et al. 1991, Wezel 1998) or even shorter periods. Due to the difficult land right situation in the area borrowed but also owned land is often tilled, dry sown and then abandoned, without any yield expectation, in order to pretend the land is being used and thus precluding others from using it. Such land is called “disguised fallow” (Taylor-Powell et al. 1991). Before again taken into production, fallow is cleared by cutting off bushes and small trees, weeding and burning the biomass. Simultaneous cropping/fallowing e.g. with bush management in fields (Wezel 1998) is not practised.

Mineral fertiliser use (triple or single superphosphate and urea) is on average below 1 kg ha⁻¹ yr⁻¹ (Bationo et al. 1999). This is due to

1. high fertiliser prices,
2. limited market access,
3. poor fertiliser availability and
4. poor technology adoption (Haigis et al. 1998).

It is usually applied broadcast in low quantities (5-20 kg ha⁻¹ y⁻¹) or placed next to the planting pockets. Crop residues, animal manure and household wastes are more important sources of nutrients and are generally applied on fields close to the homestead. Remote fields (>3 km) receive hardly any fertiliser inputs (mineral or others) (Graef and Stahr 2000).

Farmers apply manure either during the dry season by corralling livestock overnight on the fields or by manually spreading manure transported from the village. Herding contracts are made with the pastoralists (Fulani) committing the herders to keep their cattle for 3-4 nights on a field in return for money or food. Herding contracts are more likely to be made by rich farmers (Graef 1999).

Animal manure is preferred to mineral fertiliser because it is cheaper and is said to last 5-10 years, depending on the amount, manure type (cattle, goat, sheep), soil type and time of year (Taylor-Powell et al. 1991). In former times Millet stalks and other plant residues were burned after harvest or removed from the field as building material. Today they are increasingly used as mulch to cover the less productive parts or the entire field. This is done in order to

1. reduce wind and water erosion;
2. regenerate degraded land through accumulation of wind-blown sand;
3. loosen crusted surfaces by termite activity and
4. restore soil fertility (Baidu-Forson 1995).

The availability of plant residues, however, is restricted by the amount of biomass harvested.

The level of agricultural mechanisation in Niger is very low. The most common tool for field preparation and weeding on sandy soils is a long-handled hoe (hilaire), which penetrates only the upper 5-10 cm. For pocket preparation and cultivation of heavier soils a short-handled hoe is used. For deep cultivation, only necessary for rice and groundnut, a short hoe or an ox drawn plough is used. Labour inputs for field preparation and sowing range from 150 h ha⁻¹.yr⁻¹ to 2200 h ha⁻¹.yr⁻¹, depending on labour capacity, field status, field distance, soil characteristics and type of crop (Graef et al. 1998). Because of non-till, the bottleneck of cereal cropping is often the labour required for weeding, the efficiency of which is as low as 0.15 ha per adult per day for manual weeding (Achard and Banoin, 2003).

They can be alleviated, to a certain extent, by seasonal labour migration and mechanisation (e.g. ox-plowing), but this is rather seldom used. Animal traction is used for transport of people and material with carts. While males do most of the work on the millet fields, women cultivate irrigated vegetable gardens near the house.

2.5.4 Livestock

As mentioned in the preceding chapter the livestock sector plays an important role in SW-Niger. This can also be observed at the macroeconomic level. In 1997, livestock contributed about 20% to the country's overall export volume of about US\$ 270 million. (FAO 1998) Historically, the pastoral livestock keepers dominated livestock husbandry in Niger. Still today they belong to certain ethnic groups. This is to say, the Fulani (Peulh), Bororo, Farfarous, Touareg, Toubou, Arabs and to a lesser extent the Boudoumas around Lake Chad (Huelsebusch and Schlecht 2000).

According to Abdoulaye and Habou (1994), livestock production systems have since changed and can nowadays be differentiated into six main types of production system and producer:

1. Owners of large herds,
2. Agropastoralists (mainly inhabiting Western Niger),
3. Modern livestock producers with medium size holdings,
4. Smallholder livestock producers,
5. Reoriented traditional pastoralists,
6. Reinforced traditional pastoralists.

In the area under observation the smallholder livestock producer and the traditional pastoralists are of highest significance. Today the smallholder livestock producers own the major proportion of livestock in Niger's rural areas. The animals are either kept in mixed farming systems, where livestock is closely intertwined with the agricultural crop production

activities of the farming household. The pastoralists (in case of SW Niger mostly agropastoralists) on the other hand keep and manage livestock in large herds who feed on communal rangeland and crop residues on the fields in dry season and go on transhumance to far of places in wet season. In both cases they are usually allowed to graze freely or are herded on communal pasture areas, on fallow land or, after the croüing season on harvested millet fields, feeding on crop residues.

Table 3: Production factor endowment of three villages in the Fakara

Site	Territory km ³	Land use % of tot. area				Households No.	Ruminant stock TLU
		Rangeland	Fallow	Non-manured	Manured		
Bani	102.0	13.4	50.4	32.6	3.6	224	789
Tigo	106.0	14.9	44.6	35.6	4.9	198	930
Kodey	71.8	9.3	25.6	57.1	8.0	124	821
Sum	279.8	37.6	120.6	125.3	16.5	546	2540

Source: Schlecht et al. 2004

2.6 Modelling

A simulation model is a set of equations and parameters that tries to simulate a particular system. Simulation Models have become useful in modelling many natural systems in physics, chemistry, biology but also human behaviour in economics and social science. With its help one can gain insight into the operation and understand the behaviour of such systems. The development of the computer and its growing calculation capacity in the last decades made it possible to build and calculate more and more complex models.

Computer simulation was first developed during the Manhattan Project in World War II to model the process of nuclear detonation, using the so-called Monte Carlo method (Eckhard 1987).

2.6.1 Definitions

A model tries to describe a system of the real world in a more or less abstract way. The degree of realism depends on the degree of complexity of the model. The complexity the user should strive for depends on the objective of the model. An explanatory model should be simple. Its purpose is to grant the user insight in to the system and allow him to understand the most important interrelations within the system. A simulation model, in the proper meaning of the word, is a predictive model. It has to be more complex. Yet its objective is to predict certain outputs by the inputs to the system, as precise as necessary or sometimes even as possible.

A system is an assemblage of inter-related elements comprising a unified whole. These elements (or components) are typically connected in order to facilitate the flow of information, matter or energy.

Systems can be either open, closed or something in between. A closed system is self-contained within its boundaries. Outside events can have no influence upon the system, whilst an open system can be influenced by events outside of the declared boundaries. In practice many systems are a mixture of both.

Whenever time plays a role and the components or flows of the system are subdued to change over time, one speaks of a dynamic system.

In system analysis the different components of a system are pictured by abstract elements.

- Reservoirs
- Flows
- Converters
- Sink / Sources
- Interrelations

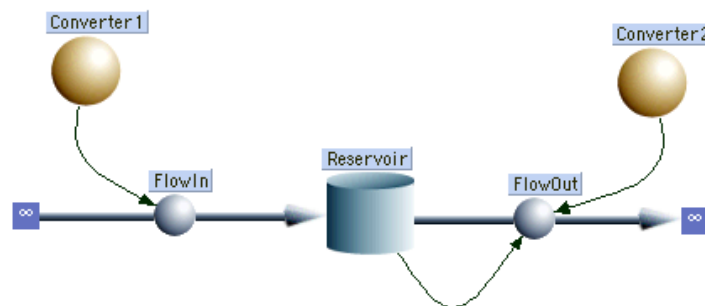


Figure 6: schematic picture of a simple system (open)

Reservoir

A reservoir can be thought of as a repository where something is accumulated, stored and potentially passed to other elements in the system. (Deaton and Winebrake 1999) This may be e.g. certain populations in a predator pray system as well as nutrients in a plant soil system. Nearly everything is imaginable.

Flows (Processes)

A Process is an ongoing activity within the system that determines the contents of the reservoirs over time. (Deaton and Winebrake 1999) This may be for example the uptake of nutrients by the plant. From the perspective of the single reservoir flows can be positive (inflow) or negative (outflow).

Converters

Converters are system variables that can play several different roles within a system. Their most important role is to dictate the rates at which the processes operate and therefore the rate at which reservoir contents change. (Deaton and Winebrake 1999) Although nutrient uptake is determined by many factors, one would certainly be the growth rate of the plant. So in the mentioned example plant growth would act as a converter.

Interrelations

Interrelations represent the intricate connections among all components of the system. These relationships are usually expressed in terms of mathematical relations. (Deaton and Winebrake 1999) In figure 6 these relationships are symbolized by small arrows, connecting the different elements of the system. As mentioned before nutrient uptake is not only dependent on plant growth but also on e.g. the availability of nutrients and many more factors. One can take all of them into account by relating them to the nutrient uptake.

Sink /Source

In an open system it is possible that a flow takes information, matter or energy from outside the system boundary into the system. On the other hand it is also possible that a flow leaves the system boundary and that information, matter or energy is lost to the system. The signs for eternity personate this in figure 6. A good example for a flow leaving the system might be the leaching of nutrients irretrievable lost to the rooting zone of the plant.

2.6.2 Classification and examples

Computer models can be classified according to several criteria:

- Stochastic or deterministic
- Discrete or continuous

Stochastic methods are also known as Monte Carlo methods (see above), they can be loosely described as statistical simulation methods, where statistical simulation is defined in quite general terms to be any method that utilizes sequences of random numbers to perform a simulation. (CSEP 1995)

Deterministic simulation models attempt to represent the underlying mechanism explicitly, and typically consist of interlocking systems of differential or difference equations.

In a discrete system, one or more phenomenon of interest change value or state at discrete points in time, rather than continuous with time. (Fishman 2001)

The discrete event simulator (DES) emulates the behaviour of an interconnected network of real processes in response to designated events. Many real world systems can be modelled as a DES where internal and external events occurring at specific times cause the system to change from one state to another, possibly generating outputs and events to occur at a future time.

A special type of discrete simulation, which does not rely on a model with an underlying equation, but can nonetheless be represented formally, is agent-based simulation. In agent-

based simulation, the individual entities (such as molecules, cells, trees or consumers) in the model are represented directly (rather than by their density or concentration) and possess an internal state and set of behaviours or rules which determine how the agent's state is updated from one time-step to the next. (Wikipedia 2005)

A continuous simulation uses differential equations (either partial or ordinary), implemented numerically. Periodically, the simulation program solves all the equations, and uses the numbers to change the state and output of the simulation. The period within this is done is also called time step and can be any unite but ranges mostly from one day to one year.

World3

One of the first widely known computer simulations was Donella Meadows “World3” introduced in the Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind (1977) and further improved in Beyond the Limits (1992).

World3 was designed to understand how human society will approach the world's changing carrying capacity, and what conditions or policies will increase the chance of a smooth approach to that capacity.

World3 accounts for interactions between population, industrial growth, food production and limits (caring capacity) of the ecosystems of the earth.

The model consists of several interacting parts. Each of these dealt with a different system of the model. The main systems are the food system, dealing with agriculture and food production, the industrial system, the population system, the non-renewable resources system and the pollution system. When first introduced it caused a storm of controversy about its grim portrayal of the future: dramatic collapse resulting from uncontrolled growth.

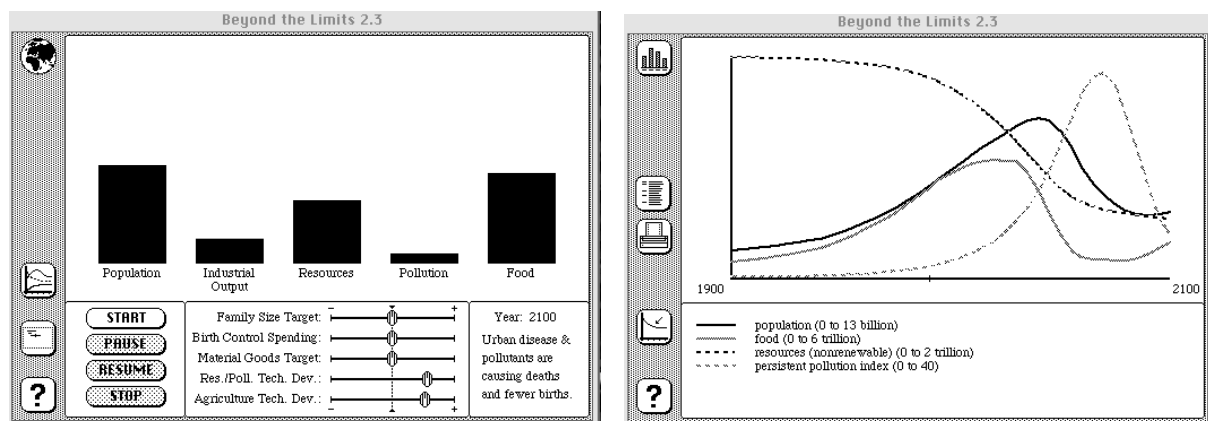


Figure 7: In- and output screen of a world3 run

GCM

The collapse World3 predicts is due to population growth causing the resources to deplete and pollution by economic growth in general. Something, which is not in deep investigated in World3, is one of the major challenges mankind faces today, the climatic change caused by greenhouse gases. Only in the last couple of years, with increasing computational power, it is possible to tackle this task. Simulations trying to predict climate for decades or even centuries are called GCM's. GMC stands for general circulation model but could also be understood as global climate model. Such computer models numerically solve fundamental equations describing the conservation of mass, energy, momentum, etc. for a atmospheric gridbox with different resolutions (e.g., $8^{\circ}\times 10^{\circ}$, $4^{\circ}\times 5^{\circ}$, or $2^{\circ}\times 2.5^{\circ}$), while taking into account the transfer of those quantities between grid boxes. Additionally they consider up 30 vertical layers in each grid box. State-of-the-art GCMs are coupled atmosphere-ocean models. The interface is the sea surface: that is where the transfers of water (evaporation/precipitation) and momentum occur. An accurate coupling of the fast atmosphere to the slow ocean (with its long memory) is essential to simulate phenomenon like El Niño/La Niña or the Gulfs stream. GCM's can further be coupled to dynamic models of sea ice and conditions on land.

An example of one sophisticated GCM is the GISS ModelE (Schmidt et al. 2006). This is the culmination of a multi-year developmental process, by the NASA Goddard Institute for Space Studies (GISS). ModelE includes the option of coupling to a variety of ocean models, including fully dynamic three-dimensional ocean general circulation models and the full incorporation into the model of a number of tracer subsystems including atmospheric chemistry and aerosol transport. Calculating this kind of simulations is very time consuming and not feasible without supercomputer.

WaNuLCAS

An example for a purely agricultural Model is WaNuLCAS, an acronym for Water, Nutrient and Light Capture in Agroforestry Systems. It was build by Noordwijk et al. (2004) for the International Centre for Research in Agroforestry (ICRAF). WaNuLCAS is a dynamic model built in the Stella modelling environment (Hannon and Ruth, 1994) linked to Excel spreadsheets for data input and output. It represents tree-soil-crop interactions in a wide range of Agroforestry systems where trees and crops overlap in space and time. The model is based on above and below ground architecture of trees and crops. With its help the user can explore positive and negative interactions for different combination of trees, crops, soil, climate and

management. This is achieved by simulating a 4-layer soil profile (see figure 8), a water- and nitrogen balance and the uptake of bough by crops and trees.

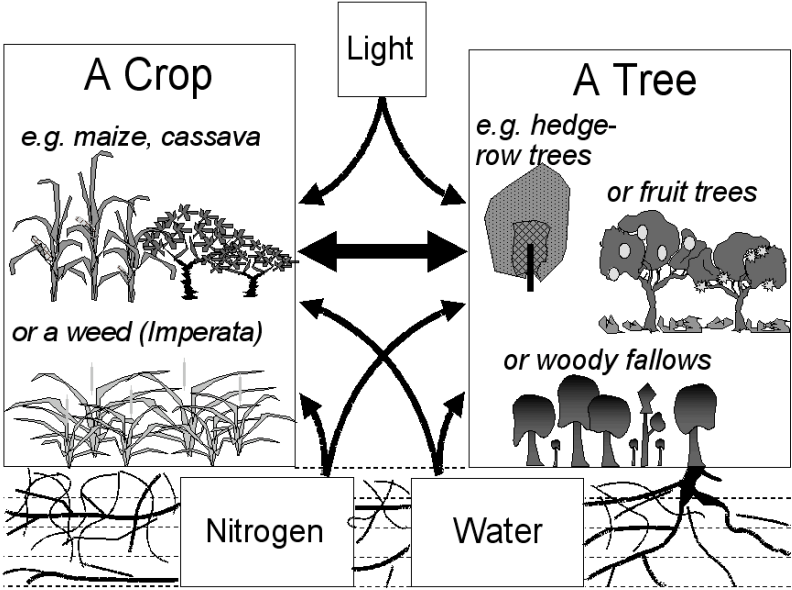


Figure 8: schematic figure of WaNuLCAS, taken from Noordwijk et al. (2004)

Some examples of management systems WaNuLCAS is able to account for are: different pruning regimes, hedrow spacing and rate of fertiliser application. Due to the Stella environment it is relatively easy for the user to modify modules and change relationships. Output is given in table form or shown as a graph (see figure 9).

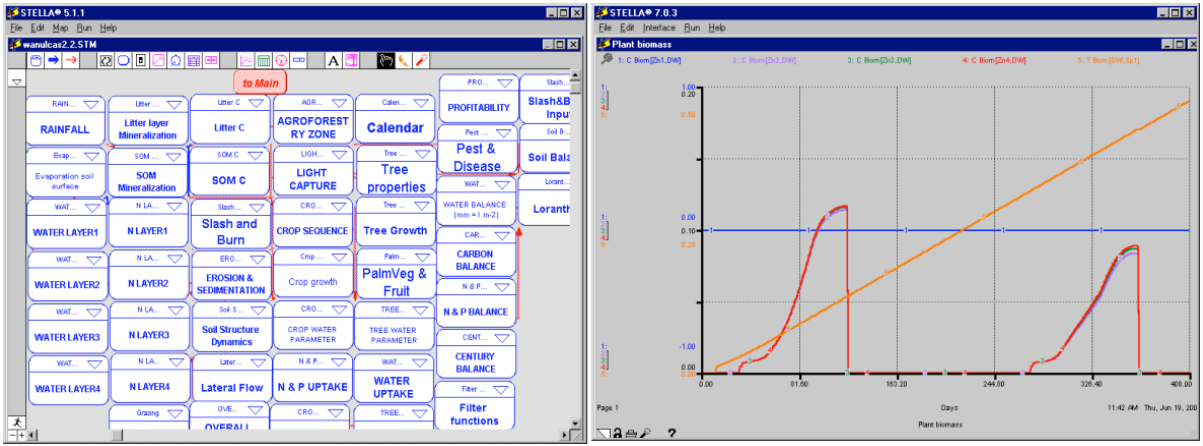


Figure 9: Stella modelling environment and output screen of WaNuLCAS

ORYZA

While WaNuLCAS accounts for different plants and their interrelations in a certain environment, the ORYZA model is more specific and only investigates one crop. It was built by the IRRI (International Rice Researcher Institute) in cooperation with the university of Wageningen and a couple of other universities in SE Asia, to forecast the growth and development of rice (*Oryza sativa*) yield under certain management regimes. This model runs in the FORTRAN modelling environment and was based on SUCROS-87 by Spitters et al. (1998). The first version ORYZA1 was only able to simulate the potential yield of lowland rice. Still today ORYZA1 is the core of the ORYZA2000 model but with the addition of eight other small sub routines it is now able to simulating either the water- or the nitrogen-limiting yield, but not bough simultaneously. ORYZA1 calculates growth and development of rice as a function of daily weather data, crop characteristics, and management parameters (see figure 10). It takes into account drought stress calculated by WSTRESS / WNOSTRESS and nitrogen limitation effects calculated by NCROP (in nitrogen-limited situations) or by NNOSTRESS (potential production). The sub routine ET simulates potential evapotranspiration of soil and plant, and based on this either WSTRESS (in water-limited situations) or WNOSTRESS (no water limitation) calculates the actual transpiration and the water uptake by the crop. NSOIL is a simple routine for tracking the daily nitrogen availability for crop uptake in the soil, whilst IRRIG calculates the daily irrigation water input for the soil-water balance as determined by user-defined management settings. PADDY is a soil-water balance that calculates the soil water content on a daily basis (IRRI 2004). ORYZA was effectively used to optimize N-fertilisation to a yield increase up to 15% in India and China (Bouman 2004). It is also used to simulate rice yield development in different climatic change scenarios and for mapping of potential rice yields in SE Asia (Grenz 2005).

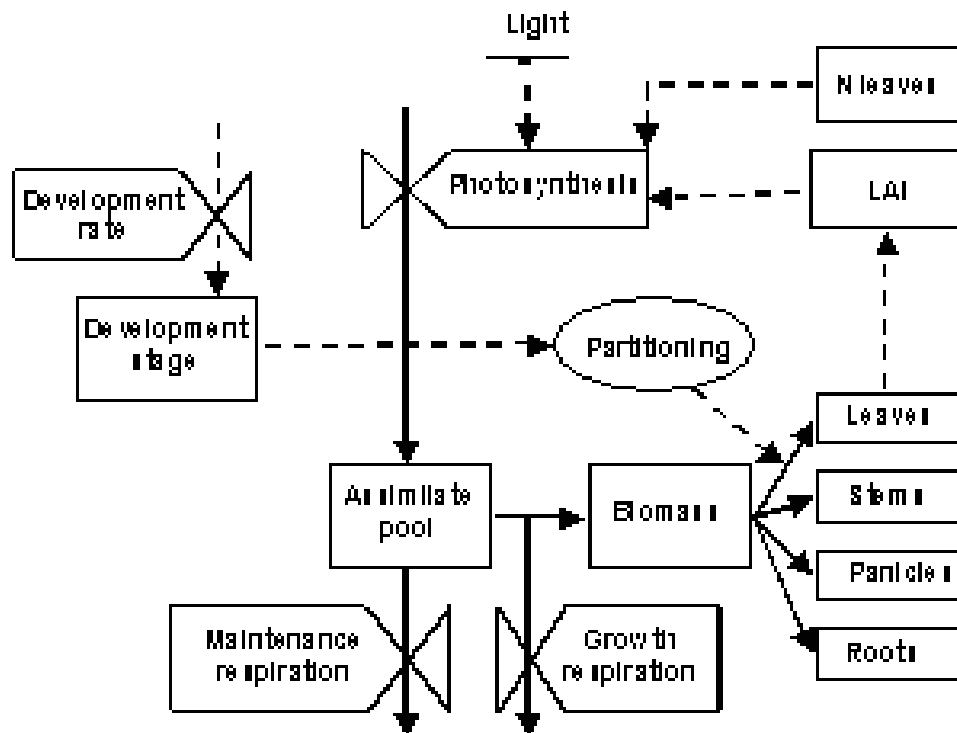


Figure 10: Scheme of the ORYZA1 model with major pools, flows and interrelations, taken from (IRRI 2004).

APSIM

One of the most complex and up to date plant simulations, to mention, is APSIM (Agricultural Production Systems Research Unit). It was developed in a joint venture of the state of Queensland, CSIRO (Australia's Commonwealth Scientific and Industrial Research Organisation) and The University of Queensland. APSIM simulate biophysical processes in farming systems with special regard to the economic and ecological outcomes of management practices in the face of climate risk (CSIRO 2005). One big advantage of APSIM is its modular structure (see figure 11). The core of this model is the calculation engine, connecting the different modules the user wants to use in his simulation. At this point in time there are 10 soil modules, 24 plant modules and some 24 additional modules available. Soil processes include N and P-dynamic, organic matter, soil pH and many more. Currently crop modules are available for barley, canola, chickpea, cotton, cowpea, hemp, fababean, lupin, maize, millet, mucuna, mungbean, navybean, peanut, pigeonpea, sorghum, soybean, sunflower, wheat and sugarcane. In addition there are general modules for forest, pasture and weed as well as specific implementations for the pasture species lucerne and stylo. (Keating et al. 2002). Management-options are manifold they include, date of sowing, sowing density, crop rotation, fallow, irrigation, soil cultivation and many more. Also included are biotic factors like pests, diseases and weeds.

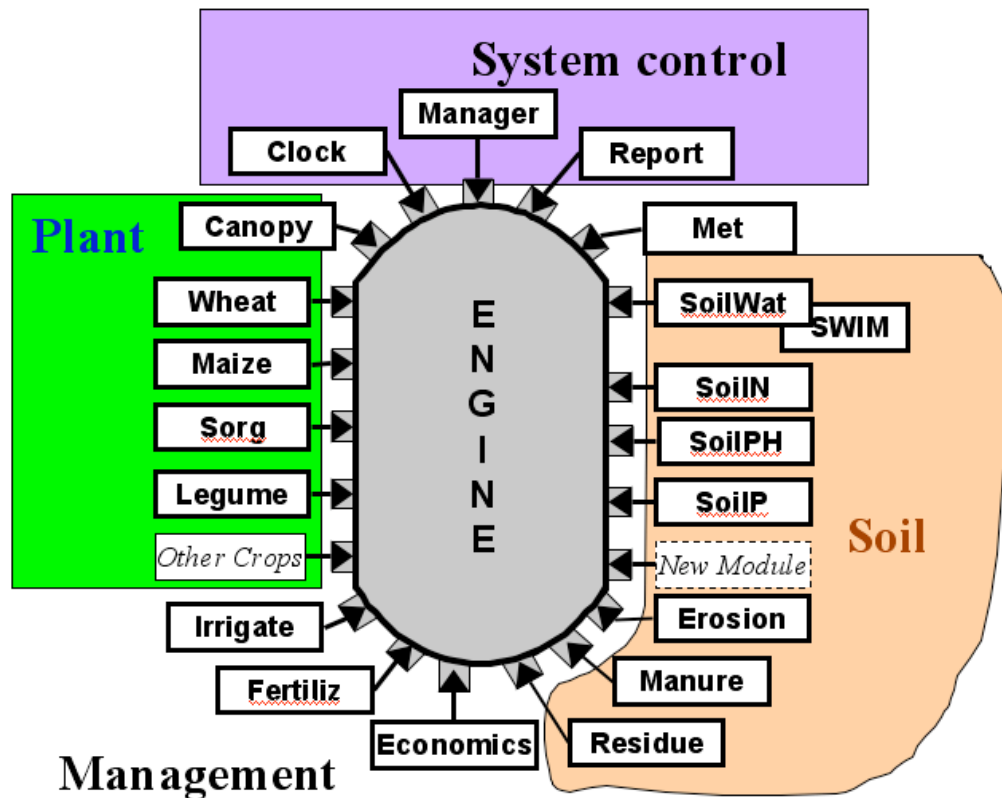


Figure 11: Modular structure of the APSIM model, taken from Grenz (2005)

The structure of all plant modules follows the same, process-orientated principle (“Genericity”-principle) (Grenz 2005). APSIM plant module simulates the basic simulation of crop growth and development in a daily time step on an area basis (per square meter). Growth and development in this module respond to weather (radiation, temperature), soil water and soil nutrients. The plant module returns information on its soil water and nutrient uptake to the soil water and nutrient modules on a daily basis for reset of these systems. Information on crop cover is also provided to the water balance module for calculation of evaporation rates and runoff. Crop- and root residues are ‘passed’ to the surface residue and soil nutrient modules respectively at harvest of the crop. Furthermore special properties of certain crops are taken into account. The millet module, for example, is specifically designed to deal with the tillering nature of that crop. In the simulation each axis of the crop is considered to be a different crop, and the competition for resources between the axes is simulated analogous to an intercrop (CSIRO 2005).

APSIM has been used in a broad range of applications including:

- support for on-farm decision making and extension service,
- farming systems design for production or resource management,
- assessment of the value of seasonal climate forecasting,
- analysis of supply chain issues in agribusiness,
- development of waste management guidelines,
- risk assessment for policy making,
- as a guide for research and educational activities, e.g. in the field of plant breeding.

The ability of APSIM to integrate models derived in fragmented research efforts enables research from one discipline to be transferred to the benefit of some other discipline. It also facilitates comparison of models on a common platform (CSIRO 2004). This is achieved by extensive testing and validation mechanisms integrated in APSIM. Currently APSIM is tested and validated for simulation of millet yield in the Fakara region (Akponikpe not yet published).

Farm simulations

As seen, there are a wide variety of models available simulating agricultural productions from the global to the plant scale. But there have been few attempts to model the ecological and economic aspects of soil fertility management at the farm scale. Dynamic models of plant production that incorporate soil nutrients tend to deal with only sole crops or intercrops at the plot scale (Shepherd and Soule 1998). De Jager et al. (1998) developed a static nutrient budget model at the farm scale. NUTMON is a research tool, which integrates the assessment of stocks and flows of the macronutrients nitrogen, phosphorus and potassium on the one hand, and economic farm analysis on the other hand. It quantifies nutrient inflows and outflows, resulting in a calculation of nutrient balances. They can be determined at spatial scales ranging from national level to field level. When determined at the level of individual activities within a farming system, a nutrient balance is a very useful variable, providing insight into causes and magnitudes of losses of nutrients from the system and so helping to target interventions (De Jager et al. 1998). However, the static nature of the model prevents assessment of the long term effects of management on the nutrient availability and plant productivity.

In the literature research two approaches to simulate soil fertility and nutrient budgets in a dynamic way, on farm scale were found. Shepherd and Soule (1998) developed an economic-ecological simulation model that links biophysical and economic processes at this

scale. The approach was developed with the objective of predicting the long-term effects of existing as well as improved farming systems on nutrient cycling and availability, plant production and farm income (Shepherd and Soule, 1996). The model has been designed to analyze improved soil management practices. Model outputs, such as time changes in available nutrient supply, serve as indicators of agronomic, on-farm sustainability. Changes in farm income are an important indicator of the potential adoptability of improved practices.

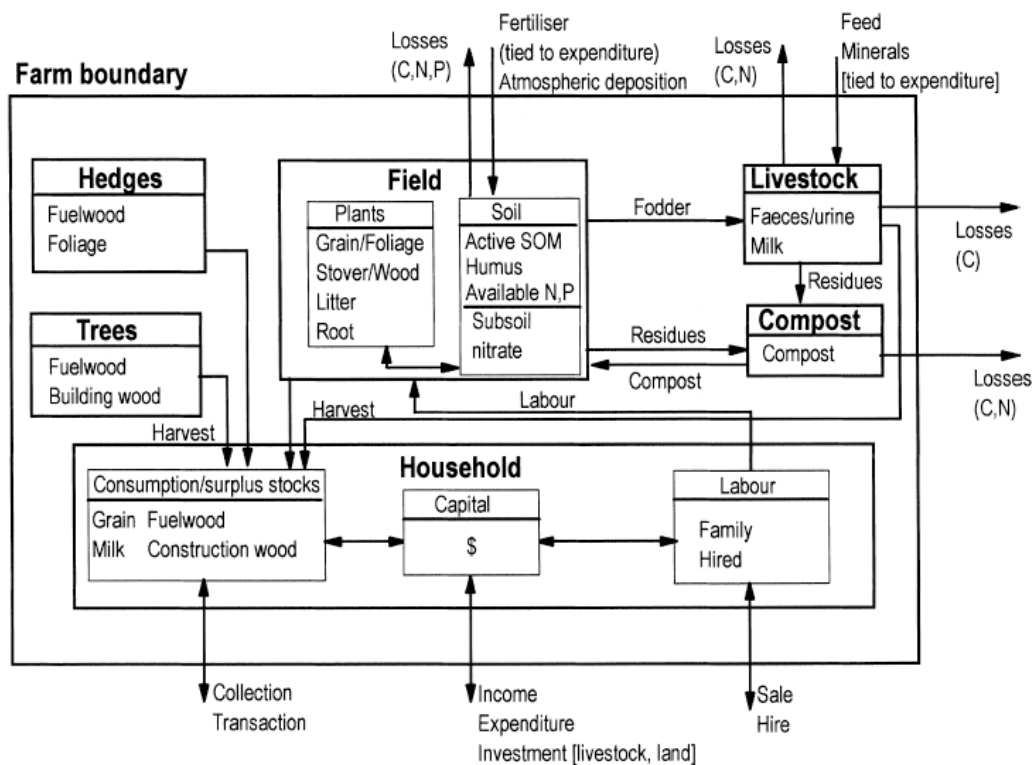


Figure 12: Conceptual diagram showing the principal compartments and material flows that are represented in the farm economic-ecological simulation model. Taken from Shepherd and Soule (1998).

The model was applied to a case study of sustainability of existing farm systems in Vihiga district in western Kenya. The highlands of western Kenya represent a zone with high agricultural potential but severe nutrient depletion. Dominant is a mixed crop/livestock farming system with the major crops maize (*Zea mays*) and beans (*Phaseolus vulgaris*). Most cattle are local zebu breeds. Because of high population densities and the sub-division of farms for inheritance, farm sizes tend to be small. Average farm size is 0.65 ha with many farms as small as 0.2 ha. Data sets were compiled for three representative farm types to reflect the differences in resource endowments. Wealth ranking (Grandin, 1988; Crowley, 1997) was used to stratify local households into three categories by resource endowment. The

households had been identified as being either resource high (HRE), medium (MRE) or low (LRE) endowed. The model uses an annual time step; major indicators tested were crop yields and soil nutrient- and org. matter budgets. The simulation run was calculated over 20 years. Yields decreased with time in LRE and MRE and increased with time in HRE, but the changes were rather small (less than 10% of their means over the simulation period). The simulated soil C, N and P balances were negative in LRE and MRE, whilst they were positive in HRE. Shepherd states that it is principally from inputs to the soil from purchased fertilisers and recycling through manure of purchased feeds. By disaggregating the nutrient balances by farm type, it is shown that the nutrient balances are negative for the LRE and MRE farms but are actually positive in the HRE case. The high resource endowment farmers (HRE) show the ability to manage their farms profitably, increase soil organic matter and achieve low levels of nutrient losses. This implies that the technologies and knowledge for sustainable production exist, but the LRE farmers cannot afford the capital required for that type of management (inorganic fertiliser, cows and manure management, hired labour) (Shepherd and Soule 1998).

Another interesting approach is SIMFIS (SIMulating Mixed Farming In the Sahel) (Bontkes 2005). It is a simulation model that permits simulating the effects of farm management decisions over a period of 5 years on crop and animal production, soil fertility and income on mixed farms in the Sahel, based on a similar model of Struif Bontkes (1999).

SIMFIS takes the following aspects into account:

- weather: rainfall and evaporation
- the different fields of the farm, their size and soil characteristics (texture, soil depth, C, N, P, and pH, and their changes over time)
- crops: crop production and crop management (crop rotation, land preparation, application of organic and chemical fertilizer, weeding, plant protection, harvesting, residue management). The crops that are taken into account are millet (local and improved variety), sorghum, maize, cowpea (local and improved variety), groundnut and andropogon.
- herd: composition (cattle, goat and sheep by age and sex), production (milk, meat, reproduction) and management (feeding, housing, herding)
- household (composition, food requirement, labour availability, off-farm income)
- prices of inputs and outputs

The model consists of a set of equations, written in the Vensim language (Vensim DSS 5.3) and an EXCEL file. The EXCEL file contains general parameters pertaining to e.g. climate data, labour requirements, crops and prices, and parameters pertaining to a specific farm, e.g. number and size of fields and their soil fertility, number of animals (cattle, goat and sheep), crops and fertilizer use.

As this work is largely based on this model and the one of 1999 by the same author, it will be discussed in more detail in chapter 2.4. In his 1999 study Bontkes investigated four farm types in the Koutiala region of southeastern Mali, where cotton production plays an important role in most farming systems. The basic characteristics of the farm types are household size, cultivated area, crop rotation, herd size, cultivation practice and livestock management. Each farm is subdivided into plots one ha each, belonging to a particular soil type. Organic matter content, organic- and inorganic N and P and soil pH may change over the 25 years simulation run. The typology of the four farm types (A, B, C and D) was developed by CMDT (Compagnie Malienne pour le Développement des Fibres Textiles). Their main characteristics are:

- Farm type A consists of many family members, own at least two pairs of draught oxen and is fully equipped with plough, cultivator, sprayer a.s.o. Herd size is 10 or higher.
- Farm B is somewhat smaller, still fully equipped, but herd size is smaller than 10
- Farm C owns some implements and one head of cattle for draught. It is able to hire labor or cattle.
- Farm D doesn't have access to draught power and carries out agricultural operations by hand.

Farm types A to C crop cotton for cash apart from millet and sorghum for food, type D doesn't crop cotton. Mineral fertilizer use is decreasing from A to C, whilst D again doesn't use any. In his standard run Bontkes compared the four farm types concerning the most important criteria to judge farm performance:

- soil org. matter
- nutrients in the soil
- soil pH
- yield
- growth rate of cattle
- and net farm income

Over the 25 years simulation run org. matter content of permanently cropped fields decreased for all four farm types. This was more the case in farm type B to D than in type A, due to the higher manure input and higher crop residue yield, because of mineral fertilizer application (Bontkes 1999). Similar behaviour was observed for N content of the upper soil layer. Total phosphorus instead increased in farm type A, B and C, whilst in D a slight decrease was observed. This again was explained by fertilizer and manure input in the better endowed farms (Bontkes 1999). Simultaneously soil pH decreased in those farms and was more or less stable in farm type D, for the same reason. Ammonium fertilizer is mentioned as the major source for soil acidification. Looking at cotton yields, only cropped by A, B and C, in the first years water is the limiting factor, but as org. matter becomes lower nitrogen limitation becomes more and more important in farm types B and C. Concerning millet the model suggests decreasing yields over the run. Official data rather shows increasing production levels for the years 1992 and 1993 (DNSI 1992). This is explained by the fact that for this survey mostly fertilized fields were used and millet fields in the simulation run don't get fertilizer (Bontkes 1999). Growth rate of cattle differ considerably between farm types again C is doing worst (note that type D doesn't own cattle at all). This is probably the case because of the scarcity of crop residues fed to the animals usually during the dry seasons (Bontkes 1999). And finally the net farm income is of course highest in farm type A. This shouldn't be surprising after all the above mentioned criteria are in favour of this farm type.

2.7 Farm types

Since 1994 research teams of ILRI and ICRISAT have studied extensively the Fakara region in south-western Niger. The general objective of this work is to assess the state and dynamics of crop-livestock agricultural systems at field, farm and regional levels. Information concerning the agro-ecological and socio-economic conditions of 532 households existing in three villages in the area has been collected at different levels of detail, both temporal and spatially (Busqué 2002). This data was collected in a detailed database including all sorts of information and variables on farming system including livestock, socioeconomic, ecology, soils and many more.

Variables of farm structure were measured at the field and farm levels, those of ecology were measured at the geographical unit (homogeneous soil and topography). Data used in this work are largely extracted from this farm database.

Farms in the Fakara differ considerably in production systems, management and endowment. While the agro pastoralists (see chap. 2.1.4) earn their living mainly on their livestock

production, the smallholder farmer concentrates more on crop production. Additionally farms differ a lot in production factor endowment. Because of this in homogeneity, farms were grouped based on location of the homestead, farm endowment in productive capital in terms of land to crop (relative to unit adult equivalent in the household), livestock managed (tropical livestock units per adult equivalent), available farm labour and equipment (cart, plough, animal traction) (Hiernaux and Turner. 2002).

