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Use strategies of native soil N for food crop productions in West-Africa

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ABSTRACT

The use of native soil nitrogen for crop production would be an ideal manner of producing food crop at low cost, in a sustainable way within a protected environment. Achieving this goal, requires the application of technical strategies aiming at maximizing N mineralization and availability in soil and ensuring its efficient use by the food crops.

In this paper, technical options to manage native soil N fluxes during the dry-to-wet season transition period (DWT) involved the use of improved fallow (pigeon pea) to retain native soil N on the upland slopes, and of nitrate catch crops (Brachiaria and Sesbania green manures) to temporarily immobilize incoming N from the slope in the lowland of the wide representative inland valleys. These types of slope management resulted in three extreme situations of interflow contribution from the slope to the lowland during the 3-months DWT.

Data from 1997 indicate a flush of mineral soil N occurring during the first half of the dry-to-wet season transition period, with higher amounts of nitrate found in lowland than in upland ecologies (92 vs 78 kg N ha^{-1}) of rice based systems of Côte d'Ivoire.

In the present experiment, the presence of planted pigeon pea fallow on the upland slope conserved some 12 kg of soil nitrate-N ha^{-1} during the transition season. In the absence of pigeon pea (bare fallow), 47 kg N were translocated from the upland into the lowland. In the lowland about 20 kg nitrate-N ha^{-1} were absorbed by the growing biomass and thus saved from loss. Upon incorporation of this biomass in the course of land preparation, lowland rice yields increased significantly by up to 1.1 Mg ha^{-1} ($p<0.04$) compared to the bare fallow lowland plots. The use of improved fallow appears to be a suitable option to capture nutrients that would otherwise be lost. The effectiveness of such options and their adoption by farmers requires further studies.

Indexing terms/Keywords

Cote d'Ivoire, denitrification, Leaching, Mineralization, Nitrogen, Oryza sativa L., Rice, Rice based systems, West Africa.

Academic Discipline And Sub-Disciplines

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INTRODUCTION

Intensification of low-input rice farming systems of small-holder in inland valleys of West Africa calls for a more efficient use of the systems' internal resources such as soil moisture and native soil nitrogen (N). On the predominantly sandy Alfi- and Ultisols of the region, traditional rainfed lowland rice dominates the valley bottoms, while landscape catena is increasingly being cleared from natural forest or bush-savanna vegetation for producing upland crops. Nitrogen is the most limiting soil nutrient, particularly in savanna environments (Becker and Johnson, 1999). In the light of the near complete absence of mineral fertilizer use, the native soil N represents the main source of N for plant nutrition (Engels et al., 1996). But, N is subject to intense chemical and microbiological transformation processes (hydrolysis, oxidation, reduction) resulting its dynamic across the soil – plant – atmosphere continuum (DeDatta and Buresh, 1989; Phongpan and Mosier, 2003; Stahl et al., 2002). The nitrate form of N is likely to follow the flow of water along the toposequence and thus, to be prone to more intense transformation and loss mechanisms.

Researchers (Carsky and Eteka, 2002; Oikeh et al., 2010) have suggested several resource base – conserving cropping options (e.g. improved legume fallows, improved residue management, contour strips, alley cropping) but their efficacy is still below the expectations. Meanwhile, applied N during cropping could be lost from soil when previously improved with fallow crops. When high amounts of nitrate in the soil are not matched with plant N uptake, the potential for N losses is increasing. Nitrate is primarily leached from upland soils to the contiguous lowlands (Bognonkpe, 1998). The extent of the prevailing loss mechanism will depend on the amount of nitrate, the intensity of the rain and the land management. Vegetation is hypothesized to be able to absorb this N as a temporary stock which can be return to the soil by incorporation for agricultural use.. Improved or planted fallows using fast-growing leguminous plants are capable of accumulating large amounts of N through biological N_2-fixation (Giller and Cadisch, 1995; Mapfumo et al., 1999) and through soil N recovery from below the rooting zone of food crop (Hartemink et al., 1996; Mekonnen et al., 1997).

Efficient use of native soil N through the development of improved crop management practices requires a quantitative understanding of N and water dynamics and their underlying processes. This paper presents results from three years (1997-1999) field experiments conducted on a model toposequence on the research farm of the West Africa Rice Centre (WARDA) near Bouake in Côte d'Ivoire. The seasonality of native soil N dynamics was quantified and management options, both on the upland topographic sections and in the lowland, were evaluated with their efficiency in lowland rice cropping.

