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Managing seasonal soil nitrogen dynamics in inland valleys of the West African savanna zone

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Declaration

Ich versichere, dass ich diese Arbeit selbstständig verfasst habe, keine anderen Quellen und Hilfsmaterialien als die angegebenen benutzt und die Stellen der Arbeit, die anderen Werken dem Wortlaut oder dem Sinn nach entnommen sind, kenntlich gemacht habe. Die Arbeit hat in gleicher oder ähnlicher Form keiner anderen Prüfungsbehörde vorgelegen.

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Dedication

To my family

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List of Abbreviations

ACIAR	Australian Centre for International Agricultural Research
AEZ	Agro-Ecological Zone
ANOVA	Analysis of Variance
BMBF	German Federal Ministry for Research and Innovations
BNF	Biological Nitrogen Fixation
C/N	Carbon to Nitrogen ratio
$CaCl_2$	Calcium Chloride
CEC	Cation Exchange Capacity
CEFCOD	Center of study, Training and Advice for Development (Burkina Faso)
DGPER	Department for the Promotion of Rural Economy (Burkina Faso)
DWT	Dry-to-wet season transition period
FAO	Food and Agriculture Organization of the United Nations
FKR	Rice variety from Farako-ba
GAEZ	Global Agro-Ecological Zones
GCS	Geographic Coordinate System
H_20	Water
IDRC	International Development Research Centre
INERA	Institute of the Environment and Agricultural Research (Burkina Faso)
IPCC	Intergovernmental Panel on Climate Change
IPNI	International Plant Nutrition Institute
ISRIC	International Soil Reference and Information Centre
KCl	Potassium Chloride
LGP	Length of Growing Period
Ndfa	Nitrogen derived from the atmosphere
Ndfs	Nitrogen Derived From the Soil
NH_4-N	Ammonium
NO_2	Nitrogen Dioxide
NO_3-N	Nitrate
NRC	National Research Council
OM	Organic Matter
RAQ	Resin Absorption Quantity
RCP	Representative Concentration Pathway
SNDR	National Strategy for Rice cropping Development (Burkina Faso)
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SSA	sub-Saharan Africa
TDR	Time Domain Reflectometry
WASCAL	West African Science Service Center on Climate Change and Adapted Land Use
WGS	World Geodetic System
ZEF	Center for Development Research

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Abstract

Most cropping systems in the Dry Savanna agro-ecological zone of West Africa qualify as low-input systems. The use of mineral fertilizers is among the lowest in the world with an average of <10 kg ha^{-1} $year^{-1}$. Nitrogen is the most limiting nutrient element for crop production in the area, and the prevailing low-input systems rely mainly on the provision of native soil N. Depending on environmental conditions and management practices, the process of soil N mineralization not only provides N for crop nutrition but can also entail substantial N losses. Alternate soil drying and wetting cycles and seasonal changes in the rainfall intensity and distribution reportedly affect soil N dynamics. Associated with changes in the soil aeration status, nitrate-N can be lost by leaching and denitrification, mainly in the period between the first rains and crops establishment, the so-called "dry-to-wet season transition period" (DWT). Besides such temporal dynamics, soil N in the undulating inland valley landscape of West Africa is also subject to spatial fluxes and translocation of water and nitrate along the toposequence. This is likely to exacerbate the intensity of nitrate dynamics, particularly in the bottomlands adjacent to valley slopes, used for producing rainfed lowland rice. Thus, managing soil native N by avoiding (mainly nitrate-N) losses during DWT is key for crop productivity in the short-term and to maintain soil fertility in long-term.