What follows is short description of the five farm types built by Hiernaux and Turner (2002) for the Fakara region:

- Village poor (VP): living in the village and owning nearly no livestock and only little land.
- Village rich (VR): living in the village and owning nearly no livestock but a high amount of cropland.
- Village herders (VX): living in the village and primary on their livestock but also crop a fairly high amount of land.
- Camp poor (CP): living in the surrounding camps and primary on their livestock but don't own/manage much livestock compared to the...
- Camp rich (CR): living in the surrounding camps and primary on their livestock. They own or manage a rather big herd.

In general the majority of village farmer (VP, VR and VX) belong to the Jerma ethnic group and, if they own livestock at all, can be classified as smallholder livestock producers. The Camp farmers (CP and CR) on the contrary are generally from the Fulani ethnic group and are classified as agropastoralists (see 2.1.4 Livestock).

Table 4: Distribution of farm types in three villages of the Fakara region

Socio-Economic Status of Farmers	Banizoumbou	Kodey	Tigo Tegui	Overall Sum
CP No. (%)	29 (31.2%)	36 (38.2%)	28 (30.1%)	93 (100%)
CR No. (%)	9 (16.4%)	21 (38.2%)	25 (45.5%)	55 (100%)
VX No. (%)	12 (46.2%)	3 (11.5%)	11 (42.31%)	26 (100%)
VP No. (%)	119 (48.6%)	41 (16.7%)	85 (34.7%)	245 (100%)
VR No. (%)	27 (38.6%)	13 (18.6%)	30 (42.9%)	70 (100%)
Overall (%)	196 (40.1%)	114 (23.3%)	179 (36.6%)	489 (100%)

Table 5: Average land and livestock endowment of farm types

Farm type	No.	area cropped/farm	TLU/farm		TLUm ¹ /ha
			managed	owned	
VP	213	9.1	0.95	0.91	0.10
VR	126	21.4	0.8	0.74	0.04
VX	27	25.2	11.81	9.78	0.47
CP	92	8.7	12.52	4.59	1.44
CR	74	12.7	20.36	15.38	1.60

1) Managed

Taken from: Hiernaux and Ayantunde (2004)

Busqué (2002) used the Fakara farm database to calculate nutrient balances for every single household. This was done employing the aforementioned NUTMON toolbox (see 2.2.2). In the 2004 Contribution to M 3106 Environmental Science Project: „The Africa Project“ Leistner et al. (unpublished) investigated the connection of farmer’s endowment and their nutrient balances using the described classification.

Nutrient balances were linked to the data on farm characteristics.

Table 6: Distribution of nutrient balances by farm types in three villages of the Fakara region

Socio-Economic Status of the Farmers	Banizoumbou	Kodey	Tigo Tegui	Overall sum
CP Mean (s.d.)	-1,88 (6,80)	-3,25 (9,74)	-1,58 (6,36)	-2,40 (8,13)
CR Mean (s.d.)	-0,13 (10,8)	1,18 (9,47)	5,57 (11,41)	5,58 (11,41)
VX Mean (s.d.)	-4,34 (5,16)	-8,84 (4,18)	-4,97 (3,30)	-5,30 (4,35)
VP Mean (s.d.)	-6,70 (4,17)	-9,89 (7,62)	-6,89 (2,36)	-7,27 (4,53)
VR Mean (s.d.)	-6,49 (3,48)	-11,81 (5,78)	-7,79 (4,95)	-8,50 (5,26)
Overall sum Mean (s.d.)	-5,49 (5,55)	-6,70 (9,34)	-5,53 (5,64)	

It was observed that the group with the lowest ratio of livestock per area cropped, which is VR, has the lowest nutrient balances, while the group with the highest ratio of livestock per area cropped (CR) has the highest nutrient balances.

Furthermore a correlation analysis was conducted to find the most important factors influencing nutrient balances. Variables under observation are listed below:

- Total number of livestock (UBTOT)
- Livestock.ha⁻¹ (UBTOTCRO)
- Area cropped (AREACROP)
- Corraling/area cropped (CORCROP)
- Short-term fallow (SJACSU)
- Long term fallow (SJALSU)

Table 7: Example of a correlation matrix: Management factors with nutrient balances of village herders (VX) in Banizoumbou

		UBTOT	AREAC ROP	UBTOTC RO	CORCRO P	SJACSU	SJALSU
NBH	Correlation	,722(**)	-,623(**)	,777(**)	,960(**)	,046	-,035
	Significance	,000	,000	,000	,000	,519	,629
	N	198	198	198	12	198	198
PBH	Correlation	,801(**)	-,583(**)	,847(**)	,984(**)	-,071	,005
	Significance	,000	,000	,000	,000	,322	,949
	N	198	198	198	12	198	198
KBH	Correlation	,316(**)	-,684(**)	,413(**)	,682(*)	,462(**)	-,034
	Significance	,000	,000	,000	,015	,000	,632
	N	198	198	198	12	198	198
UBTOT	Correlation	1	-,373(**)	,818(**)	,312	-,236(**)	,160(*)
	Significance		,000	,000	,324	,001	,024
	N		198	198	12	198	198
AREAC CROP	Correlation		1	-,515(**)	,456	-,305(**)	-,182(*)
	Significance			,000	,136	,000	,010
	N			198	12	198	198
UBTOTC TCRO	Correlation			1	,824(**)	-,198(**)	,310(**)
	Significance				,001	,005	,000
	N				12	198	198

** correlation significant on 0.01, * correlation significant on 0,05

Calculating matrix correlation for the different farm types Leistner et al. were able to find high coefficients for some relations and by this defined the three most important variables for two different groups:

Herders (CP, CR, VX):

Livestock ha⁻¹

Area cropped

Corralling

Farmers (VP, VR):

Livestock ha⁻¹

Area cropped

Fallow

2.8 FAKFARM

As mentioned above the following model description is largely based on Bontjes 1999 and 2005. It was transferred into the Berkeley Madonna modelling environment, which is quite similar to Stella (see above). Actually Madonna Berkeley was first developed to run Stella models faster. But is now a, commercial, but easy to use software of its own. Time step of the calculation run is one year, although water limiting yield is calculated on the basis of five development stages per year (see 2.4.1.2).

2.8.1 Millet production

Millet production, which is seed and straw production of millet, is determined by its potential yield and the supply of N, P and water. (see fig. 13).

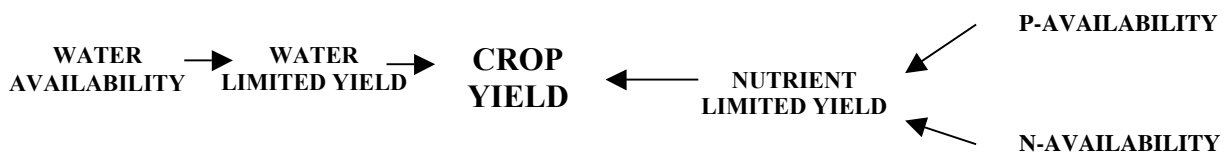


Figure 13: Schematic presentation of factors determining crop yield

2.8.1.1 Nutrient limited yield

The calculation of the nutrient limited yields is largely based on a method described by Janssen et al. (1990). This method takes into account the interaction of N and P. However, while Janssen et al. determine the yield directly, FAKFARM first calculates total biomass production, including roots, and derives from there the yield of grain and straw.

The method consists of four steps:

- In step 1 the potential supply of each nutrient is determined (see 2.4.3 Soil Processes)
- In step 2 the uptake of N and P are determined based on the potential supply of both nutrients, taking into account the fact that the uptake of one nutrient may be limited by the other.
- In step 3 a yield range as a function of N and P are established.
- In step 4 these ranges are combined and averaged to obtain the final yield estimate.

Step 1: see 2.4.3 Soil Processes

Step 2: potential supply and actual uptake

N and P concentrations in the crop may vary between an upper and a lower boundary. If for instance N-supply is very high and P-supply very low, it is likely that all N is taken up, resulting in a maximum dilution of N and a maximum accumulation of P in the crop. Based on experimental data, maximum and minimum concentrations can be established (Van Duivenbooden, 1992). Janssen et al. (1990) have developed equations (equ. 2 and 3 in Appendix) to determine actual uptake of N and P.

$$\text{Nuptake} = \text{Nmin} - \frac{0.25 * (\text{Nmin} - \text{Pavailable} * (\frac{\text{maxPconc}}{\text{minNconc}}))^2}{\text{Pavailable} * ((\frac{\text{minPconc}}{\text{maxNconc}}) - (\frac{\text{maxPconc}}{\text{minNconc}}))} \quad (2)$$

where,

Nuptake:	N taken up by the plant (kg.ha ⁻¹)
Nmin:	N available for plant uptake (kg.ha ⁻¹)
Pavailable:	P available for plant uptake (kg.ha ⁻¹)
minNconc:	minimum N concentration (kg.kg ⁻¹)
maxNconc:	maximum N concentration (kg.kg ⁻¹)
minPconc:	minimum P concentration (kg.kg ⁻¹)
maxPconc:	maximum P concentration (kg.kg ⁻¹)

Step 3: yield ranges

This allows the establishment of yield ranges corresponding with the actual uptakes: a maximum yield when the nutrient is maximally diluted and a minimum yield when the nutrient is maximally accumulated (equ. 4-6).

Step 4: combining yield ranges to one yield estimate

In this step the yield ranges are combined to first determine the yield that is obtained when N concentration is at its minimum taking into account P-uptake (yield NP) and the yield that is obtained when P concentration is at its minimum taking into account N-uptake (yield PN) (equ. 8 & 9).

Averaging total biomass NP and total biomass PN obtain the final estimate of total biomass. Maximum and minimum nutrient concentrations in biomass are determined based on the maximum and minimum concentrations in grain, roots and straw and the dry matter distribution between these parts (equ. 10).

2.8.1.2 Water limited yield

Water, besides nutrients is the most important factor limiting crop growth. In fig. 14 a schematic overview of the factors determining water availability and water-limiting yield is given.

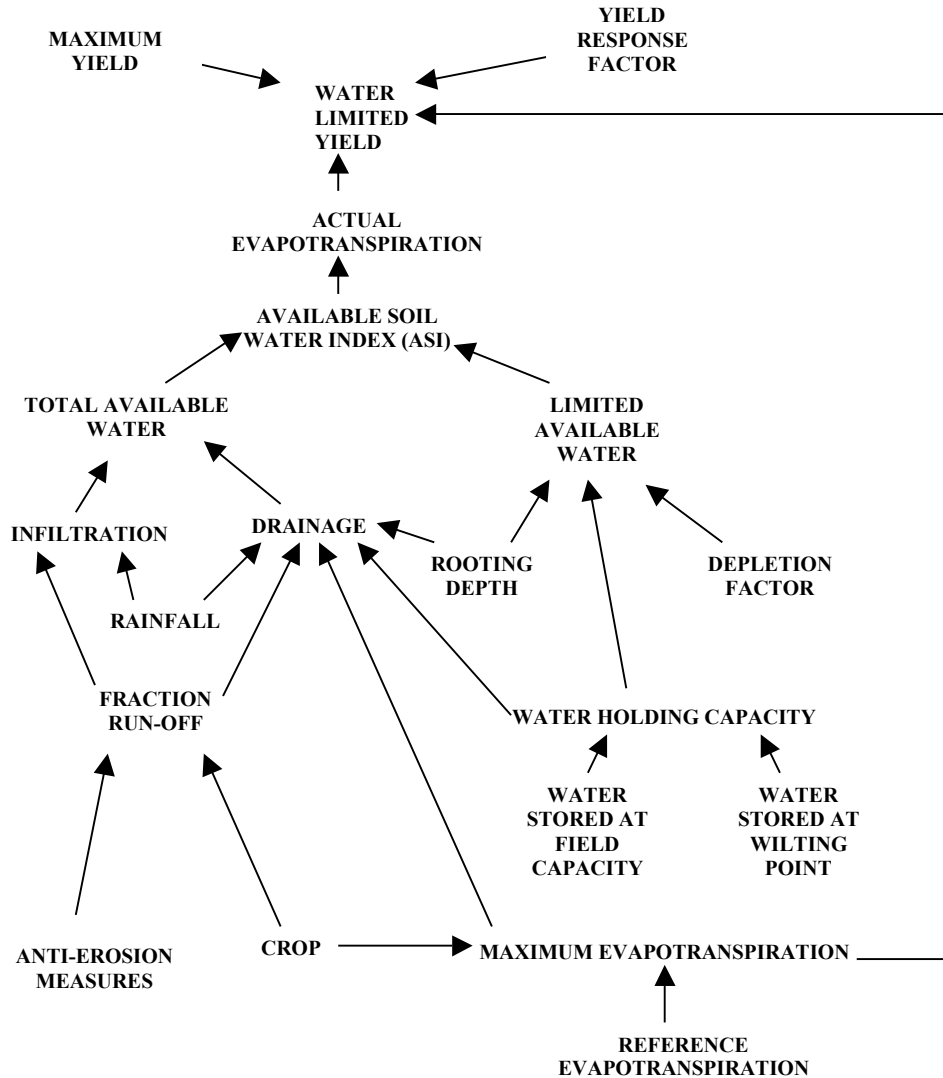


Figure 14: Factors determining water limited crop yield

Doorenbos and Kassam (1979) established the yield response factor (k_y) to quantify the effect of water supply on yield. k_y relates the relative yield decrease $(1 - Y_a/Y_m)$ to the relative evapotranspiration deficit $(1 - E_t/E_{tm})$. When the water limited yield is above 50% of the potential yield, the relationship is linear (Equ. 11 & 12). Otherwise table A2 is used.

According to Doorenbos and Kassam (1979) susceptibility of crops to water stress (k_y) depends on species and on development stage. These authors distinguish 5 stages of development:

- establishment,
- vegetative growth,
- flowering,
- yield formation
- and ripening.

So one needs to know the dates of sowing and the length of the different development stages, as well as k_y and k_c values for all five of them (see table A3). Relative yield is calculated for every development stage separately. The final estimate of the overall yield decrease is calculated by multiplying the different rel. yields of those five development stages (equ. 13).

The maximum evapotranspiration (ET_m), is the loss of water in the situation where water supply fully meets water requirements of the crop. It depends on the crop (k_c) and on the weather (E_{to}) (equ. 14). k_c is an empirically determined crop coefficient and represents the influence of the crop and its development stage (Doorenbos and Kassam, 1979). E_{to} is the reference evapotranspiration and is assumed to be equal to the evapotranspiration from a short grass cover that is adequately supplied with water and is a location specific parameter. As bough variables are fix, one can calculate ET_m for each development stag. Figures are given in table A3.

As the actual evapotranspiration depends on the crop, its development stage and the water availability, it is necessary to link the development stages to the rainfall.

This is done by the Available Soil water Index (ASI) (see table A4). ASI represents the fraction of the period that available soil water is adequate to meet the water requirements of the crop. ASI for each development stage is determined by equation 15.

It is a function of maximal evapotranspiration (ET_m) and the difference of total soil water (TSW) and the limited available water (RSW) (equ. 16 & 17). TSA depend on the rainfall, how much is infiltrated (equ. 20) and how much is drained (equ. 21). RSW depends on rooting depth, the waterholding capacity of the soil and the depletion factor (equ. 17-19).

When a certain fraction (p) of the water holding capacity has been depleted, actual evapotranspiration will be below the maximum and rel. yield will decrease.

2.8.2 Soil processes

As mentioned above uptake of nitrogen and phosphorus by crops depends on the availability of nutrients in the soil. Availability of nutrients is to a large extent determined by organic matter dynamics. So first the way organic matter dynamics has been modelled is discussed, followed by a description of the dynamics of nitrogen and phosphorus.

2.8.2.1 Organic matter dynamic

The organic matter model is based on the work of Coleman and Jenkinson (1999), Van Keulen (1995), Jenkinson (1990) and Parton et al. (1983). Soil organic matter is divided in two pools: a labile and a stabile pool. As crops obtain their nutrients mainly from the upper 20 cm, only this layer is taken into consideration.

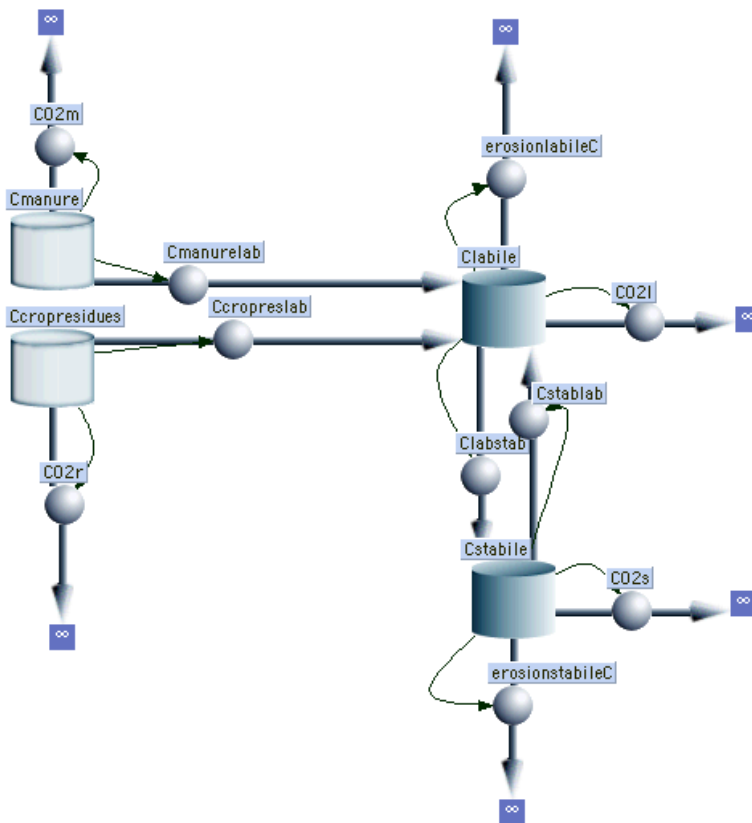


Figure 15: Schematic figure of organic matter decomposition

The two sources of org. matter are manure and crop residues. In the first year when they are added to the soil, part of it is decomposed to labile OM and a part is lost to the system as CO₂ volatilisation. In the second year the labile pool is further decomposed to CO₂, labile OM and

stable OM. The labile and stable organic matter pools continue to be transformed into CO₂, labile and stable organic matter (fig. 15).

The decomposition rates for soil organic matter (SOM) depends on the basic decomposition rates (table A5) of the substrates (labile, stable C, crop residues and manure), temperature (cf_{temp}), soil moisture (cf_{moisture}), soil texture (cf_{texture}), soil acidity (cf_{pH}) and management practises like N-fertilizer application (cf_{nitrogen}) and straw incorporation (equ. 22).

The influence of soil moisture in the Sahelian climate is set to 0.2 (Coleman and Jenkinson, 1999). The influence of temperature on decomposition (cf_{temp}) is determined by equation 23 (Coleman and Jenkinson, 1999) and for soil acidity (cf_{pH}) by equation 24 (Janssen et al. 1990). Clay and silt protect organic matter against decomposition (cf_{soil}) (Feller et al., 1991; Van Keulen, 1995; Hassink, 1995) (equ. 25). Application of nitrogen fertilizer stimulates decomposition of SOM. The same applies to the incorporation of straw, as this will increase the contact with soil micro-organisms (Stangel, 1995) (equ. 26 & 27).

During decomposition of organic matter part of the C is lost as CO₂.

According to Jenkinson (1990) and Coleman and Jenkinson (1999), the partitioning between CO₂ production and the production of labile and stable C during the decomposition of the different fractions depends on the cation exchange capacity of the clay particles of the soil (cecclay) (equ. 28 & 29)

$$cfCO_2 = (1.21 + 2.24 * e^{-0.085 * cecclay}) / (1 + (1.21 + 2.24 * e^{-0.085 * cecclay})) \quad (28)$$

where

cfCO₂ : is the part of the decomposed carbon that disappears as CO₂.

Cecclay: is expressed in cmol.kg⁻¹.

The amount of C (kg/ha.yr⁻¹) in the labile C-pool is calculated by the inflow of C from crop residues (Cropresidues), manure (Cmanure) and stable SOM (Cstablalab) subtracting the outflows to stable SOM and losses to CO₂ production (CO₂lab) and erosion (erosionClab) (equ. 30). All flows are functions of their specific decomposition rates taking the losses by CO₂ volatilisation into account (equ 31-36).

Labile and stable C are subdued to erosion. But the loss of C in kg.ha⁻¹.yr⁻¹ is not simply equal to the quantity of soil that is annually lost by erosion, multiplied by the average content

of both fractions, as the upper 20 cm of the soil layer is richer in organic matter than the deeper layers. Therefore, an enrichment factor has been taken into account ($c_{\text{enrichment}}$) (Van Keulen, 1995) (equ. 36 & 37).

Corresponding to labile SOM, stabile SOM (C_{stabile}) is calculated by inflow of C ($\text{kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$) from the labile C-pool and losses by CO_2 volatilisation and erosion. (equ. 38).

To determine contribution of crop residues to SOM the quantities taken annually from the fields, has to be known. The plant sub model calculates the total crop production (including roots) of one year. The quantities harvested is equal to the grain yield of that year and is subtracted, the quantity removed by e.g. grazing has to be put in by the user as straw removal. In a study of night parking in Niono, Mali Schlecht et al. (1995) found daily faecal output of Zebu cattle was 2.2 kg of organic matter (containing 35 g N) per tropical livestock unit (TLU) in dry-season. So the quantity of manure applied to the millet field is simply calculated by multiplying the number of TLU per ha ($\text{TLU}_{\text{perha}}$) by the daily manure production of a TLU (DailyfaecalTLU), which is set to 2.2 kg and the days it is corralled on the field (daysDryseason) (equ. 39). Harris (2002) showed that animals confined to a corral overnight deposit 43% of their daily faecal excretion in the corral. 15 g N was left in the corral by each TLU each night. Over a 180-day dry season, this results in $2.7 \text{ kg}\cdot\text{ha}^{-1} \text{ N}$ and, over a dry season, a small herd of 20 cattle would leave $54 \text{ kg}\cdot\text{ha}^{-1} \text{ N}$. So in the model it is assumed that only the first month after the harvest the full amount of manure is left on the field. Afterwards cattle have to leave the field in daytime to graze on communal pasture and spend only the night corralled at the field. So DaylyfeacalTLU is for this time multiplied by 0.43.

2.8.2.2 Nitrogen dynamics

The major part of Nitrogen in the soil is in organic form, this is way nitrogen dynamics follow closely dynamics of SOM. There is also a labile and a stabile pool of nitrogen. Additionally there is a mineral nitrogen pool. Various processes determine the changes in these pools.

Figure 16 gives a general overview of the N flows.

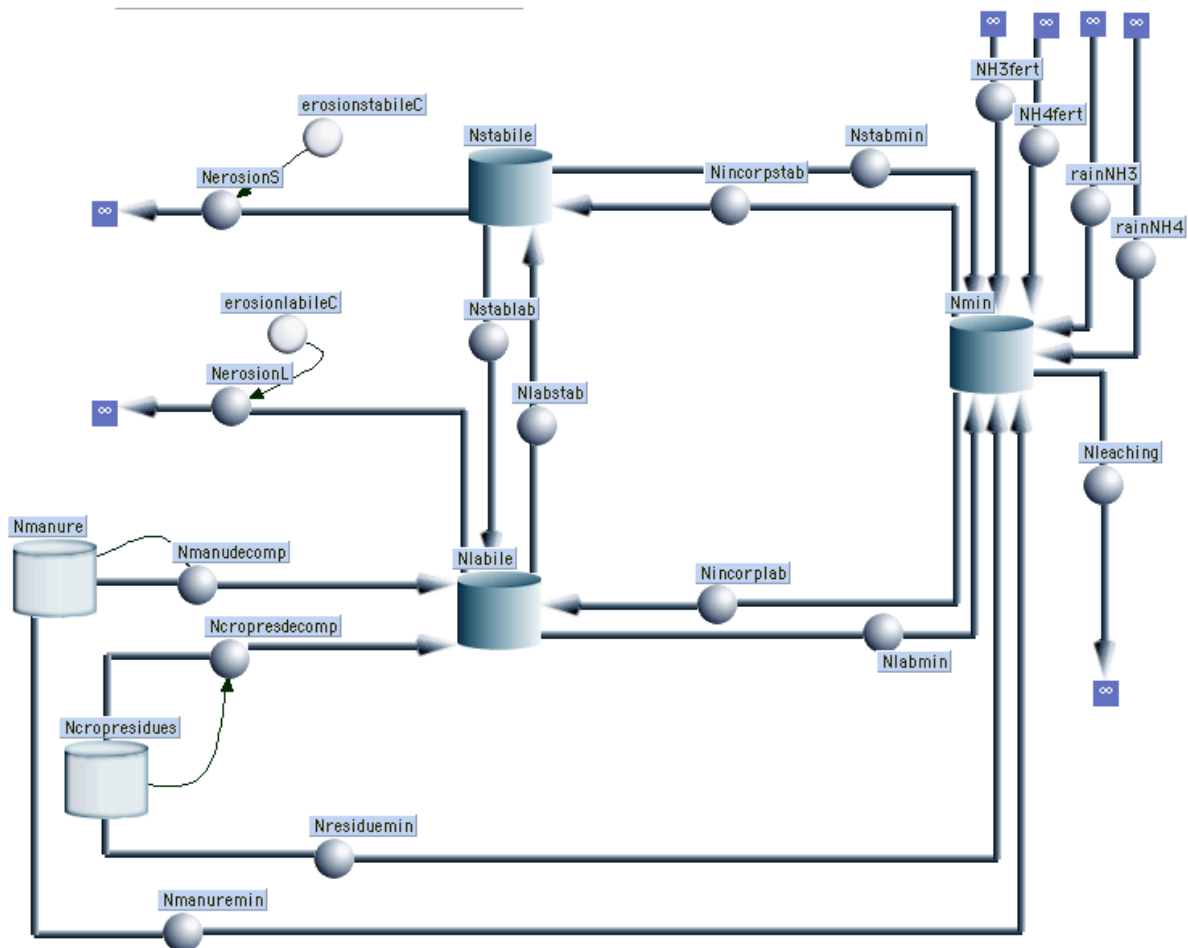


Figure 16: An overview of the nitrogen flows in the model.

As mentioned above with the decomposition of organic matter, part of the carbon is lost as CO_2 . In this model it is assumed that the nitrogen in this organic matter, is mineralised and temporarily added to the mineral N pool. Other sources of mineral N are the N deposited through rainfall (N_{rain}) and the N applied as mineral fertiliser (N_{fert}).

Mineral N is the only source for N uptake by crops (N_{uptake}), but it can also be incorporation in organic matter through microbial activity (N_{incorp}). Part of the mineral N may also be lost through leaching (N_{leaching}).

The amount of N ($\text{kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$) in the labile N-pool is calculated by the inflow from crop residues ($N_{\text{croppresdecomp}}$), manure ($N_{\text{manuredecomp}}$), stabile N (N_{stabilab}) and the amount of

N_{min} incorporated in labile SOM ($N_{incorlab}$) subtracting the outflows to stabile N ($N_{labstab}$), decomposition of labile SOM (N_{labmin}) and losses through erosion ($N_{erosionlab}$) (equ. 43).

When manure or crop residues are added to the soil and decompose their C/N ratio may differ from the C/N ratio of the SOM. If the C/N ratio of manure or residues is higher than the C/N ratio of the labile organic matter, additional N will be required. This N is withdrawn from the mineral N pool. A similar process takes place when labile organic matter is transformed into stabile organic matter as they have different C/N ratios. These two C/N ratios are initially set to 20 for labile organic matter and 10 for stabile organic matter but may change over time, depending on the mineral N available for incorporation in the organic matter.

Therefore, the amount of mineral N that is incorporated in labile and stabile organic matter is a function of the amount of N that has become available in mineral form and the demand for N by the labile and stabile organic matter to maintain their C/N ratio (Van Keulen, 1995) (equ. 44-47).

$$N_{incorp} = \text{MIN} (cfN_{incorp} * N_{min}, N_{required}) \quad (44)$$

where,

cfN_{incorp} is the part of the mineral N that is incorporated in organic matter

$$relN_{demand} = N_{required} / \text{MAX} (N_{min}, 0.1) \quad (45)$$

where,

$N_{required}$ is the sum of the N required by the labile and the stabile organic matter

$$N_{labrequired} = (C_{reslab} + C_{manurelab} + C_{wastelab} + C_{stablab}) / CN_{lab} \quad (46)$$

where

CN_{lab} : C/N ratio of the labile organic matter.

N required by the stabile organic matter is determined in a similar way:

$$N_{stabrequired} = (C_{resstab} + C_{manurestab} + C_{labstab} + C_{stabstab}) / CN_{stab} \quad (47)$$

where,

CN_{stab} : C/N ratio of the stabile organic matter

The amount of N added to the labile N pool by manure and residues depends on the amounts of N in these substrates and their decomposition rates (see above).

The labile N lost through erosion is equivalent to the C lost through erosion, divided by its C/N ratio.

The amount of N ($\text{kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$) in the stabile N-pool is calculated by the inflow from crop labile N ($N_{\text{stablalab}}$) and the amount of Nmin incorporated in stabile SOM ($N_{\text{incorpstab}}$) subtracting the outflows to labile N ($N_{\text{stablalab}}$), decomposition of stabile SOM (N_{stabmin}) and losses through erosion ($N_{\text{erosionstab}}$) (equ. 48). All other functions are similar to the ones of stabile N.

Nitrogen mineralised ($\text{kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$) is also calculated by the sum of its inflows minus the sum of its outflows. Apart from the inflows to the Nmin pool already mentioned (N_{labmin} , N_{stabmin}), the N in residues and manure that is directly mineralised ($N_{\text{residuemin}}$, $N_{\text{manuremin}}$) adds to that pool. Two other sources for Nmin are the rain and mineral fertilizer (N_{rain} , N_{fert}). Outflows already mentioned are Nmin incorporated in labile and stabile SOM ($N_{\text{incorplab}}$, $N_{\text{incorpstab}}$). Additionally Nmin is prone to leaching (N_{leaching}) and is taken up by the plant (N_{uptake}) (equ. 49).

N mineralised from the decomposition of labile and stabile organic matter as well as residues and manure are calculated by the C lost thru CO_2 volatilisation, divided by the corresponding C/N ratios (equ. 50). N deposited by rainfall is determined by adding NH_3 and NH_4 concentrations and multiplied by total rainfall over the year (equ 51).

Losses through leaching depend on the amount of water drained, the cation exchange capacity of the soil and the percentage of sand (Van Keulen, 1995) (equ. 52).

2.8.2.3 Phosphorus dynamics

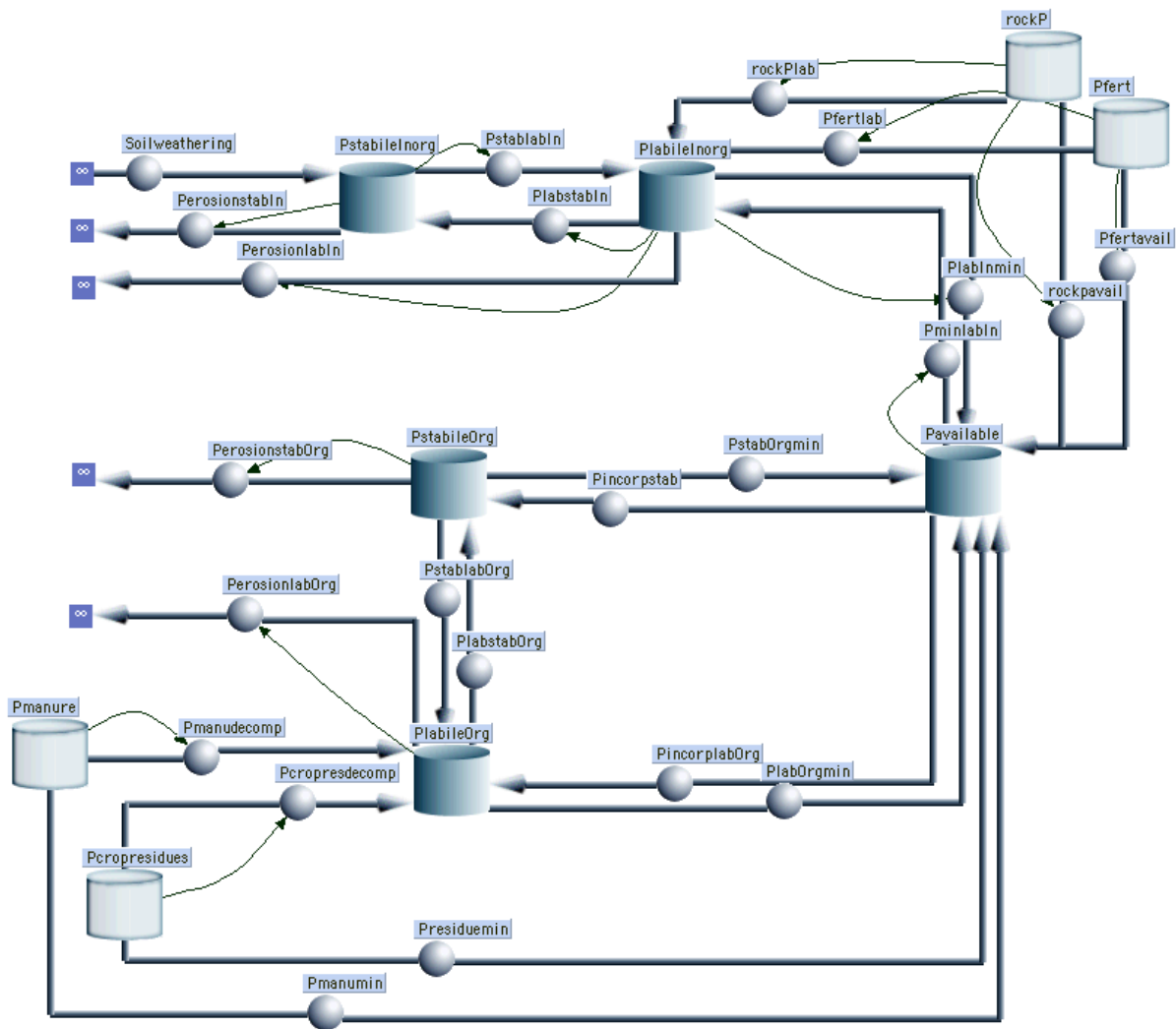


Figure 17: schematic overview of phosphorus dynamics in the model

The dynamics of phosphorous is very similar to the one of nitrogen. Additionally to the organic phosphorus there is inorganic phosphorus dynamic to consider.

Phosphorus in organic matter, added to the soil as crop residues and manure is, in the first year, either transferred to the labile organic P pool (PlabileOrg) or mineralised and added to the available P-pool (Pavailable). Decomposition of labile and stabile organic matter pools produces labile organic P, stabile organic P and mineral P. The amount of P that is mineralised depends again on the respective C/P ratios of the material and the amount that is lost thru respiration.

Inorganic P is also divided in labile and stabile P pools. Soil weathering supplies the stabile P pool (PstabileInorg) with $1 \text{ kgP} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$ (Van der Pol, 1992). Flows to labile inorganic P (PlabileInorg) and Pavailable and vice versa are governed by rate constants (see table 8)

Phosphorus fertiliser may be applied in two forms: as soluble P-fertiliser and as rock phosphate. Of the soluble P fertilizer 70 % is transformed into labile P and 30 % into available P, while for the Rock P this is 90 % and 10 % respectively.

Table 8: Rate constants (yr^{-1}) governing the inorganic P-flows.

cfPlabstab	0.00001
cfPstablalab	0.012
cfplabavail	0.027

All of the P pools as well as the N pools are prone to erosion. Although total amount of rainfall. yr^{-1} is rather low rainfall is erratic and may come in intense showers leading to substantial soil loss. On the other hand soil formation is very slow. In sub-Saharan Africa it takes 100 - 400 years to produce 1 cm of soil (Stangel, 1995). So soil can be looked at as a near non-renewable resource. The amount of soil that is lost through erosion depends on rainfall, topography, crop, anti-erosion measures and soil erodibility (Roose, 1977; Renard and Ferreira, 1993; Stroosnijder et al., 2001) (equ. 55).

2.8.2.4 PH dynamics

Acidity of soils plays an important role in agriculture. It determines the availability of nutrients as well as the mobility of toxic substances. Soils in the region under observation are quite acidic. Scientists link this to the use of acidifying fertilisers and decreasing amounts of organic matter (Stumpe and Vlek, 1991; Van der Pol, 1992; Juo et al., 1995).

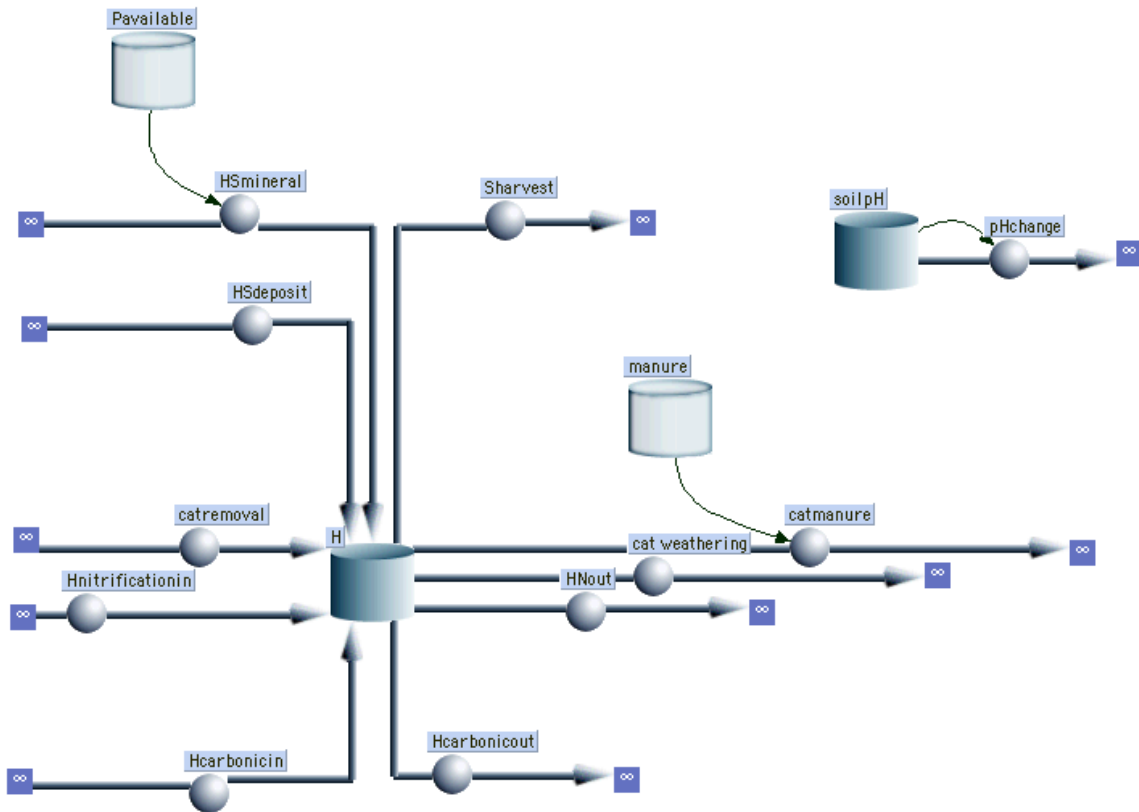


Figure 18: schematic overview of pH dynamics in the model

Soil pH depends on the balance of proton (H^+) and hydroxide ion (OH^-) Production and on the buffering capacity of the soil. Whilst the buffering capacity depends on different factors, within the pH range of 4.5 – 6, the cation exchange capacity is considered the most important. This pH range corresponds with the linear section of the soil pH titration curve (Helyar et al., 1990). They define the pH buffer capacity as the amount of acid or alkali required for an area of one ha with a soil layer of 10 cm to change soil pH by 1 unit. It is expressed as $kmolc\ H^+.ha^{-1}.10\ cm^{-1}.pH^{-1}$. They established a relationship between pH buffercapacity and the percentages of organic matter and clay for a soil with a bulk density of $1400\ kg.m^{-3}$.