MATERIALS AND METHODS

Côte d'Ivoire is part of the humid zone of West Africa, located between 4° to 11° N latitude and 3° to 9° W longitude. The majority of Côte d'Ivoire is characterized by the gently undulating landscape of the inland valleys, which are the main sites of rice production. The transitional "derived savanna" zone in the country's center has a pseudo-bimodal rainfall distribution and a mean annual precipitation of 1200 – 1300 mm. The valley selected for the detailed studies is part of the watershed of M'bé and is located within the experimental farm of the Africa Rice Center (WARDA) about 400 km northwest of Abidjan, the capital of Côte d'Ivoire. The watershed lies within the derived savanna zone. The M'bé valley comprises 40 hectares of irrigated or rainfed lowland. Mean annual rainfall ranged from 860 to 1100 mm with two clearly defined rainfall seasons. A first rainy season from April to mid-August is followed by the short dry season and a second rainy season from September to November. Mean temperatures vary between 25 and 30° C with extreme values ranging from 20 to 40° C. The average relative humidity is about 77 %. Mean potential evapo-transpiration ranges from 4 - 7 mm d-1 with a maximum during the short dry season.

The landscape includes uplands and sides that drain into a seasonally wet lowland. The lowland is about 1200 m in length, and has variable width, ranging from 20 m at the valley head to over 50 m in the down-stream part of the valley. Altitude ranges from about 265 meters above sea level (m.a.s.l.) in the valley bottom to 310 m.a.s.l. at the upper-most plateau. The crest and upper slopes are almost flat (0 – 2%), giving way to somewhat steeper middle and lower slopes (2 - 4%) that are slightly convex. Slightly concave colluvial footslopes form the transition between the upper slopes and the valley bottom. The valley's cross sectional width increases with distance from the valley head towards the downstream areas. It has three major physiographical units: the upland (slopes), the hydromorphic zone, and the valley bottom (Figure 1). In the field, the different zones often overlap, creating intermediate environments of mixed characteristics. The slope area overlies a hardened impermeable iron pan, referred to as the "cuirasse", at about 50 – 70 cm below the soil surface. The cuirasse appears as an outcrop in some locations. Depth to groundwater upper aquifer in the uplands is at least 6 m below ground level. The valley bottom forms an ephemeral stream that also serves as the central drainage channel for the watershed. The groundwater level is close to the surface, resulting in soil submergence during the peaks of the rainy season.

Soils in the experimental watershed at M'bé are mainly Alfisols. Formed from granitic gneisses and quartzites, they are granular in structure and composed mainly of quartz. Fields are often colonized by Imperata cylindrica (uplands), Cyperus spp., Echinochloa spp., Leersia hexandra (lowlands and hydromorphic valley fringes). The cultivated upland slopes stretch approximately 250 m from the crest to the valley fringe.

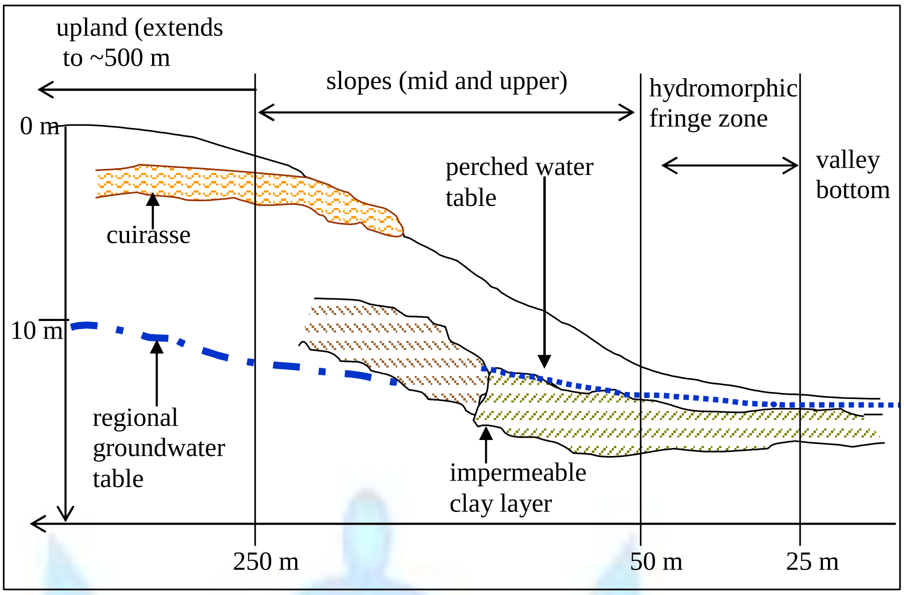

Figure 1. A schematic cross section of the M'bé experimental watershed adapted from Masiyandima (2000)

