PREDICTION OF SOIL LOSS AND CROP YIELDS WITH DIFFERENT MANAGEMENT SCENARIOS IN BARRIER SYSTEM USING THE SCUAF MODEL IN SEMI-ARID BURKINA FASO

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Abstract

The influence of different barriers on soil conservation and thus on sustainable crop yields in semi-arid zone of Burkina Faso was evaluated. A predictive computer model SCUAF was used to simulate four scenarios of different farming management to predict soil loss and crop yields over a period of 28 years. The simulation was based on the results of a field experiment assessing the effect of vegetation barriers Andropogon gayanus (perennial grass), Ziziphus mauritiana (shrub) and stone rows. The model predicted that vegetation and stone barriers significantly reduce soil losses compared to the control without barriers, and that higher soil losses occur in years with high rainfall. When additions are not applied sorghum yields decline over time in all four treatments. This is due to a decreasing amount of available nutrients in the soil due to nutrient mining, combined with loss of soil organic matter. Application of organic manure has a larger positive effect on the crop yields than inorganic fertilisers.

Key words: *Andropogon gayaus*, erosion, soil conservation, Sorgum, *Ziziphus maritiana.*

INTRODUCTION

In the semi-arid regions in sub-Saharan African (SSA) desertification as a result of soil degradation is posing a serious threat to dry-lands. This in mainly caused by three factors: overgrazing of rangelands, excessive cutting of trees and shrubs for fuel wood and inappropriate agricultural practises. The last factor is most prominent in rainfed agricultural land, especially through inappropriate management of rainwater and nutrients, causing a decrease in organic matter content and a loss of soil fertility. Improvement should be sought in developing more productive and sustainable farming practises (Hoogmoed, 1999), with conservation of soil and water as driving force.

However, the development of such farming practices is not an easy task considerig the conditions farmers are confronted with in the semi-arid regions in SSA. Most soils have poor physical and chemical conditions. Rainfall is erratic and rain storm size and intensity vary considerably (Hoogmoed, 1999). Agriculture is problematic, due to the seasonal rainfall distribution and the rate at which water is lost by evapotranspiration and runoff.

Vegetation barriers along contour lines present an appropriate sustainable farming practice, since they slow down runoff, retain sediment and organic debris and still allow drainage of excess water due to its semi-permeable nature (Kiepe, 1995). When using locally available species in the barrier, this system is cheap and easy to install (Spaan et al., 2004).

The objective of this study was to evaluate the influence of different barriers on soil loss and soil fertility conservation and thus on sustainable crop yields. The predictive computer model SCUAF was used to simulate four management scenarios to predict soil changes under these systems over a period of 28 years. The simulations were based on field experiments with barrier systems made by Spaan (2003) in Burkina Faso.

MATERIALS AND METHODS

General description of the SCUAF model

SCUAF (Soil Changes Under AgroForestry) is a simple computer model, which predicts the effects of specific land-use systems upon soils under given environmental conditions (Young et al., 1998). SCUAF is a process-response model, whereby the user has to specify: physical environment; land use system; initial soil conditions; initial rates of plant growth; rates of operation of soil-plant processes. The model is primarily intended for simulation over long-term periods (20 to 30 years). It is designed to include the distinctive features of agroforestry, including both trees and crops. However, it can also be used to compare agroforestry with land use under agriculture or forestry. SCUAF assesses changes in perennial plant and annual crop yield, soil loss, soil organic matter (SOM) and soil nitrogen (N) and phosphorus (P) content. It predicts crop yield as a function of changes in SOM, N and P content. These changes in the soil result from soil loss, recycling of plant materials and mineral uptake by plants. Soil loss is predicted using a simplified version of the universal soil loss equation (USLE, now RUSLE), based on climatic conditions, soil erodibility, slope characteristics and crop cover factors.

Agroforestry system is based on two plant components: trees and crops. The primary basis for description of this system is the proportion of trees and crops in each successive year. Other characteristics of the land-use system, which the user has to specify for simulation, are additions (organic additions, fertilizers), removals (harvest, losses), pruning (of the trees) and transfer (e.g. transfer of tree pruning to soil under crops), as well as the above- and belowground parts of the plants (leaf, fruit, wood, root) growth and composition. The model simulates changes in soil condition and their effects upon plant growth and crop yields on an annual basis.