The equation was customised to fit the model in the following way:

$$\text{pHbuffercapacity} = (\text{sbd} / 1400) * (\text{sdom} * \text{OMfactor} * \text{fOM} * 100 + \text{sdclay} * \text{fclay} * 100) \quad (58)$$

where,

pH buffer capacity	is expressed in $\text{kmolc} \cdot \text{ha}^{-1} \cdot \text{pH}^{-1}$
sbd:	bulk density of the top soil ($\text{kg} \cdot \text{m}^{-3}$)
sdom:	soil depth over which the effect of organic matter is determined (dm)
sdclay:	soil depth which the effect of clay is determined (dm)
OMfactor:	effect of organic matter on pH buffercapacity
clayfactor:	effect of clay content on pH buffercapacity
fOM:	fraction of organic matter (multiplied by 100 to yield percentage)
fclay:	fraction of clay (multiplied by 100 to yield percentage)

The organic matter factor is set to 4.2 (Helyar et al., 1990). The clay factor depends on the clay mineral and is estimated at 0.6 for kaolinite, 2.5 for illite and 5.6 for montmorillonite (Helyar et al., 1990).

- as kaolinite is the most important clay mineral in southwest Niger (Akponikpe communicated orally), the clay factor is set to 1;
- as bulk density in the top soil in the Fakara is assumed to be higher than $1400 \text{ kg} \cdot \text{m}^{-3}$, the effect of the soil bulk density has been included in the calculation of the pH buffer capacity;
- as throughout the model, changes in organic matter are calculated for the upper 20 cm, buffercapacity has been calculated for the top 20 cm.

The change in the pH per year (dpH), within a pH range of 4.5 to 6.5, is then determined as:

$$\text{dpH} = - \text{total proton production} / \text{pHbuffercapacity} \quad (59)$$

with total proton production expressed in $\text{kmolc} \text{ H}^+ \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$.

To determine soil acidification, the model has also to consider the proton (H^+) producing and consuming processes. There are four important cycles influencing H^+ balance, the ones of carbon (C), nitrogen (N), sulphur (S) and the base cations (K^+ , Ca^{2+} and Mg^{2+}). In the current model Na^+ and Cl^- are not taken into consideration, as it is assumed that these elements are present in more or less the same amounts.

The net production of protons can be described by:

$$\Delta H = \Delta H_{\text{carbon}} + \Delta H_{\text{nitrogen}} + \Delta H_{\text{cation}} + \Delta H_{\text{sulphur}} \quad (60)$$

where,

- ΔH : net production of protons (kmolc.ha⁻¹.yr⁻¹)
- ΔH_{carbon} : net production of protons due to the carbon cycle (kmolc.ha⁻¹.yr⁻¹)
- $\Delta H_{\text{nitrogen}}$: net production of protons due to the N cycle (kmolc.ha⁻¹.yr⁻¹)
- ΔH_{cation} : net production of protons due to the cation cycle (kmolc.ha⁻¹.yr⁻¹)
- $\Delta H_{\text{sulphur}}$: net production of protons due to the sulphur cycle (kmolc.ha⁻¹.yr⁻¹)

The carbon cycle affects the proton balance of the soil when carbon enters or leaves the system as carbonic acid or organic acid. In this model only the effect of carbonic acid has been taken into consideration. Carbonic acid is a result of the dissociation of CO₂

It may enter the soil system through rainfall and leave it through leaching. So ΔH_{carbon} is determined by the quantity of HCO₃⁻ in the rain and drainage water (equ. 62). There HCO₃⁻ concentrations depend on partial CO₂ pressure and pH (equ. 63).

Several processes within the nitrogen cycle involve the transfer of protons (Helyar and Porter, 1989; Bolan et al., 1991; De Vries, 1994). In the model it is assumed that all ammonium is nitrified, so that plants take up N as nitrate. Uptake of nitrate by Plants results in the consumption of one proton per NO₃⁻ ion taken up. The same applies to incorporation into the soil organic matter by micro-organisms (N-immobilisation).

Ammonification requires one proton for every ammonium-ion produced. These ammonium ions are further oxidised to nitrate. In this process two protons are released for each NO₃⁻ ion produced. Similarly, nitrification of ammoniac fertiliser produces two protons per nitrogen molecule as well. On the other hand oxidation of urea to nitrate yields only one proton per nitrate ion. This is why the model differentiates between these two fertiliser forms.

The net balance of protons is therefore determined by:

$$\Delta H_{\text{nitrogen}} = H_{\text{nitrification}} - H_{\text{ammonification}} - H_{\text{Nuptake}} - H_{\text{Nincorp}} - H_{\text{Ndenitrification}} \quad (66)$$

where,

$\Delta H_{\text{nitrogen}}$:	net balance of protons due to the N cycle ($\text{kmol}_c.\text{ha}^{-1}.\text{yr}^{-1}$)
$H_{\text{ammonification}}$:	consumption of protons due to ammonification of organic matter ($\text{kmol}_c.\text{ha}^{-1}.\text{yr}^{-1}$)
$H_{\text{N-uptake}}$:	consumption of protons due to uptake of NO_3^- ($\text{kmol}_c.\text{ha}^{-1}.\text{yr}^{-1}$)
$H_{\text{nitrification}}$:	production of protons due to nitrification of ammonium ($\text{kmol}_c.\text{ha}^{-1}.\text{yr}^{-1}$)
$H_{\text{N-incorp}}$:	consumption of protons when nitrate is incorporated in micro-organisms ($\text{kmol}_c.\text{ha}^{-1}.\text{yr}^{-1}$)
$H_{\text{N-denitrification}}$:	consumption of protons due to denitrification ($\text{kmol}_c.\text{ha}^{-1}.\text{yr}^{-1}$).

$H_{\text{ammonification}}$ depends on the quantity of crop residues left on the field, the animal manure applied to the field and the N contents and decomposition rates of the various substrates (equ. 67). $H_{\text{N-uptake}}$ and $H_{\text{N-incorp}}$ depends on the amount of N flowing to these pools (equ. 68 & 69). $H_{\text{nitrification}}$ takes all N pools into consideration (N_{labile} , N_{stable} N_{residues} and N_{manure}) additionally ammonia in rain and mineral fertiliser are considered (equ. 70).

Sulphur is taken up plants as SO_4^{2-} , a process that consumes two protons. When organic matter mineralises, two protons are produced. Deposition of Sulphur is mainly as SO_2 which oxidises to SO_4^{2-} , producing two protons.

Net production of protons is calculated as:

$$\Delta H_{\text{sulphur}} = H_{\text{S-deposition}} + H_{\text{S-mineralisation}} - H_{\text{S-harvest}} \quad (71)$$

where,

$\Delta H_{\text{sulphur}}$:	net production of protons due to the S cycle ($\text{kmol}_c.\text{ha}^{-1}.\text{yr}^{-1}$)
$H_{\text{S-deposition}}$:	production of protons due to oxidation of deposited SO_2 ($\text{kmol}_c.\text{ha}^{-1}.\text{yr}^{-1}$)
$H_{\text{S-mineral}}$:	production of protons due to mineralization of org. matter ($\text{kmol}_c.\text{ha}^{-1}.\text{yr}^{-1}$)
$H_{\text{S-uptake}}$:	consumption of protons due to uptake of sulphate by crops ($\text{kmol}_c.\text{ha}^{-1}.\text{yr}^{-1}$)

$H_{S\text{-deposition}}$ is determined by the amount of SO_2 that is annually deposited and the molecular weight of sulphur (mol_S). This amount is estimated at 4 kg per ha per year (Pieri, 1985) (equ. 72). In this model it is assumed that S contents of SOM is equal to their P contents (Veldkamp et al., 1991), therefore $H_{S\text{-mineral}}$ on the base of the amount of P that is mineralised from organic matter (equ. 73). $H_{S\text{-uptake}}$ is determined by the amount of dry matter removed from the field and the S fraction in the crop (equ. 74).

Uptake of base cations (Ca^{2+} , K^+ and Mg^{2+}) results in the release of protons. If uptake of base cations exceeds uptake of NO_3^- and SO_4^{2-} , harvesting has an acidifying effect. Similarly, if manure with an excess of base cations is added to the soil, soil pH increases. The same applies to soil weathering (De Vries, 1994).

$$\Delta H_{\text{cation}} = H_{\text{mnetremoval}} - H_{\text{mmanure}} - H_{\text{mweathering}} \quad (75)$$

where,

ΔH_{cation} : net production of protons due the cation cycle ($kmol_c \cdot ha^{-1} \cdot yr^{-1}$)

$H_{\text{mnetremoval}}$: production of protons due to net removal of base cations by the vegetation, i.e. total uptake minus the residues left ($kmol_c \cdot ha^{-1} \cdot yr^{-1}$)

H_{mmanure} : consumption of protons due to net release of cations by mineralisation of manure ($kmol_c \cdot ha^{-1} \cdot yr^{-1}$)

$H_{\text{mweathering}}$: consumption of protons due to net release of cations through weathering ($kmol_c \cdot ha^{-1} \cdot yr^{-1}$)

To determine the effect of removal and addition of organic matter, their quantities should be known as well as the anion and cation content of the material, expressed in $kmol\text{-ion-}$ equivalents ($kmol_c$) (Ulrich, 1991) (see table A12).

3. Results

Model behaviour can be validated by comparing results with historical data, which have not been used to develop the model. In rural areas of developing countries it is rather difficult to find reliable historical data for construction and even more so, for validation.

Another way of evaluating a model is to examine its plausibility. If the behaviour of some key variables is plausible according to experts and literature, it can be regarded as valid.

A sensitivity analysis can be helpful to judge consequences of wrong parameters and determine the effects of key input variables.

FAKFARM was tested by comparing calculated yield ranges to independent yield data obtained by demonstrations in the years 2000 to 2001. Furthermore key variables of soil fertility were tested comparing model runs of FAKFARM and SIMFIS with the same initial conditions. Finally a sensitivity analysis for these key variables was executed.

3.4 Model evaluation

In the years 2000 to 2002 demonstrations were conducted in the Fakara region by ICRISAT to show farmers the effect of hill placed application of small amounts of mineral fertiliser. This was done in 120 to 150 plots in different sites, among others Banizoumbou; Tigo Tegi; and Kodey. The experimental design was the following:

- Different manuring strata for each site: no manure; transported manure; corralling in 2002; and corralling in 2001.
- Within each manuring strata, a multi-factorial design with 3 millet varieties (landrace, ICMV IS 89305, Zatib) and 3 mineral fertilizer treatments (control, 2 g DAP per planting hill, 2 g DAP per planting hill + 1 g urea per planting hill at tillering) in 3 blocks.
- Plot size of 10x10 m.

Millet was sown in hills at a density of 10,000 hills.ha⁻¹. Yield was measured and data collected for each of the plots separately. Rainfall data was collected by sixty rain gauges distributed over the landscape for the years 2000 and 2001.

For the model run stocking rates were derived from table 5 (Bani 2.15 TLU.ha⁻¹, Tigo 1.79 TLU.ha⁻¹, Kodey 1.43 TLU.ha⁻¹). Application of mineral fertiliser was 20 kg DAP and 10 kg urea.ha⁻¹. This is about 9 kg P₂O₅.ha⁻¹ or 4 kg P.ha⁻¹. Nitrogen application via DAP is 3.6 kg N.ha⁻¹ in the form of ammonium-N. Addition of urea would add another 4.6 kg N.ha⁻¹. Soils are assumed to be equal. By fare the majority of the plots were Arenic lixisoils with just a few Ferralic arenosols mixed in.

Duration of the vegetation period of millet in the Fakara is about 108 days in the mean of 2000 – 2002. Sowing date is about the 165th day of the year or June 13. Harvest is 108 days later at September the 30th (274th day of the year). Vegetation is split in five development stages (see 2.3.1.2): establishment lasts from the first rain to end of June, vegetation to beginning of August, flowering to 23rd of August, yield formation to 8th of September and ripening to harvest. This is of special interest as the daily rain data is added up for each development stage. The two improved millet varieties did not show any clear comparative advantage for any site and any fertility management. The variety ICMV IS 89305 outperformed for grain yield the landrace in some treatments (especially in Banizoumbou) but the landraces had always the higher straw yields. (Gerard & Dougbedji 2003). That is why for the model test run yield data was averaged for each site, no distinction was made between corraling, transported manure or other ways of organic fertilisation. This leaves us with three major input variables: application of manure in any kind of form (stocking rate see above), application of mineral fertiliser (amount see also above) and rainfall (calculated site specific).

Table 10 & 11: Yields (kg.ha⁻¹) of demonstrations of three different sites in the year 2000 and 2001

2000			
village	Bani	Tigo	Kodey
control	216	89	130
manure	271	395	374
min. fert.	225	204	297
man.+ fert.	438	344	422

2001			
village	Bani	Tigo	Kodey
control	64	65	128
manure	203	180	341
min. fert.	83	131	303
man.+ fert.	246	204	403

Table 12: Yields (kg.ha⁻¹) of SIMFIS test run for three different sites in the year 2000

2000			
village	Bani	Tigo	Kodey
control	104	101	95
manure	174	151	136
min. fert.	154	155	138
man.+ fert.	222	101	177

Table 13: Yields (kg.ha⁻¹) of FAKFARM test run in three different sites in the year 2000

2000			
village	Bani	Tigo	Kodey
control	49	32	137
manure	49	32	145
min. fert.	49	32	345
man.+fert.	49	32	334

According to the FAKFARM model 2000 in Bani and even more so in Tigo was a water-limiting year. In the models calculation millet grain yield is equal to the smaller of the two, water-limiting yield and nutrient-limiting yield (Liebig-principle). This is unfortunately a rather binary solution, but this fact leads to the 49 kg.ha⁻¹ millet yield in all three fertiliser variations in Bani 2000 (32 kg.ha⁻¹ in Tigo). The calculation of water-limiting yield depends on the distribution of the rainfall. Dose one development stage falls short of water it may influence the yield drastically. Rainfall data was averaged for 1-4 rain gauges. In some cases rainfall in a certain gauge for a certain development stage was only a little higher, but sufficient to lift water-limiting yield to the level of nutrient-limiting yield. Another factor of uncertainty is the exact duration of the development stages. In some cases one additional week of vegetation would also have been enough to support the nutrient-limiting yield. On the contrary 2000 in Kodey was not water limiting (580mm.y⁻¹). So one can distinguish between the different factors. The biggest problem in Kodey 2000 was the lack of knowledge of the exact amount of organic fertilisation as well as the duration of the manuring practise. The simplified assumption of 1.43 LTU.ha⁻¹ does not seem to hold, although the trend is clear. If one follows the model, stocking rates should be higher. At stocking rates of around 2.5 TLU.ha⁻¹ the demonstration yields are achievable. Another possibility is that stocking rates of around 1.5 TLU.ha⁻¹ are maintained for some years. Actually already in year 3 of the run, simulated yields (year3: 310 kg.ha⁻¹, year4: 324 kg.ha⁻¹) move in to the proximity of the demonstration yields.

2001 with about 350mm of rain was a very dry year. FAKFARM calculated for each location the water-limiting yield with about 20 kg.ha⁻¹ as the determinant. Like in the year 2000 in Bani and Tigo simulated yields do not differentiate in fertility management. This was primary because of the low rains in the flowering stage of the millet development. Flowering is, of all development stages, the most susceptible to water stress. Changing duration of development stages by a couple of days dose not help much in adapting simulated and demonstrated yields.

One simple way of adapting the calculated yield to the observed one is to increase the potential yield of millet. This parameter is only used to calculate the water-limiting yield (equ. 11). Increasing the potential yield increases water-limiting yield and by this decreases the susceptibility of the crop to water stress. Doubling the potential yield (total dry matter production.ha⁻¹) to the value to 18,000 kg.ha⁻¹ lifts the simulated yield to about 40 kg.ha⁻¹. Which is still far from the control.

Finally one has to admit that FAKFARM is not a good tool to predict the exact yearly yield of millet on the basis of rainfall data. But it newer was intended to do so. There are other models trying to achieve this, like APSIM (see 2.2.2 Classification and examples). FAKFARM is a tool to predict soil fertility over a period of 10 years or longer.

To validate the quality of soil fertility prediction, first one has to define the key variables of soil fertility. Apart from water availability yield is determined by the availability of nutrients. The two most important macronutrients in this region are nitrogen and phosphorus. So they are of course included in the key variables of soil fertility. Under West-African conditions organic matter content and pH are also very important variables. Because of the lack of long-term data on these variables the models behaviour is validated comparing model runs from FAKFARM and SIMFIS with the same initial conditions.

Test run was done on the base of rainfall data of 2000 in Kodey. These conditions were chosen because, water was not limiting in the FAKFARM calculation of millet yields. The same rainfall data were used for each year of the 10 years run of the FAKFARM simulation and 5 years for the SIMFIS run. As SIMFIS run time is restricted to 5 years. Variables were calculated for one ha repeatedly cropped with millet. Two different fertility levels were investigated: the control and the high input level of the demonstration (1 TLU.ha⁻¹ plus 60 kg NPK.ha⁻¹). As SIMFIS takes herd composition, age groups and development into account, it was not possible to input TLU, but one 4 year old zebu cow per ha, corresponding to 1 TLU.ha⁻¹ (Schlecht E. communicated orally).

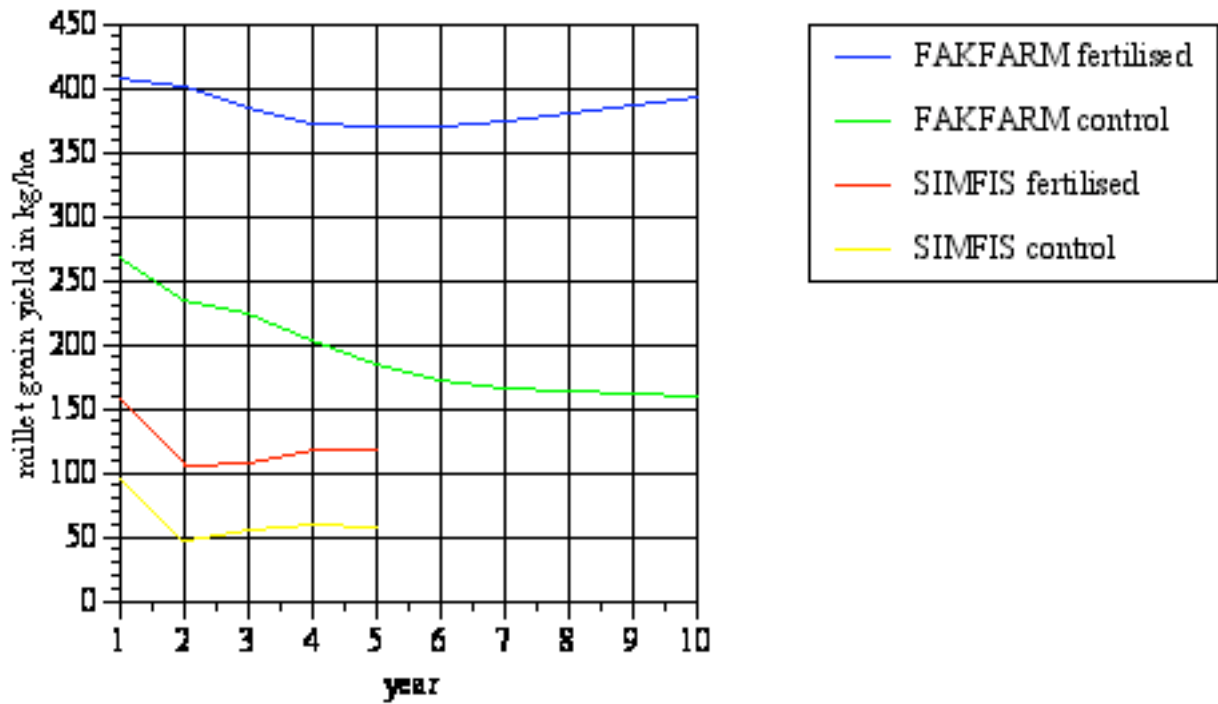


Figure 19: Yields calculated by FAKFARM and SIMFIS for a 10 resp. 5 years simulation run with the same initial conditions

Millet yields of the two simulation runs differ notably. FAKFARM yields are a lot higher but correspond more to the ones observed in the demonstrations. SIMFIS yields may be limited by water availability and by *Striga* (*Striga hermonthica*), a severe weed in West Africa. Both simulations calculate water-limiting yield in a different way and FAKFARM doesn't account for yield decrease by weeds.

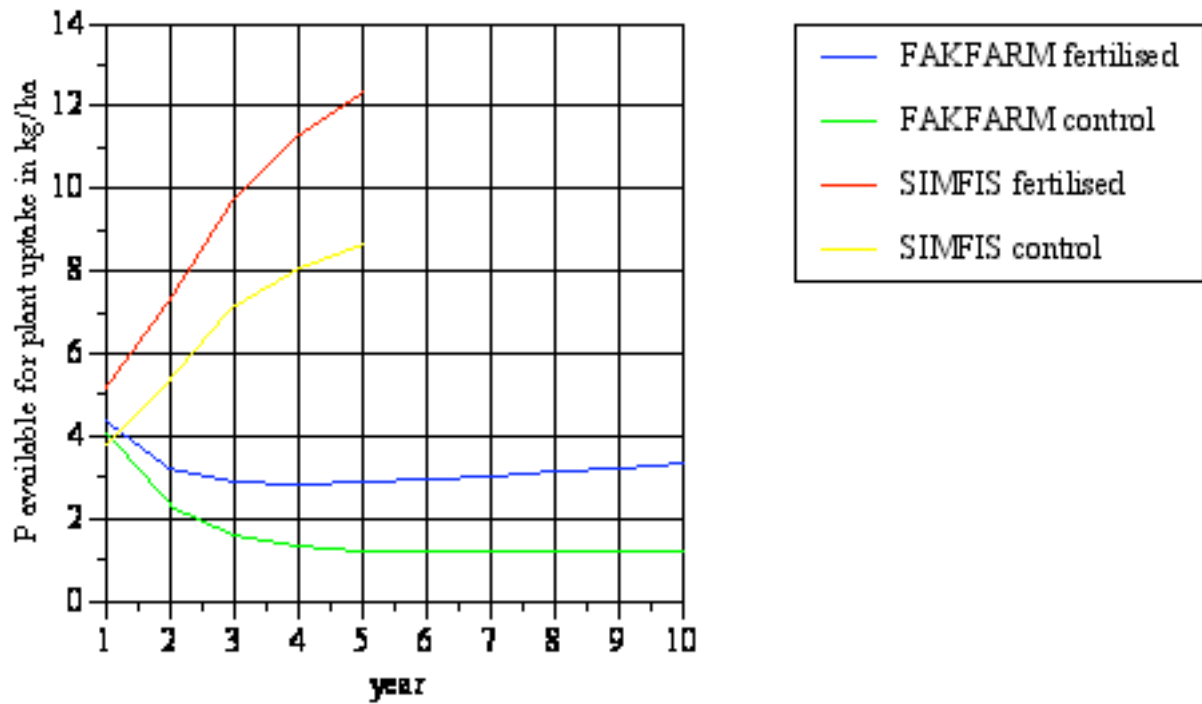


Figure 20: P available content of upper soil level in $\text{kg}\cdot\text{ha}^{-1}$ calculated by FAKFARM and SIMFIS for a 10 res. 5 years simulation with the same initial conditions

Burkert and Hiernaux (1998) as well as Batiano et al. (1992) stated that phosphorus is the first limiting factor of millet production in the objective area. In FAKFARMs calculation this is also the case. The crop takes up nearly all the available P. This can be proven by comparison of the Puptake and the Pavailable curves. They meet in year 3 and correlate afterwards. In SIMFIS yields are lower, limited by other factors than P. So Pavailable content of the soil will not be exhausted, but rather increase over time.

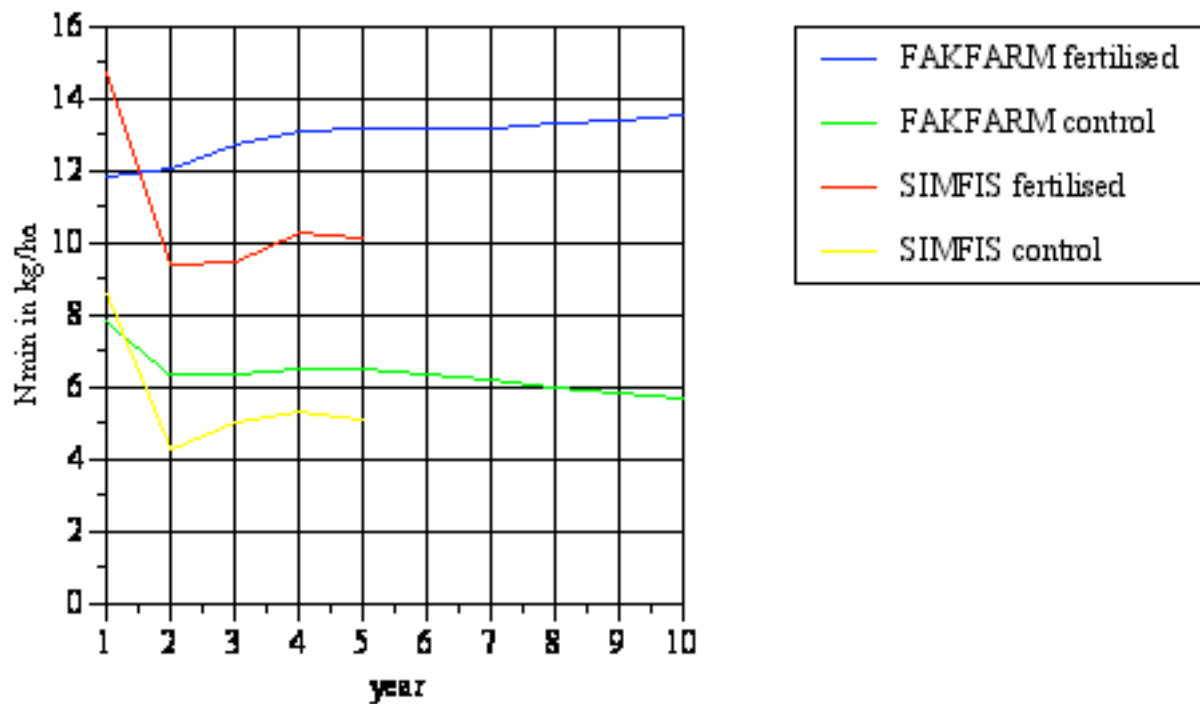


Figure 21: Nmin content of the upper soil layer (in $\text{kg}\cdot\text{ha}^{-1}$) calculated by FAKFARM and SIMFIS for a 10 resp. 5 years simulation with roughly the same initial conditions

Looking at yield development and Nmin content of the simulations it is obvious that in SIMFIS nitrogen is the first limiting factor of millet production. The curves of millet yield (fig. 19) and the ones of Nmin development correspond. As in FAKFARM P is limiting, one would expect increasing Nmin content at least at the high input level, which is the case. The Nmin development in the low input run is decreasing. If this trend would persist N might be limiting at one point in the future, but in the 10 years run this is not the case as P available is also decreasing (see fig. 20).

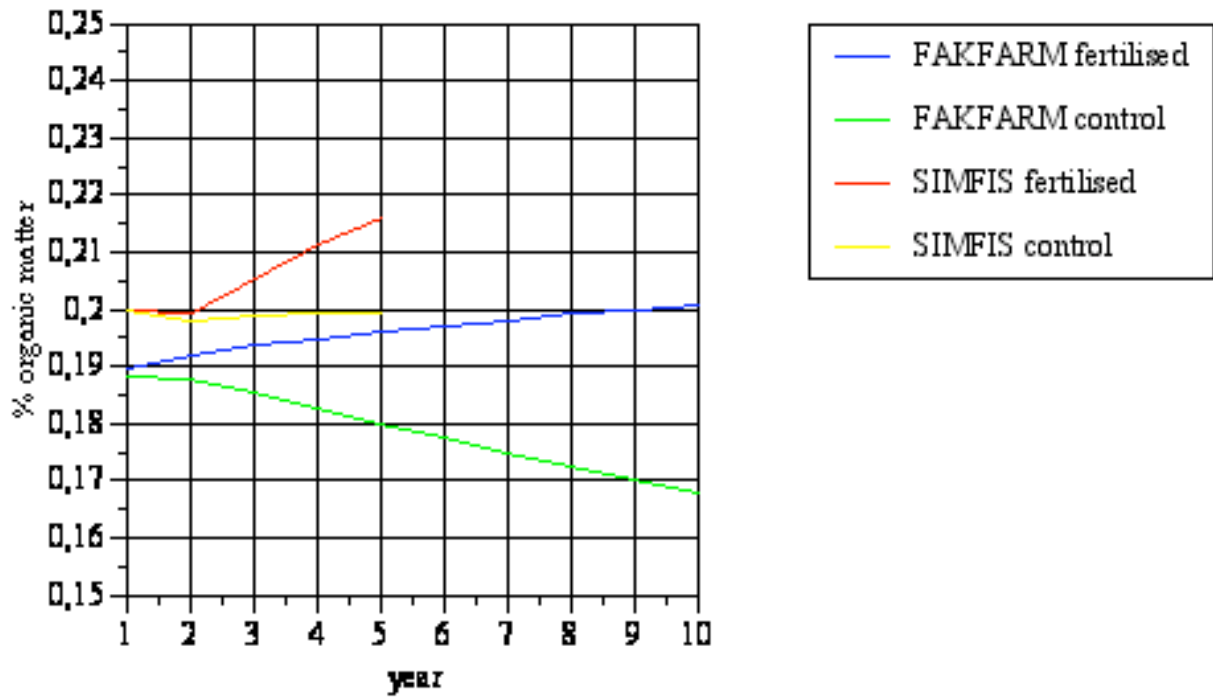


Figure 22: Percent org. matter calculated by FAKFARM and SIMFIS for a 10 resp. 5 years simulation run with roughly the same initial conditions

Organic matter contents start from slightly different initial conditions (INITs). This is because one cannot directly input INITs for org. matter in neither of the simulations.

Comparing the two simulations SIMFIS and FAKFARM bough show the same trend for the high input level. In SIMFIS (control) org. matter is decreasing only at the beginning of the simulation run, where yields are still quite high. Afterwards the curve flattens out and OM is stagnating. In FAKFARM yields are higher, even in the low input simulation. This is why the trends of OM in bough FAKFARM simulations are more pessimistic.

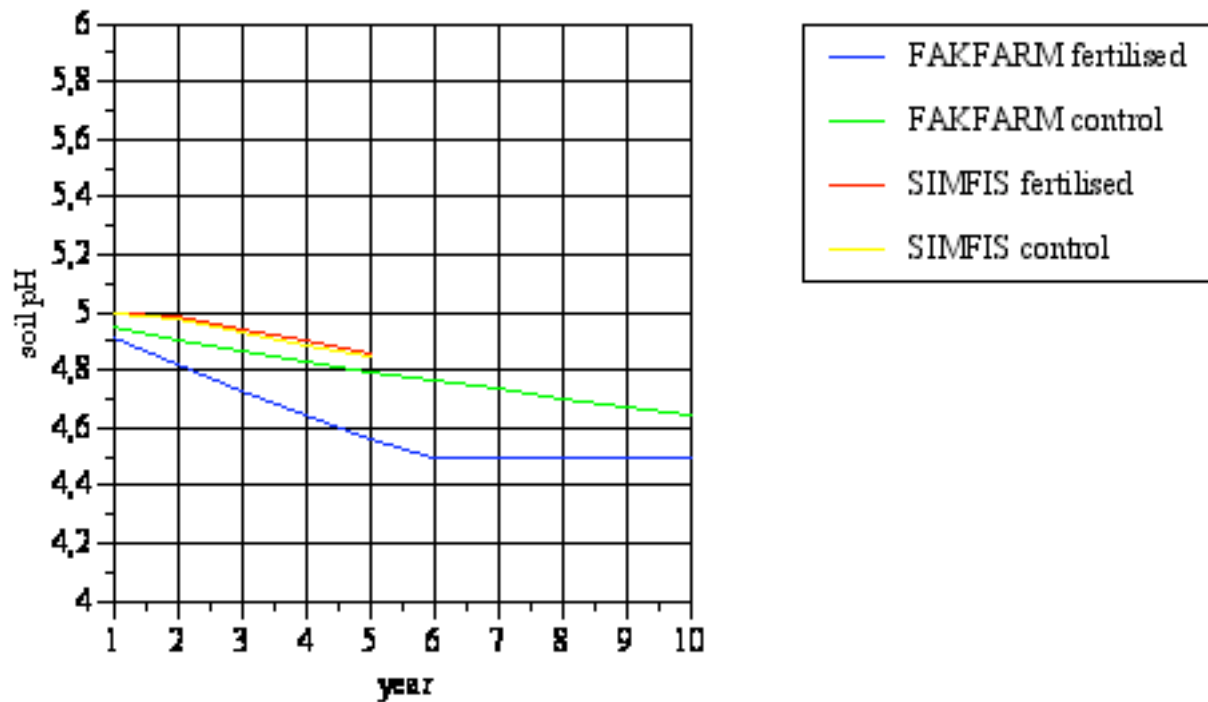


Figure 23: Soil pH calculated by FAKFARM and SIMFIS for a 10 resp. 5 years simulation run with the same initial conditions

Soil pH development of all test runs is quite similar. Nearly no difference can be observed between the two factors in SIMFIS simulation. FAKFARM simulations differ considerably. Various authors reported on acidification in West African soils, blaming it on the use of acidifying fertilisers and on the decreasing levels of soil organic matter (Sement, 1980; Pieri, 1989; Stumpe and Vlek, 1991; Veldkamp et al., 1991; Van der Pol, 1992; Juo et al., 1995). This development is reproduced in the all simulations. The pH development of FAKFARMs high input run is quite extreme, but considering high yields, strong decrease of org. matter and rather high input of min. fertiliser it is not all to nonsense. The curve flattens out abruptly in year 6 of the simulation, as FAKFARM is only able to simulate pH ranges from 6 to 4.5. As this pH range corresponds with the linear section of the soil pH titration curve (see 2.3.2.4).

3.5 Sensitivity analysis

In the sensitivity analysis it is tested how sensitive the model output reacts on variation of input parameters and variables. If the model reacts only slightly to a changing parameter it is considered as insensitive to this parameter and an error in its value would not lead to wrong assumptions. But if the model reacts strongly and is considered sensitive to this parameter, one has to be careful and maybe invest more research on this parameter to avoid errors, which would lead to wrong assumptions. Bontkes (1999) already did a sensitivity analysis for a couple of parameters. For the parameter basic decomposition rate he found a large influence on decomposition of organic matter. This is of special importance as on the one hand organic matter is regarded as the most important factor of soil fertility and on the other hand the decomposition of OM releases nutrients, influencing millet yield under non-water limiting conditions strongly. He concluded that real decomposition rates might be slightly higher than the ones used. As this would explain the higher yields of the official data he used in 1999. The decomposition rates used in FAKFARM are the corrected ones he used in his SIMFIS (2005) model.

Another interesting use of a sensitivity analysis is to test input variables like rainfall, use of min. fertiliser or stocking rate on its effect on output variables like yield or organic matter content. Because this research is largely based on Bontkes (1999 and 2005), parameters are considered tested. To not repeat his work it will concentrate on the analysis of the sensitivity of input variables.

As mentioned before the most important variables of soil fertility are:

- organic matter content of the soil (SOM in %),
- nitrogen available for plant uptake (N_{min} in $kg \cdot ha^{-1}$),
- phosphorus available for plant uptake (P_{ava} in $kg \cdot ha^{-1}$)
- pH value of the upper soil layer (pH value)

Additionally it is important to test input variables on its effect on the yield of millet ($kg \cdot ha^{-1}$). Most interesting input variables to be tested are of course the ones who can be influenced by the farmer. Additionally for two reasons the effect of rain is also tested. First is expected to decrease on average in the next couple of decades due to climatic change and second because it is expected to have a strong influence on all output variables.

So input variables tested on its effect on soil fertility and yield development are:

- stocking rate of cropped area (SR in TLU.ha⁻¹)
- amount of crop residues left on the field after harvest (CR in %)
- application of composite fertiliser NPK 15/15/15 (NPK in kg.ha⁻¹)
- and development of total yearly rain fall (in % of historic rainfall)

For all further simulations in the sensitivity analysis the historic rainfall data of the years 1991 to 2000 gained from ICRISATs weather station in Sadore (long. 13° 13' 60N, lat. 2° 16' 60E) are used.