Field experiments were conducted in Burkina Faso and Benin in 2013 and 2014 to quantify the intensity and dynamics and to evaluate options for managing seasonal soil nitrate-N in inland valleys of the Dry Savanna zone of West Africa. In addition, factors modulating seasonal N dynamics such as rainfall intensity, soil tillage, and location effects were assessed. With the onset of the first rains and the rewetting of dry bare soil, and depending on the toposequence position, mineralization processes lead to an accumulation of 20-45 kg nitrate-N ha^{-1} in the topsoil. Initial vertical leaching and subsequent lateral subsurface flows of water from the slopes contributed an additional 10-15 kg of nitrate N ha^{-1} to the valley bottom wetland. In the absence of vegetation cover, this *in-situ* N mineralization and nitrate influxes had little effects on the performance of rainfed lowland rice in the valley bottom, indicating the occurrence of substantial N losses and pointing out the need for management approaches that contribute to conserving native soil N for enhancing rice production. The integration of transition season crops (either the leguminous green manures *Mucuna pruriens* and *Vigna unguiculata* or the non-N_2-fixing grass *Panicum maximum*) in the lowland could capture and temporarily immobilize soil N, reducing the extractable soil nitrate content to 8-25 from 50-75 kg N ha^{-1} in the bare fallow control treatment. The resulting N accumulation in the transition season biomass was 41-70 kg ha-1 in panicum and 76-86 kg ha^{-1} in the legumes, where biological N_2 fixation contributed 30-50%. Nitrate-catching vegetation, and particularly N_2-fixing cowpea and mucuna, effectively reduced the build-up of native soil N_{min}, thus potentially reducing nitrate-N losses and, upon biomass incorporation, enhanced the productivity of wet season rainfed rice with grain yield increases of 1-2 t ha^{-1} above the bare fallow control (1.7 t ha^{-1}).

The extent of such effects strongly depends on environmental conditions and management practices, affecting soil N mineralization and changes in the moisture regime. Thus, soil tillage tended to increase N mineralization and the extent of the nitrate peak during DWT. While a 30% reduced rainfall during DWT increased the nitrate accumulation, the absence of drastic changes in soil aeration status limited apparent nitrate losses. On the other hand, a 30% increased rainfall during DWT lead to a rapid soil saturation and little nitrate remained once the volumetric soil moisture exceeded 25%. Differences in the N-supplying capacity of soil types did affect the extent of the N mineralization, but neither the temporal dynamics nor the grain yield of rice. The reported finding point to the need for management approaches contributing to conserve native soil N for enhancing lowland rice production, such as nitrate-catching vegetation during DWT. The targeting of such approaches, however, is highly site specific and their relevance and effectiveness depend on the speed of change in soil aeration status during DWT and thus on rainfall, valley slope and management attributes, but also on the projected type of climate change.

Kurzfassung

Die meisten Produktionssysteme in der Trockensavanne Westafrikas sind durch geringen Einsatz externer Produktionsmittel gekennzeichnet. So ist die Anwendung von <10 kg/ha mineralischer N-Dünger die niedrigste weltweit. Gerade in den „low-input“ Systemen ist Stickstoffmangel weit verbreitet und die N-Versorgung der Kulturpflanzen basiert im Wesentlichen auf die Nachlieferung aus Bodenvorräten. Je nach Umweltbedingung und Managementsystem trägt die Mineralisierung von Boden-N aber nicht nur zur Nährstoffversorgung der Kulturen bei, sie kann auch zu erheblichen N-Verlusten führen. Gerade wiederholte Zyklen von Austrocknung und Wiederbefeuchten des Bodens sowie saisonale Schwankungen in Niederschlagsintensität und –verteilung kann nachweislich die Boden-N-Dynamik beeinflussen. In Abhängigkeit des Belüftungszustandes des Bodens geht in besonderem Maße Nitrat-N durch Auswaschung und Denitrifizierung verloren, vor allem in der Übergangsperiode zwischen Trocken- und Regenzeit. Neben solchen zeitlichen Dynamiken ist Nitrate auch räumlich mobil und führt in der Landschaft von Inlandtälern zu vertikalen wie auch horizontalen Nitrat-Flüssen entlang der Catena, welche die Nitratdynamiken besonders in den Talsohlen weiter verstärken. Das Management dieser Nitratdynamik und die Vermeidung von N-Verlusten während der Übergangsperiode ist somit kurzfristig der Schlüssel für steigende Erträge und wird langfristig zum Erhalt der Bodenfruchtbarkeit beitragen.