SCUAF is not a plant growth simulation model. The user enters the initial rates of plant growth (trees, crops, and their component parts) as biomass increases per year. The model then estimates the effects of changes in soil properties upon subsequent rates of plant growth.

The values employed in the model, parameters and variables, are accessible to the user. There is a set of default values, varying according to the physical environment: climate, soil, slope, etc. This set provides reasonable estimates for variables whose values are unknown for a particular site. Data from research trials provide the basis for calibration of SCUAF to local conditions.

Application of SCUAF is reported (a.o.) by Tambula and Sinden (2000), Menz et al. (1998), Magcale-Macandong et al. (1998), Nelson et al. (1998) and Vermeulen et al. (1993). The model has been applied widely to problems similar to the current study, and appears suitable for the present research.

Calibration of SCUAF

Site characteristics

The study was conducted on a 3 ha site located in the central part Burkina Faso near Gampela (1° 20' W, 12° 20' N) 18 km north east of the capital Ouagadougou, at an altitude of about 275 m above sea level and average slope of 2%. The soil is classified as a Chromic Luvisol and is characterised by low fertility and productivity. It consists of sandy loam in the top layer, but is rich in clay in deeper layers with hydromorphic properties. Soil aggregates are small and unstable with a tendency for auto-compaction (soil bulk density 1600 kg m^{-3}) owing to the impact of raindrops and/or cultivation. Soil depth varies between 0.7 and 1.3 m. The soils are prone to crusting due to their low structural stability caused by a low SOM content (<1%). Under these conditions surface infiltration is poor (from 10 to 25 mm h^{-1}) and subsequently run-off is high. The nutrient availability and cationt exchange capacity are low. Soil conditions are given in Table 1. The soils are moderately suitable for cultivation of groundnuts, sorghum, millet, maize and cowpea (Anonymus, 1988).

With an average rainfall of 790 mm y^{-1} the area has a North Sudanian climate with rains from June to October. There is a large variability in rainfall distribution over the year and between years. The natural vegetation is of the savannah type. Most important woody species are *Accacia, Combretaceae, Guiera, Piliostigma* and *Ziziphus* (Anonymus, 1988). Annual grasses are dominated by *Pennisetum pedicellatum, Loudetia togoensis* and *Eragrostis tremula* and dominant perennial grasses are *Andropogon gayanus* and *Hyparrhenia dissoluta* (Anonymus, 1988). Little natural vegetation is found in the area because of clearing activities for agriculture. The experimental site was an abandoned agricultural field with only some useful trees left.

Experimental set up

In 1994 twenty-one plots of 20x20 m were laid out in the direction of the slope and protected with 0.5 m high earthen bunds at three sides to prevent influences from outside. The downstream end of the plot was left open to drain excess water. A vegetation barrier of 1m wide was established along the contour, with the centre of the barrier at 15 m down-slope from the plot, dividing the plot roughly into 14.5 m alley, 1 m vegetation barrier and 4.5 m down-slope section. Seven barrier species were planted in three replications, randomly distributed over the research area. The species were chosen on basis of their local availability, vegetative growth and soil and water conservation properties. In this study the results of *Andropogon gayanus* (a perennial grass), *Ziziphus mauritiana* (a shrub) and stone row barriers are considered. In addition plots without barrier (no barrier) are analysed. Andropogon developed a fine structured dense biomass at soil surface level and is considered for soil and water conservation as representative of the "effective group". Ziziphus developed at soil surface level a coarse structured more open barrier referred to as representative of the "less effective group" (Spaan, 2003). Stone rows are very effective in blocking runoff and decreasing soil loss. At the 14.5 m alley sorghum *(Sorghum bicolor subsp. Arundinaceum* cv. SARIASO 10) was sown. Just before sowing manure (3000 kg ha^{-1}) was applied as source of SOM and nutrients (approximately 15 kg N ha^{-1}) and additional N (about 70 days after sowing) was applied as urea 46% (50 kg N ha^{-1}).

In the period 1996 to 1998 runoff and soil loss (sediment) were measured after each rainstorm in two replications from 10 m^2 runoff plots (slope length of 12.5 m) that were installed inside the test plots.

Parameter input

The study area is identified in SCUAF model as 'semi-arid lowland' and soils are considered to be sandy with poor drainage, because of crust development (Anonymus, 1988). The initial soil condition follows from Table 1. The slope is gentle with average of 2%. The pH of the soil varies between 5.3 and 6.5 and for modelling is considered to be acid. For other parameters the appropriate default values in SCUAF were used.