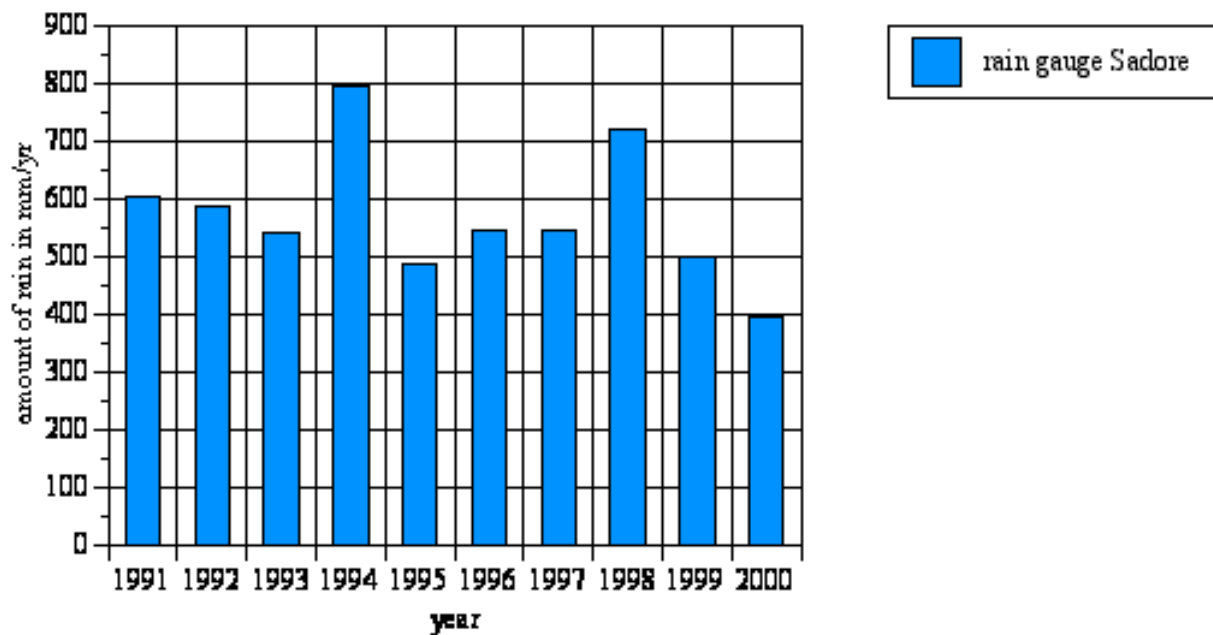


Figure 24: Total amount of yearly rainfall over the period of 10 years at the weather station in Sadore

Average rainfall of this decade was 570 mm.yr⁻¹. Two years of exceptional good rains stand out, 1994 and 1998, whilst rains in 1995 and even more so in 2000 were quite poor.

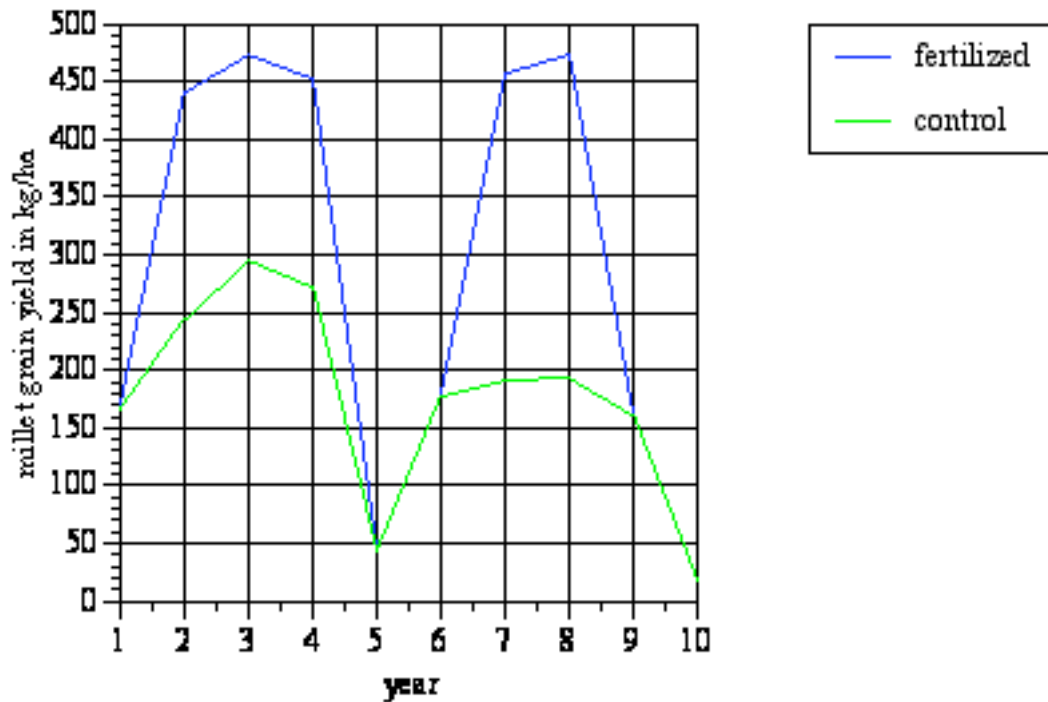


Figure 25: Yields calculated by FAKFARM 10 years simulation run based of rainfall data obtained in Sadore

Yield data correspond nicely with rainfall data. The years 1995-96 and 1999-2000 are considered water limited, so yields of the two fertility factors are the same. In all other years yields differ in fertility management. Fertilized again stands for 60kg NPK.ha⁻¹ and one TLU.ha⁻¹. Control stands for neither of bough.

For the Sensitivity analysis one input variable at a time is observed. While investigating sensitivity of e.g. stocking rate (TLU.ha⁻¹) the other input variables are set to default. For TLU.ha⁻¹ default is 0, for straw removal it is 1, meaning 100% of straw is removed from the field, for mineral fertiliser this is 0 kg NPK.ha⁻¹ and for rainfall this is 1, meaning 100% of the historical rainfall data for 1991-2000 from the weather station Sadore.

Sensitivity of stocking rate was investigated taking 2 TLU.ha⁻¹ as base. Stocking rate varied from 0 to 4 TLU.ha⁻¹. The effect on output variables is measured in percent variation from this base. Data for the 10 years simulation run were averaged.

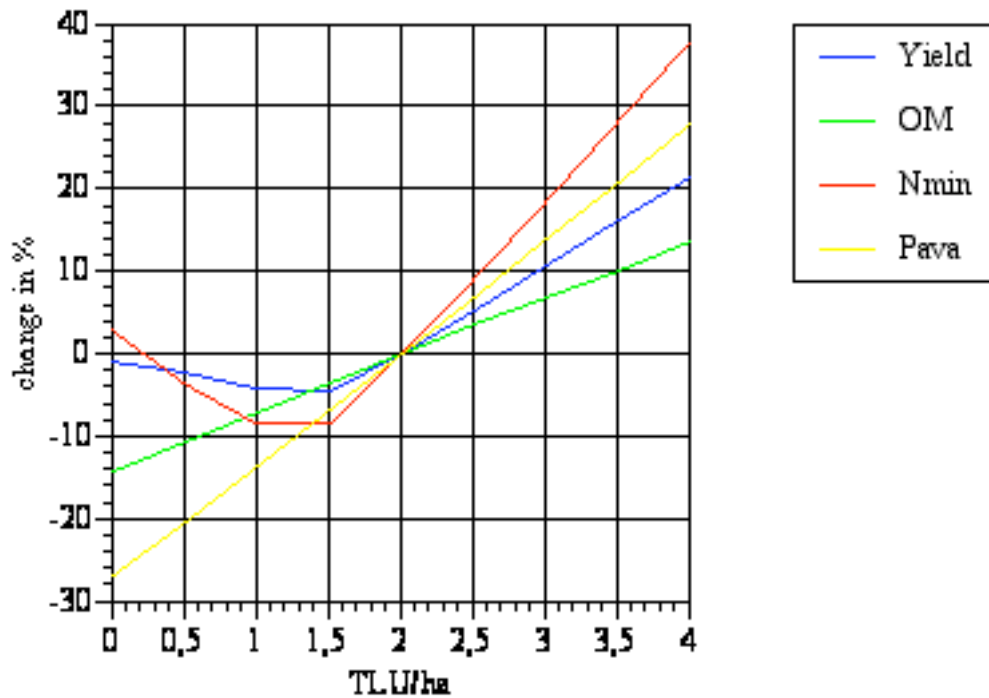


Figure 26: Effect of stocking rate (TLU.ha⁻¹) on yield, org. matter, Nmin and P available content of the soil (in %).

The effect of TLU.ha⁻¹ on OM and Pava is linear. The higher the stocking rates the higher are both variables. The effect of TLU on yield and Nmin is positive only for stocking rates higher than 1.5 TLU.ha⁻¹. Stocking rates lower than 1 TLU.ha⁻¹ seem to have a negative effect on Nmin and yield. If we consider yield at low stocking rates N limited it is obvious that the yield line follows the Nmin line. But why is Nmin content decreasing with increasing stocking rate at lower levels. One possible explanation for this phenomenon is the competition of OM and plant biomass for nutrients, especially nitrogen. In the model SOM shows a positive effect on increasing stocking rate but looking at N incorporated in stable OM (Nincorpstab) one can observe that its overall trend, over the 10 years run, is positive only at stocking rates higher than 1 TLU.ha⁻¹. At stocking rates lower than that, less Nmin is demanded by stable SOM. Additionally at lower yield levels less Nmin is demanded by the plant subsystem.

Sensitivity of straw removal was tested with no manure and no min. fertiliser. Historic rainfall data of 1991-2000 (Sadore) was used. Straw removal of 1 stands for “all straw removed from the field”, straw removal 0 is “all straw grown the resp. year is left on the field” and straw removal of -1 is additional crop residues transported to the field in the same amount as grown

the res. year, effectively doubling the amount of crop residues on the field. As base no straw removal (factor = 0) was chosen.

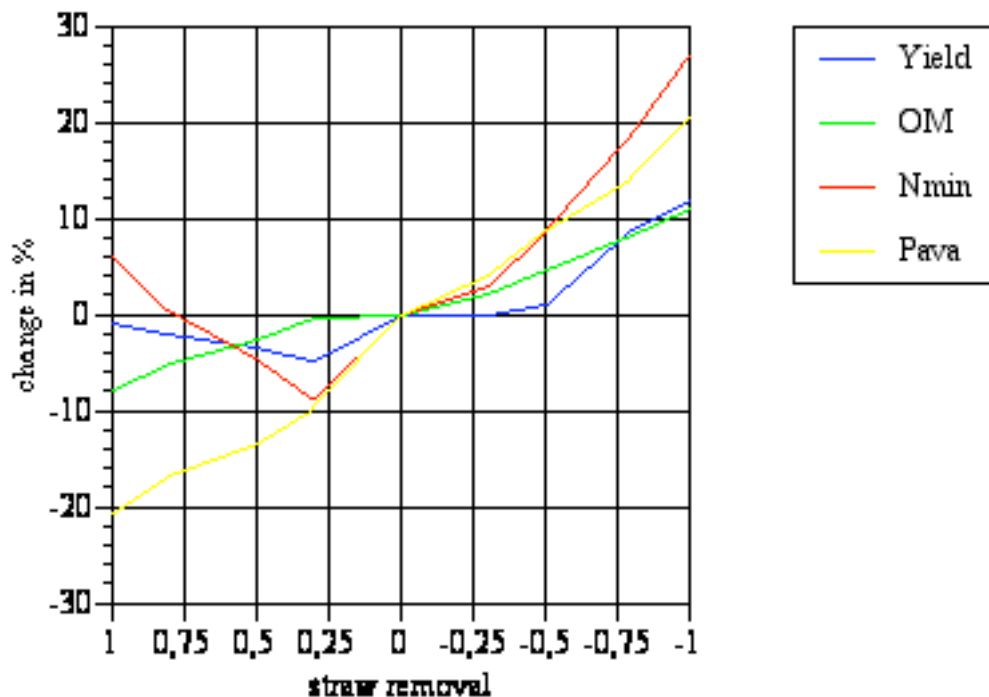


Figure 27: Effect of straw removal (factor of removal) on yield, org. matter, Nmin and P available content of the soil (in %).

Sensitivity of Straw removal shows the same effect on Nmin and yield as $\text{TLU}\cdot\text{ha}^{-1}$ dose. If more than 30% of the straw is removed from the field, the effect is positive. Only for straw removal lower than 30% additional straw shows an increase in Nmin. Again this could be explained by the competition of SOM and plant biomass (see sensitivity of stocking rate). The overall effect of straw removal, at the ranges under observation, is not as high as the ones of stocking rate. All of the curves show minor slopes compared to the ones of $\text{TLU}\cdot\text{ha}^{-1}$. But it is to note that the range of stocking rate is chosen quite generously. Typical stocking rates in the area vary between 0 and 2 $\text{TLU}\cdot\text{ha}^{-1}$. Considering this it is to admit that it might be easier for the local farmer to forbear from straw removal than lift its stocking rate to 4 $\text{TLU}\cdot\text{ha}^{-1}$.

Sensitivity analysis of mineral fertiliser was conducted with compound fertiliser NPK 15/15/15, apart from Urea one of the more readily available min. fertiliser in the Fakara. But still it is rather expensive and hard to come by, for the regional farmer. The base was set to 60 $\text{kg NPK}\cdot\text{ha}^{-1}$, corresponding to 9 $\text{kg N}\cdot\text{ha}^{-1}$ and 9 $\text{kg P}_2\text{O}_5\cdot\text{ha}^{-1}$, because this was about the input

level of the demonstrations 2000-2002 (see 3.1). Fertiliser use was varied from 0 to 120 kg NPK.ha⁻¹.y⁻¹.

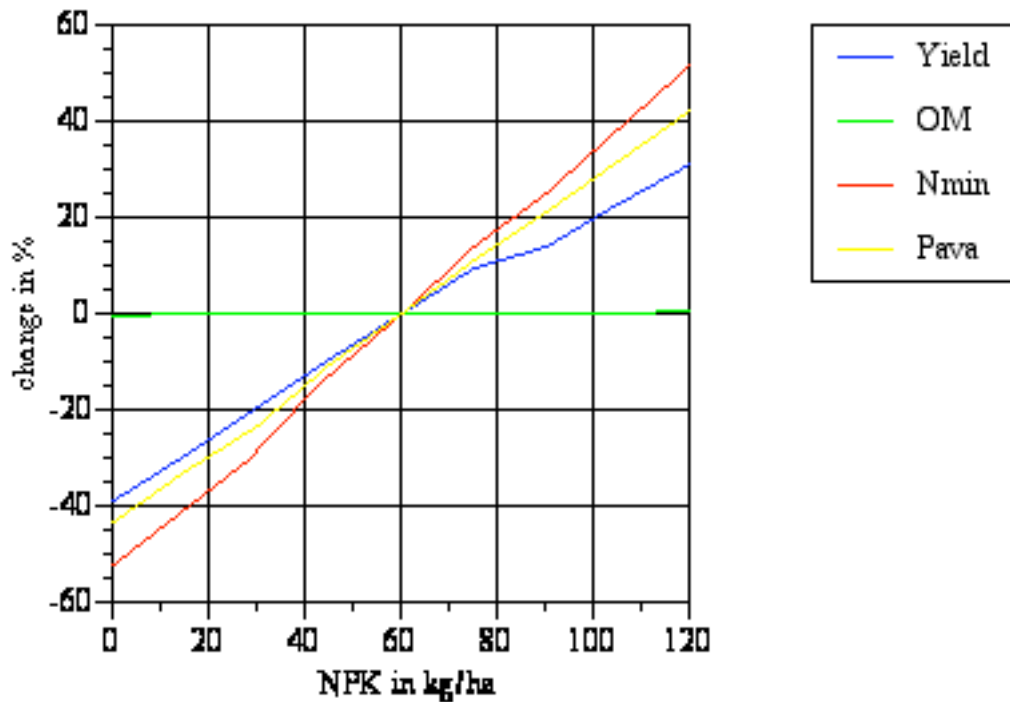


Figure 28: Effect of mineral fertiliser use (kg NPK.ha⁻¹) on yield, org. matter, Nmin and P available content of the soil (in %).

All output variables are positively related to the increase of mineral fertiliser and all response curves are quite linear. The effect of NPK on Nmin and Pava is greatest but yield of course reacts also strongly on increase of NPK. For SOM one also can detect a positive effect on fertilizer use but its increase is by far smaller than the ones for the other variables.

At high fertiliser inputs one would expect a decreasing yield effect, but at fertiliser levels of 120 kg NPK.ha⁻¹ (18 kg N.ha⁻¹) yield is still growing nearly linear. To plot the classical yield response curve fertiliser input was increased to 300 kg NPK.ha⁻¹ (45 kgN.ha⁻¹).

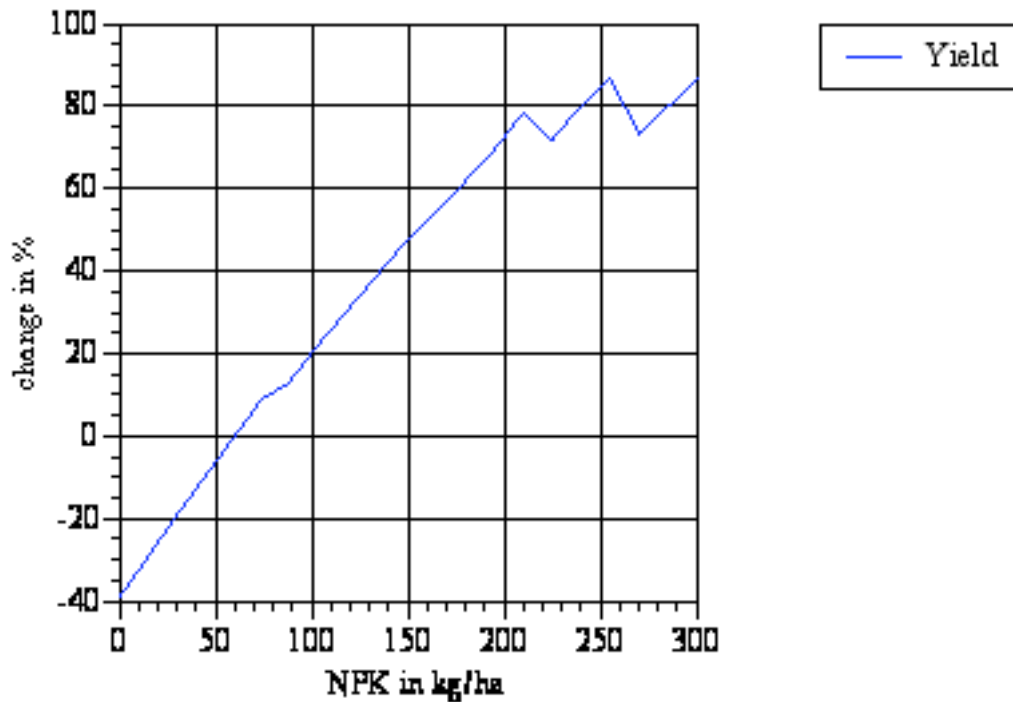


Figure 29: Classical yield response curve (in % yield increase) to application of mineral fertiliser (in kg NPK.ha⁻¹).

At fertilizer input levels of more than 200 kg NPK.ha⁻¹ the yield response curve flattens out. The rather strange behaviour of the upper part of the curve can be explained by the interrelation of the years. If in one year the water limiting yield is reached, yield will no longer react on increasing NPK. The NPK input is not completely lost, but is stored in the soil and may be taken up by the next years yield. This may lead to fluctuations in Nmin and Pava pools, which mirror in the yield response curve.

The interesting information derived from fig. 29 is the point where the yield response curve flattens out. With all input variables set to default this is at around 30 kg N.ha⁻¹. The highest yield at this level is the one of year 8 (1998) with nearly 1200 kg.ha⁻¹.

This is very similar to findings of Batiano et al. (1989) (see fig. 30).

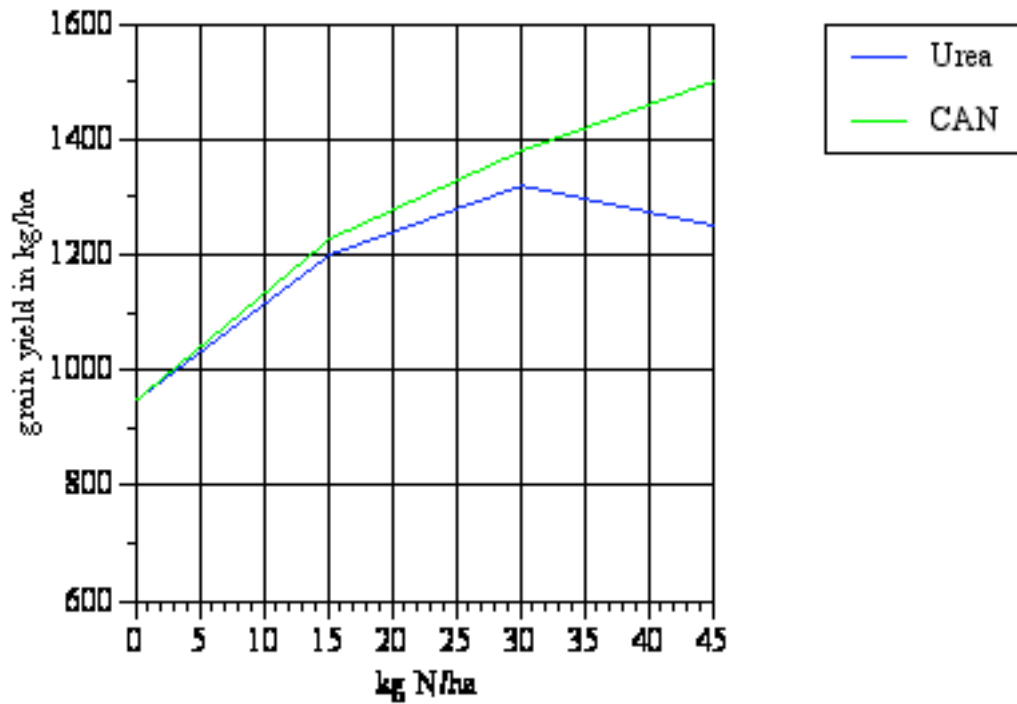


Figure 30: Yield response curve (in kg grain yield.ha⁻¹) to application of mineral fertiliser (in kg N.ha⁻¹) from urea and calcium ammonium nitrate (taken from Bationo et al. (1989)).

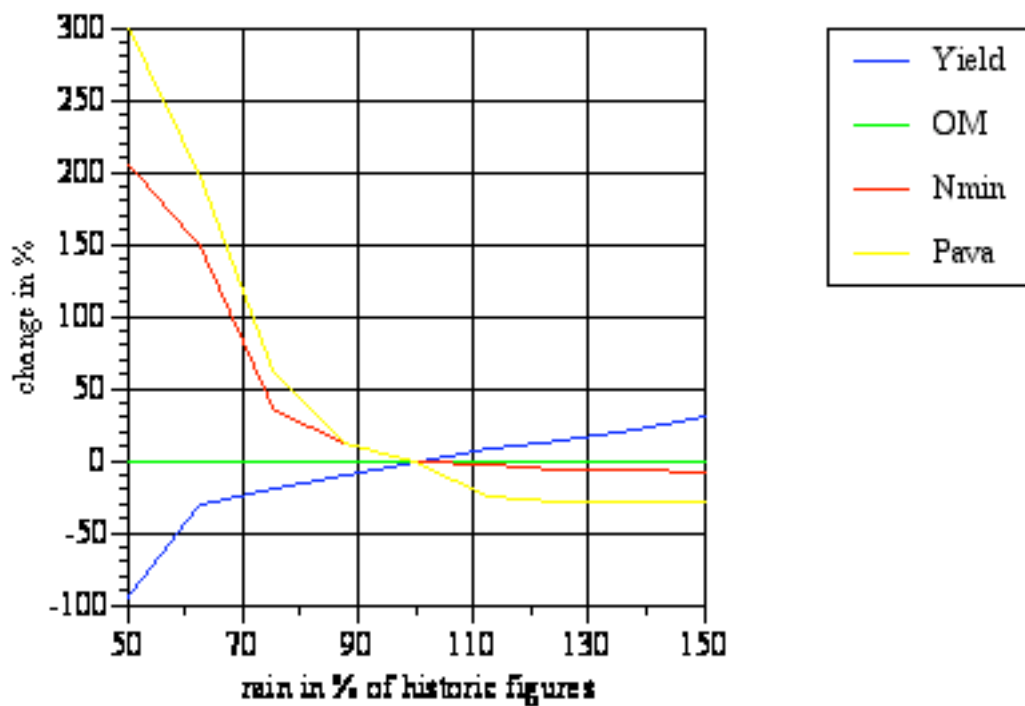


Figure 31: Effect of rainfall (in % of historic values) on yield, org. matter, Nmin and P available content of the soil (in %).

Sensitivity of rainfall (fig. 31) was again tested with default values for all other input variables. Rainfall data from the weather station in Sadore of the years 1991 to 2000 was varied from 50% at the minimum to 150% at the maximum.

The availability of nutrients (N as well as P) is negatively correlated to the amount of rainfall. Yield and SOM are positively correlated. Diminishing rains lead to a decrease in yield, as the water-limiting yield is more dominant the lower the total amount of rainfall is. This leads to a decrease in uptake of nutrients by the plant and more nutrients will stay in the soil. At 50% of the historic rainfall nearly no yield is to be obtained. The next couple of mm.yr^{-1} increases the yield strongly, while from 80 – 150% of historic rain the yield increase is nearly linear. SOM on the other hand is high at very low rainfall but decreases with decreasing availability of nutrients. At rainfall higher than 80% SOM slowly increases again. This effect is very small and does not show on the diagram. SOM can be considered as insensitive to the amount of rainfall, at least when all straw is removed from the field, as it is the case in this run.

The model shows very high sensitivity for yield on water availability especially at lower rainfall than the ones observed in the 1990's (see fig. 31). Additionally yield is strongly affected by the availability of nutrients (see fig. 26 & 27). Nutrients again are most sensitive to stocking rate and application of mineral fertiliser (fig 26 & 28). The addition of crop residues also shows positive effects on nutrient availability and yield but to a smaller extent (fig. 27). SOM is rather insensitive to mineral fertiliser and rainfall but still slightly effected. The best way to increase SOM is of course to input organic matter to the field via manure or crop residues.

3.6 Scenarios

In this chapter it is investigated how sustainable the low input farming systems of the Fakara are. Following the Brundland report sustainability is defined by “meeting the needs of the present generation without compromising the ability of future generations to meet their own needs” (WCED 1987). For farming systems in the Sahel this implies two things: First cereal harvest has to be kept at a level that all family members in the farmers household are well fed and none suffers hunger. And second soil fertility has to be kept at a level that allows harvest of cereals at this level for coming generations. According to the FAO, the production of 230 kilograms of cereals a year is required to meet the minimum daily calorie requirement for an average person (FAO 1974).

3.6.1 Farm types

Considering the above mentioned, one could estimate the minimum cereal harvest for each farm type on the base of the information given in table 5 (repeated in table 14). The average number of consumers/farm needs at least 230 kg millet grain.yr⁻¹, divided by the area cropped.farm⁻¹ shows the minimum millet yield.ha⁻¹ the family has to achieve to keep all family members well fed. Figures for all farm types are given in table 14.

Table 14: Endowment, family size and min. nutritional requirements of the different farm types

Farm type	No.	area cropped /farm	TLUm ¹⁾ /farm	TLUm ¹⁾ /ha	Consumer in adult equivalent/farm	Min. cereal production/ha ²⁾
VP	213	9.1	0.95	0.10	8.8	222.5
VR	126	21.4	0.8	0.04	5.3	56.9
VX	27	25.2	11.81	0.47	9.8	89.4
CP	92	8.7	12.52	1.44	6.8	179.7
CR	74	12.7	20.36	1.60	6.1	110.5

1) TLU managed 2) consumer*230kg/area cropped

Taken from: Hiernaux and Ayantunde (2004)

This simple calculation dose not takes into account the need for seeds in the following planting period as well as the risk of total failure because of drought or a plague of locusts like in 2004. For this reason lets simply double the minimum min. cereal production.ha⁻¹, giving the farmer enough seed material to plant the next years fields in a good year and buffers to a certain extend the risk of total failure in a bad year. With these prevailing conditions the development of soil fertility is investigated. Is it possible, for all five farm

types to harvest millet at the above mentioned level and conserve soil fertility? And if not, what can be done to achieve this?

Village poor farmers

VP are with 213 households in the area the strongest and by this the most important group of all five farm types. At the same time the VP are poorly endowed in bough land (9.2 ha.farm⁻¹) and livestock (0.95 TLU.farm⁻¹). Additionally VP families are big, owning with 8.8 adult equivalent.farm⁻¹ the greatest family size of all. This can be seen as curse and blessing. On the one hand the area under cultivation has to support many people leading to a min. cereal production level of 222.5 kg.ha⁻¹ (445 kg.ha⁻¹ resp.). On the other hand in this group of farms labour shortage is rather unlikely.

Standard run was conducted with historical rainfall data (1991- 2000 from Sadore), 0.1 TLU.ha⁻¹, all of the millet straw removed and no min. fertiliser application.

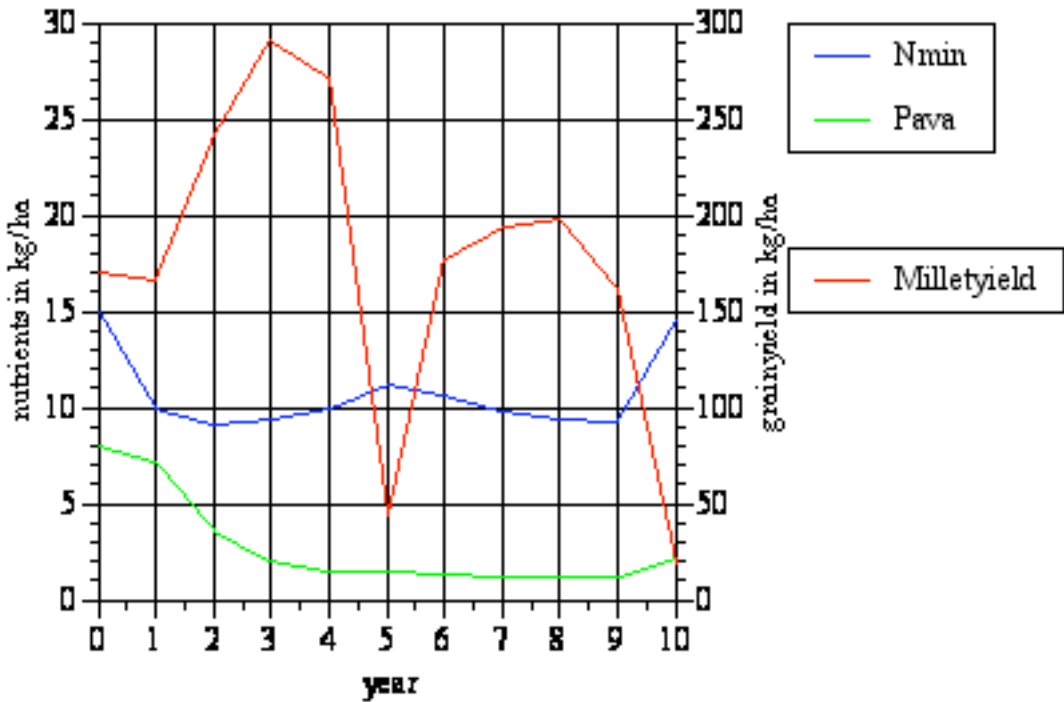


Figure 32: VP standard run of yield and available N and P (kg.ha⁻¹) development over 10 years

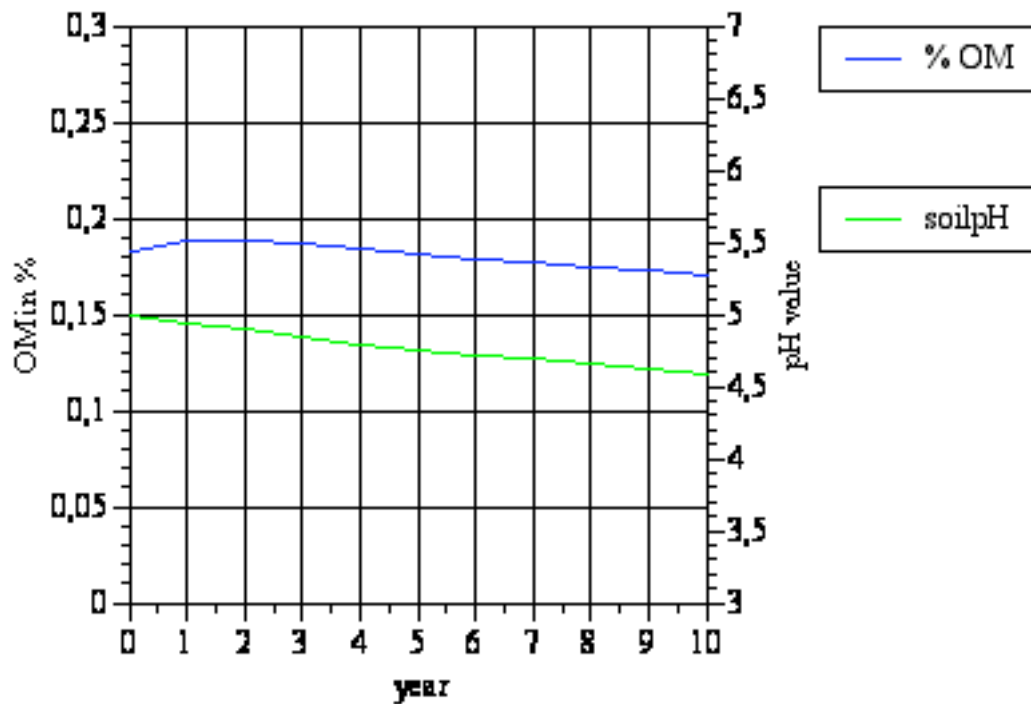


Figure 33: VP standard run of org. matter (%) and soil pH development over 10 years

Under given preconditions the group of VP can achieve neither objective. The yield level in most of the years is in the range of 150 to 250 kg.ha⁻¹ only in two years (1993 and 1994) it is able to top this. In the dry years of 1995 and 2000 it is way below the minimum level.

Nutrient development follows this trend reciprocally, but the over all trend is downward. The same applies to the development of organic matter content and pH value of these soils. This means the VP farmer is not always able to feed his family at the aimed level. Additionally his soil fertility is decreasing over time.

As mentioned above the VP farmers single one advantage is his labour potential. So how could he exploit this resource to put him in the position to crop his fields more sustainable? The easiest way to do so is to simply crop more land. This is what was done the last couple of decades and led to the increasing pressures on the land, with all its negative consequences, mentioned in the introduction. Land pressure in Niger as well as in the Fakara varies considerably and in some areas this might be a option for another decade or so. But this practise would only postpone problems. Another solution would be off-farm-income. If the family is able to earn money in any form not related to cropping and is willing to invest this money into the farm, the farmer could buy mineral fertiliser or increase his stocking rate. Livestock itself could yield off-farm-income, in this sense, if it is not fed on farmer's fields but on communal pasture only. Sensitivity analysis (see 3.2.) showed that the effect of mineral fertiliser on millet yields is stronger than the one of additional livestock. A major precondition

for min. fertiliser use is its availability and price. At this point in time prices are high and availability short, primary because of poor infrastructure and the lack of domestic production. Lets consider min. fertilizer is more easily available and cheaper, so VP farmers are willing to invest in 30 kg NPK.ha⁻¹.y⁻¹. Lets further consider the farmer is able to increase his stocking rate to 0.5 TLU.ha⁻¹ and at the same time leaves all crop residues at the field.

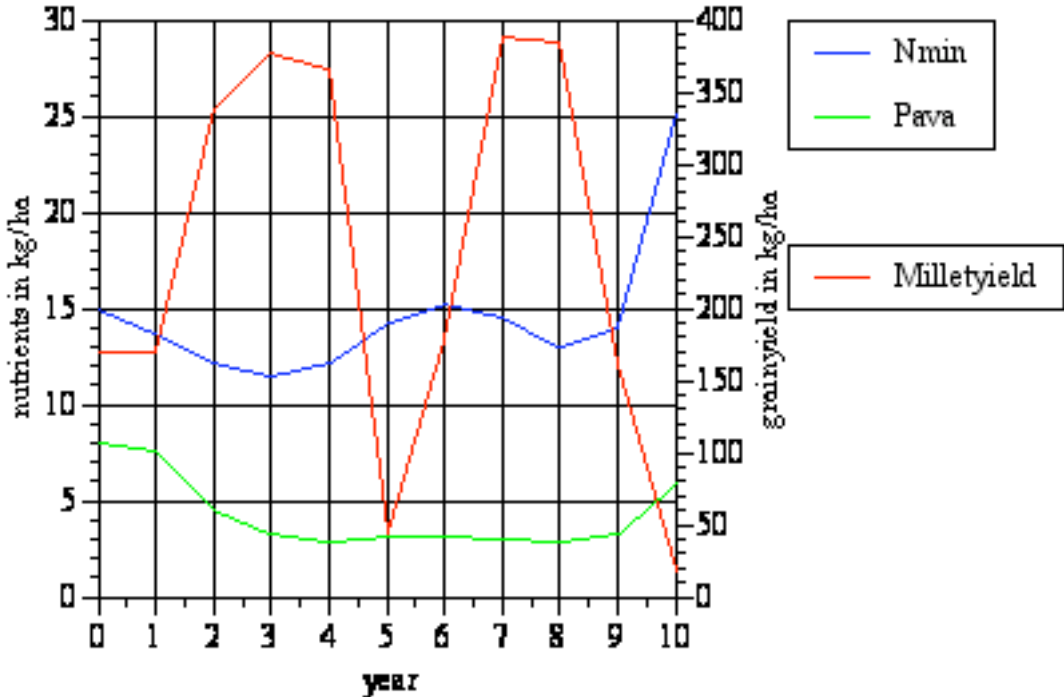


Figure 34: VP improved run of yield and available N and P (kg.ha⁻¹) development over 10 years

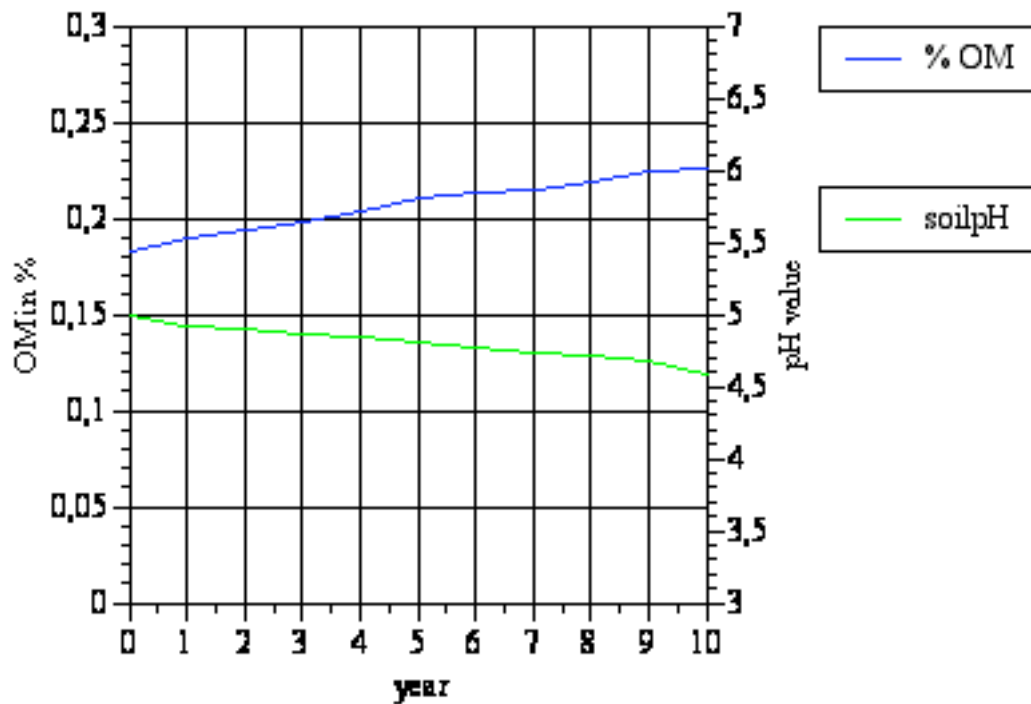


Figure 35: VP improved run of org. matter (%) and soil pH development over 10 years

In this scenario the objective of conservation of soil fertility is at least partly met. Organic matter is increasing by 0.06 % in the 10 years run. But pH development is still negative. This is caused by high yields, still to low OM returned to the soil and relatively high min. fertiliser input. OM returns by crop residue seams not enough to stabilise the pH value. Available nutrients fluctuate with the development of millet yields but can be considered as stabile in the long run. Still the VP farmer is not able to achieve the 445 kg millet grain yield.ha⁻¹.y⁻¹, even in the non-water limiting years. This can only be achieved at NPK input levels of 60 kg.ha⁻¹.y⁻¹ and higher. Livestock, in the sense of additional TLU.ha⁻¹, is hardly able to lift millet yield in this range. At stocking rates of 2 TLU.ha⁻¹ millet yields will reach 400 kg.ha⁻¹ in the first part of the decade, only in the second part yields of about 450 kg.ha⁻¹ are achievable (30 kg NPK.ha⁻¹.y⁻¹ included). If the farmer is not able or not willing to increase fertiliser input the only other alternative would be to crop additionally land.