Feldversuche wurden 2013 und 2014 in Burkina Faso und Benin durchgeführt, um die Intensität und die Dynamik der Boden-N Mineralisierung während der Übergangsperiode von Trocken- zu Regenzeit zu quantifizieren und Management-Optionen hinsichtlich ihrer Bedeutung zur Verminderung von N-Verlusten und zur Ertragssteigerung von Nassreis vergleichend zu bewerten. Zudem wurde die Bedeutung ausgewählter Standort- und Managementattribute (Bodentyp, Niederschlagsmenge und Art der Bodenbearbeitung) auf die saisonale Boden-N-Dynamik ermittelt. Mit Einsetzen der ersten Regenfälle nach der Trockenzeit und der Wiederbefeuchtung des trockenen Bodens konnte in Abhängigkeit der Toposequenz-Position eine Anreichung mit mineralischem Stickstoff in der Größenordnung von 20 bis 45 kg Nitrat-N/ha im Oberboden nachgewiesen werden. Durch zunächst vertikale Auswaschung und anschließend durch horizontale Verlagerung mit dem Wasserfluss wurden 10-15 kg Nitrat-N vom Hang in die Talsohle verlagert. Ohne eine Bodenbedeckung mit lebender Biomasse zeigten weder in-situ Mineralisierung noch laterale Einträge von Nitrat während der Übergangsperiode signifikante Effekte auf Leistungsmerkale von Nassreis. Diese Beobachtung stützt die Vermutung, dass die substantiellen Mengen an Nitrat im saturierten Boden der Talsohle verloren gingen du somit ein verbessertes Management des nativen Boden-N für Produktionssteigerungen erforderlich ist.

Der Anbau einer Zwischenfrucht während der Übergangsperiode (entweder in Form der Gründüngungs-Leguminosen *Mucuna pruriens* oder *Vigna unguiculata* oder des nicht N_2-fixierenden Futtergrases *Panicum maximum*) vermochte Nitrat aufzunehmen und zeitweise in der Biomasse zu immobilisieren, und somit die verfügbare (und potentiell Verlusten ausgesetzte) Nitratmenge von 50-75 kg/ha in der Nacktbrache auf 8-25 kg/ha zu reduzieren. Die daraus resultierende N-Anreicherung war 41-68 kg/ha im Fall von *Panicum* und 76-86 kg/ha in den beiden Leguminosen, wobei der Anteil des durch biologische N_2 Bindung zugeführten Anteils bei 30-50% lag. Der Erhalt von Boden-N sowie die zusätzliche Zufuhr von Luft-N (Leguminosen) vermochte die Reiskornerträge um 1-2 t/ha über die Kontrollparzelle (Nacktbrache) zu erhöhen. Das genaue Ausmaß solcher Effekte differierte allerdings in Abhängigkeit der edaphischen und klimatischen Bedingungen sowie der Art der Bodenbearbeitung. Eine wendende Bodenbearbeitung stimulierte die N-Mineralisierung am Hang in der Übergangsperiode und erhöhte somit die lateralen Einträge von Nitrat in die Talsohle.

Eine 30%ige Verminderung der Niederschlagsmenge während der Übergangsperiode erhöhte die Nitrat-Anreicherung im Oberboden. Durch den Wegfall drastischer Änderungen im Belüftungszustand des Bodens waren Nitratverluste stark reduziert. Umgekehrt führte eine 30%ige Erhöhung der Niederschläge zwar zu einer verminderten Nitrat-Anreicherung im Boden, durch den raschen Wechsel von aeroben auf anaerobe Bedingungen wurden dafür die Nitrat-Verluste drastisch erhöht und bei Überschreitung einer 25% volumetrischen Bodenfeuchte konnte kein Nitrat mehr im Boden nachgewiesen werden. Unterschiede in der N-Nachlieferungskapazität der Böden bestimmt das Ausmaß des Nitrat-Peaks, nicht aber die saisonale Dynamik oder den Kornertrag von Reis.

Die vorgelegten Ergebnisse unterstreichen den Bedarf für ein verbessertes Management des Boden-N, speziell in der kritischen Übergangsphase zwischen Trocken- und Regenzeit. Der Anbau von Zwischenfrüchten vermochte so Boden-N zeitweise zu konservieren und Reiserträge nachweislich zu steigern. Die Relevanz und die Effektivität solcher Ansätze hängt im Wesentlichen vom der Intensität des Wechsels der Bodenbelüftung ab und ist somit hochgradig Standort-spezifisch. Neben Bodentyp, Niederschlagsmenge und Art der Bodenbearbeitung, dürfte hier auch künftige Entwicklung des Klimawandels entscheidend für die Ausweisung von Extrapolations-Domänen der Technologie-Optionen sein.

