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Potential Soil N Mineralization in Upland and Lowland Soils of Inland Valleys of Cote d'Ivoire, West-Africa

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Authors' contributions

This work was carried out in collaboration between all authors. Author JPB designed the study and wrote the first draft of the manuscript under the supervision of MB who wrote the protocol. Authors GD and MM managed new statistical analyses for the present paper. All authors read and approved the final manuscript.

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ABSTRACT

This article studied soil samples from the various rice-based environments of the inland valleys of Cote d'Ivoire to evaluate their native capacity of mineralization of N. Soil N, is subject to intense chemical and microbiological transformation processes (hydrolysis, oxidations, reduction). All these transformation processes are subject to water availability and therefore show a strong variability related to soil grains size and vegetative cover. In order to applied appropriate technical strategies aiming at conserving soil N or using it for food crop, it is important to evaluate its mineralization potential in the concerned soils. In this paper, the nitrogen supplying potential of soils from the ten major rice-based production systems of Côte d'Ivoire was determined by incubation experiments in 1997. The net N mineralization potential (N supplying capacity during 6 weeks of anaerobic incubation) from soils of the various rice-based systems of Côte d'Ivoire varied between 4 and 16 mg N kg^{-1} of soil. It was generally less in the savanna than in forest upland soils and intensified land use reduced soil N supplying capacity more in savanna than in forest ecosystems. It may be concluded that N mineralization from soils of the various rice-based systems of Côte d'Ivoire strongly varied. Soil N supply was generally less in the

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sandy than in clay soils. Land use intensification affected N release more in the savanna than in the forest and tended to reduce the N supplying capacity more in lowland than in upland soils. As soil nutrient mineralization rates are also controlled by the specific character of the vegetation occupying a site, plant-soil-plant feedback loops in agricultural systems will influence the N dynamics over time.

Keywords: Cote d'Ivoire; mineralization; nitrogen; rice; rice based systems; West Africa.

1. INTRODUCTION

The subsistence-oriented farming systems in the inland valleys of Côte d'Ivoire are in the hands of smallholder farmers. Production is lagging behind demand because of numerous biotic and abiotic stresses but particularly because of the low native fertility of the predominant Alfisols and Ultisols [1]. The current intensification of production is achieved by clearing of new land, a decrease of the length of fallow periods on upland-slopes and the expansion of cultivation in adjacent lowlands.

Most tropical soils are deficient in N. In the inland valleys of West Africa, N deficiency is the most prominent constraint to the production of rice [2]. This N deficiency is more severe in upland soils, particularly in the sandy Alfisols of the savanna agroecological zone, than in the valley bottom lands, where soils tend to have high soil organic matter content. Irrespective of the amounts of N available in a given soil, this N is subject to intense transformation processes that are governed by the prevailing ecological conditions and can contribute to further exacerbating the N deficiency problem. Native soil nitrogen is predominantly found in the organic matter fraction. It is subject to intense chemical and microbiological transformation processes (hydrolysis, oxidation, reduction) and is therefore a very mobile nutrient element in the soil – plant – atmosphere continuum [3,4,5]. The amount of mineral and therefore plant-available native soil N is determined by the soils' organic matter content and the ecological conditions favoring its mineralization [6,7]. In a first step, organic N is hydrolyzed, forming ammonium as showed by the following formula.

$$\text{R-NH2} + \text{H2O} \rightarrow \text{NH4}^{+} + \text{R-OH}$$

The resulting ammonium may be adsorbed onto clay particles and thus be protected from leaching and volatilization [8]. In the presence of molecular oxygen and at near neutral pH, this ammonium can be oxidized into nitrate in a two-step reaction by lithotrophic microorganisms (using mineral compounds as electron donors): (1) In the process of nitritation, ammonium is oxidized into nitrite (NO_2^-) by microorganisms of the nitroso group (e.g. Nitrosomonas, Nitrosococcus, Nitrosolobus, etc…); (2) the nitratation is the second oxidation phase resulting in the formation of nitrate (NO_3-N) mediated by the oxidative action of microorganisms belonging to the nitro group (e.g. Nitrobacters, Nitrocystis, etc…).