Although stocking rate was increased its effect on OM at his rates is neglect able. Most important for the maintenance of org. matter is the abandonment of straw removal, this management practice alone helps to maintain SOM. The effect of livestock at these low levels on available nutrients and millet yield is also quite small.

To conclude, it is possible for the VP farmer to crop his fields sustainable. Organic matter can be maintained by leaving crop residues at the field. To lift millet yield to an appropriate level, nutrient inputs are required. Mineral fertiliser, even in low quantities, can increase yield

considerably and faster than an increase in stocking rate is able to do. The risk of low yields because of water limitation and even total failure still exists. This is why the VP farmer is not likely to adopt this management practice easily. But lower min. fertiliser prices and better availability would help a lot to make him do so. To stabilise pH, additional OM in the form of manure, crop residues or fallow is required.

Village rich farmers

VR are with 126 farms in the area the second biggest group. They crop 21.4 ha.farm⁻¹ on average, additionally there family size is, with 5.3 adult equivalent quite small. So the calculated min. cereal production of 56.9 kg.ha⁻¹ (113.8 kg.ha⁻¹) is the smallest of all farm types. That is why it very likely that this farmer will achieve the yield objective. On the other hand is the average stocking rate of 0.04 TLU/ha on this farms the lowest of all farm types. So what's about the second objective of sustainable crop production, to maintain soil fertility? Standard run was again conducted with historical rainfall data, average stocking rate of 0.04 TLU.ha⁻¹, all of the millet straw removed and no min. fertiliser.

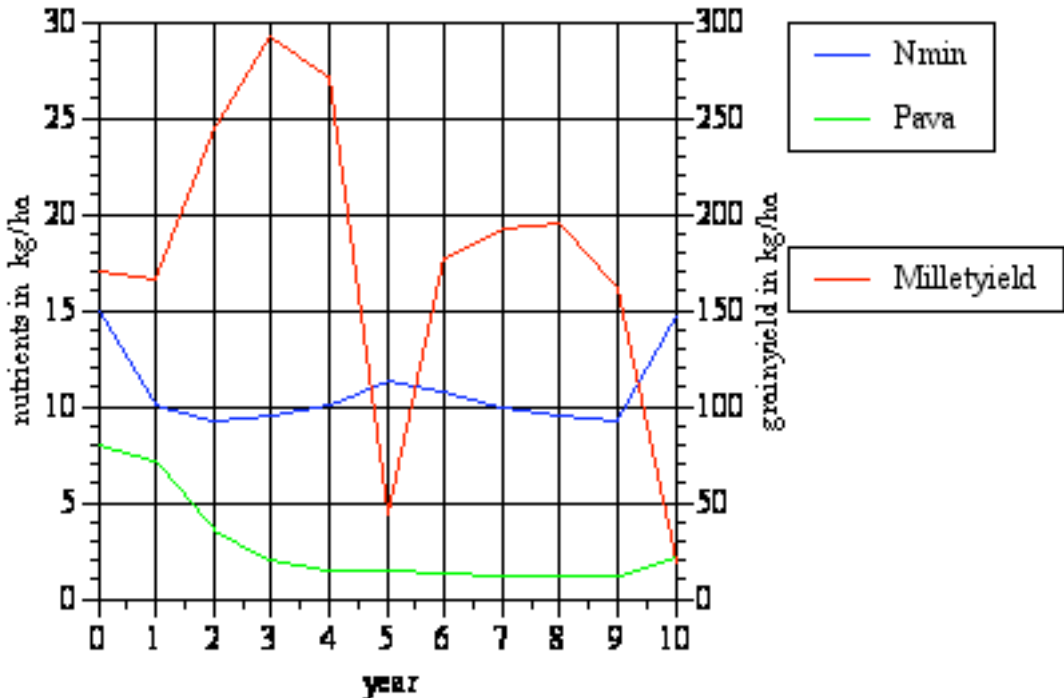


Figure 36: VR standard run of yield and available N and P (kg.ha⁻¹) development over 10 years

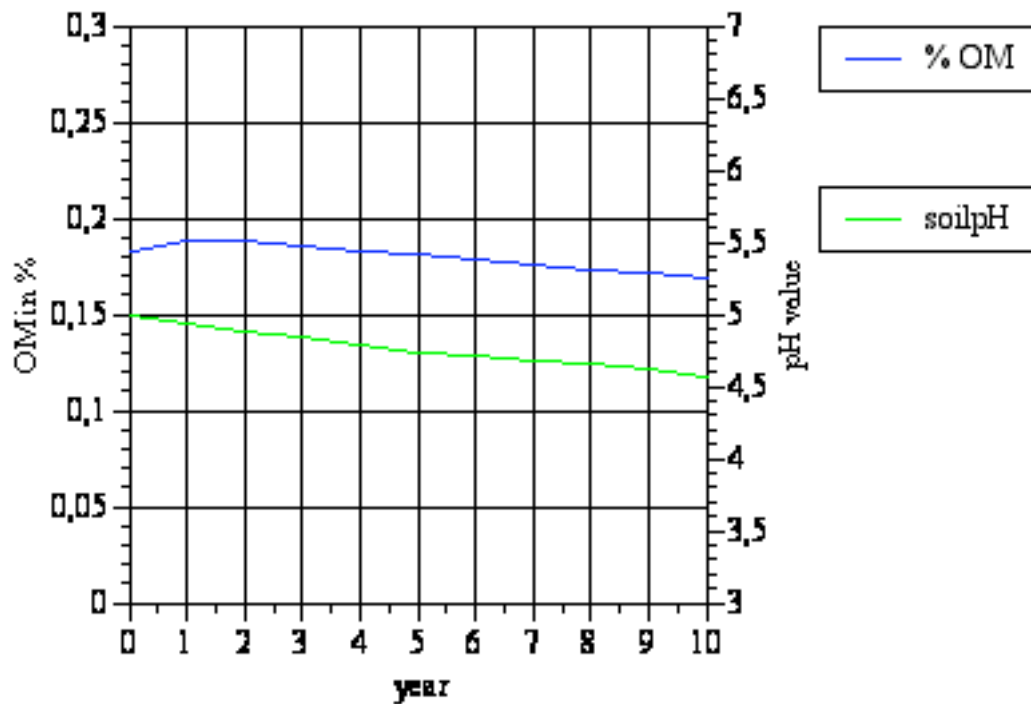


Figure 37: VR standard run of org. matter (%) and soil pH development over 10 years

Standard run of VR is very similar to the one of VP. Yield ranges between 150 and 300 kg/ha in good years and 20 and 50 kg.ha⁻¹ in the two water-limiting years. Because of the high amount of land under cultivation in relation to mouths to feed, this is sufficient for the VR to keep his family well fed. Over the 10 years run he is even able to yield some surplus stock of millet grain. This can be used to sell on local markets or as concentrate feed for livestock. Bough could be used to increase nutrient input to the fields. Organic matter and pH development of the soil is negative, so the second objective of sustainable crop production is not met.

For the improved scenario let's consider the VR farmer is able increases his stocking rate to 0.4 TLU.ha⁻¹ either by purchase of additional livestock, by corralling of herds of contract herders year round or by intensifying of his existing livestock production (concentrate feed). Let's further consider he does not remove all of his crop residues from the field but only 50% of it. The remaining 50% is used as mulch. As his millet yield level is high enough to meet the needs of his family he is not likely to use expensive and hard to come by min. fertiliser.

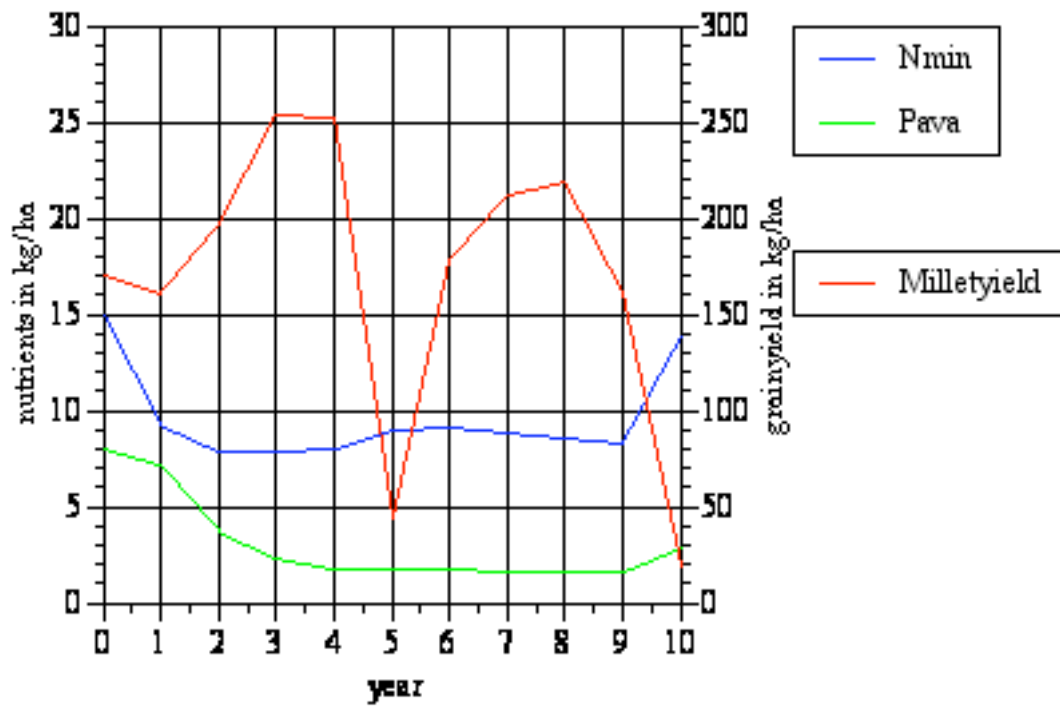


Figure 38: VR improved run of yield and available N and P (kg.ha⁻¹) development over 10 years

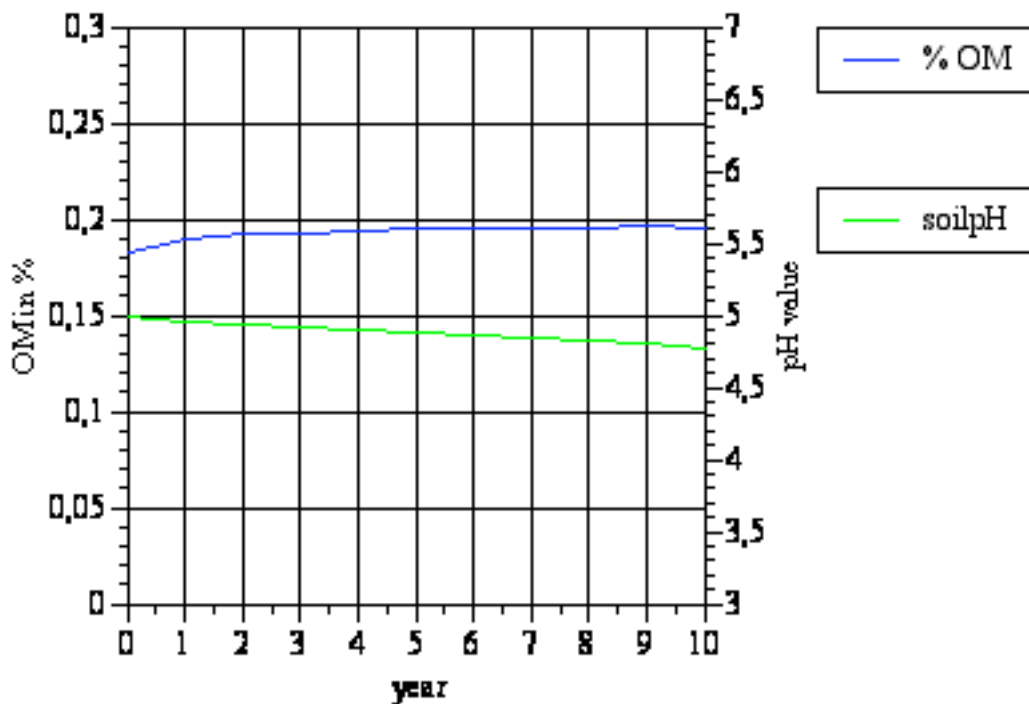


Figure 39: VR improved run of org. matter (%) and soil pH development over 10 years

Decreasing millet yields can be observed in the first part of the decade. In the second part yields are higher than in the standard run. The overall trend is more optimistic. Average yield over the 10 years run is about the same. Still the VR farmer is able to support his family and

yield some surplus. Little changes in available nutrient stocks can be observed. Nitrogen is slightly lower, phosphorus slightly higher compared to the standard run.

Organic matter content of the soils is increasing slightly in the first couple of years and stagnates in the second half of the decade. Soil pH is still slightly decreasing, although no min. fertiliser is used. To keep soil pH stable still more OM input is required. From the perspective of sustainable soil use this scenario is considered as acceptable. About the same effect could be achieved by reducing straw removal to 25%, leaving 75% of millet straw as mulch, while stocking rate is kept at the 0.04 TLU.ha⁻¹ level. For stable soil pH the VR farmer might increase his stocking rate or leave his fields fallow every couple of years. This is assumed to have the same effect as additional crop residue inputs to the soil. Contrary to the VP the VR farmer is able to do so as he is able to harvest surplus millet grain.

For the VR farmer it is easier to crop sustainable compared to the VP. The fact that his yield level to sustain his family is way below the one of VP leads to a reduction of pressure on his cropland. He is not reliant on min. fertiliser, but has to keep an eye on OM content of his soils. If he is able to increase his stocking rates by one of the options mentioned above, he has to increase it up to 0.4 TLU.ha⁻¹ to keep SOM stable. The abandonment of straw removal to a certain extent would yield the same effect to SOM with a smaller, but still positive effect on soil pH.

Village herders (VX)

VX are the smallest group of the five farm types, with only 27 households in the objective area. They crop the highest amount of land.farm⁻¹ (25.2 ha.farm⁻¹) and manage a fairly high amount of livestock (11.8 TLU.farm⁻¹). From this perspective they could also be seen as “Village very rich”. On the other hand the VX farmers family is the biggest, with 9.8 consumers in adult equivalent on average. This means his sustainable min. cereal production is 89.4 kg.ha⁻¹ (or 179 kg.ha⁻¹ to play it safe).

Standard run was again calculated with historical rainfall data, average stocking rate of 0.47 TLU.ha⁻¹, all of the millet straw removed and no min. fertiliser.

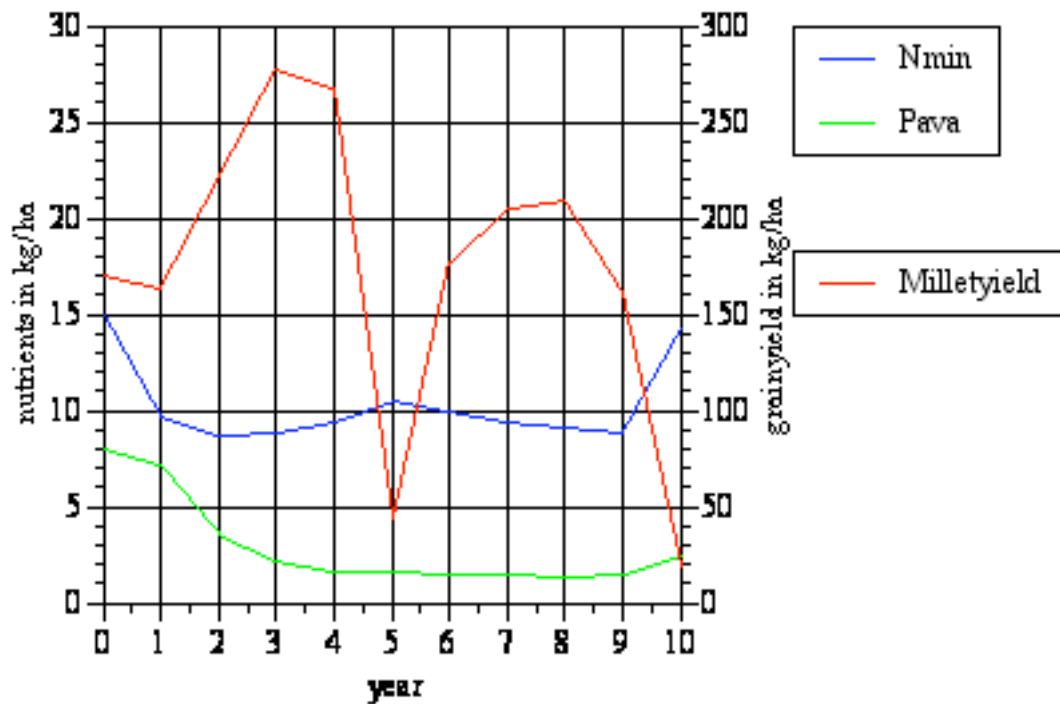


Figure 40: VX standard run of yield and available N and P ($\text{kg}\cdot\text{ha}^{-1}$) development over 10 years

Compared to the two standard runs already seen (VP and VR) millet yields are slightly lower in the first part of the decade and slightly higher in the second part. This is due to the fact that all runs start from the same initial conditions (because of the lack of reliable data). So at higher stocking rates, more nutrients (esp. N) are required by SOM at the beginning (see also 3.2 Sensitivity analysis). But over time the higher nutrients input becomes more and more obvious and shows in available nutrients and even more so in millet yields.

With yields ranging between 150 and $280 \text{ kg}\cdot\text{ha}^{-1}$ the VX farmer is, with the exception of the two drought spells in 1995 and 2000, absolutely able to sustain his family. He is even able to yield some surplus to overcome the dry years or earn cash at local markets.

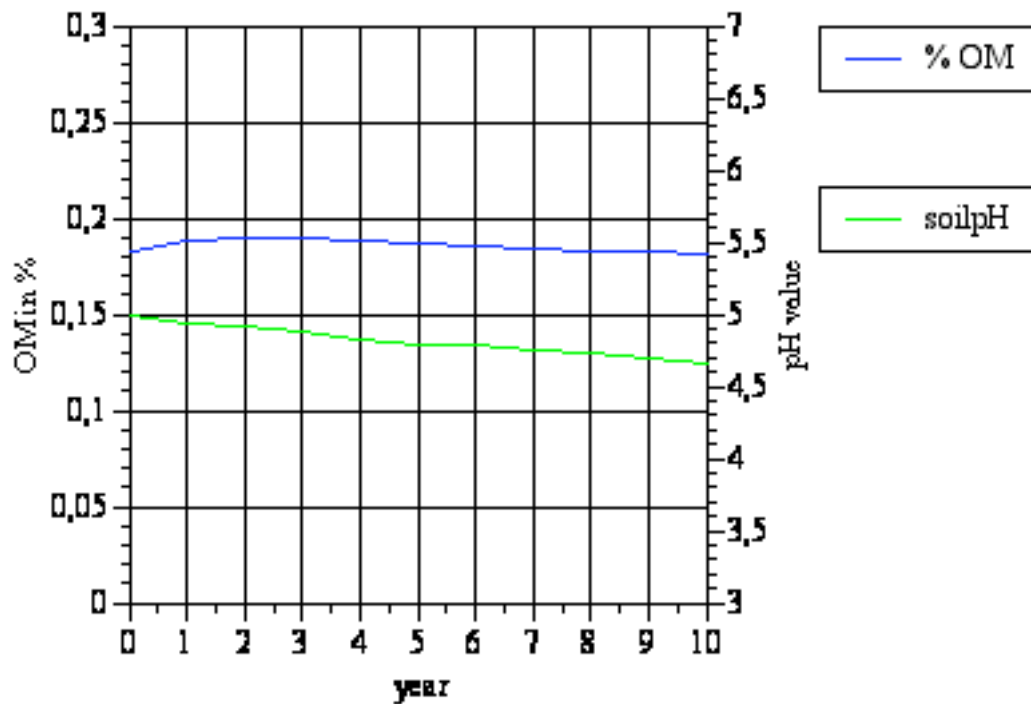


Figure 41: VX standard run of org. matter (%) and soil pH development over 10 years

Organic matter of the VX soils is increasing in the first years and slightly decreasing afterwards. Considering the INIT problem (see above), the overall trend is downward. Soil pH is slightly decreasing but not as much as in the two previous standard runs. The stocking rate of the VX standard run is very similar to the one in the improved run of VR. So another improved run for VX can be forgone.

To keep OM stable the VX farmer has to leave half of the crop residues grown annually at the field (see fig. 39). Soil pH will only be stable at stocking rates of 1 TLU.ha⁻¹ or higher. To keep soil pH stable at his actual stocking rate (0.47 TLU.ha⁻¹) additional crop residues are required. If the VX farmer were able to take additionally 50% of the CR that grew at 1 ha to his field (all grown straw remains and an additional 50% is added) his soil pH would be stable as well. Short-term fallow every 5 to 10 years would yield the same effect.

Millet yield in the VX improved run (see fig. 38) is still high enough to easily sustain his family. As half of the crop residues are left at the field as mulch, the above mentioned trend of lower yields in the first and higher yields in the second decade is strengthened by additional OM, demanding more nutrients at the beginning of the calculation run.

Camp poor

CP are with 92 households in the objective area still an important group. On average the CP farmer crop an area of 8.7 ha, which is the smallest of all farm types, and manages a herd of 12.52 TLU. This corresponds to a stocking rate of 1.44 TLU.ha⁻¹. His family is with 6.8 consumers in adult equivalent small to medium sized. The minimum millet yield he has to achieve is consequently 179.7 kg.ha⁻¹ (360 kg.ha⁻¹ resp.). Standard run again was calculated with historical rainfall data, average stocking rate of 1.44 TLU.ha⁻¹, all of the millet straw removed and no min. fertiliser.

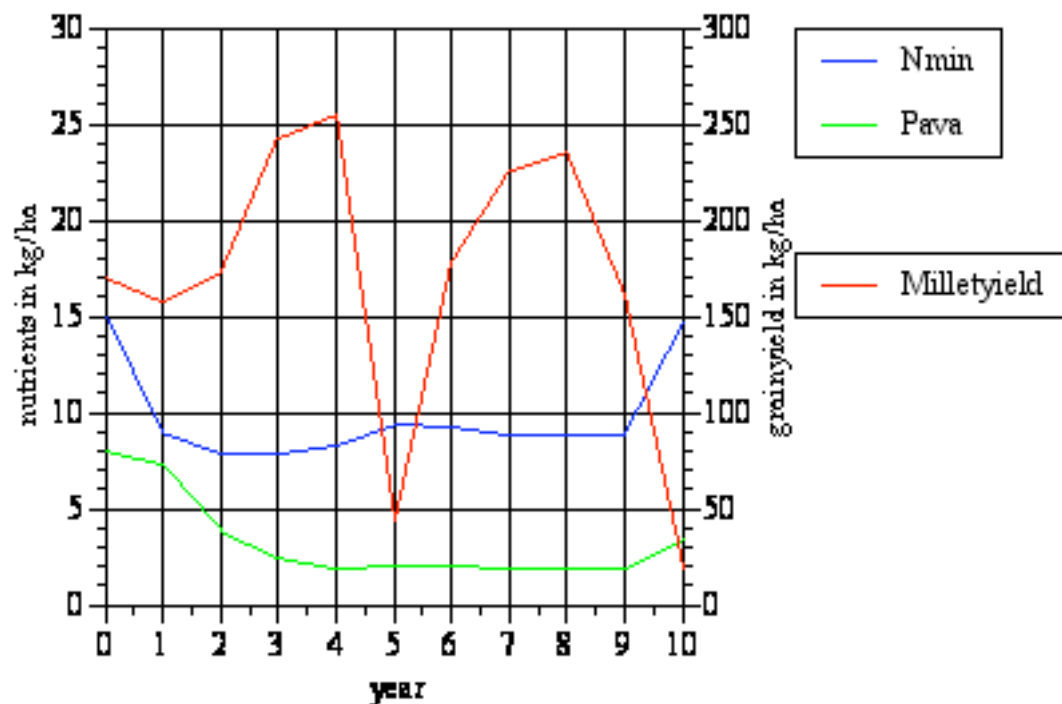


Figure 42: CP standard run of yield and available N and P (kg.ha⁻¹) development over 10 years

Millet yields range again between 150 and 250 kg.ha⁻¹, without the two exceptional years of 1995 and 2000. This is barely enough to feed all family members. The supposition to harvest the double amount of millet grain (360 kg.ha⁻¹) at least in the non-water limiting years, to make provision for bad years is not met. Nutrient contents of the soil can be considered as stable in the long run.

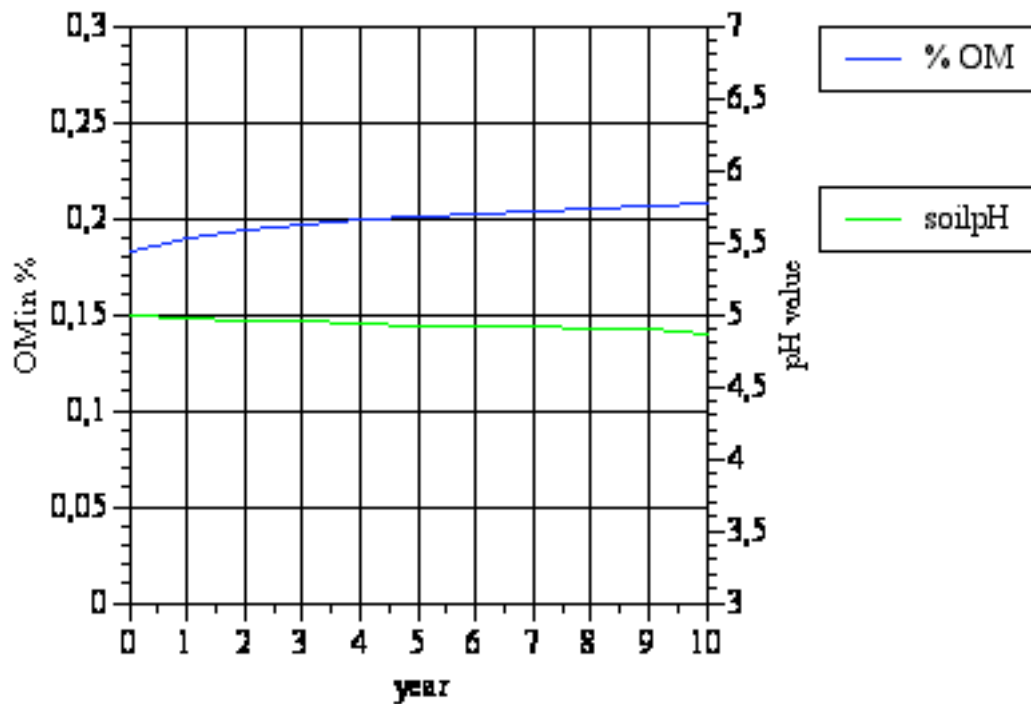


Figure 43: CP standard run of org. matter (%) and soil pH development over 10 years

Organic matter content is increasing by about 0.03 % in the 10 years run. Soil pH development still slightly decreasing, but 0.1pH over a period of 10 years is considered as acceptable. Because of his high stocking rate CP standard run is already satisfying concerning sustainability of soil fertility.

CP farmers have to increase their yield.ha⁻¹ to ensure the nutrition of their families. Previous calculations as well as the sensitivity analysis showed, that the best way to do so is to use min. fertiliser. The comparative advantage of the CP farmer to the other farm types is his herd size. The question is how could he capitalise on this production factor, to buy some min. fertiliser. Some options would be to corral his herd on other farmer's fields in exchange for money, he could sell some livestock (not very likely for Fulani herders, for whom herd size is the most important status symbol), or by herding contracts. The usual practise in Niger is that the contract herder, taking other farmers cattle e.g. on transhumance, is retaliated for his service by the calves born at the time he is responsible for that animal. Receiving money for this service or selling the newborn calves, the CP farmer would be in the position to buy min. fertiliser, without decreasing his stocking rate. The other two options mentioned above would yield cash by simultaneously decreasing his stocking rate.

So lets consider the CP farmer is able to earn enough cash to invest in 40 kg NPK.ha⁻¹.yr⁻¹ by corraling his herd on e.g. VR farmer's fields, leaving him with a stocking rate of 1 TLU.ha⁻¹. All straw is still removed.

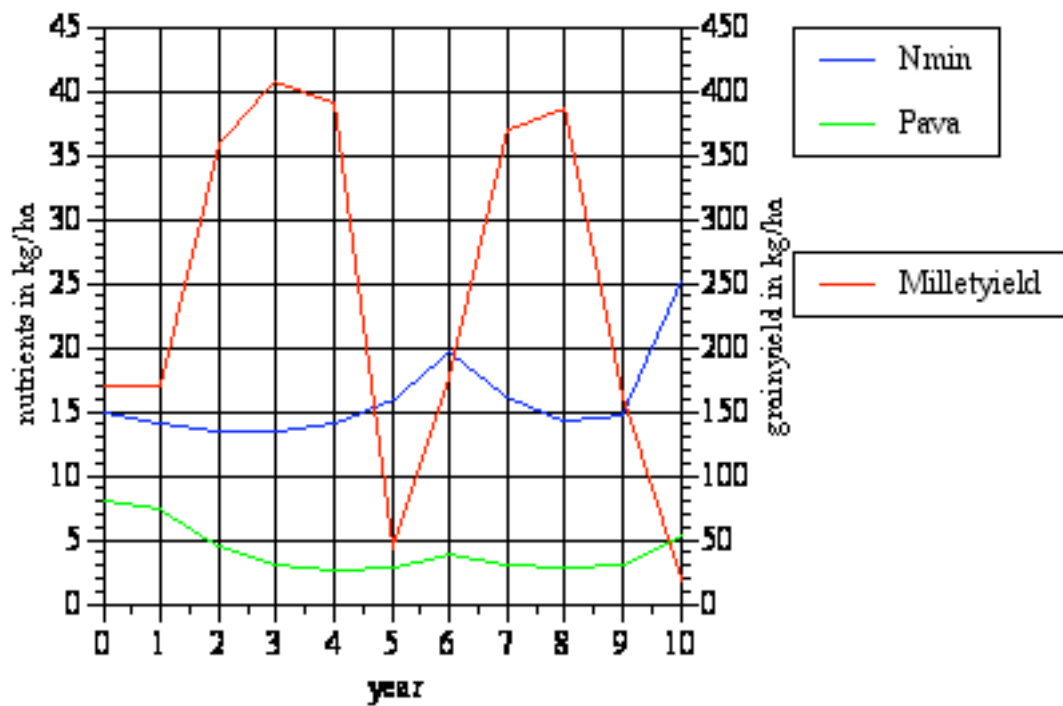


Figure 44: CP improved run of yield and available N and P ($\text{kg}\cdot\text{ha}^{-1}$) development over 10 years

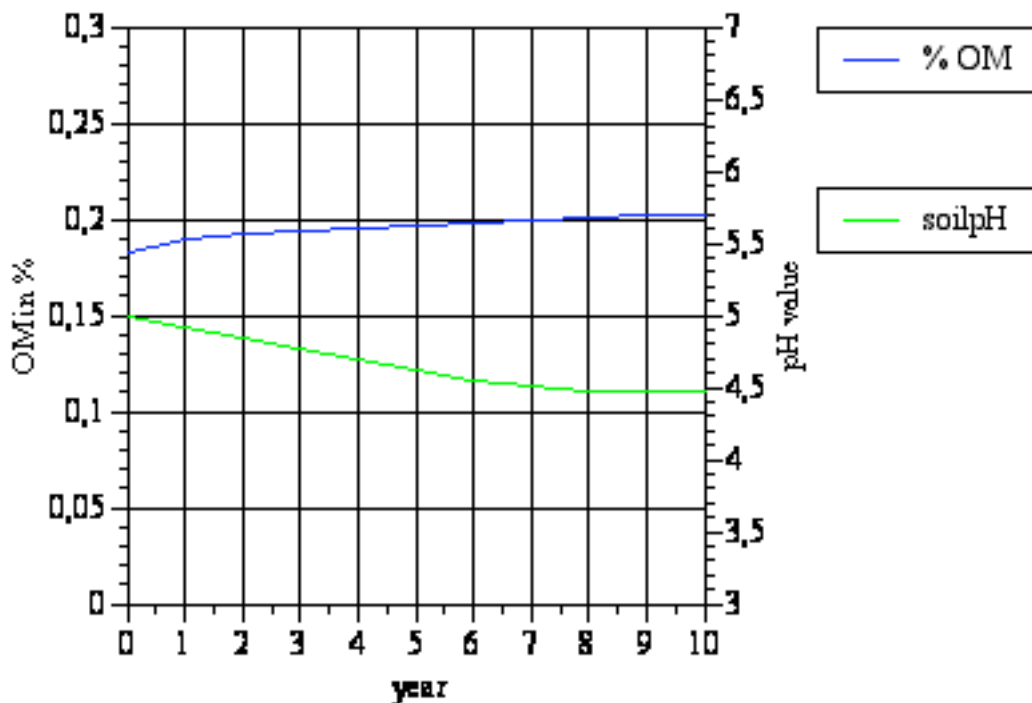


Figure 45: CP improved run of org. matter (%) and soil pH development over 10 years

In five of ten years millet yield is at the aimed level. The other five years can be considered as water limited. The sequence of a bad year followed by two good years makes it likely to keep

the CP farmer's family well fed. In 1999 and 2000 two water limited years follow each other. This is might very well cause a nutritional bottleneck. Hopefully the CP farmer is able to survive on his livestock, but from the cropping perspective there is nothing he can do to avoid this.

Organic matter development is still positive. But for soil pH there is a major decrease detectable. This is due to the high min. fertiliser input of 40 kg NPK.ha⁻¹. This development would also show with his original stocking rate of 1.44 TLU/ha. To avoid this he would have to add OM in the form of crop residues to the field. This means, not only leave all crop residues grown the res. vegetation period at the field but also add 75% of this amount annually. This is not an easy task for a farmer with a high stocking rate, like the CP. Although CP farmers have a comparatively big herd at there disposal, they still need additional nutrient input to achieve there aimed yield level. So what was said about min. fertiliser prices and availability for VP applies to the CP farmer as well. Organic matter content is not a problem at stocking rates higher than 1 TLU/ha. But manure alone is not enough to counter act the acidifying effect of min fertiliser. Again the important role of crop residues was shown.

Camp rich

With 74 households CR are the second smallest group of farm types. They are considered rich because of their herd size, with 20.36 TLU.farm⁻¹ on average. Additionally they crop a fairly great area of 12.7 ha.farm⁻¹, only surpassed by VR and VX. This leads to an average stocking rate of 1.6 TLU.ha⁻¹. With his average family size of 6.1 adult equivalent, the CR farmer has to produce 110.5 kg millet grain.ha⁻¹. The sustainable level, drought spells or losses because of other calamities accounted for, would be about 220 kg.ha⁻¹.

Standard run is conducted with 1.6 TLU.ha⁻¹, no min. fertiliser and all straw removed from the field.