1 GENERAL INTRODUCTION

1.1 Background

In the dry savannah agro-ecological zone (AEZ) of West Africa, over half of population lives in rural areas. This area is part of the most vulnerable in the world due to severe climate conditions and poverty. A major share of the population is comprised of small-scale farmers (for example, 80% of the population in Burkina Faso), depending on local crops for their food production, mainly sorghum (*Sorghum bicolor* L.), millet (*Pennisetum* glaucum L.), maize (*Zea mays* L.) and rice (*Oryza sativa* L.). Agriculture is practiced on soils inherently low in soil organic carbon (SOC), associated with low cation exchange capacity (Bationo et al. 2007). Besides low-input orientation of farmers and unfavorable soil attributes, increasing land degradation affects production levels (Sanchez, 2002; Koning and Smaling 2005). Proximate causes include soil biophysical characteristics, climatic factors and unsustainable land management practices (Ayoub 1998; Salvati and Zitti 2009) while the underlying drivers encompass population pressure, poverty, land tenure insecurity and other socio-economic factors (Douglas 2006; Nkonya et al. 2008; Jorgenson and Burns 2007; Van et al. 2008; Qasim et al. 2013). Thus, traditional fallow rotation systems that were used until the recent past to restore soil fertility and reclaim degraded soil have been largely eliminated in favour of permanent crop uses. Thereby, continuous and intensive cropping without soil fertility conservation and restoration measures has depleted the nutrient base of most soils (Soler et al. 2011). Furthermore, the environment is characterized extreme climatic conditions with wind and water erosion leading to removing the nutrient-rich topsoil (Ker and IDRC 1995; Zougmore et al. 2003). The extent of their effects is expected to be further exacerbated by climate change and a predicted future increase of climate variability. In his analysis of the climate trend in Africa during the last two centuries, Nicholson (2001) estimated that: "*the most significant climatic change that has occurred in Africa has been a long-term reduction in rainfall in the semi-arid regions of West Africa*". Particularly the increasingly variable and hence unpredictable onset of the rainy season challenges crop farmers. Also, the area experiences recurrent and increasingly frequent drought episodes since the 1970s (Nicholson, 2001, p. 140) and several models predict an increased frequency of erratic heavy precipitation events (IPPC 2007), though model predictions are often conflicting regarding expected change scenarios of future rainfall (Cooper et al. 2008). For a WASCAL target area in the semi-arid zone of West Africa, the climate-related uncertainty is particularly large and reduced rainfall combined with more extreme rainfall events, leads to a reduced vegetative cover, aggravates water and wind erosion, and enhances uncertainties in farmers' cropping calendar planning. As a consequence, farmers tend to delay the establishment of their crops to cope with rainfall uncertainty (Ibrahim et al. 2012; Lodoun et al. 2013), thus further reducing the length of the already short growing season, while increasing the dry-to-wet season transition period during which the land lays bare.

Most cropping systems in the Dry Savanna AEZ qualify as low-input systems, with the use of external inputs such as mineral fertilizers being among the lowest in the world with an average of <10 kg ha^{-1} year^{-1} (Fairhurst 2012). These low-input farmers depend on indigenous source of nutrient supply for their crop production, particularly in rainfed crop production systems. Nitrogen (N) is the most limiting nutrient element for crop production in the area, although phosphorus (P) deficiency is an emerging issue (Segda 2006). The process of N transformation in the soil leading to its availability or loss is influenced by environmental conditions. The climate in the Dry Savanna is characterized by a wet season (from May to October) following a long dry season. The resulting length of crop growing period ranges from 90 to 180 days (FAO 2016; Saito et al. 2013). The resulting patterns but also the changes in the distribution of rainfall have been reported to affect soil N dynamics, and most N is expected to be lost during the period between the first rains and the crops establishment so-called "dry-to-wet season transition period" (DWT) (George et al. 1995; Bognonkpe and Becker 2009). With the onset of the rains after a prolonged dry season, SOC is mineralized by the microbial biomass, leading to a transient peak of mainly nitrate-N, the such-called Birch effect (Birch 1960).

The extent of this N peak depends on the native fertility of the soil (mainly the SOC and N content), the intensity of the rains and the land management (Pande and

Becker 2003). In inland valleys and in the absence of growing crops (usually the case during the DWT) or other conservation measures, this nitrate can be vertically leached into deeper soil layers, and subsequently horizontally translocate along the toposequence depending on soil attributes (infiltration, permeability, hydraulic conductivity) and rainfall characteristics (Smethurst et al. 2013). The fate of the nitrate once arriving in the valley bottom depends on soil organic carbon (SOC) content (proton donors) and the redox potential (electron acceptors). With soil saturation / flooding, facultative anaerobic soil microorganisms use the nitrate as terminal electron acceptor (alternative to oxygen) of carbon-based energy sources from the SOC, resulting in gaseous losses in the forms of N_2 and N_2O (Becker et al. 2007).