Tab. 1. : Initial soil conditions (Chromic Luvisol) at the research site Gampela, Burkina Faso.

Horizon	Depth (cm)	Organic C (%)	Total N (%)	Organic P (%)	Avail. P (mg kg^{-1})	Total P (mg kg^{-1})	Bulk density (g cm^{-1})	pH
1	20	0.75	0.05	0.005	3	110	1.6	7.5
2	50	0.45	0.03	0.003	2	80	1.65	6.1
3	100	0.25	0.02	0.002	1	60	1.7	5.3

The SCUAF model does not include rainfall parameters input. In order to take the high inter-annual rainfall fluctuation into account, wet and dry years were defined for the simulation. According to known climatic patterns from the period 1976-1990, 3 wet and 3 dry periods were defined each lasting from 1 to 3 years. As the SCUAF is used for simulation in time of about 20-30 years, 28-year long period (two of these repetitions) was chosen for prediction of annual soil loss and sorghum yield. Initial yields of sorghum were taken from the reference period 1998-1999 (1998 dry year, 1999 wet year), when the influence of the different barriers no barriers on sorghum yields was monitored (Spaan, 2003). Table 2. shows the average yields of the different treatments for a wet and a dry year. The initial yield for the control treatment (no barrier) was taken as 20% less than stone row treatment, because the barriers have a positive effect on water availability and thus on crop yield (Spaan, 2003). There are large differences in grain and straw yields between wet and dry year for all plots. In a wet year grain yields are 3 to 4 times higher, and the yields of straw about 1.5 times higher than in dry years.

Tab. 2.: Sorghum yields in 1998 and 1999 at the research site Gampela, Burkina Faso.

Treatment	Wet year (1999) in kg ha^{-1}			Dry year (1998) in kg ha^{-1}		
	straw	grain	total	straw	grain	total
Stone row	6430	2300	8730	4200	600	4800
Andropogon	6170	2300	8470	4370	670	5040
Ziziphus	6470	2400	8870	4570	770	5340
Average	6360	2330	8690	4380	680	5060
Control without barrier[a]	5145	1835	6980	3360	480	3840

[a] estimation (20% less than stone bunds)

A root/shoot ratio of 0.4 and 0.5 for wet and dry year respectively was applied for the root develpment. As the model lack a grass component *Andropogon* and *Ziziphus* were treated in the model as a tree component. The dry matter production for *Andropogon* and *Ziziphus* was estimated as 5000 and 4000 kg ha^{-1} respectively. This gives a whole-field level of biomass production, but in the simulation the barriers occupy only 10% of the total area. For the plant composition the average values of N and P content in different plant parts found in literature (Powell, 1985; Stroosnijder and van Rheenen, 2001; Toky and Bisht, 1993) were used.

Management scenarios used for simulation

Traditional farming systems in the Sahel consist of few years of cropping followed by several years of fallowing, assuming that soil fertility is restored. In densely populated areas of Central Plateau of Burkina Faso land is becoming scarce and therefore more arable land is in continuous use. A simulation assuming farming without fallow is thus realistic.

Table 3 shows the farming management for different scenarios. In the area crop residues are taken as fodder or for other purposes, removing all residues from the field. Ziziphus shrubs must be regularly pruned and it is assumed that this biomass is applied to as mulch. The area covered by vegetative barriers is about 10% of the field size.

Tab. 3. : Description of simulated farming management scenarios used in the SCUAF-model (Gampela, Burkina Faso).

Farming intensity	Description
Scenario 1 - no add.	No addition
Scenario 2 - basic fert.	Fertilisation 20 kg N and 5 kg P per ha
Scenario 3 - manure	Cattle manuring of 3000 kgha^{-1} [a]
Scenario 4 - manure +	Cattle manuring (3000 kg ha^{-1}) with fertilisation (10kg N and 2kg P per ha)

[a] nutrient content of manure is 2% N and 0.2% P

RESULTS

Predicted soil loss

Linear regression showed that there exists a relationship between soil loss and rainfall (Spaan, 2003). This regression was used to calculate average annual soil loss for wet and dry years. A comparison of these data with those calculated using SCUAF's USLE formula is given in Table 4. It shows that computations with the USLE formula overestimate soil loss about 2 to 4 times. A possible explanation is that the soil erodibility factor (K factor) is much lower because of the soil crust development, which induce runoff in the beginning of the rain event but as the hard soil crust developes it protects the soil against the scouring action of the runoff water. Formation of bonds between the particles of the surface layer can fuse aggregates into a more cohesive layer, rather than separating them into individual aggregates. In this case, erodibility is likely to decline with the number of wetting and drying cycles. Taking this into consideration, and in order to better predict soil loss by the SCUAF model, a soil loss adjustment factor of 0.3 was applied.