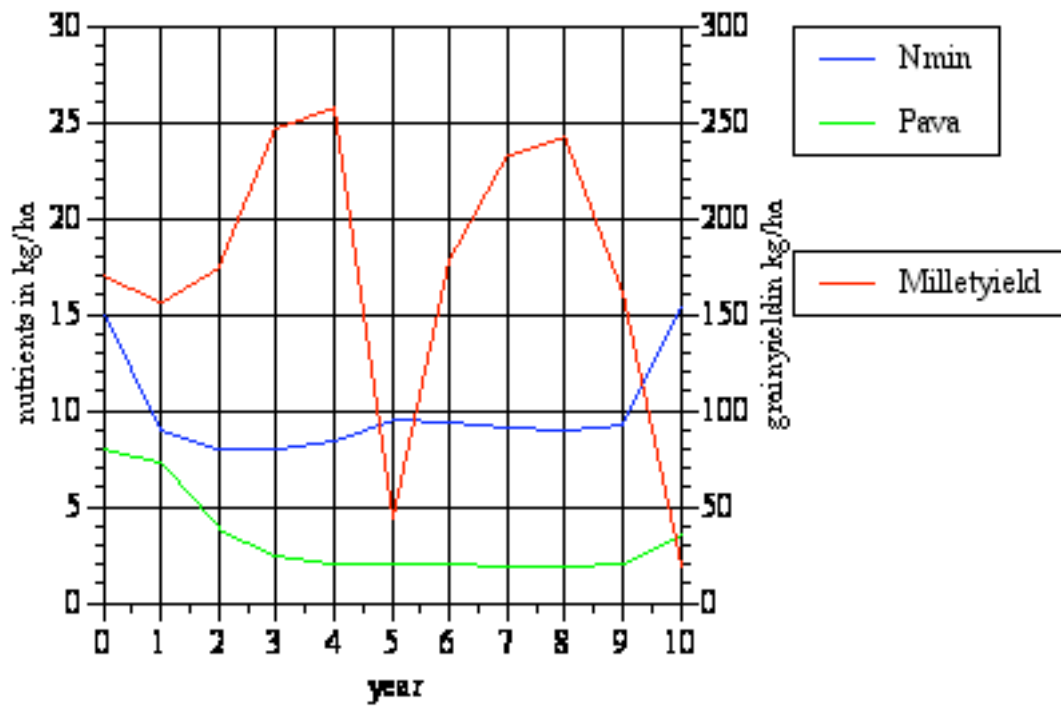


Figure 46: CR standard run of yield and available N and P (kg.ha⁻¹) development over 10 years

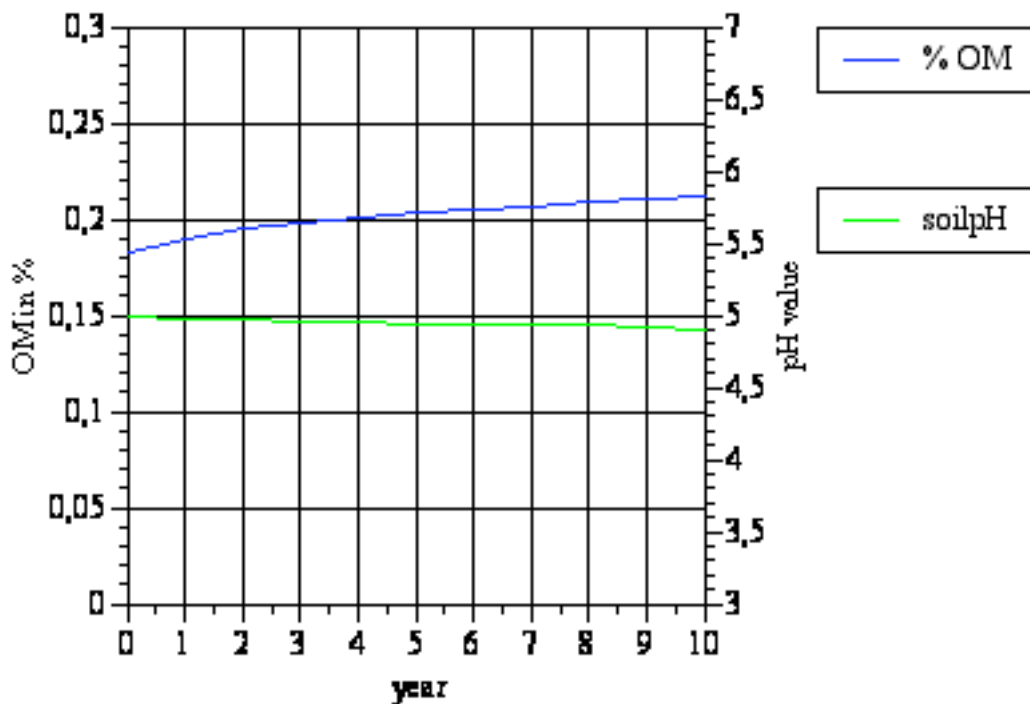


Figure 47: CR standard run of org. matter (%) and soil pH development over 10 years

In CR standard run already bough requirements of sustainability are met. Millet yield in the five non water limiting years of the calculation run are next to the required 220 kg.ha⁻¹,

leaving enough surplus for the water limiting years. Nutrients, esp. nitrogen follow the rather extreme development of yields, but show an overall positive development.

Soil organic matter is increasing by 0.04 % in the ten years run and soil pH is nearly stable.

So in the sense of sustainable land use there is no need to improve the situation of CR farmers. But why not considered, from this position of safety, a more economic question. Is it worthwhile to invest in min. fertiliser at present costs?

For this calculation a yearly NPK input of 20 kg/ha is assumed. All other input variables, including stocking rate, are left unchanged.

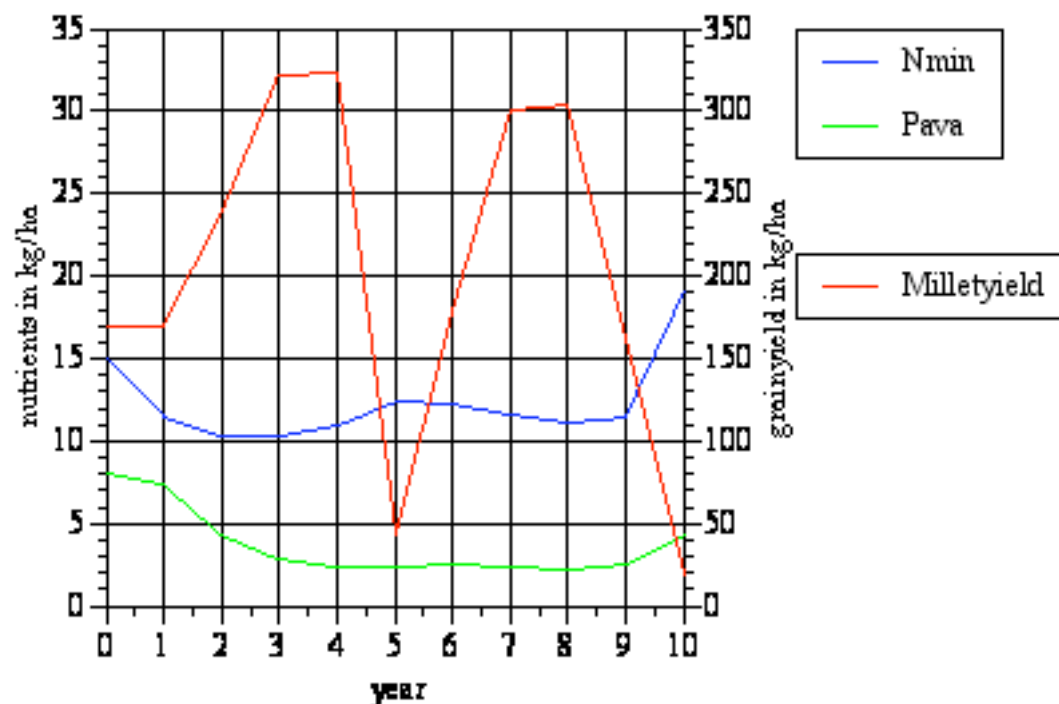


Figure 48: CR improved run of yield and available N and P ($\text{kg}\cdot\text{ha}^{-1}$) development over 10 years

Millet yields fluctuate even more extreme. Fertiliser use in dry years shows no effect. This is of course because of the binary structure of the model, the smaller of the two (water limiting or nutrient limiting yield) is considered as the dominant. Actually this is not too far from reality. In an experiment in 1984 with very low rainfall (260mm) Bationo et al. (1989) observed no significant respond to N-fertilisation. In 1985 on the contrary, with moderate rainfall (543mm) yield increased by 60%.

Yields in non-water limiting years range up to $330 \text{ kg}\cdot\text{ha}^{-1}$. If we now take the year 1992, with sufficient rainfall (586 mm) as an example, NPK use seams quite economic. The cost of NPK is set to $230 \text{ fcfa}\cdot\text{kg}^{-1}$ (Franc de la Communauté Financière Africaine. kg^{-1}), the price of millet

seeds to 90 fcfa.kg⁻¹ (Bontkes 2005). In 1992 the additional millet yield, because of fertiliser use, was 65 kg.ha⁻¹.yr⁻¹ (37%), or 5850 fcfa.ha⁻¹. Subtracting the costs of 20 kg NPK (4600 fcfa.ha⁻¹.y⁻¹) leaves the CR farmer a profit of 1250 fcfa.ha⁻¹.y⁻¹.

But this is just a part of the truth. The same calculation with the total costs of ten years NPK inputs (46,000 fcfa.ha⁻¹) subtracted from the total yield increase of the ten years simulation run (347 kg.ha⁻¹ or 31,233 fcfa.ha⁻¹) shows another picture. Unfortunately the farmer don't know how much rain will fall in the forthcoming vegetation period. This is why he cannot tell if the use of fertiliser input will yield any effect. In some years it will in others it will not. In the decade under observation the overall yield increase was not high enough to cover the costs of the NPK use.

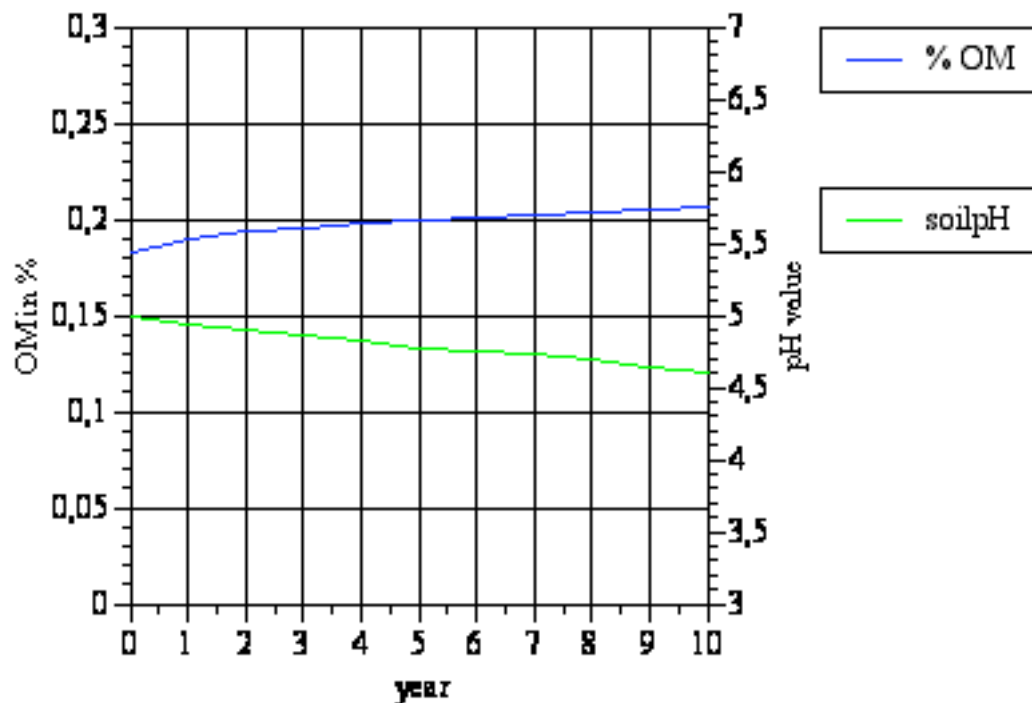


Figure 49: CR improved run of org. matter (%) and soil pH development over 10 years

Additionally to the above mentioned the CR farmer's soil would acidify, due to the use of min. fertiliser. To stop this trend he would have to resign his practise of straw removal. Which is not an easy task considering his herd size.

CR farmers are the only group of farmers who can be considered as cropping already sustainable. This is because of their high stocking rate and their favourable consumer to cropland ratio. Use of mineral fertiliser is neither necessary nor is it, at present prices, economically, considering the insecurity of yields.

3.6.2 Climate change

In the previous chapter some important input variables determining yield and soil fertility were investigated. These input variables were all related to the management practise of the farmer. To put it in other words, the farmer is able to change these variables like stocking rate, straw removal or min. fertiliser use. A fourth very important input variable mentioned in chapter 3.2 Sensitivity analysis is weather. To predict the rainfall and temperature for the coming week is difficult, to predict this variables for the next decade or even century is next to impossible. The only thing scientists can do is to try to estimate the climate in a statistical sense i.e. the means and variability. The first question to consider is: Dose the climate change?

In there most recent report “Climate Change 2001: The Scientific Basis” the Intergovernmental Penal on Climatic Change (IPCC 2001) state that:

- The global average surface temperature has increased over the 20th century by about 0.6°C.
- The increase in temperature is likely to have been the largest of any century during the past 1000 years.
- It is also likely that, in the Northern Hemisphere, the 1990s was the warmest decade and 1998 the warmest year since 1861.
- There has been a widespread retreat of mountain glaciers in non-polar regions during the 20th century.
- Northern Hemisphere spring and summer sea-ice extent has decreased by about 10 to 15% since the 1950s.

The reason for this is still discussed among scientists. Changes in climate occur as a result of both internal variability within the climate system and external factors (both natural and anthropogenic). The influence of external factors on climate can be broadly compared using the concept of radiative forcing. A positive radiative forcing, such as that produced by increasing concentrations of greenhouse gases (GHG), tends to warm the surface. A negative radiative forcing, which can arise from an increase in some types of aerosols (microscopic airborne particles) tends to cool the surface. Natural factors, such as changes in solar output or explosive volcanic activity, can also cause radiative forcing. Characterisation of these climate forcing agents and their changes over time is required to understand past climate changes in the context of natural variations and to project what climate changes could lie ahead (IPCC 2001). Scientists agree on the positive radiative forcing effect of GHG's but disagree on the

effect on the variation of the climate. How much of this observed effects are internal variability of the climate, how much is caused naturally and how much anthropogenic. Looking at forcing agents, by far the most important GHG is carbon dioxide.

Some facts about CO₂, taken from IPCC's report (2001):

- The atmospheric concentration of carbon dioxide (CO₂) has increased by 31% since 1750.
- The present CO₂ concentration has not been exceeded during the past 420,000 years and likely not during the past 20 million years. The current rate of increase is unprecedented during at least the past 20,000 years.
- About three-quarters of the anthropogenic emissions of CO₂ to the atmosphere during the past 20 years is due to fossil fuel burning. The rest is predominantly due to land-use change, especially deforestation.
- The rate of increase of atmospheric CO₂ concentration has been about 1.5 ppm (0.4%) per year over the past two decades. During the 1990s the year to year increase varied from 0.9 ppm (0.2%) to 2.8 ppm (0.8%). A large part of this variability is due to the effect of climate variability (e.g., El Niño events) on CO₂ uptake and release by land and oceans.

So to estimate climatic change one first has to estimate the anthropogenic CO₂ emission and concentration in the atmosphere for the time span under observation.

Future greenhouse gas emissions are the product of very complex dynamic systems, determined by driving forces such as demographic development, socio-economic development, and technological change. Their future evolution is highly uncertain. In 2000 the IPCC published their Special Report on Emissions Scenarios (IPCC 2000). In this report 40 different scenarios of future GHG emissions for the next century were set up. These scenarios are alternative images of how the future might unfold and function as a tool to analyse how driving forces may influence future emission outcomes and to assess the associated uncertainties. They assist in climate change analysis, including climate modelling and the assessment of impacts, adaptation, and mitigation. Emissions of GHGs are the basic input for determining future climate patterns with simple climate models, as well as with complex general circulation models (see chapter 2.2.2 Classification and examples).

The 40 scenarios put up by IPCC are grouped into four different scenario families. Each with different assumption of the great driving forces like global population, economic growth, social development and final energy use. An illustrative “marker” scenario represents each family.

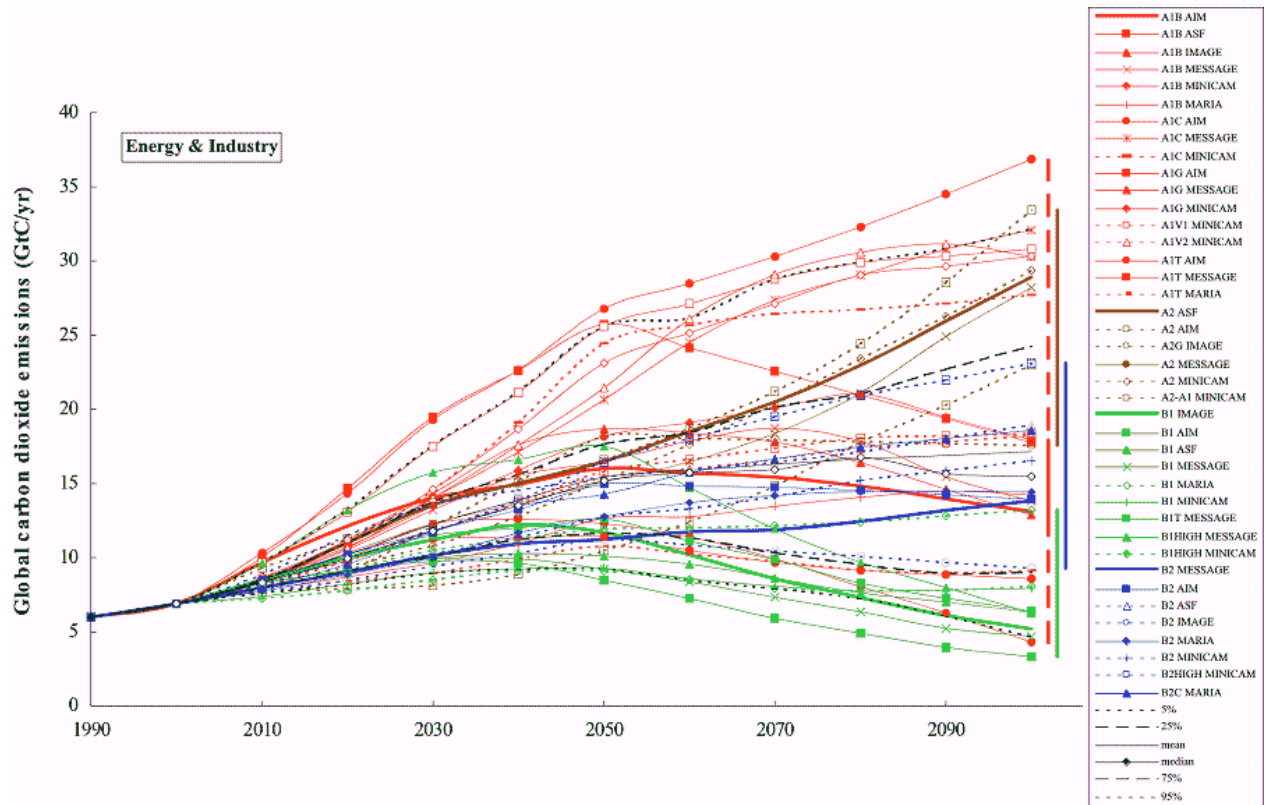


Figure 50: Global CO₂ emissions (1990 – 2100) for different IPCC scenarios. Scenario families are represented in the same colour (A1 red, A2 brown, B1 green and B2 blue). (IPCC 2000)

The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. There are three A1 groups distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B).

The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines.

The B1 storyline and scenario family describes a convergent world with the same global population that peaks in midcentury and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient

technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.

The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

Two scenarios were chosen to predict climatic change on basis of the estimated CO₂ emissions. Scenario A1FI is something like the worst-case scenario, with rapid economic growth based on fossil fuel, as well as unhampered population increase. This scenario leads to a doubling in CO₂ concentration in the atmosphere in 2042 (see fig. 51).

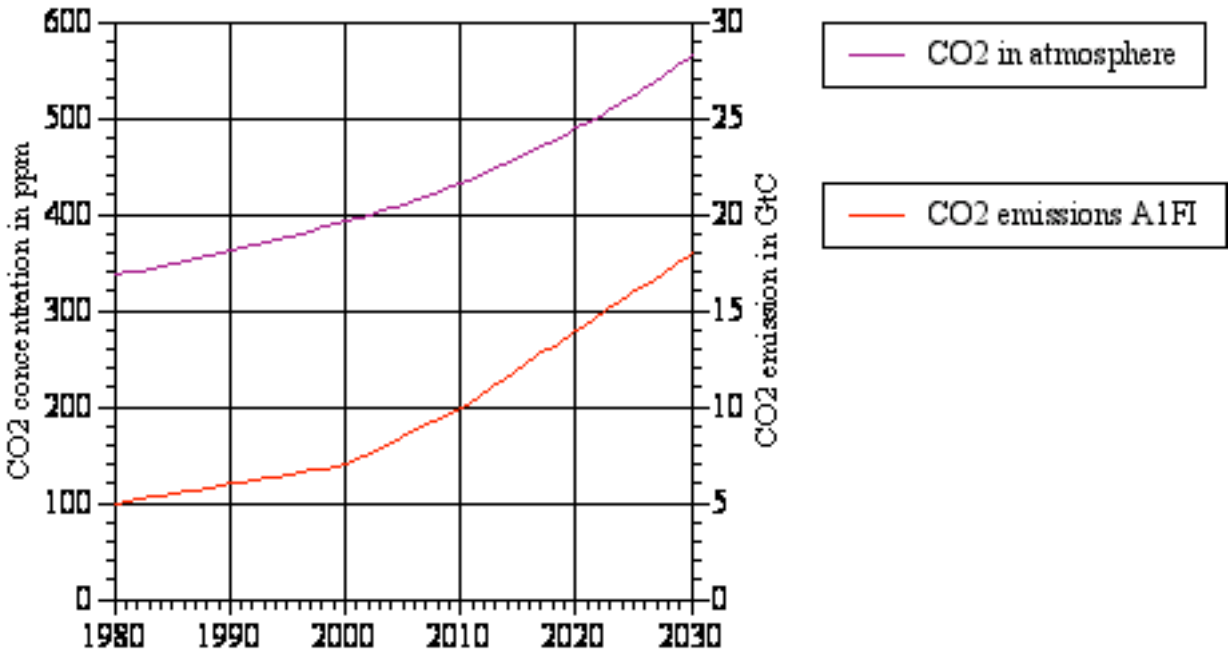


Figure 51: CO₂ emissions and concentration in the atmosphere (1980 – 2030) for the A1 fossil intensive scenario.

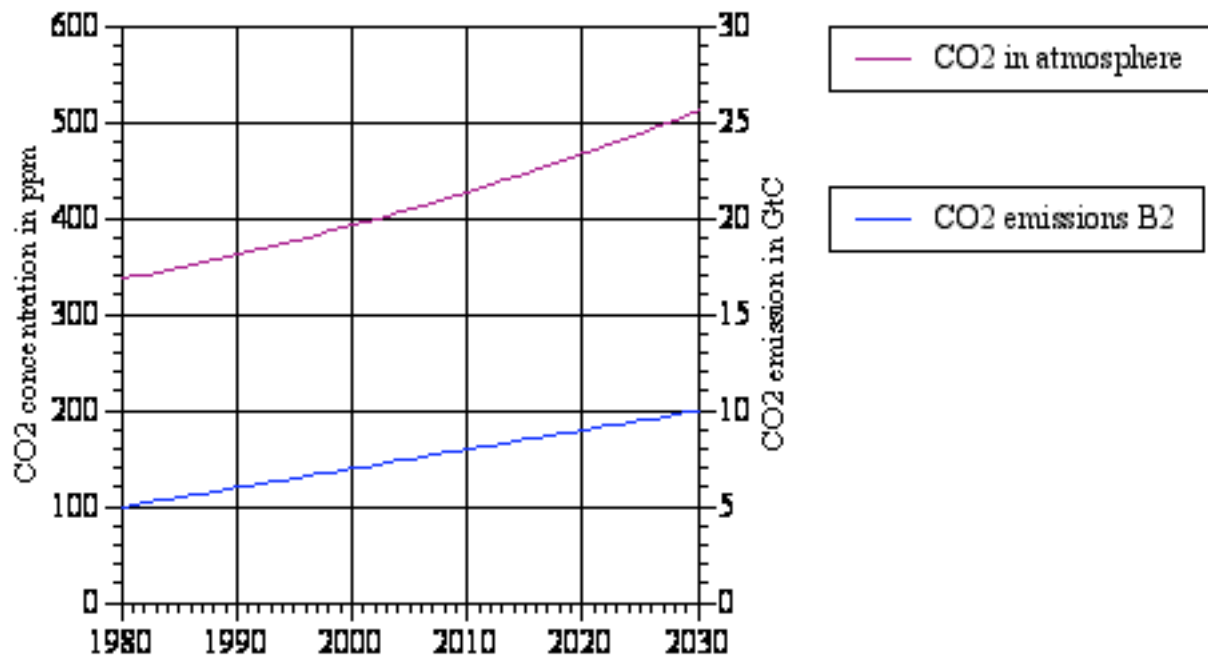


Figure 52: CO₂ emissions and concentration in the atmosphere (1980 – 2030) for the B2 marker scenario.

A more optimistic scenario was also chosen. In B2 marker scenario the population increase is at a lower rate and much emphasis is put on environmental protection and social equity. This still leads to a doubling of CO₂ concentration, but only in 2068 (see fig. 52), with stagnating emissions afterwards.

These two predictions of future GHG emissions were put in the EdGCM to model the future climate in the objective area. EdGCM is a suite of software that enables students without in deep knowledge of modelling techniques to set up, run, analyze and report on global climate model simulations. GCMs generally required supercomputing facilities and skilled programmers to operate. EdGCMs easy to use graphical user interface and output analysing application allows broader access to GCMs for unskilled persons. The heart of EdGCM is NASA's GISS (Goddard Institute for Space Studies) Model II (Hansen et al. 1998).

The GISS GCM divides the atmosphere into a three-dimensional grid system. The version incorporated into EdGCM uses an 8° x 10° latitude by longitude grid system, and has nine vertical layers in the atmosphere and two ground layers. The model accounts for both seasonal and diurnal solar cycles in its temperature calculations. Cloud particles, aerosols, and radiatively important gases (e.g., carbon dioxide, methane, nitrous oxides) are explicitly incorporated into the radiation scheme. Large-scale and convective cloud covers are predicted, and precipitation is generated whenever supersaturated conditions occur. Snow depth is based on a balance between snowfall, melting and sublimation. Sea surface

temperatures (SSTs) are calculated using model-derived surface energy fluxes and specified ocean heat convergences. The ocean heat convergences vary both seasonally and regionally, but are otherwise fixed.

Running the climate model entails the solving of a series of complex physics equations for every cell in the grid, and a single simulated year involves many billions of calculations (an iMac G4 800MHz still needs at least 24 hours calculation time for the simulation of about 30 years). That is why the simulation was restricted to 50 years (1980- 2030).

Radiative forcing factors put in the model were solar luminosity of 1366.56 W/m^2 (observed value of 1990) and initial value of CO_2 concentrations of 337.9 (observed value for 1980).

While CO_2 increase was set to $1.25\%.\text{yr}^{-1}$ (after 2000) for A1 scenario, it was set to $0.85\%.\text{yr}^{-1}$ (after 2000) for the B2 scenario. All other GHGs (N_2O , CH_4 and CFCs) were fixed at 1980s values.

For the evaluation of the simulation average values for the 90s (1990-2001) were compared to average values for the last 5 years of the simulation run (2025-2030). The grid box ($8^\circ \times 10^\circ$ latitude by longitude) of interest is the Sahel by the NASA although it spreads far south to most of Nigeria, Togo and Benin.

For the A1 scenario an increase in temperature was detected. While in the 90s average annual temperature was 26°C (see fig 53), it rose till the end of the 2030s to 28°C (see fig 54).

Average yearly rainfall also increased slightly, from 2.6 mm.d^{-1} (949 mm.yr^{-1}) (see fig 55) in the 90s to 2.8 mm.d^{-1} (1022 mm.yr^{-1}) (see fig 56) for this specific grid box. Unfortunately this is way too high from the beginning as the Sahel is defined by the 75th and 450th isohyet. The next grid box to the north, labelled southern Sahara (by NASA), shows on average 255 mm.yr^{-1} in the 90s and 292 mm.yr^{-1} at the end of the 2030s. This again is too low for millet cropping.

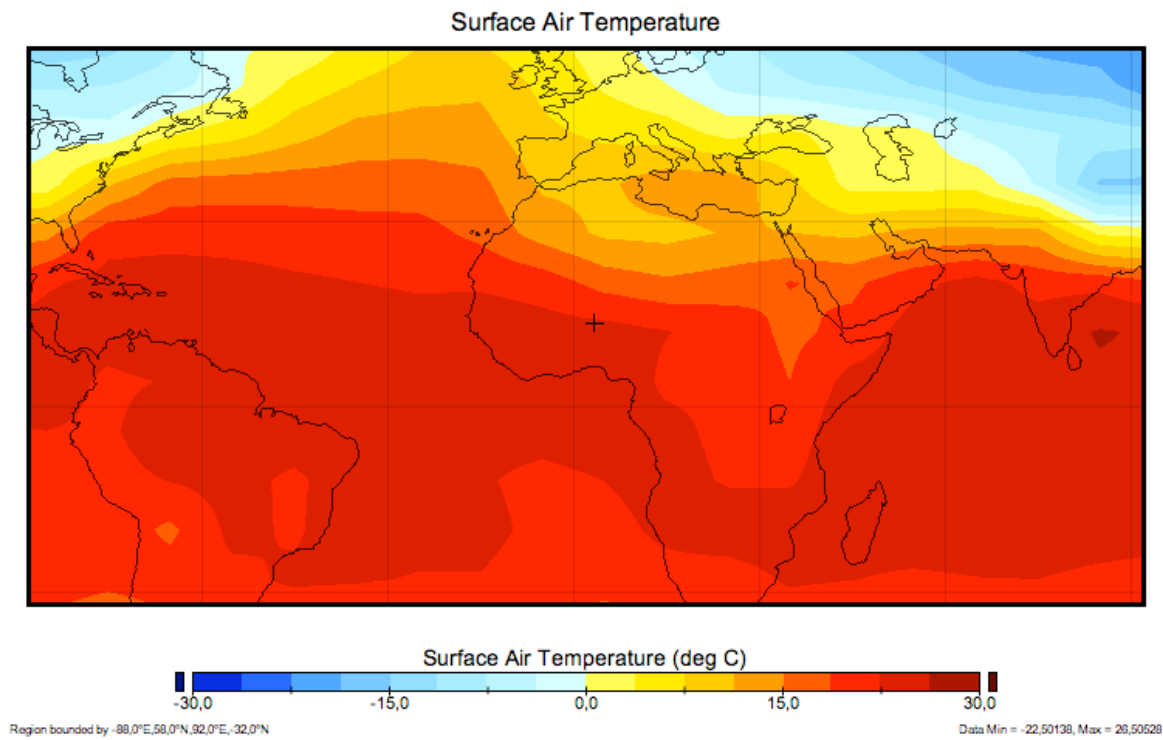


Figure 53: Average annual surface temperature for the time span of 1990 to 2001. Sadore is positioned in the very centre of the map.

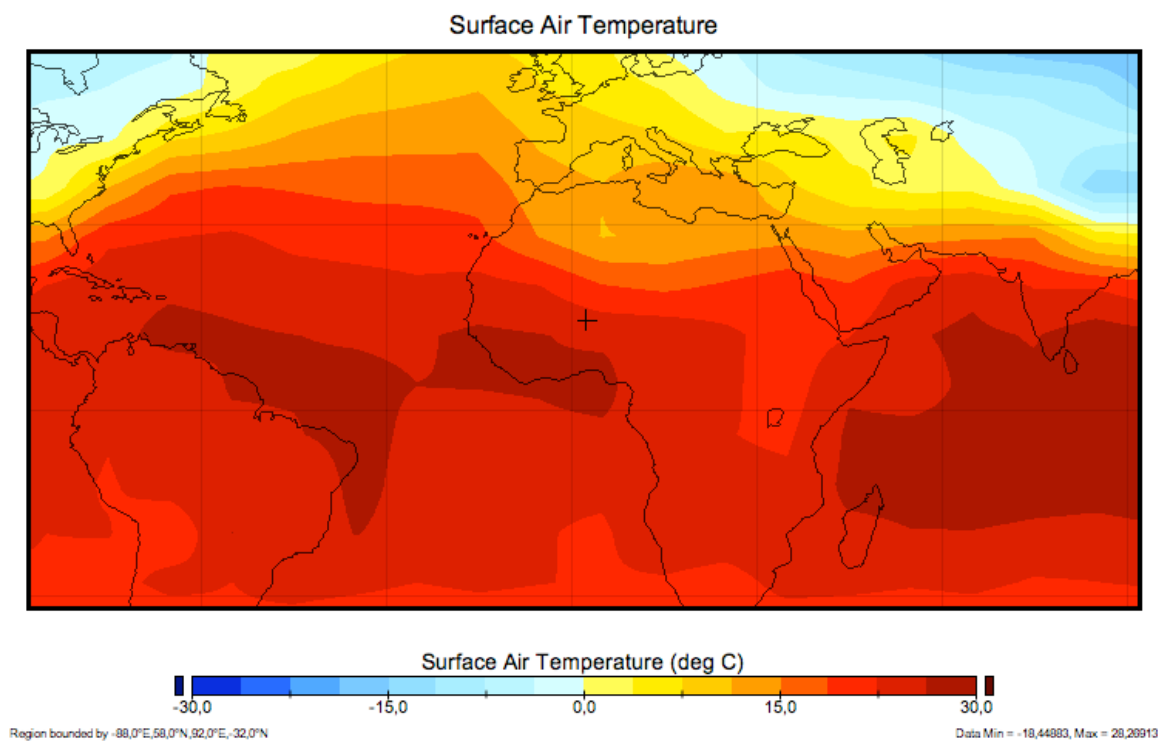


Figure 54: Average annual surface temperature for the time span of 2025 to 2030. Calculated by EdGCM for climatic change based in IPCCs A1FI scenario

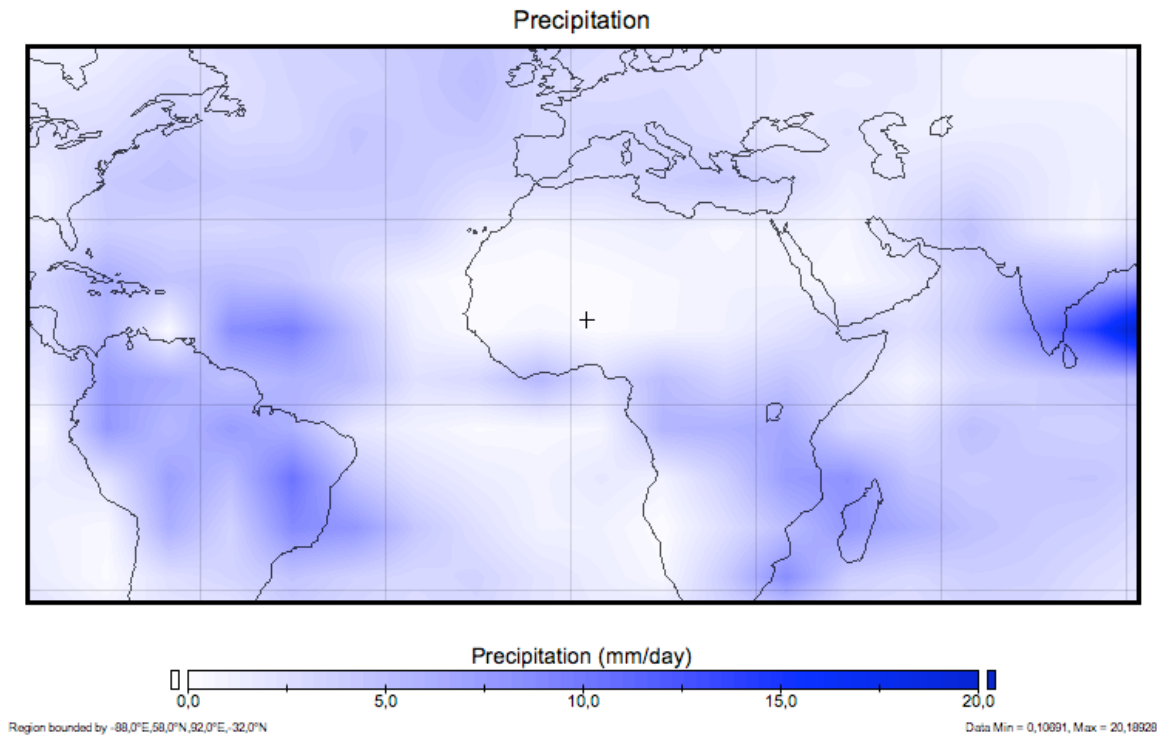


Figure 55: Average annual rainfall for the time span of 1999 to 2001.

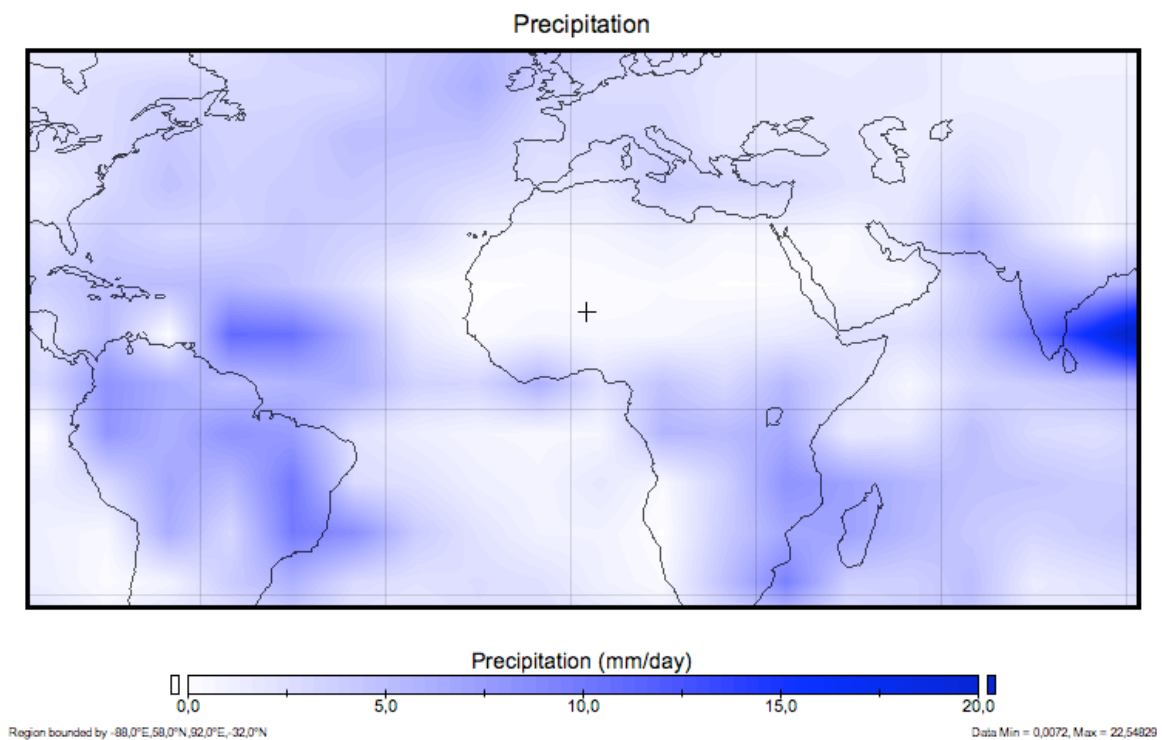


Figure 56: Average annual rainfall for the time span of 2025 to 2030. Calculated by EdGCM based on IPCCs A1FI scenario.