(1) $NH_4^- + 3/2\ O_2 \rightarrow NO_2^- + H_2O + 2H^+$ + energy (76 Kcal)
(2) $NO_2^- + ½\ O_2 \rightarrow NO_3^-$ + energy (24 Kcal)

These oxidation processes occur in neutral soils for the synthesis of ATP. However, nitrite and nitrate can also occur in large amounts in the predominating acid soils in the inland valleys of West Africa. Here, ammonium oxidation has been hypothesized to be a "co-oxidation" in the process of NH_4-N detoxification [9]. Irrespective of the process prevailing, in the presence of molecular oxygen, the anion nitrate is formed. Contrary to ammonium, nitrate is not adsorbed onto clay mineral surfaces and can move with water flows. When nitrate encounters anoxic conditions, e.g. in saturated soils of the valley bottomlands, nitrate may be used as an alternative electron acceptor by soil microorganisms. In the process of this anaerobic respiration, N_2, NO and N_2O gasses are formed and are thus lost from the soil [10,11,12]. Chemo-lito-autotrophic (*Paracoccus denitrificans* and *Triobacillus denitricans*) and heterotrophic organisms (Pseudomonas, Bacillus, *Enterobacters* spp.) are responsible for this anaerobic respiration, which sets in when the redox potential becomes less than 500mV. This is likely to occur in poorly drained soils or in the valley bottoms of inland valleys during the rainy season.

$$NO_3^- \rightarrow N_2O\ ,\ N_2,\ (NO) + \text{energy (gaseous N losses).}$$

The present paper reports the results obtained from an experiment performed on soil samples from the various rice-based environments of the inland valley of Cote d'Ivoire to evaluate their native capacity for mineralization of N. This evaluation was a precondition to set appropriate strategies aiming at maximizing the effective use of native soil N by food crop particularly rice.

2. 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 longitudes. The majority of the country is characterized by the gently undulating landscape of inland valleys. Inland valleys are the dominant physiographic units in the region. Valleys are formed in the two major agroecological zones (AEZ) of the country, namely the sub-equatorial humid forest with a bimodal rainfall regime and annual mean precipitation of 2500 mm in the south of the country and the moist savanna with a monomodal rainfall regime and annual mean precipitation of 1000 mm in the north of the country. A pseudo-bimodal rainfall regime in the derived savanna creates a transition between the two zones with 1400 mm annual rainfall. 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. The experiments on the relative importance of soil N mineralization potential involved soil samples from sites covering the diversity of rice-based systems in Côte d'Ivoire.

The sampling sites chosen for the diagnostic survey are spread across the different rainfall regimes and agroecological zones and are differentiated by parent rock/soil types and position along the toposequence (Table 1). Selected physical and chemical characteristics of the soils are shown in Table 2.

Table 1. Sites of the diagnostic survey in Côte d'Ivoire shown in gray color

Parent Rock Soil texture Valley shape	**Granite/Gneiss Loamy-sand convex**			**Schist Loamy-clay concave**		
Agro-ecological zones	**Upland**	**Hydro-morphic**	**Lowland**	**Upland**	**Hydro-morphic**	**Lowland**
Guinea savanna			XXXXXX	XXXXXX		
Derived savanna		XXXXXX	XXXXXX	XXXXXX		
Bimodal forest		XXXXXX	XXXXXX			XXXXXX
Monomodal forest	XXXXXX		XXXXXX			XXXXXX

Table 2. Physical and chemical characteristics of soils at the moist savanna, derived savanna and humid forest sites adapted from Becker and Diallo [13]