Plant material

Planting material used in the various experiments comprised rice, pigeon pea, Bracharia grass and Sesbania green manure. The modern high-yielding 120 day rice (Oryza sativa L.) variety IDSA 8 was used in all lowland experiments. It has been selected from an Asian O. sativa cross by the national research program (Centre National de Recherche Agronomique - CNRA formerly IDESSA) for its adaptation to various ecosystems, from drought-prone uplands to rainfed lowlands. Seeds were obtained from the rice germplasm collection of the International Network of Germplasm Evaluation of Rice (INGER – Africa), Bouaké – Côte d'Ivoire. In the lowland, 25 day-old seeding were transplanted at a 20 x 20 cm spacing. A red-seeded, strongly branching semi-perennial accession of Pigeon pea (Cajanus cajan L.) was obtained from the fallow legume germplasm collection at WARDA, now integrated in the IITA seed bank. It was row-seeded at a rate of 20 kg ha^{-1} in 20 cm rows. The seeds of the stem-nodulating aquatic green manure legume, Sesbania rostrata, were obtained from the same fallow legume germplasm collection of WARDA. The tropical forage grass Bracharia spp. and was also obtained from IDESSA. Local wild bananas (Musa paradisica L.) were transplanted densely in the hydromorphic fringe in three lines perpendicular to the runoff direction.

Soil sampling and analysis

Composites of 2-3 soil samples were collected from three depths (0 – 20, 20 – 40 and 40 – 60 cm) using a gravimetric auger. The samples were stored in a cool box and transported to WARDA's laboratory for extraction and analysis. Sampling points in the field were marked with colored sticks.

Bulk density was determined in the course of a physical characterization of the soils in order to translate gravimetric into volumetric values according to the method described by (Schlichting et al., 1995) using a soil volume of 100 cm3. The volume-samples were carefully removed from the profile using 100 cm^3 metal rings, dried at 105°C to a constant weight which was recorded. Bulk density values presented are the mean of two samples taken at the onset of the dry and the rainy season. Soil moisture was measured using Time Domain Reflectometry (TDR). The TDR equipment used was a Trime FM 2 (IMCO GmbH, Ettlingen, Germany) with unmovable probe rods of 25 cm length. Measurements were taken at each soil sampling date and expressed as volumetric soil moisture (% water volume per soil volume).

The pH was measured in 10 g air-dried soil (Ø < 2 mm) samples, in H_2O and 1 M KCl, using a soil: solution ratio of 1:2.5 according to the procedure of (Hendershot et al., 1993) using a digital pH-meter (HI 9214 / HANNA Instruments, Frankfurt, Germany). Dispersion of soil aggregates was performed by chemical and ultrasonic means with the separation of particles according to size limits through sieving and sedimentation. The procedure of (Schlichting et al.,(1995) was employed in the soil laboratory of WARDA.

To determine mineral ammonium and nitrate content in field samples, soil was ground, extracted with 0.5 M KCl and processed on a distillation unit with the addition of 0.2 g of MgO for ammonium and 0.2 g of Devarda's metal for nitrate determination. The resulting condensate was titrated with 0.01 N H_2SO_4. Total N content in soil was determined by distillation after heat digestion (370 °C) of air-dried samples in concentrated sulfuric acid with a catalyst (selenium), following the Kjeldhal procedure. Soil mineral N concentration was calculated as follows:

$$\frac{(v1-v2)\times mN\times Vo}{V1\times Pe}\times (h\times Da)= NH_4^+ or NO_3^- (kgN/ha)$$ for 20 cm depth.

v1: acid volume used for titration of measured sample (ml)
v2: acid volume used for control sample (ml)
mN: atomic mass of nitrogen (14 g)
Vo: volume of extraction solution (80 ml)
V1: extract used for distillation (20 ml)
Pe: dry weight of extracted sample (g)
h: considered depth (20 cm)
Da: bulk density of the considered soil (g / cm³)

Plant sampling and analysis

Above ground plant biomass was sampled on 2 m² sampling areas. Weeds were identified and their biomass was sampled at the beginning of the cropping season before field clearing and on a monthly basis, during the cropping period. Dry matter was determined on 100 g of fresh biomass after 24 hours air-drying (60°C) and weighing.