Tab. 4.: Annual rate of erosion according to linear regression and USLE in kg ha^{-1} at the research site Gampela, Burkina Faso.

	Linear regression		USLE	
Variant	Wet	Dry	Wet	Dry
Control/sorghum	1872	1229	6566	5380
Andropogon/sorghum	410	270	985	807
Ziziphus/sorghum	597	392	1970	1614
Stone rows/sorghum[a]	---------	----------	657	538

[a] erosion with stone rows variant was not measured, because of the later establishment

Under unchanged conditions (Scenario 1: no addition) vegetative or stone barriers significantly reduce soil losses compared to the control without barriers (Fig. 1). Higher soil losses are predicted in wet years, because of the higher rainfall erosivity. Annual soil loss increases progressively over time in Scenario 1, mainly because of the decreasing vegetation soil cover, which is caused by a decreasing stock of available nutrients and hence decreasing plant growth. The increase of annual soil loss over time is most pronounced for the control treatment, from 6.2 ton ha^{-1} (wet year) and 4.7 ton ha^{-1} (dry year) in the beginning to 10.6 ton ha^{-1} (wet year) and 5.9 ton ha^{-1} (dry year) after 28 years. This increase is not much pronounced in the treatments with barriers. With organic or inorganic addition (scenario 2-4) this trend of increasing soil loss can be further diminished, which is most effective in combination with the treatment of Andropogon barriers and stone rows (Fig. 2). Predicted average annual soil losses in 28-year period are shown in Table 5. Andropogon vegetation strips and stone rows have the best potential in preventing soil loss, Ziziphus vegetation strips are less effective but still soil losses are rather low.

Tab. 5.: Predicted average annual soil loss in kg ha-1 for barrier interventions and control without barrier at the research site Gampela, Burkina Faso.

	Control – no barrier	Stone rows	Andropogon	Ziziphus
Sc1 - no add.	7032	610	757	1145
Sc2 - basic fert.	5827	503	447	922
Sc3 - manure	5623	480	425	892
Sc4 - manure +	5623	448	405	825

SCUAF simulation of sorghum yields

Sorghum yields differ between wet and dry years, because of the water availability. It would be misleading to compare average yields of each treatment for each scenario. It is more appropriate to compare cumulative yields and also the overall trends of yields in time. Table 6 shows the predicted cumulative grain yields of sorghum[1] in the period of 28 years.

Tab. 6.: Predicted cumulative grain yields of sorghum over a period of 28 years in kg ha-1 at the research site Gampela, Burkina Faso.

	Control – no barrier	Stone rows	Andropogon	Ziziphus
Sc1 - no add.	21,353	22,066	20,463	21,687
Sc2 - basic fert.	30,851	33,983	32,423	33,938
Sc3 - manure	31,503	35,474	34,015	35,488
Sc3 - manure +	31,503	40,018	36,978	39,480

In Scenario 1 without addition sorghum yields (Fig. 3a) decline in all four treatments, due to a decreasing amount of available nutrients in the soil - nutrient mining - combined with loss of soil organic matter. The decline is more pronounced in wet years, when there is enough water available for higher production, and nutrients are limiting factor. The differences in sorghum yields between the four treatments are not significant for management scenario 1, indicating that the negative effect of nutrient mining on sorghum yields rules out the positive effect of water conservation due to the barriers.

In Scenario 2, the application of N and P fertilisers has a positive effect on the sorghum yields in wet years in all variants (Fig. 3b.). But the overall trend is a decline of sorghum yields over time, caused by decreasing amount of soil organic matter, and a delayed nutrient mining. The amount of nutrients consumed by the crop is not fully replaced by additional fertilisers. Cumulative yields are slightly higher for treatments with barriers than the control treatment, but yield decline increases over time.