Location / Geology	Toposequence level	Horizon	Clay content	CEC (meq 100 g^{-1})	Base saturation (%)	pH	Observations
Moist savanna / transition schist-granite	Crest	A1	22.5	4.84	74	6.6	red gravelled clay
		B2	55.3	4.78	78	6.3	
		B3	29.3	1.29	42	5.7	
	Slope	A1	10.8	2.06	60	5.8	light gray sand and ochre sandy
		B2	39.2	2.42	54	4.7	
	Bottom land	A1	18.2	1.36	32	4.6	gray sandy clay with gley
		A3	31.5	0.59	17	5.1	
Derived savanna / Granitoide	Crest	A1	8.9	2.48	35	6.1	ochre sandy clay
		A2	18.6	0.82	16	5.7	
	Slope	A1	4.9	3.01	48	6.5	gray ochre sandy clay
		A2	11.9	2.95	41	5.7	
	Bottom land	A1	7.2	2.84	59	6.6	beige sandy with little clay
		BC	19.9	2.98	52	6.6	
Humid forest / Gneiss	Crest	A1	18	10.7	85	5.9	ochre gravelled clay surface
		B2	53.3	2.45	30	4.8	
	Upper slope	A1	13.7	1.75	23	4.8	beige yellow sandy clay
		B21	60	0.81	12	5	
	Lower slope	A1	6.8	2.5	38	5	
		A3	19.5	1.01	24	5.3	
	Bottom land	A1	13.7	3.78	29	4.5	gray beige sandy loam & gley
		B2g	18.7	1.94	35	5.4	

2.1 Soil sampling and analysis

Composites of 2-3 soil samples were collected from 0–20 cm depth using a gravimetric auger. The samples were stored in a cool box and transported to the laboratory of the West Africa Rice Centre (WARDA) for incubation, extraction and analysis. Sampling points in the field were marked with colored sticks. The soil samples were transferred to an incubator at WARDA and were individually incubated in 3 replications per sample to evaluate their soil N supply capacity. Sample tubes were extracted for exchangeable NH_4-N at bi-weekly intervals for duration of 8 weeks.

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 (370ºC) of air-dried samples in concentrated sulfuric acid with a catalyst (selenium), following the Kjeldhal procedure. Soil mineral N concentration was calculated as follows for 20 cm depth:

$$\frac{((v1-v2)\times mN\times Vo)}{V1\times Pe}\times(h\times Da)=NH_4^+ orNO_3^-(kgN/ha)$$

Net N mineralization was calculated by subtracting the initial NH_4-N from samples' N content and the cumulative net N mineralization was determined as the sum of all successive N_{min} increases. The bulk density was used to express sample N content on a per unit area basis. Bulk density was determined in the course of a physical evaluation of the soils in order to translate gravimetric into volumetric values according to the method described by Schlichting et al. [14] using a soil volume of 100 cm^3. The volume-samples were carefully removed from the profile using 100 cm³ metal rings, dried at 105ºC to a constant weight and weighed. 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).

2.2 Experimental Design and Treatment Application

To investigate potential soil N mineralization, one farmers' rice field each was selected in the 11 production systems. The systems differed by agroecological zones with regards to cropping intensity in uplands (short fallow less than 5 years and long fallow, from 6 years onward) and to water management in lowlands (bunded vs. unbunded plots). Total and net-N mineralization were determined by anaerobic incubation for 6 weeks and subjected to ANOVA and multi-regression analysis. Accordingly, the N supplying capacity was classified by independent variables and differentiated into forest and savanna agro-ecological zones (AEZ), upland and lowland ecologies (TOP), light- and heavy-textures soils (STX) and extensive and intensive land use (LUI) - Table 3.

Table 3. Environmental and production system descriptors used as independent variables in a multiple regression analyses with soil N supplying capacity

Agro-ecological zone (AEZ)	Toposequence level (TOP)	Soil texture (STX)	Land Use Intensity (LUI)
Forest: >270 days LGP (length of growing period).	**Upland** with a mean annual groundwater table below 1.2 m	**Sand**: comprising textural classes S, lS and sL;	**Extensive**: >4 years of fallow, 1 year of cropping (forest); <4 consecutive years of cropping before fallow (savanna)
S**avanna:** 180 – 270 days LGP; sites with both monomodal and bimodal rainfall distribution patterns	**Lowland** with seasonally flooded valley bottom land	**Clay**: comprising textural classes L, sC, lC and C	**Intensive**: <3 years of fallow, 1-2 years of cropping (forest); >4 consecutive years of cropping before fallow (savanna)