Grain yield of both rice and maize was estimated based on 2 m² of representative yield plots of 2 m² of all harvest areas and expressed at 14% grain moisture. Total N in the plant biomass was determined after drying and grinding (Tecator Cyclotec 1093 Sample Mill with 1 mm sieve) using the Micro-Kjeldhal method (Page et al., 1982).

Experimental design and treatment application

Three types of alternative land management strategies were evaluated on an isolated toposequence of 36 m length in the M'bé valley with the aim of checking alternative options to reduce soil native nitrogen losses and its use efficiency by lowland rice (each treatment strip had a width of 5 m). Three main plot variants of slope use were compared, representing extreme cases of subsurface interflow management to the adjacent lowland. These strategies comprised extreme cases of slope management, namely (a) tilled bare soil (maximal N leaching and subsurface flow contribution), (b) improved fallow (N retention in the upland through deep-rooting vegetation of dense stand of a 2-year-old crop of Pigeon pea Cajanus cajan L.) and (c) a complete interception of interflow water and N by three parallel rows of banana (Musa paradisica L.) in the hydromorphic valley fringe (

Figure 2).

Two subplot treatments were laid out in the bunded rainfed lowland below the slope management treatments to study the potential of a vegetative cover during the dry-to-wet season transition season for temporarily immobilizing soil nitrate (bare fallow vs. flood-tolerant Sesbania rostrata in 1998 and Brachiaria spp. in 1999). N accumulation in the biomass of the pre-rice lowland vegetation and of rice at harvest was complemented by weekly determination of soil Nmin (0-20 cm).

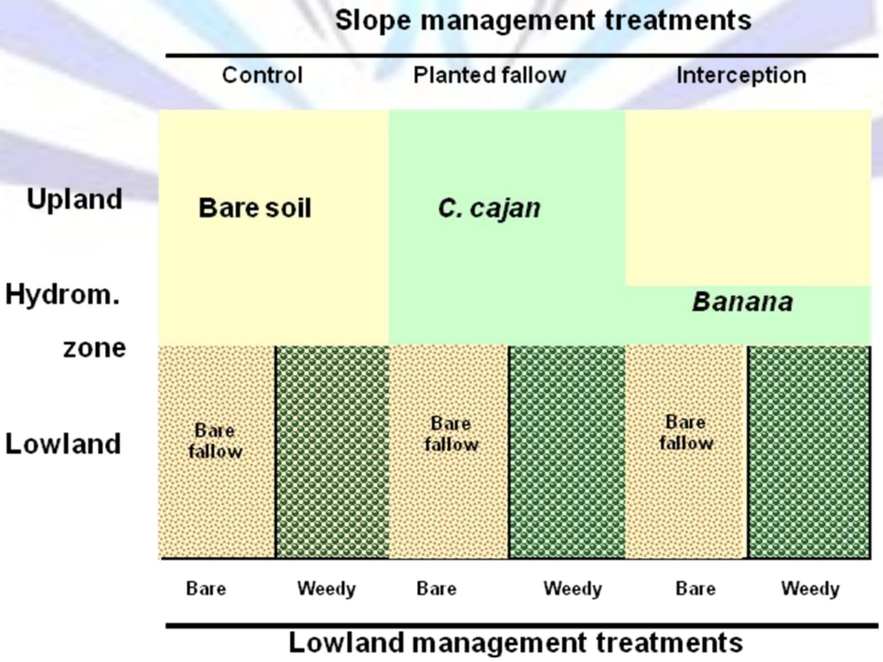

Figure 2: Schematic experimental design

RESULTS

Since land management plays a key role in N mineralization and translocation from the upland into the lowland, different vegetative covers are likely to differentially affect N dynamics. A conceptual dynamics of N along the toposequence has been described (Figure 3).