Application of organic manure in Scenario 3 (Fig. 3c.) has a higher positive effect on the crop yields than application of inorganic fertilisers. This is due to the additional nutrients from manure (60 kg of N and 6 kg of P), which become available over a longer period. Sorghum yields of the control variant seem stable, but the yields of the treatments with barriers are high at first in wet years but then decline quite rapidly. Apparently, the amount of withdrawn nutrients and the fertilizer input is still not in balance. The nutrients that cannot be used in dry years are accumulating in the soil and are used mainly in the first wet year, but if another wet year follows there is a nutrient deficiency in that year.

Application of organic and inorganic fertilisers together simulated in Scenario 4 (Fig. 3d) can overcome this deficiency of nutrients). There is no yield decline under this scenario; the best yields are predicted for treatments with stone rows and Ziziphus barrier, followed by the Andropogon barrier. The treatments with barriers show better efficiency in the use of fertilisers and better potential to conserve soil fertility. In the systems with barriers nearly no nutrients are lost due to soil loss and nutrient removed by harvest are replaced in fertilisers.

DISCUSSION

The results of simulation indicate that addition of organic and inorganic fertiliser reduces soil loss. Even the small addition of inorganic fertiliser (scenario 2) can reduce soil loss by about 15-20% in control without barrier, stone rows and Ziziphus treatments and by about 40% in Andropogon barrier treatment. This reduction in soil loss can be explained by crop growth and thus better-developed soil cover, but also by the development of barrier vegetation and thus better effectiveness of vegetative barrier to catch sediment. The more organic or inorganic addition is applied to the system the more sustainable it becomes in the sense of reduced soil loss. These results confirm the statement of Kiepe (1995), that vegetation barriers along contour lines present an appropriate sustainable farming practice considering reduction of soil loss.

The barriers alone do not improve yields drastically. However, when these barriers are accompanied with other management practices, like organic and inorganic fertilisation (Scenario 2-3), simulation shows that the yields can rise considerably. The barrier treatments perform much better than control treatment without barriers, which means that in these systems the nutrients are conserved and used more effectively. In the full fertilisation scenario, treatments with stone rows and Ziziphus barrier reach the highest yields, followed by Andropogon barriers and no barrier variant with the lowest yields. The results of this modelling confirm the results of field trials made by Ouédraogo (2004). He

[1] Sorghum yields for treatments with vegetative barriers are reported on a full area basis, including the area occupied by barriers.

concludes that farmers in semi-arid West Africa should not consider the mineral nutrients as a replacement solution for organic resources but as a necessary complementary input.

The problem with vegetation strips is that they occupy the area which would otherwise be used for cropping and the vegetative barrier competes with crops for scarce resources. This replacement and competition effect is probably the reason for poorer performance of Andropogon vegetation strips. However by-products like fodder, fruit, building material and mulch can compensate for the reduced crop yields (Kidanu *et al*, 2002).

CONCLUSIONS

Simulation results show that water availability is the limiting factor for sorghum production in dry years, whereas nutrient availability is limiting in wet years. During dry years, soil fertility recovers, but extra fertilisation is still needed to assure sustainable yields over a long period.

Results also show the importance of vegetation and stone rows barriers in reducing soil loss. But due to nutrient mining these soil and water conservation measures must be combined with additional management practices to stabilize or to increase yields in semi-arid zones of Burkina Faso. The main problem appeared to be nutrient mining. Without (any) organic or inorganic fertilization, the soil conservation measures will not help to make the farming system more sustainable. The inexpensive organic fertilisers in the form of animal manure or compost seem to be the most effective way to improve yields, probably with combination of small amount of inorganic fertilisers. Under these conditions vegetation barriers can perform much better than systems without barrier and they produce other products like fodder, mulch and building material. Stone rows are not capable to reach that objective. Barrier systems with adequate additions seem to sustain higher yields than no barrier systems.

Any model has strength and weaknesses. The SCUAF model is easy to use, and this is its major strength. The model can be used to identify data gaps and hence can be a useful tool in designing future research activities. The main problem is the precise calibration of SCUAF to specific site conditions, which asks for a lot of input data. If they are not available, the default values can than be used but this makes the prediction less reliable. The SCUAF model does only calculate the competition of the different components for nutrients according to their root depth and interaction, but unfortunately the competition for water and light is not calculated. Andropogon grass grows vigorously, hence competition with the sorghum for water and sunlight can be great. In agricultural systems with vegetation barriers this can be a disadvantage of using SCUAF model.

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