3. RESULTS

The wide prevailing diversity of agricultural soils and soil use systems is likely to differentially affect soil N supply. Depending on the environment and the production system, initial soil N_{min} ranged from 4.5 to 25.5 mg N kg^{-1} soil (Table 4a - 4b). Subtraction of the initial N_{min} value from measured soil N_{min} after 2, 4 and 6 weeks of incubation resulted in net-N mineralization values (soil N supplying capacity). The patterns of this N supply differed by production system. It was higher in the savanna while differences between toposequence positions were more in soils of the forest zone (Table 5 and Table 6).

Table 4a - 4b. Total and net N mineralization of soils collected from the major rice-based systems of Côte d'Ivoire [13] with the characteristics of the sampling fields

Majors rice based systems of Côte d'Ivoire	Soil N mineralization (mg N kg^{-1})			
	Incubation period			
	Initial 0	2 weeks	4 weeks	6 weeks
Krou	4.5±0.8	10.9±1.4	13.9±0.3	13.4±1.5
Yacouba	11.1±1.1	16.9±1.9	17.3±2.8	22.6±1.9
Traditional savanna upland	6.2±0.6	10.7±1.4	18.5±6.2	16.2±1.7
CIDT savanna upland	13.5±2.6	18.1±0.2	16.8±5.8	20.9±2.0
Mechanized savanna upland	10.4±2.2	14.5±1.3	13.6±3.5	18.2±2.0
Dioula immigrant	8.1±1.9	9.2±1.1	11.3±0.4	11.5±2.3
Yacouba rainfed lowland	20.6±0.7	26.3±1.1	30.4±1.3	31.8±1.0
Dioula irrigated lowland	24.0±2.9	28.4±1.9	26.6±4.6	32.7±0.8
Yacouba irrigated lowland	25.5±0.8	28.9±0.9	30.5±3.8	31.2±3.1
Savanna rainfed lowland	11.0±1.9	20.5±1.1	25.6±0.4	26.1±2.3
Floodplain	17.5±3.9	25.7±1.5	21.3±3.1	31.7±1.1
Savanna irrigated lowland	9.4±3.9	10.4±2.5	10.9±5.9	11.1±0.9

± standard deviation

Majors rice based systems of Côte d'Ivoire	Characteristics				Net soil N mineralization (mg N kg^{-1})		
	AEZ	TOP	STX	LUI	2 weeks (Net 2)	4 weeks (Net 4)	6 weeks (Net tot.)
Krou	forest	upland	sand	intensive	6.4	9.4	9.4
Yacouba	forest	upland	clay	extensive	5.8	6.2	11.5
Traditional savanna upland	savanna	upland	clay	extensive	4.4	12.3	12.3
CIDT savanna upland	savanna	upland	clay	intensive	4.6	3.3	7.4
Mechanized savanna upland	savanna	upland	clay	intensive	4.0	3.2	7.7
Dioula immigrant	forest	lowland	sand	intensive	1.2	3.2	3.5
Yacouba rainfed lowland	forest	lowland	clay	extensive	5.7	9.8	11.2
Dioula irrigated lowland	forest	lowland	sand	extensive	4.4	2.6	8.7
Yacouba irrigated lowland	forest	lowland	clay	intensive	3.4	5.0	5.7
Savanna rainfed lowland	savanna	lowland	clay	extensive	9.4	14.6	15.1
Floodplain	savanna	lowland	clay	extensive	8.2	3.8	14.2
Savanna irrigated lowland	savanna	lowland	clay	intensive	1.1	1.5	1.7

Table 5. Relationships between environmental and cropping system descriptors and "early" soil N supplying capacity (net N mineralization after 2 weeks) as determined by multiple regression analysis