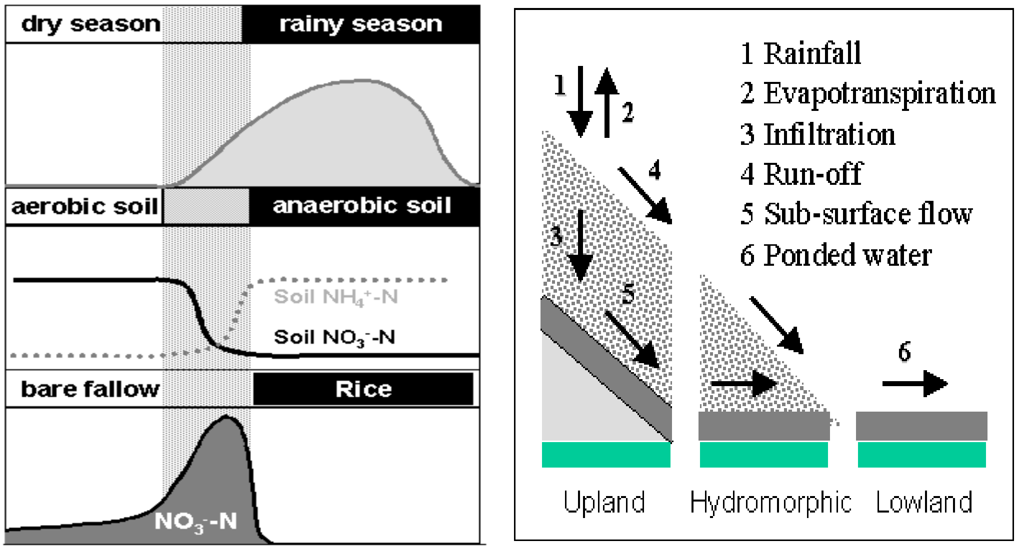

Figure 3. Conceptual relationships between rainfall, soil aeration status and soil N dynamics in a rainfed lowland (left) and of water dynamics along a toposequence (right).

The slope management applied in the present study resulted in three extreme situations of interflow contributions from the slope to the lowland during the 3-month DWT. In the case of the banana total interception, no native soil N import from the slope into the lowland occurred since surface and subsurface flows were all intercepted. Lowland below this treatment locally mineralized a mean of 65 kg N ha^{-1}. When this figure is considered to be the potential mineralization of the lowland ecology of the study plot, the bare fallow has a substantial additional N contribution of 47 kg N ha^{-1} to the lowland. Between these two extreme case, the improved fallow vegetation on the slope reduced this N contribution from the slope to 35 kg N ha^{-1} during DWT (annual rainfall of 1046 mm – Table 1). These results were significantly different with means LSD (0.05) of 36 trough treatment and were determined through lowland rice N uptake at harvesting time.

Table 1: Effect of land use (slope management) on the nitrate N influx into the lowland from an adjacent upland slope (M'bé valley, Côte d'Ivoire)

Subsurface flow interception	Lowland soil Nmin (kg N ha	U

Yes: Three rows of banana plants in the hydromorphic valley fringe for full interception of water and nitrate flows Partial: Upland covered by an 8-month-old pigeon pea fallow to limit nitrate-N exports from the slopeNo: So il maintained bare during the cropping season to maximize water and nitrate flows into the lowland LSD (0.05) = 36

In order to improve the effective use by the lowland rice of the N translocated from upland to lowland, a pre-rice fallow of Bracharia and Sesbania green manure were grown in the lowland before rice transplanting. In the plots where this fallow was established during DWT, about 20 kg nitrate-N ha^{-1} were absorbed by the growing biomass and thus saved from loss (**Error! Reference source not found.**). Upon incorporation of this biomass in the course of land preparation, lowland rice yields increased significantly by up to 1.1 Mg ha^{-1} ($p<0.04$) compared to the bare fallow lowland plots. The actual figure presented in Table 2 are 5.55 Mg ha^{-1} of rice grain yield in the plots with incorporated fallow compared to 4.52 Mg ha^{-1} of rice grain yield in bare plots both under maximum N input from slope (bare slope) with a means between treatments significantly different at p(0.05).

Table 2 : Effect of lowland use during the dry-to-wet season transition period on N conservation and the yield response of lowland rice (M'bé valley, Côte d'Ivoire)

Lowland management in the transition season	***Upland slope mana***

* values with same letters are not significantly differents at probability level 0.05

The results obtained in this experiment validated the N translocation hypothesis from the slope to the lowland. But, potential N losses remain possible in the lowlands particularly when no conservation technique is applied. Lowlands can lose up to 20 kg N ha^{-1} through drainage and/or denitrification (Bognonkpe, 2000). Still, it can be hypothesized that in the slope ecology, N losses can also occur through denitrification during high rain period when soils are saturated if not sorbed by soil particles.