So to get some practicable rainfall data, the calculated precipitation of the two grid boxes (Sahel and southern Sahara) were averaged, yielding annually precipitations between 300 and 660 mm.yr⁻¹ (see fig. 57)

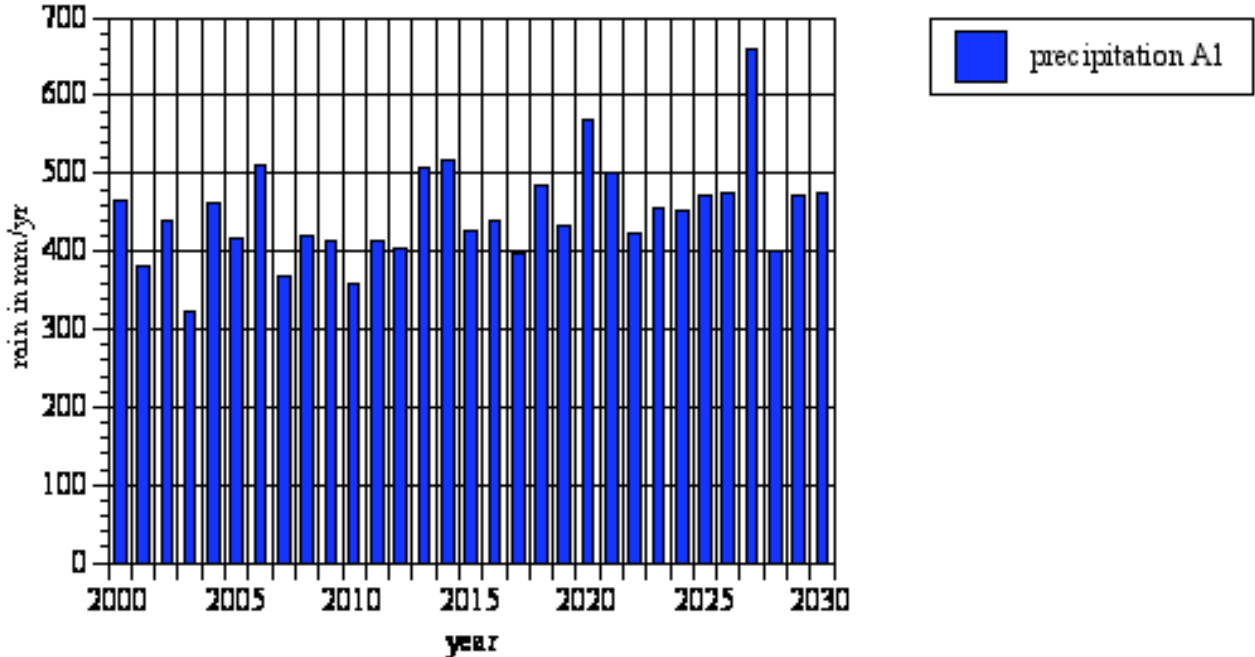


Figure 57: Yearly precipitation calculated by EdGCM for scenario A1 and adapted to the conditions in the objective area.

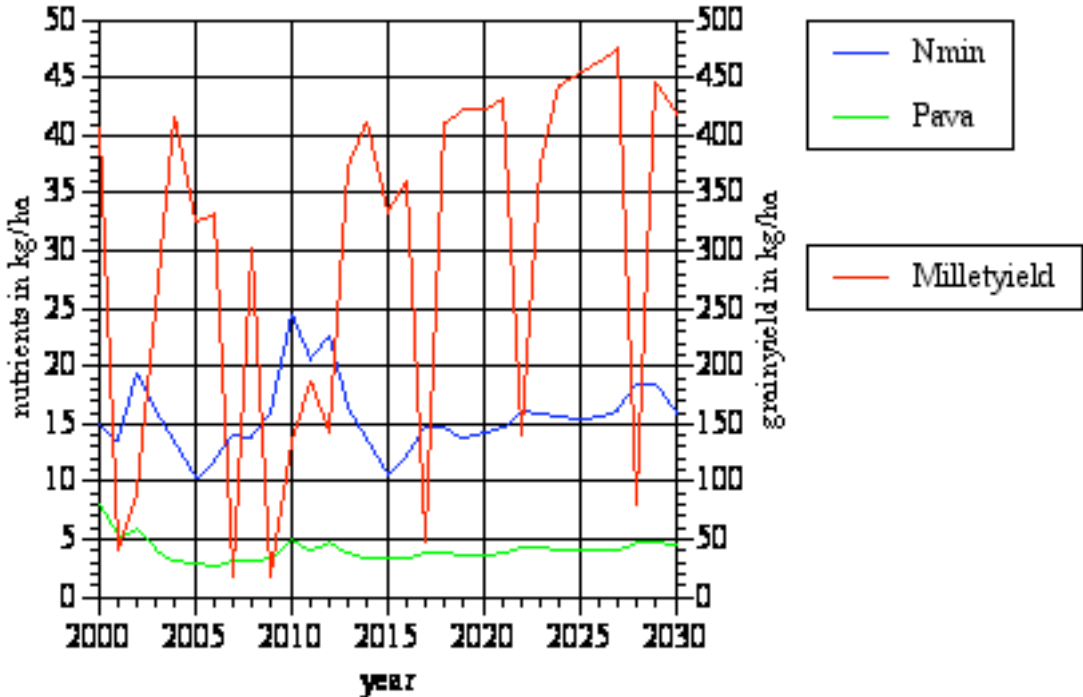


Figure 58: Development of millet yield (kg.ha⁻¹) and available nutrients (kg.ha⁻¹) under climatic change conditions (IPCC scenario A1FI).

Based on this rainfall data simulation run for millet yield and soil fertility for the years 2000 to 2030 were calculated employing FAKFARM. Input variables on the management side were a stocking rate of 0.46 TLU.ha⁻¹, which is the average stocking rate in the Fakara, over all farm types, no straw removal, leaving all straw on the field as mulch and a mineral fertiliser input of 30 kg.ha⁻¹.yr⁻¹. This management practises were chooses because scenarios in chapter 3.3.1 showed that abandonment of straw removal is crucial to maintain soil fertility, for the major share of farmers (poorly endowed) the use of at least small amounts of min. fertiliser is inevitable and overall stocking rate in this area is rather unlikely to increase because of the carrying capacity of rangeland and communal pasture.

Figure 59 shows a quit optimistic picture of future yield development. Trends of available nutrients and grain yield are all upward. Millet yields range between 300 and 470 kg.ha⁻¹ in non-water limiting years. Still five years are very dry with millet yields lower than 100 kg.ha⁻¹. Additionally it can be observed that water-limiting years become more and more rare from decade to decade. This of course is caused by the higher rains in the corresponding decades (see fig 58).

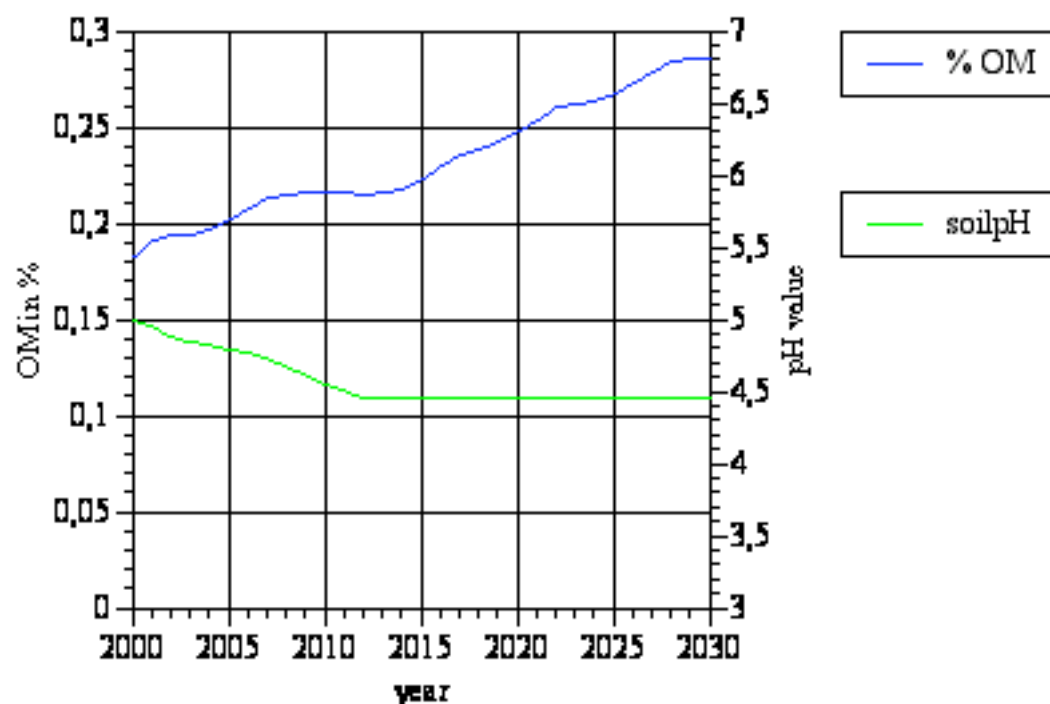


Figure 59: Development of millet yield (kg.ha⁻¹) and available nutrients (kg.ha⁻¹) under climatic change conditions (IPCC scenario A1FI).

Soil organic matter also shows a rather strong increase over the 30 years simulation. This is due to the fact that no millet straw is removed from the field. Additionally higher millet yields

involve also higher straw yields. But still together with manure of $0.46 \text{ TLU}\cdot\text{ha}^{-1}$ organic matter inputs are not sufficient to counteract acidifying effect of min. fertiliser and organic outputs (grain yield). Again (see chapter 3.3.1) an additional input of CR as high as the yearly straw harvest would stabilise pH value.

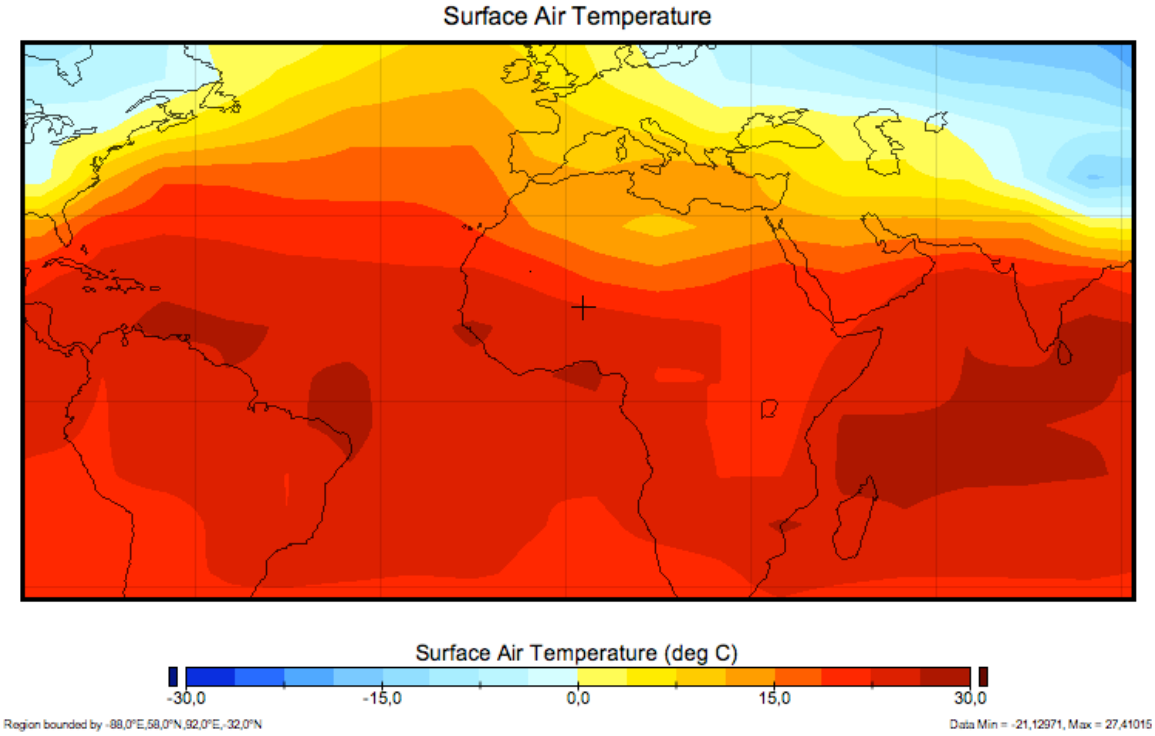


Figure 60: Average annual surface temperature for the time span of 2025 to 2030. Calculated by EdGCM for climatic change based in IPCCs B2 scenario.

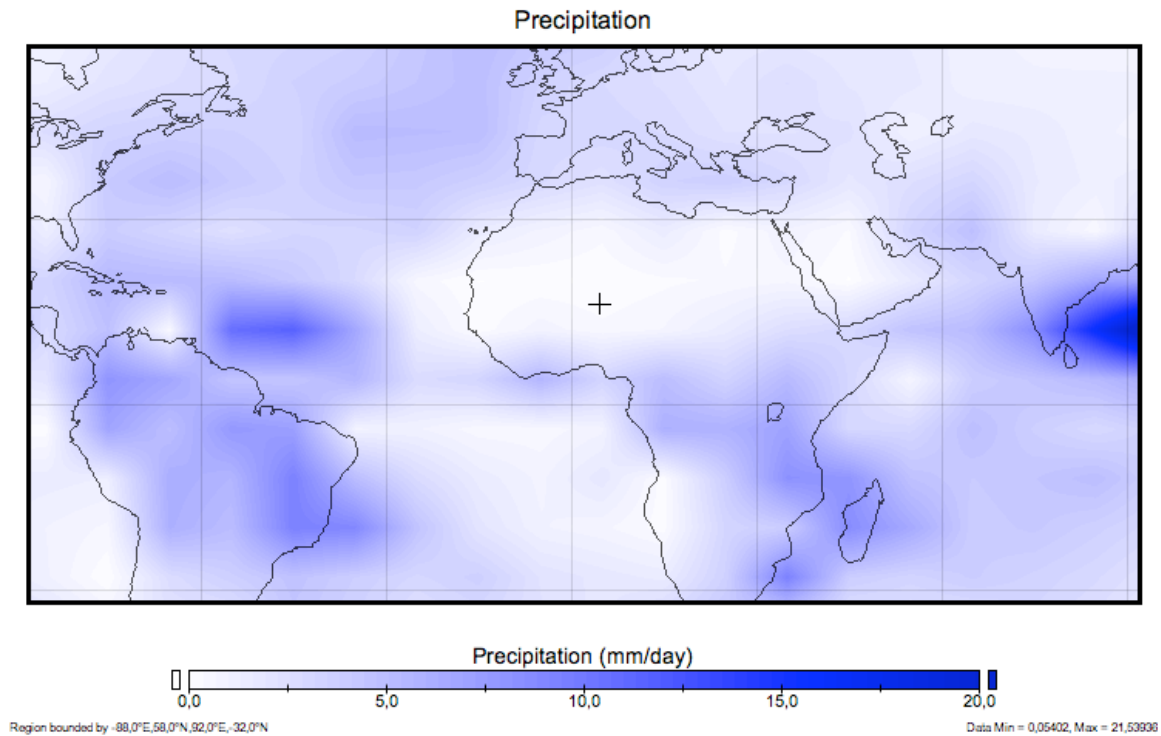


Figure 61: Average annual rainfall for the time span of 2025 to 2030. Calculated by EdGCM based on IPCCs A1FI scenario.

Average temperature for the years 2025 to 2030 in B2 scenario is 26°C (see fig. 60). This is an increase by 1°C compared to average values of the 90s. Average precipitation increased by the same amount as in the A1FI scenario. It is again 2.8 mm.d⁻¹ (1022 mm.yr⁻¹) by the end of the 2020s (see fig. 61). Values for the southern Sahara grid box are with 0.7 mm.d⁻¹ (255 mm.yr⁻¹) slightly smaller than in A1FI scenario.

Again the two grid boxes Sahel and southern Sahara were averaged to get a better estimate precipitation in the Fakara (see fig. 62)

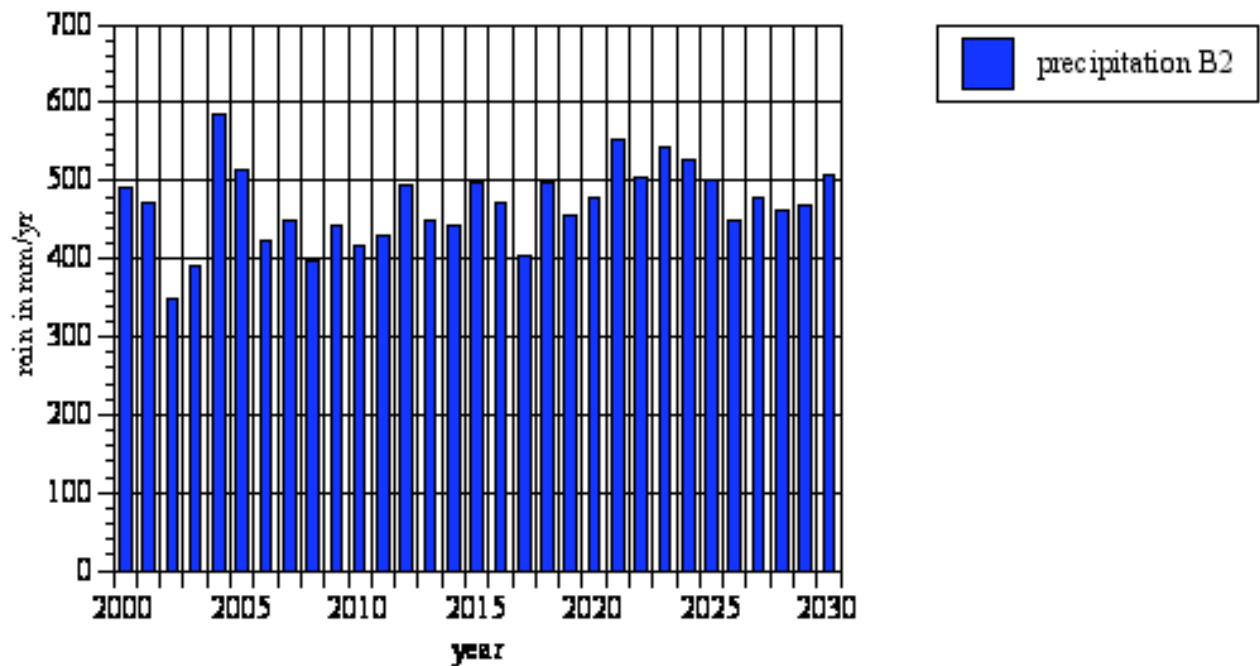


Figure 62: Yearly precipitation calculated by EdGCM for scenario B2 and adapted to the conditions in the objective area.

A slight increase in the precipitation trend is detectable. Additionally rainfall is getting more and more stable. While in the first decade of the 21st century annual precipitation fluctuate between $350\text{mm}\cdot\text{yr}^{-1}$ and $590\text{mm}\cdot\text{yr}^{-1}$ in the following decades extreme dry years as well as extreme wet years become more and more scarce. In the 2020s annual precipitation ranges between 450 and $540\text{mm}\cdot\text{yr}^{-1}$.

Additionally one can observe a slight shift in rainfall distribution. Especially in the 2020s the distribution of precipitation shifts from the early months to the late months of vegetation. This leads to a better water supply in the development stages of millet that are highly susceptible to water stress, like flowering and yield formation.

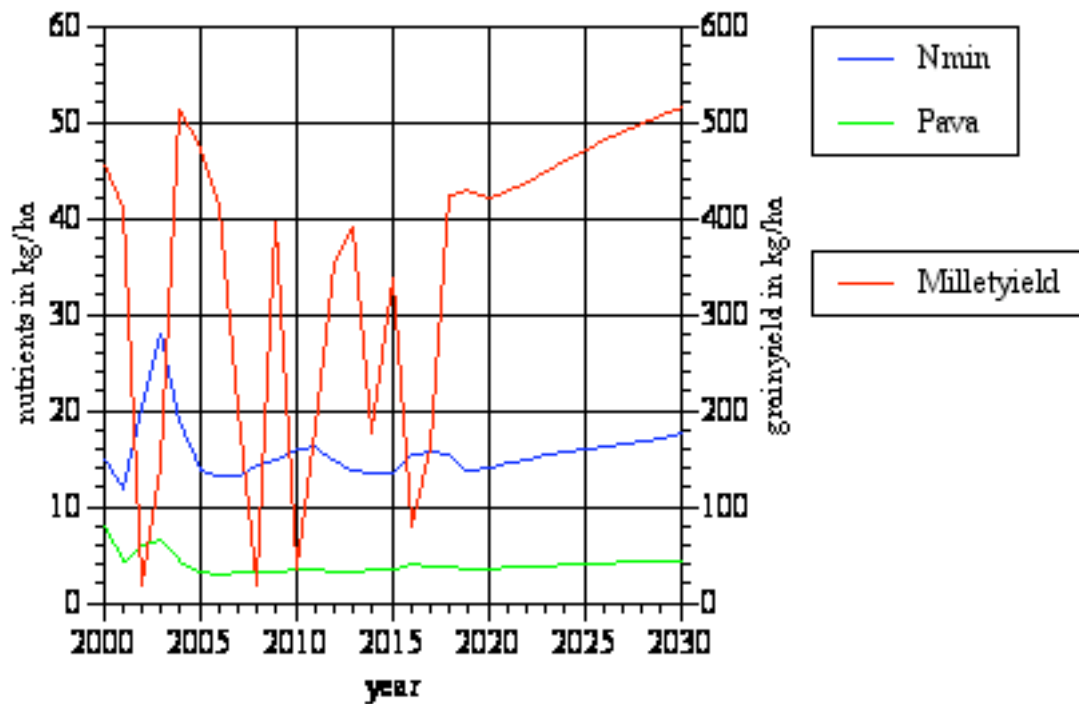


Figure 65: Development of millet yield ($\text{kg}\cdot\text{ha}^{-1}$) and available nutrients ($\text{kg}\cdot\text{ha}^{-1}$) under climatic change conditions (IPCC scenario B2).

FAKFARM calculation of available nutrients and millet yield development over 30 years show a high fluctuation in the first half of the simulation run and stabile conditions in the second half. The positive trend of nutrient availability is due to the management practises, again set to $0.46 \text{ TLU}\cdot\text{ha}^{-1}$, no straw removal and $30 \text{ kg NPK}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$. The stabilisation of millet yield in the second half of the run is because of higher rains, but more important because of the favourable distribution of rainfall. This can be proven by looking at the relative yield decreases for each development stage. While rel. yields for development stages flowering to ripening are in the year 2008 around 0.2 (reducing potential millet yield by 80%), in the 2020s they only once fall short of 0.6 (reducing potential yield by 40%). This leads to the assumption that in this decade nutrient limiting yield is always smaller than water limiting yield and therefore the dominant.

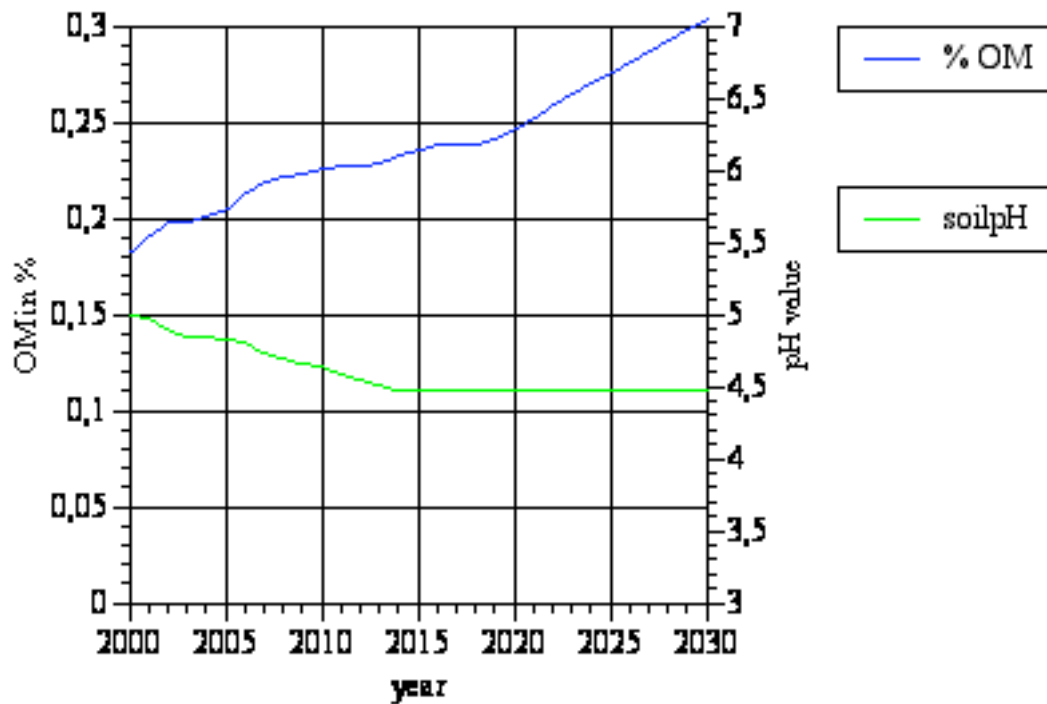


Figure 66: Development of millet yield ($\text{kg}\cdot\text{ha}^{-1}$) and available nutrients ($\text{kg}\cdot\text{ha}^{-1}$) under climatic change conditions (IPCC scenario B2).

Development of organic matter and pH is very similar to the ones observed in the A1FI scenario. The slope of organic matter increase is a little steeper than in the previous scenario. This is because of the differences in average temperature. The colder climate in B2 scenario leads to lower decomposition rates and slower decomposition of SOM.

pH decrease is also a little slower than in A1FI scenario. The reason for this most probably the higher crop residue yields, which are left at the field as mulch. But what was said about pH stabilisation in the previous scenario also applies here.

The simulation of millet yields and soil fertility development under climatic change conditions shows a very optimistic picture. In both scenarios rainfall in the objective area is increasing. Temperatures rise by 1°C in B2 scenario and 2°C in A1FI scenario. Higher rains lead to increasing and stabilising millet yields, especially in B2 scenario. The higher decomposition of SOM because of the temperature rise can easily be counteracted with mulching of crop residues. The higher straw yields reinforce this trend.

4. Discussion

4.4 The model

FAKFARM at its present state is not a farm model (it was intended to be one, but isn't). It's a field model at best. Although the sub models soil, water and millet are quit complex, FAKFARM still lacks sub models household and livestock. It was intended to include a dynamic model of a cattle herd, responding to feed available from crop residues and communal pasture (depending on weather) and serving the millet model as nutrient input via manure production. But modelling livestock herds in the Fakara is a tricky thing. Apart from the problems of estimating feed availability from communal pasture, the practise of lending or giving away cattle to other farmers (e.g. bride price), herd contracting and sending herds or just parts of it on transhumance makes modelling herd development a M.Sc. thesis of its own (Hiernaux P. & Gerard B. communicated orally). Furthermore it was intended to include a household sub model. On the one hand this sub model should estimate some economic parameters like revenue, profit or return on investment (especially return on fertiliser investment). Additionally the household model is crucial to estimate nutritional requirements the farm has to achieve and labour available for cropping as well as earning off farm income. Some of these questions were investigated in the scenarios chapter (see 3.3.1 Farm types). As mentioned in chapter 3.1 Model evaluation, FAKFARM's ability to predict millet yield is not very reliable. Although the ways nutrient- as well as water-limiting yield are calculated is quite complex. The final calculation of millet grain yield is just a simple MIN function. In other words in FAKFARM the smaller of bough yields is taken as millet yield. This is a rather binary solution and dose not takes into account the interrelations of nutrient and water availability over the vegetation period. The calculation of nutrient limiting yield for each development stage, like it is done for the water-limiting yield, could improve the millet sub model considerably. This would enable the comparison of nutrient- and water-limiting yield for each development stage, taking always the smaller of the two and would lead to a final yield estimate with a higher nutrient-water-limitation interrelation. This yield estimate could take e.g. nutrient limitation in the development stage vegetation and water limitation in the development stage flowering into account. To be able to do so the time step of the model has to be decreased. At its present state FAKFARM as well as its predecessor SIMFIS calculates with a time step of one year. Calculation of nutrient availability, and based on it nutrient limiting yield, would presuppose a time step of at least two weeks. With this time step nearly all parameters and most of the equations of the soil sub model would have to be adjusted. Unfortunately this was beyond the scope of this study.

There are more yield limiting factors not considered by FAKFARM, like pests and diseases or labour availability. As mentioned the most important weed in West Africa is Striga (*Striga hermonthica*) a parasitic plant on millet and sorghum. It sucks nutrients and energy from the host plants root system and later develops its own leave apparatus. Although most of the damage is done before Striga emerges, its severity depends on the effort put into weeding. 2-3 weedings with the hilaire are common in the area. This is very labour intensive, so yield reduction by weeds is closely related to labour availability. As labour availability is not considered by FAKFARM (see above) there is little sense in including weeds as yield limiting factor. Pests like the locusts calamity in 2004, are next to unpredictable and by this extremely hard to simulate. Although some approaches exist (e.g. Deveson 2001), it is very labour and information intensive and not feasible without the help of geographic information system (GIS).

Model evaluation (chapter 3.1) showed that when water is not considered limiting by FAKFARM Simulated yields are in the range of the observed ones. Especially when looking at yields without organic fertiliser (manure and compost). Yields calculated for manured plots are lower than the observed one (see tab. 10 & 13). This might be explained by the simple assumption of average stocking rated underlying this calculation. Another aspect to consider is the fact that demonstrations put up by the farmer itself will rather be situated at his best plots near the village. These plots are likely to have received more nutrient input over the last couple of years than the worse plots located far from the village (Gerard & Dougbedji 2003). FAKFARM is not a good tool to predict millet yield on a yearly basis. Its major objective is to estimate important variables of soil fertility. Readers interested in millet yield prediction under sahelian conditions are referred to Akponikpe P. (not yet published). Who is at the moment validating APSIM for simulating millet yield in the Fakara region.

Nevertheless is an exact yield estimate of high importance for simulating soil fertility.

Chapter 3.1 (Model evaluation) showed that variables like nutrient availability are strongly correlated to nutrient output by millet grain harvest. In this chapter it was also shown that millet yields of FAKFARM simulations are rather P limited than N limited. According to experts (Burkert & Hiernaux, 1998; Batiano et al., 1992) this is the case in SW-Niger.

Variables like organic matter content and soil pH seems to be more correlated to inputs like manure and crop residues in the case of OM and mineral fertiliser in the case of pH. While the development of OM (see fig. 22) looks quite realistic for the FAKFARM simulation the development of pH at high input level (fig. 23) is rather extreme. Although experts (Stumpe and Vlek, 1991; Van der Pol, 1992; Juo et al., 1995) agree that a decrease of OM and the use

of min. fertiliser leads to strong acidification of this kind of soils, more data on long term effects of fertiliser use in this area is required to validate FAKFARM. The pH value influences decomposition (equ. 22 & 24) and by this availability of nutrients. Fortunately FAKFARM stops decreasing pH at 4.5 (end of linear section of the soil pH titration curve). So in case this pH development is based on wrong assumptions, the effect on decomposition and nutrient availability not to extreme.

Some more research is needed on the behaviour of the model at low input levels of manure and crop residues. To proof the assumption of competition between SOM and the plant, explaining the decreasing nutrient availability at low input levels (see chapter 3.2 Sensitivity analysis of stocking rate and straw removal), more data on Nmin and Pava development over time, in these farming systems is required.

Further more the model doesn't seems to be to reliable at very high input levels (see chapter 3.2 Sensitivity analysis of mineral fertiliser) but this fact isn't of great concern as the primary objective of FAKFARM is to observe soil fertility development in low input farming systems of the Sahel, where high NPK inputs ($>200\text{kg NPK}\cdot\text{ha}^{-1}$) are not very likely.

And finally it is to admit that FAKFARM only accounts for millet. Although this crop is the predominant staple crop (85%) especially the incorporation of legumes (cowpea) and fallow in the model would be desirable.

4.5 The farm types

The investigation of sustainable land use led to different results for the different farm types. The only farm type who is at present state (standard run) able to crop sustainable (according to the definition in 3.3.1) is the camp rich farmer (CR), accounting for only 14% of all farms in the region. His yearly millet harvest is high enough to keep his family well fed and at the same time available nutrients and SOM of his soils are steadily or increasing. This corresponds to findings of Shepherd and Soule (1998) in Kenia and Bontkes in Mali (see chapter 2.2.2). Bough authors found positive nutrient balances and best SOM development in the high-endowed group of farms. Although Bontkes reported decreasing SOM even in the high-endowed farm type, it is to notice that his farm type A cropped a lot of cotton. A high intensity crop not compare able to millet production in the Fakara. Furthermore Busqué (2002) showed that VR are the only farm type in the Fakara with positive nutrient balances (see chap. 2.3).

86% of farms in the objective area do not achieve one or bough objectives of sustainable land use, defined in chapter 3.3.1. Village rich (VR) and Village herders (VX) are bough able to sustain their families, bough yield millet grain surplus to amount reserve for bad years. This is primary due to the fact that bough crop a fairly high amount of land per consumer. Stocking rate is very low for the VR and medium for the VX. But in bough farm types it is not high enough to meet the second objective, to keep soil fertility, especially organic matter content, stabile. For the VX leaving half of the crop residues as mulch on the field is sufficient to stabilise SOM. VR need additional OM input either by crop residues/mulch, fallow or by manure.

Camp poor on the other hand are able to maintain soil fertility, but are short on millet yield to keep all household members satisfied. A solution proposed in chapter 3.3.1 is the use of inorganic fertiliser to increase millet yield.ha⁻¹. To be able to invest in fertiliser it was proposed to yield income by corralling CP herds on VR fields in exchange for money. Stocking rate of the improved run of VR was set to 0.4 TLU.ha⁻¹. To achieve this the average VR farmer would need 8.56 additional TLU.farm⁻¹. In the improved run of CP stocking rate was still at 1 TLU.ha⁻¹, leaving the CP with 8.7 TLU.farm⁻¹. This means one average CP farmer is only able to abstain from 3.8 TLU.farm⁻¹. Additionally the number of CP farmers in the area (92 farms) is only about three-quarter of the VR farms (126 farms). So looking at the whole area CPs livestock alone is not sufficient to increase stocking rate of VR farmers to the aimed level. But CR farmers do have enough reserve in stocking rate to do so, although they are not as much depended on agricultural inputs and income, as CP farmers are.

Village poor farmers are the single one group who can achieve neither of the objectives of sustainability in the standard run. The millet yield they are able to harvest ranges between 150 and 250 kg.ha⁻¹.yr⁻¹ in non-water limiting years. This is not always enough to feed all family members (222.5 kg.ha⁻¹.yr⁻¹). Least of all they are able to yield reserve for dry years. This fact and additionally the fact that they represent with 213 farms (40%) by far the biggest group of farm types, should concentrate research, development and extension activities on them. In the improved run it was provided that VP are able to yield off-farm income to invest in mineral fertiliser. The amount of NPK used was set to 40 kg.ha⁻¹.yr⁻¹. It was shown that this amount is still not enough to reach the 445 kg.ha⁻¹.yr⁻¹ yield level. But at least lift millet yield to more than 350 kg.ha⁻¹ in 5 out of ten years. Two major preconditions have to be met to enable the VP farmer to invest in mineral fertiliser. The first is the possibility to earn off-farm income. Off-farm income in this sense is defined by income not related to millet production. So livestock production fed on communal pasture as well as vegetable (e.g. tomato, tobacco) production on intensive cropped plots next to the homestead would fall under this category. To earn money on marketing these goods the organisation of local markets has to be strengthened.

Another option for income for CP is seasonal labour migration. An ever-increasing number of young males (primary bachelors) leave Niger after millet harvest to work in the richer neighbouring countries of Ghana, Burkina Faso or Nigeria. Either they do very-small-scale business or work in the growing service sector of these countries. At the end of the dry season they return to their fields to prepare them for sowing. Because of the relative proximity of the Fagara to Niamey, the capital of Niger, some farmers may be in the position to market their goods on this great sales market or are even be able to find a job in this metropolis.

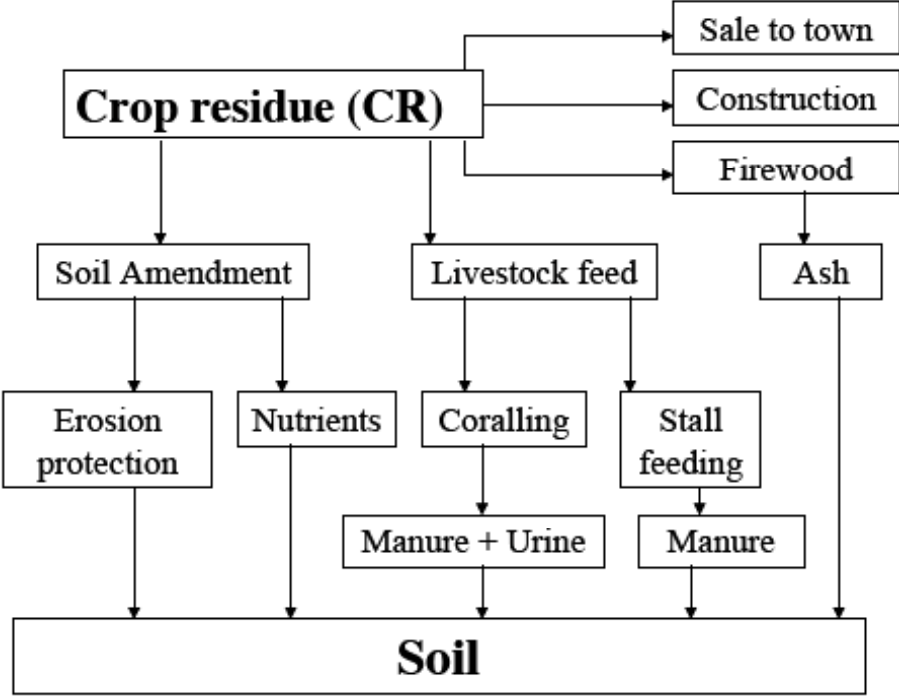
Preconditions for this are improved infrastructure and transportation systems. But the majority of rural population live in far of places and local markets are the only possibility for them to yield cash.

The second precondition for fertilizer use in these farming systems is low prices and availability. 70% of farmers in Niger name the high costs of fertiliser as well as the unavailability of credit as the major constraints to the use of mineral fertiliser (Vlek 1990). High prices are again strongly related to the quality of infrastructure and transportation systems. As the improvement of roads and the railroad system of a country like Niger is certainly beyond the ability of most development organisations, this task has to be referred to the government.

The simple calculation in chapter 3.3.1 showed that even for CR min. fertiliser use at present prices is not economic. In the ten years simulation run he was only able to yield an additional value of 31,233 fcfa.ha⁻¹ in millet, spending 46,000 fcfa.ha⁻¹ on NPK. This corresponds to a value cost ratio (VCR) of -0.32. VCR is defined as the ratio of the value of additional grain produced to the cost of the fertiliser inputs necessary to achieve this yield. According to FAO economic limit above which a farmer will likely adopt a crop management practice are VCRs of 2.0 or higher (Bationo 1992). This implies that at 34% of its present costs the use of mineral fertiliser would be of interest to the CR farmer (based on VCR of 2). In other words fertiliser prices have to decrease by two-third to make CR farmers adopt this management practise. This seems to be a huge margin to overcome. But considering the fact that West African prices for fertiliser are extremely high (c.i.f. price is 30-60% higher than in Asia) (Vlek 1990), there is still a huge window of opportunity. Additionally farmer associations could buy fertiliser in great quantities collectively and by this make use of the advantage of economies of scale and additionally decrease transportation costs.

The important role of crop residues to maintain soil fertility, and to stabilise millet yields was again affirmed. This corresponds to findings of Muehlig-Versen et al. (1997), Bationo et al. (1995 & 1998), Yamoah et al. (2002) and many more.

Crop residues experience a wide variety of uses in West Africa. They are used for fuel, animal feed, or housing and fencing material. Figure 67 gives a schematic representation of the different uses of crop residues.