	Total		Forest (AEZ 1)		Savanna (AEZ 2)	
	Std. Error	P	Std. Error	P	Std. Error	P
Intercept	3.5	0.03 **	2.4	0.00 ***	3.9	0.06 ns
AEZ	1.1	0.42 ns	-	-	-	-
TOP	0.9	0.74 ns	1.1	0.04 *	1.5	0.37 ns
LUI	0.9	0.01 **	1.0	0.13 ns	1.5	0.07 ns

Std Err.: standard error; p: probability level

,,*** significance level of probability of 0.05, 0.01 and 0.005, respectively – ns: no significant difference*

AEZ: agroecological zone; TOP: toposequence position; LUI: land use intensity

Table 6. Relationships between environmental and cropping system descriptors and “late” soil N supplying capacity (net N mineralization after 6 weeks) as determined by multiple regression analysis

	Total		**Forest (AEZ 1)**		**Savanna (AEZ 2)**	
	Std. Error	**P**	**Std. Error**	**P**	**Std. Error**	**P**
Intercept	10.5	0.00***		7.9	0.00***	
AEZ	3.6	0.05 ns		-	-	
TOP	3.0	0.08 ns		3.5	0.04 *	
LUI	3.1	0.01 **		3.3	0.07 ns	

Std Err.: standard error; p: probability level

,,*** significance level of probability of 0.05, 0.01 and 0.005, respectively – ns: no significant difference*

AEZ: agroecological zone; TOP: toposequence position; LUI: land use intensity

The factor agroecological zone (AEZ) was confounded with the factor soil texture (STX) with clay soils dominating the savanna and sandy soils dominating the forest environments. The net-N release differed by toposequence positions of these agroecological zones. Thus, in the forest, upland soils had a significantly higher N supplying capacity than the lowland soils. After 2 weeks of incubation, net N_{min} reached 6.1 mg NH_4-N kg^{-1} soil in uplands but was only 3.6 mg in lowland soils ($p<0.05$). The opposite trend was observed in the savanna zone, where lowland soils cumulated up to 10.4 mg NH_4-N kg^{-1} compared to the 8.4 mg in upland soils after 6 weeks of incubation. However, these differences were not significant ($p>0.05$).

Furthermore, the N supplying capacity of savanna soils was generally equivalent to that of the soils from the forest. Thus mineralization maxima of 10.4 mg NH_4-N kg^{-1} were observed in lowland soil samples from the savanna zone while 10.2 mg NH_4-N kg^{-1} were reached in upland samples from the forest environments. Land use intensity generally affected the net-N mineralization patterns but the extent varied by agroecological zone and soil texture. Intensified land use reduced net N release more in lowland soils from savanna than from forest environments and generally more in upland than in lowland soils (Fig. 1). Thus, land use intensification-induced reductions in net N release ranged from 0.1 mg NH_4-N kg^{-1} in lowland soils of the forest zone to 4.7 mg NH_4-N kg^{-1} in upland soils from the savanna zone after 2 weeks of incubation (Fig. 2). A comparison of different toposequence positions regarding the N mineralization under changing land use is presented in Table 7 and Fig. 3.

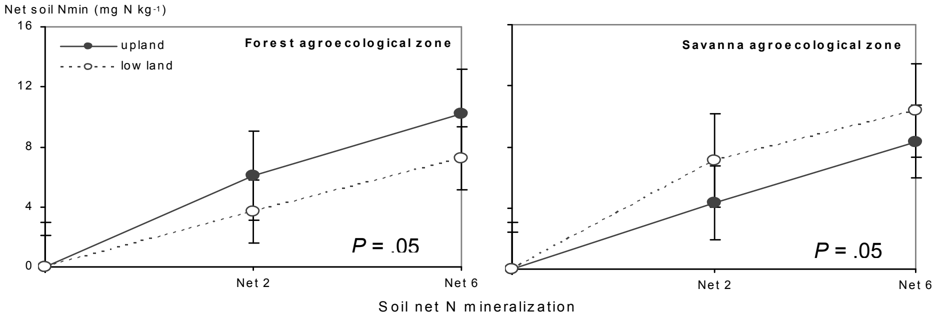

Fig. 1. Early and late net N mineralization in different toposequence positions (upland and lowland) of the forest and the savanna irrespective of land use intensity (anaerobic incubation for 8 weeks, Côte d'Ivoire).