DISCUSSION AND CONCLUSION

Soils of inland valleys of west Africa mineralize large amount of N in the upland and lowland ecologies. Although N losses through leaching from the slope diminish later in the DWT due to unavailability of N, there is a 3-4 week period immediately after the first rain of the season and/or incorporation of leguminous residues when substantial N-mineralization occurs before crops begin to take up nitrate (Sarrantonio and Scott 1988), making the system susceptible to large nitrogen leaching. The general concern about nitrate losses from arable soils emphasizes the need for more efficient ways of nitrate management, including the use of fallow vegetation, different land use alternatives and techniques that reduce N losses from soil – plant system. The success of N management strategies for the reduction of N losses and its effective use by crops depends on several factors and processes, e.g. N availability, rainfall regimes, soil management techniques and valley characteristics. Evaluation of the efficiency of these management strategies under a given set of climatic and environmental conditions requires an integrated approach.

The presence of the perennial Cajanus cajan L on the slope reduced the N quantities translocated to the lowland by 12 kg N ha^{-1} compared to a bare slope. One important function of green manures is related to the cycling or saving rather than the fixation of N. The green manure fallow absorbs nitrate from the root zone during DWT and thereby reduces nitrate leaching. Researchers have always advised the use of annual legumes on the slope to supply N to crops, reduce soil erosion and nitrate leaching, increase soil organic matter, and improve aggregate stability and other soil structural properties (Drinkwater et al. 1998; Roberson et al. 1991). When N_2-fixing species are used during the fallow period, there is a substantial addition of N to the soil-plant system on the upland (Giller et al. 1997). Akanvou et al. (2000) advised the replacement of natural fallow re-growth with legumes in short-fallow rotation systems in order to increase the yield of upland rice in both forest and savanna agroecological zones.

Both native soil N as well as applied mineral N fertilizers are generally not efficiently used by lowland crops and are prone to gaseous or leaching losses (Buresh and DeDatta 1991). When Bracharia and Sesbania green manure were utilized as pre-rice fallow during the DWT and incorporated in soil before the lowland rice crop, a substantial 20 kg N were added to soils. Stahl et al. (2002) found in their study on improved fallows in Kenya that Sesbania had the highest total N content and N contributions to subsequent crops compared to other types of fallow.

The “nitrate-catching” is another method of N-saving by green manures (George et al. 1992). Growing a short-cycled green manure as a “nitrate-catch crop” during the transition season can assimilate soil N and protect substantial quantities from leaching and denitrification losses. Cultivating nitrogen-fixing legumes (grain legumes with a low N harvest index or green manure) can further add nitrogen from the atmosphere (George et al. 1992). The effectiveness of such nitrate catching green manure on reducing native soil N losses, enhancing legume N accumulation and increasing the N uptake and grain yield of a subsequent crop of rainfed lowland rice has been shown in both tropical and subtropical environments and in a range of soil types (Clement et al. 1995; 1998; George et al. 1998; George et al. 1994). Published amounts of “saved” nitrate-N range from 12 to over 90 kg N ha^{-1} (Pande and Becker 2003). Reported yield increases in rainfed lowland rice, resulting from nitrate catch crops (both legumes and non-legumes) range from 0.2 to 2.3 Mg ha^{-1}.

Improved fallow vegetation may be beneficial for crop production by increasing soil fertility and supplying plant nutrients, however, any raise of the soil organic matter content may increase the potential nitrate leaching. Furthermore, the effect of alternative N management on N availability for subsequent crops may vary from strong positive effects (Elers and Hartmann 1987) to significant negative effects (Jensen 1991).

To achieve the optimal environmental and economical effect of fallow vegetation, the new management tools should reduce the need for N fertilizer inputs. Such an evaluation may also be supported by simulation models which are able to predict the effects of management strategies on the N cycle in the soil-plant system, e.g. the simulation model DAISY (Hansen et al. 1990)

The presented results highlight the ability of vegetative cover to reduce nitrate losses in both uplands and lowlands and improve its effective use. In a further step, alternative residue management practices that retain the organic matter and nutrients accumulated by the fallow vegetation in situ are required in order to maximize the beneficial effect of improved fallow (Akanvou et al. 2000). Rotation and intercropping of legumes with subsistence crops may alleviate N deficiency through biological N_2 fixation and redistribution of subsoil N to the surface (Ikerra et al. 1999). Improved fallow may also increase P content in labile fractions of soils (Giller et al. 1997) and thus, increase crop yield on nutrient deficient soils (Jama et al. 1998). Even not discuss here, the interception role of interflow water by row of banana plants can be added to the list of immobilization strategies on the upland to profit food crop on the slope. These immobilization strategies may be considered as an integrative research subject on N dynamic in inland valleys of west Africa.

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