Source: Bationo et al., 1995

Figure 67: Different uses of crop residues in West African farming systems.

Sandford (1989) reported that in the mixed farming systems, cattle derive up to 45% of their total annual intake from crop residues and up to 80% during periods of fodder shortage. Up to 50% of the total amount of crop residue and up to 100% of the leaves are eaten by livestock (Van Raay and de Leeuw, 1971). In West Africa, grazing animals remove more biomass and nutrients from cropland than they return in the form of manure. Therefore, Breman and Traore (1986) concluded that a sustainable nutrient supply in the southern Sahel based on a net transfer of nutrients from rangelands to cropland required between 4 and 40 ha of rangeland per hectare of cropland.

Field experiments in millet showed that from a plant nutritional standpoint the optimum level of crop residue to be applied to the soil, as mulch, may be as high as $2\text{t}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ (Rebafka et al., 1994). However, McIntire and Fussell (1986) reported that on fields of unfertilized local cultivars, grain yield averaged only $236\text{ kg}\cdot\text{ha}^{-1}$ and mean residue yields barely reached $1300\text{ kg}\cdot\text{ha}^{-1}$. To add to the problem up to 90% of crop residues are removed for construction or burned for cooking (Lompo, 1983).

FAKFARM calculates even lower CR yields for unfertilised fields. For the ten years simulation average CR yields are $530\text{ kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$, varying between 883 and $55\text{ kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$. Optimising management practise like an increase in stocking rate ($1\text{ TLU}\cdot\text{ha}^{-1}$), mulch and the use of NPK ($40\text{kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$), can increase mean CR yield to $773\text{ kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$, with top yields as high as $1389\text{ kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$.

Crop residues used as mulch are crucial to maintain soil fertility. But often they are removed from the field for various purposes. To make farmers abandon this practise researchers, extension services and aid organisations are facing a huge task. Plant breeders are called upon to not only concentrating on higher grain yield but also consider high straw yield in breeding new varieties. Researcher and extension services may try to implement agro forestry systems, like hedgerow cropping, to provide farmers with construction material and fuel wood. The practise of feeding cattle on crop residues has to be reconsidered. This might oppose the claim to corral livestock to farmer's fields after harvest. But Incorporation of crop residues into the soil right after harvest would conserve the major share of CR from digestion by livestock. And finally again the importance of affordable and available mineral fertiliser is highlighted, to elevate total millet yield, grain as well as CR yield.

4.6 The climate

EdGCM climatic change simulation predicts rising temperature and an increase in precipitation for the Sahel for both scenarios. Especially the later might appear confusing at first sight, because historical rainfall data shows an opposite trend. Hulme et al. (1992) reported a decrease in precipitation for the African Sahel of 10-20% comparing the periods of 1931 to 1960 and 1961 to 1990. How far these recorded changes are related to radiative forcing due to increased greenhouse gases is controversial. In a recent study, which draws on 80 simulations of global climate from five state of the art computer models Hoerling et al. (2005) relate Sahelian droughts of the late 20th-century to the progressive warming of the South Atlantic relative to the North Atlantic sea surface. But the increasing concentrations of greenhouse gas and the consequent global warming leads to a reverse in this trend as the Northern hemisphere, due to its higher share of landmass, warms faster than the southern hemisphere. This would also lead to a swing in Sahelian rainfall regime from drought to more moist conditions, the researchers believe. Greenhouse gas forced experiments (Hurling et al. 2005), conducted as part of the Third Assessment Report (IPCC 2001) generated a wet trend that emerges in the last decade of the 20th century and accelerates during the 21st century. They project that the Sahel monsoon will be some 20% to 30% wetter by 2049 compared to the 1950-99 average. This is even higher than the predicted precipitation of the EdGCM simulation runs in this work, where the calculated increase in 30 years time ranges between 4% (B2 Scenario) and 8% (A1FI scenario). As a side note, the same study (Hurling et al. 2005) predicts an increase in droughts for the semi arid part of southern Africa (Angola, Zambia, and Zimbabwe), because of a dramatic warming of the Indian Ocean.

Although the model capabilities of GCMs have improved significantly with increasing computing power and the incorporation of ocean, sea ice and land condition models, still a great uncertainty is associated with the output of even the most sophisticated GCMs. Results have to be averaged over a larger scale; EdGCM averages results for a grid box of about 1000 x 1000 km. Regarding the very erratic nature of rainfall events in the Sahel, this is a major source of uncertainty. Adding to the problem, daily rainfall data is not accessible using EdGCMs. Instead monthly averages were used to calculate the amount of rain in each development stage. That is why GCMs are also unsuited to predict climatic extremes. The complexity of GMSs makes them a black box for users not familiar with climatic modelling. It is not obvious if and to what extent climatic phenomenon are incorporated in the model. Bryden et al. (2005) for example reported that the Atlantic meridional overturning circulation (Gulf Stream) has slowed by about 30% between 1957 and 2004. This was

explained by the higher runoff of sweet water from northern Europe and Greenland counteracting the Gulf Stream. Climate models based on this assumption, suggested a cooling of northern European climate by up to 6°C. How and if this theory is accounted for in EdGCM and Hurlings findings is unclear. Another source of uncertainty is the actual release of CO₂ and other GHG. Although two scenarios (an optimistic and an pessimistic one) were investigated, the exact increase of GHG is maybe the factor of highest uncertainty in the simulation. The impact of global warming on peat land and permafrost seems to be a momentous but controversial factor. There is little doubt that an increase in temperature would lead to higher GHG emissions from these sources, some scientists even claim that this sources could surpass CO₂ emissions by burning of fossil fuels by 2060 (BBC 2004). The same applies to the GHG sink side as well. Little is known, but much is speculated about the impact of global warming on world oceans plankton, a major sink of CO₂. Considering all this, the climate prediction of even the most sophisticated GCM is always just one possible scenario of future climatic development.

If we take bough the increase in sahelien monsoon and temperature as a base, prospects for the Fakara and the West African Sahel are better than expected. Yields are increasing and stabilising over the next two decades and soil fertility can be maintained, bearing in mind the management practises mentioned in precious chapters. Yield calculation of FAKARA simulation did not account for the increase in evapotranspiration. IPCC stated in their (1997) report “The regional impact on Climatic change” that the projected temperature increases are likely to lead to increased open water and soil/plant evaporation. Exactly how large this increased evaporative loss will be would depend on factors such as physiological changes in plant biology, atmospheric circulation, and land-use patterns. They estimate, potential evapotranspiration over Africa to increase by 5-10% by 2050. The sensitivity of FAKFARM on an increase in ET_m in this range is rather low. Only a slight yield decrease is detectable. But when ET_m is increased to 15 or even 20 % yield decreases especially in the second half of the simulation run is more drastic. This is because at this ET_m water limitation becomes again dominant.

Maintaining soil fertility is also easier under climatic change conditions. Although decomposition rates increase with temperature, the higher yields lead to higher organic matter inputs via crop residues. In scenario A1FI mulching of 25 % of crop residues (with given stocking rate and fertiliser use) is sufficient to maintain SOM.

To maintain soil pH again higher OM inputs are required. But without fertiliser use soil pH would only decrease by 0.3 over the 30 years simulation (no straw removal, 0.46 TLU.ha⁻¹).

4. Conclusion and perspectives

FAKFARM at its present state is not mature to be employed by extension services to estimate the development of soil fertility under given management practices and farm specific input variables. The improvement of water nutrient limitation interrelation, the incorporation of a livestock and household sub model and the implementation of fallow and legumes like cowpea lies still ahead. Nevertheless it is hoped to contribute to the project “Improved livelihoods in the Sahel through the development and implementation of household level bio-economic decision support systems” by raising questions and maybe giving some hints.

In the present situation 86% of the farms in the Fakara do not crop their fields sustainable. 29% are able to harvest enough millet to feed their families but soil fertility, esp. SOM, is decreasing. 57% are struggling to yield enough cereals for human nutrition. The major share of this group is additionally destroying their base of existence by mining their soils.

Simulation results showed that it is possible to achieve the objectives of sustainable crop production for all farmers, although for some it is easier than for others. Attention is turned on the poor, dwelling in villages as well as in camps. Because of their small cropping area they are most dependent to nutrient inputs. Livestock alone is not able to fill this gap. So access to credit and affordable min. fertiliser is crucial for this group of farmers.

The importance of crop residues as mulch to maintain SOM and soil pH can hardly be rated to high. All farmers, with the exceptions of CR, need to leave at least parts of the CR at the field to keep SOM stabile. Again Livestock at usual stocking rates in this area seems to have less effect on SOM compared to CR. The use of CR as mulch has to compete with a wide variety of other uses in these farming systems. To find alternatives for e.g. building material and fuel wood is one of the most important challenges of research and development. Feeding of CR to livestock also seems to be adversarial to the maintenance of soil fertility. But alternatives are hard to find regarding the limited capacity of rangeland and pasture.

Based on GCM simulations in this work and other recent findings, the West African Sahel seems to be one of the few regions benefiting from climatic change. An increase in GHG and the subsequent warming of earth’s climate may lead to an increase in precipitation in the area under observation. Although uncertainties are still numerous, this scenario would lead to an increase and stabilisation in millet yields. This would also have positive effects on soil fertility, as higher CR yields would more than compensate higher decomposition rates caused by the rise in temperature.

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APPENDIX

Millet production

$$\text{Milletgrainyield} = \text{MIN} (\text{nutlimitGrainyield}, \text{waterlimitGrainyield}) \quad (1)$$

where,

Milletgrainyield: crop production (kg dm.ha⁻¹)

nutlimitGrainyield: yield limited by N and P (kg dm.ha⁻¹)

waterlimitGrainyield: yield limited by the availability of water (kg dm.ha⁻¹)

MIN (...): the smaller of the two value of the variables within the brackets

Nutrient limiting yield

$$\begin{aligned} \text{Nuptake} = \text{Nmin} - \frac{0.25 * (\text{Nmin} - \text{Pavailable} * (\text{maxPconc}/\text{minNconc}))^2}{\text{Pavailable} * ((\text{minPconc}/\text{maxNconc}) - (\text{maxPconc}/\text{minNconc}))} \end{aligned} \quad (2)$$

$$\begin{aligned} \text{Puptake} = \text{Pavailable} - \frac{0.25 * (\text{Pavailable} - \text{Nmin} * (\text{maxNconc}/\text{minPconc}))^2}{\text{Nmin} * ((\text{minNconc}/\text{maxPconc}) - (\text{maxNconc}/\text{minPconc}))} \end{aligned} \quad (3)$$

$$\text{max N yield} = \text{minNconc} * \text{N-uptake} \quad (4)$$

$$\text{min N yield} = \text{maxN conc} * \text{N-uptake} \quad (5)$$

$$\text{max P yield} = \text{minP conc} * \text{P-uptake} \quad (6)$$

$$\text{min P yield} = \text{maxPconc} * \text{P-uptake} \quad (7)$$

$$\begin{aligned} \text{yield NP} = \text{minPyield} + \frac{2 * (\text{maxPyield} - \text{minPyield}) * (\text{nupt} - \text{minPyield}/\text{minNconc})}{\text{maxPyield}/\text{maxNconc} - \text{minPyield}/\text{minNconc}} \\ - \frac{(\text{maxPyield} - \text{minPyield}) * (\text{nupt} - \text{minPyield}/\text{minNconc})^2}{(\text{maxPyield}/\text{maxNconc} - \text{minPyield}/\text{minNconc})^2} \end{aligned} \quad (8)$$

$$\text{yield PN} = \text{minNyield} + \frac{2 * (\text{maxNyield} - \text{minNyield}) * (\text{pupt} - \text{minNyield} / \text{minPconc})}{\text{maxNyield} / \text{maxPconc} - \text{minNyield} / \text{minPconc}} - \frac{(\text{maxNyield} - \text{minNyield}) * (\text{pupt} - \text{minNyield} / \text{minPconc})^2}{(\text{maxNyield} / \text{maxPconc} - \text{minNyield} / \text{minPconc})^2} \quad (9)$$

$$\text{minNconc} = \frac{1}{\text{minNgrain} * (\text{hi} * \text{srr} / (\text{srr} + 1)) + \text{minNshoot} * ((1 - \text{hi}) * \text{srr} / (\text{srr} + 1)) + \text{minNroot} / (\text{srr} + 1)} \quad (10)$$

where,

minNgrain: minimum N concentration in the seed (kg.kg⁻¹)
minNshoot: minimum N concentration in the vegetative parts (kg.kg⁻¹)
minNroot: minimum N concentration in the roots (kg.kg⁻¹)
hi: harvest-index (production of grain / total above-ground dry matter)
srr: shoot / root ratio

Table A1: Harvest indices, shoot-root ratio and minimum and maximum concentrations of N and P in different organs of crop (Van Duivenbooden, 1992; Groot, 1995; Hengsdijk et al., 1996; Omokanye et al., 2003).

	millet	millet (imp)
harvest index	0.25	0.3
shoot/root	4	4
minNgrain	0.013	0.013
minNshoot	0.005	0.005
minNroot	0.003	0.003
minPgrain	0.002	0.002
minPshoot	0.0008	0.0008
minProot	0.0005	0.0005
maxNgrain	0.025	0.025
maxNshoot	0.015	0.015
maxNroot	0.015	0.015
maxPgrain	0.004	0.004
maxPshoot	0.0015	0.0015
maxProot	0.001	0.001

Water limiting yield

$$(1 - Y_a/Y_m) = k_y * (1 - E_{Ta} / E_{Tm}) \quad (11)$$

or

$$Y_a/Y_m = 1 - k_y * (1 - E_{Ta} / E_{Tm}) \quad (12)$$

where,

- Y_a: actual yield (kg.ha⁻¹)
- Y_m: potential yield (kg.ha⁻¹)
- K_y: empirically derived yield response factor
- E_{ta}: actual evapo-transpiration (mm)
- E_{Tm}: maximum evapo-transpiration (mm)
- Y_a/Y_m: rel. yield

When equ. 13 gets below 0.5, it is assumed that the yield is still stronger reduced.

Table A2: Effect of drought (i.e. $1 - k_y * (1 - E_{Ta} / E_{Tm}) < 0.4$) on relative yield (Y_a/Y_m).

$1 - k_y * (1 - E_{Ta} / E_{Tm})$	Y _a /Y _m
0.6	0.7
0.5	0.2
0.4	0.05
0.3	0.01
0.2	0.0

$$cf_{waterlimitingyield} = rel_{yielddestab} * rel_{yieldveg} * rel_{yieldflow} * rel_{yieldripe} * rel_{yieldform} \quad (13)$$

where,

- cf_{waterlimitingyield}: total yield decrease by water shortage
- rel_{yielddestab}: rel. yield in development stage establishment
- rel_{yieldveg}: rel. yield in development stage vegetative
- a.s.o.

$$E_{Tm} = k_c * E_{To} \quad (14)$$

Table A3: Date of sowing, length of the different development per crop stages, yield response factor (ky), crop coefficient (kc) and depletion factor (p) per crop and development stage. (Doorenbos and Kassam, 1979)

	Millet	
	local	improved
date of sowing	1/7	15/6
length of development stages in days		
- establishment	15	15
- vegetative	45	30
- flowering	15	15
- yield formation	15	15
- ripening	15	15
total growing period	105	90
establishment		
- ky	0	
ETm (mm/d)	2.7	
- p	0.82	0.82
vegetative		
- ky	0.2	
ETm (mm/d)	5.4	
- p	0.66	0.66
flowering		
- ky	0.55	
ETm (mm/d)	5.9	
- p	0.56	0.53
yield formation		
- ky	0.45	
ETm (mm/d)	4.2	
- p	0.68	0.67
ripening		
- ky	0.2	
ETm (mm/d)	2.7	
- p	0.83	0.81

$$ASI_d = (TSW_d - RSW_d) / \text{totETm}_d \quad (15)$$

where,

- TSW_d: total amount of available soil water (taking into account the rooting depth) during development stage d (mm)
- RSW_d: threshold amount of soil water (mm).
- totET_m_d: ET_m * length of development stage (mm), as ET_m is given in mm/d one has to multiply it with the length of the sp. development stage

$$TSM_d = \text{MAX} (TSW_{d-1} - ET_{m,d-1} * \text{lenth}_{d-1} + \text{Infiltration}_d - \text{drain}_{d-1} + (\text{rootdepth}_d - \text{rootdepth}_{d-1}) * \text{waterwiltingpoint}, 0) \quad (16)$$

where,

- TSM_d: total amount of soil water at the end of development stage d;
- TSM_{d-1}: total amount of soil water at the beginning of development stage d;
- infiltration_d: quantity of water that infiltrates into the soil during that stage (mm);
- drain_d: the quantity of the infiltrated water that exceeds the storage capacity of the soil during stage d (mm.stage⁻¹).
- rootdepth_d: average rooting depth during stage d (mm)
- wiltingpoint: amount of water at wilting point (mm)

Table A4: Determination of actual evapotranspiration (ET_a)

Development-stage	Available Soil water Index					
	0	0.17	0.34	0.51	0.68	0.85
Establishment	0.8	1.1	1.3	1.6	1.8	1.9
Vegetative	0.9	1.7	2.5	3.3	4.1	4.9
Flowering	1.3	2.4	3.2	4.2	5.1	5.7
Yield formation	1.0	1.8	2.4	3.0	3.4	3.8
Ripening	0.9	1.3	1.7	2.2	2.6	2.9

$$RSW_d = (1-p_d) * Wstorage_d \quad (17)$$

$$Wstorage_d = rootdepth_d * waterholdingcap \quad (18)$$

$$waterholdingcap = fieldcap - wiltingpoint \quad (19)$$

where,

p : depletion factor
 rootdepthd : rooting depth (m)
 fieldcapacity : amount of water at field capacity (mm)
 wiltingpoint : amount of water at wilting point (mm)

$$infiltration_d = (1-cfrunoff_d) * rain_d \quad (20)$$

Table A3: Run-off fractions for the development stages

	millet
establishment	0.8
vegetative	0.3
flowering	0.1
yield formation	0.1
ripening	0.1

$$drain_d = \text{MAX} ((TSW_d - ETa_d * lenth_d - Wstorage_d), 0) \quad (21)$$

where,

draind: amount of water drained during a particular period (mm);
 TSWd: total amount of available soil water during the period (mm);
 lenthd: length of the period;
 ETad: actual evapo-transpiration (mm.d⁻¹);
 Wstoraged: storage capacity during that period (mm);

Soil processes

Organic matter dynamics

$$\text{decompositionrate} = \text{basedecomprate} * \text{MIN}(\text{cfCN}, \text{cfCP}) * \text{cfmoist} * \text{cftemperature} * \text{cfpH} * \text{cftexture} * \text{cfnitrogen} \quad (22)$$

Table A5: Basic decomposition rates of labile and stabile organic matter (% per year under optimum conditions) (based on Coleman and Jenkinson (1999) and Van Keulen (1995)).

substrate	basic decomposition rate
residues	100
manure	100
labile organic matter	40
stabile organic matter	4

$$\text{cftemp} = 47.9 / (1 + e^{106/((\text{tjune} + \text{tjuly} + \text{taug} + \text{tsept} + \text{toct}) / 5 + 18.3)}) \quad (23)$$

$$\text{cfpH} = 0.25 * (\text{pH} - 3) \quad (24)$$

$$\text{cftexture} = 1 - 0.75 * (\text{silt fraction} + \text{clay fraction}) \quad (25)$$

$$\text{cfnitrogen} = 1 + 0.0035 * \text{Nfertiliser} \quad (26)$$

where N-fertiliser is expressed as kg N. ha⁻¹.

$$\text{cfstraw} = 1.2 \text{ following incorporation of straw, otherwise } 1 \quad (27)$$

$$\text{cfCO}_2 = (1.21 + 2.24 * e^{-0.085 * \text{cecclay}}) / (1 + (1.21 + 2.24 * e^{-0.085 * \text{cecclay}})) \quad (28)$$

where

cfCO₂ : is the part of the decomposed carbon that disappears as CO₂.
 Cecclay: is expressed in cmol.kg⁻¹.

The cation exchange capacity of clay is estimated at 50 meq/100 g, based on existing soil data of the Soum region in Burkina Faso (BUNASOILS, 2002).

$$\text{cec_clay} = \text{clayfraction} * 50 \quad (29)$$

where,

cec_clay: cec of the soil due to its clay content (mmolc/100 g)

clayfraction: percentage of clay (%)

labile C-pool

The change in the labile C-pool (dClabile) during the year is calculated by:

$$\text{dClabile} = \text{Ccroreslab} + \text{Cmanurelab} + \text{Cstablab} - \text{Clabstab} - \text{CO2lab} - \text{erosionClab} \quad (30)$$

where,

Creslab: C from residues added to the labile C pool (kg.ha⁻¹.yr⁻¹)

Cmanurelab: C from animal manure added to the labile C pool (kg.ha⁻¹.yr⁻¹)

Cstablab: stabile C transformed into labile C (kg.ha⁻¹.yr⁻¹)

CO2lab: labile C decomposed and lost throu CO2 production (kg.ha⁻¹.yr⁻¹)

erosionClab: labile C lost through erosion (kg.ha⁻¹.yr⁻¹)

The quantities of labile C, produced as a consequence of adding organic material to the soil or as a consequence of decomposition processes, are determined as:

$$\text{Ccroreslab} = (1 - \text{decomprateresid}) * \text{Ccroresidues} + (1 - \text{cfCO2}) * \text{Ccroresidues} * \text{decomprateresid} \quad (31)$$

$$\text{Cmanurelab} = (1 - \text{decompratemanure}) * \text{Cmanure} + (1 - \text{cfCO2}) * \text{Cmanure} * \text{decompratemanure} \quad (32)$$

where,

cfCO2: the proportion of the decomposed substrate transformed into CO2

decomprateresid: decomposition rate of crop residues

decompratemanu: decomposition rate of manure

Cresidues: C applied to the field as crop residues (kg.ha⁻¹.yr⁻¹)

Cmanure: C applied to the field as manure (kg.ha⁻¹.yr⁻¹)

$$C_{stabilab} = C_{labile} * decompratelabile * cfC_{stab} * (1 - cfCO_2) \quad (33)$$

$$C_{labstab} = C_{stabil} * decompratestabil * cfClab * (1 - cfCO_2) \quad (34)$$

$$CO_{2lab} = C_{labile} * cfCO_2 * decompratelabile \quad (35)$$

where,

- cfClab: fraction of C entering the labile C pool (0.46)
- cfCstab: fraction of C entering the stabil C pool (0.54)
- cfCO₂: part of the decomposed carbon that disappears as CO₂
- decompratestabil: decomposition rate of stabile C
- decompratelabile: decomposition rate of labile C

$$c_{enrichment} = 7.4 * (1000 * soil\ loss)^{-0.2} \quad (36)$$

where, soil loss is expressed in tons per ha.

$$erosionClab = c_{enrichment} * C_{labile} * 1000 * soil\ loss / (0.2 * 10000 * sbd\ topsoil) \quad (37)$$

where,

- C_{labile}: the quantity of labile C in the upper 30 cm of the soil (kg.ha⁻¹)
- soil loss: loss of soil (t.ha⁻¹.yr⁻¹)
- sbd topsoil: bulk density of the top soil (kg.m⁻³)

$$dC_{stabile} = C_{labstab} - CO_{2stab} - erosionC_{stab} \quad (38)$$

$$Manure = DailyfeacalTLU * TLUperha * daysDryseason \quad (39)$$

Table A6: Composition of organic amendments (Van den Bosch et al. 1998; Defoer, 2000)

	C	N	P
Cattle manure	0.35	0.015	0.0024
Crop residues	0.21	0.012	0.0015

Nitrogen dynamics

$$dN_{\text{labile}} = N_{\text{manuredecomp}} + N_{\text{cropresdecomp}} + N_{\text{incorplab}} + N_{\text{stabilab}} - N_{\text{labstab}} - N_{\text{labmin}} - N_{\text{erosionlab}} \quad (43)$$

where,

$N_{\text{manuredecomp}}$:	N from manure added to the labile N pool ($\text{kg} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$)
$N_{\text{cropresdecomp}}$:	N from crop residues added to the labile N pool ($\text{kg} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$)
$N_{\text{incorplab}}$:	mineral N incorporated in labile organic matter ($\text{kg} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$)
N_{stabilab} :	stable N transformed to labile N ($\text{kg} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$)
N_{labstab} :	labile N transformed to stable N ($\text{kg} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$)
N_{labmin} :	labile N decomposed ($\text{kg} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$)
$N_{\text{erosionlab}}$:	labile N lost through erosion ($\text{kg} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$)

$$N_{\text{incorp}} = \text{MIN} (\text{cf}N_{\text{incorp}} * N_{\text{min}}, N_{\text{required}}) \quad (44)$$

where,

$\text{cf}N_{\text{incorp}}$ is the part of the mineral N that is incorporated in organic matter

$$\text{rel}N_{\text{demand}} = N_{\text{required}} / \text{MAX} (N_{\text{min}}, 0.1) \quad (45)$$

where,

N_{required} is the sum of the N required by the labile and the stable organic matter.

Table A7: The relationship between the relative demand for N by the organic matter and the part of the mineralised N that is immobilised by the organic matter

	relative N demand										
	0	0.3	0.6	0.9	1.2	1.5	1.8	2.1	2.4	2.7	3.0
$\text{cf}N_{\text{incorporated}}$	0.2	0.5	0.86	0.88	0.89	0.90	0.91	0.92	0.93	0.94	0.95

$$N_{labrequired} = (C_{reslab} + C_{manurelab} + C_{wastelab} + C_{stablab}) / CN_{lab} \quad (46)$$

where

CN_{lab}: C/N ratio of the labile organic matter.

$$N_{stabrequired} = (C_{resstab} + C_{manurestab} + C_{labstab} + C_{stabstab}) / CN_{stab} \quad (47)$$

where,

CN_{stab}: C/N ratio of the stabile organic matter

$$dN_{stable} = N_{incorpstab} + N_{labstab} - N_{stablab} - N_{stabmin} - N_{stab_erosion} \quad (48)$$

where,

N_{incorpstab}: mineral N incorporated into stabile organic matter (kg.ha⁻¹.yr⁻¹)

N_{stabmin}: stabile N decomposed (kg.ha⁻¹.yr⁻¹)

N_{erosionstab}: stabile N lost through erosion (kg.ha⁻¹.yr⁻¹)

$$dN_{mineral} = N_{labmin} + N_{stabmin} + N_{residuemin} + N_{manuremin} + N_{fert} + N_{rain} - N_{incorplab} - N_{incorpstab} - N_{leaching} - N_{uptake} \quad (49)$$

where,

N_{labmin}: N mineralised from labile organic matter (kg.ha⁻¹.yr⁻¹)

N_{stabmin}: N mineralised from stabile organic matter (kg.ha⁻¹.yr⁻¹)

N_{residuemin}: N mineralised from crop residues (kg.ha⁻¹.yr⁻¹)

N_{manuremin}: N mineralised from animal manure (kg.ha⁻¹.yr⁻¹)

N_{rain}: N added from rainfall (kg.ha⁻¹.yr⁻¹)

N_{fert}: N from fertiliser (kg.ha⁻¹.yr⁻¹)

N_{leaching}: N lost trough leaching (kg.ha⁻¹.yr⁻¹)

N_{uptake}: N taken up by the plant (kg.ha⁻¹.yr⁻¹)

$$N_{labmin} = decomClab / Cn_{labile} \quad (50)$$

where,

decomClab: labile C that is decomposed (kg.ha⁻¹.yr⁻¹)

CN_{labile}: C/N-ratio of labile organic matter

$$N_{rain} = 0.0065 * rainfall \quad (51)$$

$$N_{\text{leaching}} = N_{\text{min}} * c_{\text{drain}} * c_{\text{sand}} * c_{\text{cec}} \quad (52)$$

where,

N_{leaching} : N lost through leaching
 c_{drain} : effect of amount of water drained on leaching (Table A8)
 c_{sand} : effect of proportion of sand on leaching (Table A9)
 c_{cec} : effect of cation exchange capacity on leaching (Table A10)

Table A8: The effect of water drained on leaching of nitrogen (Van Keulen, 1995).

	amount of drain water (mm)			
	0	250	750	1500
c_{drain}	0	1	1	1

Table A9: The effect of the percentage of sand on leaching of nitrogen (Van Keulen, 1995).

	percentage of sand				
	0	25	50	75	100
C_{sand}	0.3	0.5	0.8	0.9	1

Table A10: The effect of the cation exchange capacity on leaching of mineral nitrogen (Van Keulen, 1995)

	cec (meq/100 g)						
	0	5	10	15	20	25	30
c_{cec}	1	0.8	0.6	0.57	0.53	0.5	0.4933

$$\text{erosion} = c_{\text{frain}} * c_{\text{topography}} * c_{\text{crop}} * c_{\text{antiero}} * c_{\text{erodibility}} \quad (55)$$

where,

erosion : the amount of soil loss ($\text{t} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$)
 c_{frain} : the rainfall-runoff erosivity factor
 c_{crop} : the effect of crop cover
 c_{antiero} : effect of anti-erosion measures
 $c_{\text{erodibility}}$: soil erodibility factor

$$c_{\text{rain}} = 0.5 * \text{rainfall} \quad (56)$$

where,

rainfall: expressed in mm.yr^{-1}

Table A11: The effects of anti erosion measures (Stroosnijder et al. 2001)

	c_{antiero}
grass strips	0.2
mulch	0.2
stones	0.5

The soil erodibility for this type of soils is estimated at 0.25 (Roose, 1977).

Soil acidity

$$\text{pHbuffercapacity} = (\text{sbd} / 1400) * (\text{sd}_{\text{om}} * \text{OMfactor} * \text{fOM} * 100 + \text{sd}_{\text{clay}} * \text{fclay} * 100) \quad (58)$$

where,

pH buffer capacity is expressed in $\text{kmol}_c \cdot \text{ha}^{-1} \cdot \text{ph}^{-1}$
sbd: bulk density of the top soil (kg/m^3)
 sd_{om} : soil depth over which the effect of organic matter is determined (dm)
 sd_{clay} : soil depth which the effect of clay is determined (dm)
OMfactor: effect of organic matter on pH buffercapacity
clayfactor: effect of clay content on pH buffercapacity
fOM: fraction of organic matter (multiplied by 100 to yield percentage)
fclay: fraction of clay (multiplied by 100 to yield percentage)

$$\text{dpH} = - \text{total proton production} / \text{pHbuffercapacity} \quad (59)$$

with total proton production expressed in $\text{kmol}_c \text{H}^+ \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$.

$$\Delta H = \Delta H_{\text{carbon}} + \Delta H_{\text{nitrogen}} + \Delta H_{\text{cation}} + \Delta H_{\text{sulphur}} \quad (60)$$

where,

ΔH :	net production of protons ($\text{kmol}_c \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$)
ΔH_{carbon} :	net production of protons due to the carbon cycle ($\text{kmol}_c \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$)
$\Delta H_{\text{nitrogen}}$:	net production of protons due to the N cycle ($\text{kmol}_c \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$)
ΔH_{cation} :	net production of protons due to the cation cycle ($\text{kmol}_c \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$)
$\Delta H_{\text{sulphur}}$:	net production of protons due to the sulphur cycle ($\text{kmol}_c \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$)



$$\Delta H_{\text{carbon}} = (\text{HCO}_3^-_{\text{drain}} - \text{HCO}_3^-_{\text{rain}}) / 1000 \quad (62)$$

where,

ΔH_{carbon} :	net production of protons in the carbon cycle ($\text{kmol}_c \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$)
$\text{HCO}_3^-_{\text{drain}}$:	quantity of HCO_3^- drained ($\text{mol}_c \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$)
$\text{HCO}_3^-_{\text{rain}}$:	quantity of HCO_3^- from rainfall ($\text{mol}_c \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$)

$$[\text{HCO}_3^-] = (\text{KCO}_2 * \text{pCO}_2 / [\text{H}]) \quad (63)$$

where,

$[\text{HCO}_3^-]$	concentration of carbonic acid ($\text{mol}_c \cdot \text{l}^{-1}$)
KCO_2 :	product of Henry's law constant for the equilibrium between CO_2 in soil water and soil air, and the first dissociation constant of H_2CO_3 ($\text{mol}_c^2 \cdot \text{l}^{-2} \cdot \text{bar}^{-1}$) and is set to $10^{-7.8}$ (De Vries, 1994)
pCO_2 :	partial CO_2 pressure (bar); pCO_2 is set to 0.0003 bar in the atmosphere and to 0.003 bar in soil air (Helyar and Porter, 1989).
$[\text{H}]$:	proton concentration ($\text{mol}_c \cdot \text{l}^{-1}$), derived from the pH of the rainwater or the soil pH

$$\text{HCO}_3^-_{\text{rain}} = 10000 * \text{infiltration} * \text{rainfall} * [\text{HCO}_3^-]_{\text{rain}} \quad (64)$$

where

$\text{HCO}_3^-_{\text{rain}}$:	quantity of HCO_3^- from rainfall ($\text{mol}_c \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$)
infiltration:	rainfall infiltrating the soil in $\text{mm} \cdot \text{yr}^{-1}$
$[\text{HCO}_3^-]_{\text{rain}}$:	concentration of carbonic acid in rainwater ($\text{mol}_c \cdot \text{l}^{-1}$)

$$\text{HCO}_3^- \text{ drain} = 10000 * \text{drain} * \text{HCO}_3^- \text{ drain} \quad (65)$$

where,

$\text{HCO}_3^- \text{ drain}$: quantity of HCO_3^- drained ($\text{mol}_c \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$)
 drain: amount of drainage water ($\text{mm} \cdot \text{yr}^{-1}$)

$$\Delta H_{\text{nitrogen}} = H_{\text{nitrification}} - H_{\text{ammonification}} - H_{\text{N-uptake}} - H_{\text{N-incorp}} - H_{\text{N-denitrification}} \quad (66)$$

where,

$\Delta H_{\text{nitrogen}}$: net balance of protons due to the N cycle ($\text{kmol}_c \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$)
 $H_{\text{ammonification}}$: consumption of protons due to ammonification of organic matter ($\text{kmol}_c \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$)
 $H_{\text{N-uptake}}$: consumption of protons due to uptake of NO_3^- ($\text{kmol}_c \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$)
 $H_{\text{nitrification}}$: production of protons due to nitrification of ammonium ($\text{kmol}_c \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$)
 $H_{\text{N-incorp}}$: consumption of protons when nitrate is incorporated in micro-organisms ($\text{kmol}_c \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$)
 $H_{\text{N-denitrification}}$: consumption of protons due to denitrification ($\text{kmol}_c \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$).

$$H_{\text{ammonification}} = \frac{(\text{minNlab} + \text{minNstab} + \text{minNresidue} + \text{minNmanure} + \text{minNwaste})}{\text{mol_N}} \quad (67)$$

where,

minNlab: labile organic N that is mineralised ($\text{kg} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$)
 minNstab: stabile organic N that is mineralised ($\text{kg} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$)
 minNresidue : mineralised organic N from residues left in the field ($\text{kg} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$)
 minNmanure : mineralised organic N in animal manure ($\text{kg} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$)
 mol_N: atomic weight of N

$$H_{\text{Nuptake}} = \text{N-uptake} / \text{mol_N} \quad (68)$$

where,

N-uptake: uptake of nitrogen by the vegetation ($\text{kg} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$)

$$H_{\text{incorp}} = \text{N-incorp} / \text{mol_N} \quad (69)$$

where,

N-incorp: incorporation of nitrate into soil-organic matter ($\text{kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$)

$$\text{Hnitrification} = (\text{NH}_3\text{fert} + \text{rainNH}_3 + 2 * (\text{Nlabmin} + \text{Nstabmin} + \text{Nmanuremin} + \text{Nresiduemin} + \text{rainNH}_4 + \text{NH}_4\text{fert})) / \text{molN} \quad (70)$$

where,

NH₃fert: nitrogen applied as urea fertiliser ($\text{kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$)

rainNH₃: amount of NH₃ from rainfall ($\text{kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$)

Nlabmin: labile organic N that is mineralised ($\text{kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$)

Nstabmin: stabile organic N that is mineralised ($\text{kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$)

Nresiduemin: organic N that is left on the field ($\text{kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$)

Nmanuremin: organic N in animal manure ($\text{kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$)

rainNH₄: amount of NH₄ from rainfall ($\text{kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$)

NH₄fert: amount of NH₄ from chemical fertiliser ($\text{kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$)

$$\Delta H_{\text{sulphur}} = H_{\text{S-deposition}} + H_{\text{S-mineralisation}} - H_{\text{S-harvest}} \quad (71)$$

where,

$\Delta H_{\text{sulphur}}$: net production of protons due to the S cycle ($\text{kmol}_c\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$)

$H_{\text{S-deposition}}$: production of protons due to oxidation of deposited SO₂ ($\text{kmol}_c\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$)

$H_{\text{S-mineral}}$: production of protons due to mineralization of org. matter ($\text{kmol}_c\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$)

$H_{\text{S-uptake}}$: consumption of protons due to uptake of sulphate by crops ($\text{kmol}_c\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$)

$$H_{\text{S-deposition}} = 2 * \text{S-deposited} / \text{mol_S} \quad (72)$$

$$H_{\text{S-mineralisation}} = 2 * \text{S-mineral} / \text{mol_S} \quad (73)$$

$$H_{\text{S-harvest}} = 2 * \text{DMremoved} * \text{S-fraction} / \text{mol_S} \quad (74)$$

where,

DMremoved: amount of dry matter removed from the field ($\text{kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$)

S-fraction: fraction of S in dry matter (see Table 24)

mol_S: atomic weight of S ($\text{kg}\cdot\text{mol}_c^{-1}$)

$$\Delta H_{\text{cation}} = H_{\text{mnetremoval}} - H_{\text{mmanure}} - H_{\text{mcompost}} - H_{\text{mwaste}} - H_{\text{mweathering}} \quad (75)$$

where,

- ΔH_{cation} : net production of protons due the cation cycle ($\text{kmol}_c \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$)
- $H_{\text{mnetremoval}}$: production of protons due to net removal of base cations by the vegetation, i.e. total uptake minus the residues left ($\text{kmol}_c \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$)
- H_{mmanure} : consumption of protons due to net release of cations by mineralisation of manure ($\text{kmol}_c \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$)
- H_{mcompost} : consumption of protons due to net release of cations by mineralisation of compost ($\text{kmol}_c \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$)
- H_{mwaste} : consumption of protons due to net release of cations by mineralisation of household waste ($\text{kmol}_c \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$)
- $H_{\text{mweathering}}$: consumption of protons due to net release of cations through weathering ($\text{kmol}_c \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$)

Table A12: Estimated cation excess for grain and straw of different crops (kmol_c/kg) (Veldkamp et al., 1991; Van Duivenbooden, 1992; Van Reuler, 1996)

	Cation excess ($\text{kmol}_c / \text{kg}$)	
	grain	straw
millet	0.00025	0.00062
millet (improved)	0.00020	0.00062
animal manure	0.00133	
compost	0.001217	