** Net 2, Net 6 : net N mineralization after 2 and 6 weeks of incubation periods respectively (ns: no significant difference)*

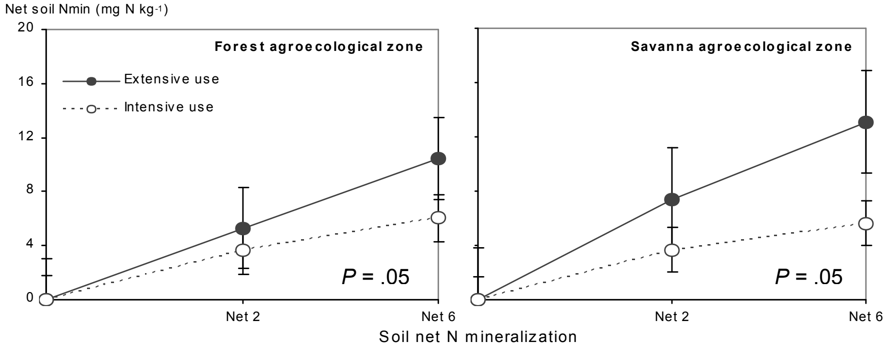

Fig. 2. Net N mineralization patterns during a 6-week incubation period in forest and savanna soils with different land use intensity irrespective of toposequence position.
** Net 2, Net 6: net N mineralization after 2 and 6 weeks of incubation periods respectively*

Table 7. Net N mineralization of upland sandy soils and lowland clay soils under different intensities of land use irrespective of agroecological zone

Toposequence (texture)	Land use intensity	Net N mineralization (mg.kg^{-1})	
		2 weeks	6 weeks
Upland (sand)	Intensive	5	8
	Extensive	5.1	10.7
	Significant difference	ns	**
Lowland (clay)	Intensive	2.2	3.6
	Extensive	6.9	12.3
	Significant difference	*	*

,,*** significance level of probability of 0.05, 0.01 and 0.005, respectively – ns: no significant difference*

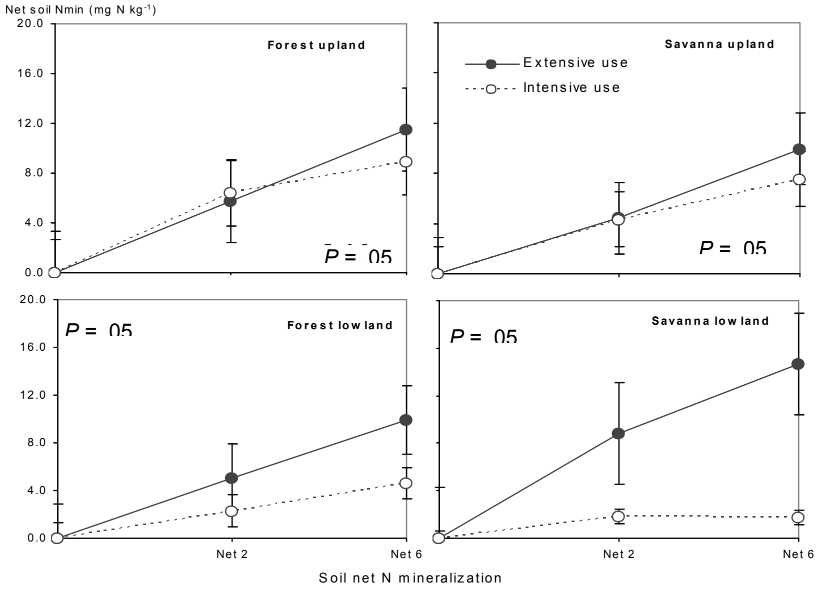

Fig. 3. Net N mineralization of upland and lowland soils under different intensities of land use in the forest and savanna agroecological zones irrespective of soil texture
** Net 2, Net 6: net N mineralization after 2 and 6 weeks of incubation periods respectively*

4. DISCUSSION

The soil N mineralization from incubation studies is commonly used as an indicator of soil mineral N supplying capacity [15]. Transformations of nitrogen (N) in soil have been investigated in laboratory studies by incubating soil cores in containers under controlled laboratory and growth chamber conditions. In different experiments, widely different depths, weights of soil and sizes of incubation container have been used [16]. A review of publications on incubation studies showed a large variability in the mineralization potential of rice soils across the world [17]. In the present study, the predominant factor which influenced soil N mineralization was soil particle size, which was agro-ecology dependent. Forest rice soils (mostly sandy) showed the highest N mineralization and the largest part of this soil N was supplied earlier than in savanna soils, particularly in the upland ecosystem. This is likely to be due to the appreciable soil-aeration in this environment, as organic matter transformation via ammonium into nitrate is an aerobic process. Upland soils are usually better aerated than other segments of the toposequence, namely the hydromorphic zone and the lowland [18]. Egelkraut et al. [16] found that the clay concentration in surface soil was positively correlated with aerobic N mineralization in a Georgia coastal plain field (carbon sequestration by clay). Thus, the large ammonification found in rainfed lowland soils of the savanna is probably the result of a combination of high organic matter content and relatively good aeration [19]. It appears that the organic matter content of the soil is the main factor contributing to the intensity of N_{min} turn-over, provided there is good aeration [20,21]. Gigou [22] related this higher N mineralization in the forest than in the savanna zone to the higher organic matter content, resulting from the density of biomass and reduced lixiviation processes. Intensively used lowland soils mineralized less N than upland soils. This could be the result of a deficiency of the substrate (organic matter), the absence of actors (micro-organisms) and/or the presence of another bio-physical factor which reduced the mineralization in lowland soils.

The acid pH of Ivorian forest soils may have protected the organic matter from microbial decomposition and reduced the N_{min} supply. Consequently, pH variations resulting from the flooding of the soil have probably created favorable conditions for N mineralization. Flooding is known to be a suitable method for the establishment of a bicarbonate buffer which will neutralize the pH of the soil solution [23]. Sahrawat [24] reported low mineralization in tropical soils with pH below 6 but, on the other hand, N mineralization was described at pH 5.3 in sandy soil poor in humus by Bruin et al. [25] during an incubation study with alternative phases of moistening. Bruin et al. [25] also showed that under laboratory conditions a C/N ratio of over 13 in an unfertilized Sahelian soil can lead to a lag in N mineralization.

Soil exhaustion as a result of intensified land use in different agro-ecological zones significantly reduced net N mineralization. The intensive use of land for crop production decreases the soil organic N content, thus the net N supply capacity [26]. Van Reuler and Janssen [27] found a decrease of nutrient fluxes, particularly soil mineral nitrogen, in shifting cultivation of the Ivorian forest zone where mineralizable N reserve in soil was low because of intensive land-use. Krul et al. [28] previously reported that a low net N mineralization was the result of a low mineralizable N content in soils.

5. CONCLUSION

It may be concluded that N mineralization from soils of the various rice-based systems of Côte d'Ivoire strongly varied. Soil N supply was generally less in the sandy than in clay soils.

Land use intensification affected N release more in the savanna than in the forest and tended to reduce the N supplying capacity more in lowland than in upland soils. As soil nutrient mineralization rates are also controlled by the specific character of the vegetation occupying a site, plant-soil-plant feedback loops in agricultural systems will influence the N dynamics over time.

A quantitative study on water and N dynamics conducted in Côte d'Ivoire (experimental farm of the West Africa Rice centre - WARDA) showed that the soils of the inland valleys of the region can naturally mineralize large quantities of inorganic N. The amounts differ by soils, rice-based systems and land use.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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