Low crop productivity along the toposequence is thus closely related to soil N dynamics and N losses during DWT in inland valleys. Thus, managing soil native N by avoiding (mainly nitrate-N) losses during DWT appears to be of a particular importance for crop productivity in the short-term and to maintain soil fertility in long-term in low-input systems of the Dry Savanna AEZ of West Africa.

1.2 Hypotheses and objectives

The research questions addressed in this thesis are the following:

- What is the extent and what the dynamics of seasonal soil N along the toposequence and how do they affect lowland rice yield?
- Can an improved soil nitrogen management during DWT improve the rice agronomic performances in the lowland?
- What are the effects of modulating factors such as soil tillage, rainfall intensity and site attributes on soil N dynamics?

Accordingly to the research questions, and because largest soil N dynamics are expected to occur during the DWT, we formulate the following hypotheses:

Soil nitrate-N translocation from the slope affects rice agronomic performances in the lowland, and adapted and adoptable soil N management strategies during DWT can increase rice productivity. In addition, soil disturbance via tillage, rainfall variability and other site attributes (location) will differentially influence native soil N dynamics during the DWT and hence lowland rice performance.

The development of sustainable land management practices for low-input systems of West Africa involves generating knowledge on key components and processes affecting nutrient fluxes and budgets.

The main objective of this study was to evaluate options for managing seasonal soil nitrate-N dynamics in the Dry Savanna zone of West Africa. The specific objectives were:

1. Quantify seasonal soil N dynamics along the toposequence and its effect on lowland rice yield;
2. Assess the effect of seasonal soil nitrogen management on agronomic performances of lowland rice;
3. Assess the effect of modulating factors such as rainfall, tillage and location effects on soil nitrogen dynamics.

Accordingly, the present thesis is structures as follow. After setting the general scene by defining the research questions (Chapter 1), and presenting the general material and methods (Chapter 2), the main thesis body is comprised of 3 chapters presenting the results of research activities undertaken between 2013 and 2014.

Chapter 3: presents the key findings on dynamics of soil NO_3-N along the toposequence and the effect of nitrate contributed from the slope on the performance of lowland rice. It addresses objective 1.

Chapter 4: describes the dynamics of soil NO_3-N and the performance of rainfed lowland rice in response to pre-rice crops development during the dry-to-wet tansition season. It discuss the ability of transition season crops to immobilize soil nitrogen and additional N fixation from the atmosphere in view of addressing objective 2.

Chapter 5: analyses the effect of soil disturbance, various soil moisture regimes and location on soil nitrogen dynamics which addresses objective 3.

2 GENERAL MATERIAL AND METHODS

This chapter presents the general material and methods used and applied in the thesis, including a general description of the study sites (geographic location climatic conditions, soil physico-chemical attributes), methods of soil and plant sampling and analysis, as well as data management. Further, more chapter-specific aspects of material and methods will be elaborated in the three respective research chapters.

2.1 Geographic location of the study area

The present study was carried out from 2013 to 2014 in the Dry Savanna AEZ of West Africa of Burkina Faso and Benin with similar landscape attribute (Figure 2.1). The length of growing period (LGP) for upland crops is 135-160 days (FAO-GAEZ 2016). Activities were carried out at the research sites of the West African Science Service Center on Climate Change and adapted Land Use (WASCAL) project, supported by the German Federal Minsitry for Research and Innovations (BMBF).

In Burkina Faso, the study area is located near the town of Dano (11° 09′ 00′′ Nord, 03° 04′ 00′′ West) within a watershed catchment situated in the south-western region of the country. According to the Köppen–Geiger classification (Peel et al. 2007), the bio-climate of the study sites belongs to the “Tropical Savannah” type (Aw). The climate is sub-humid with average rainfall varying from 900 to 1200 mm per year (Ibrahim et al., 2012), distributed in a uni-modal pattern with one rainy season from May to October (LGP=135-140 days) and a dry season from November to April. The mean temperatures vary from 21 to 32°C. The gently-undulating landscape comprises plateaux with an average altitude of 450m above sea level, interspersed with second- or third-order inland valleys. The vegetation of the region is mainly savanna with all the under-types varying from wooded to grassy savanna and some gallery forests. The main activity sectors are agriculture and livestock farming, with lowland rice in the valley bottom lands and subsistence maize and sorghum as well as some cotton cash crop on the valley slopes and plateaus.

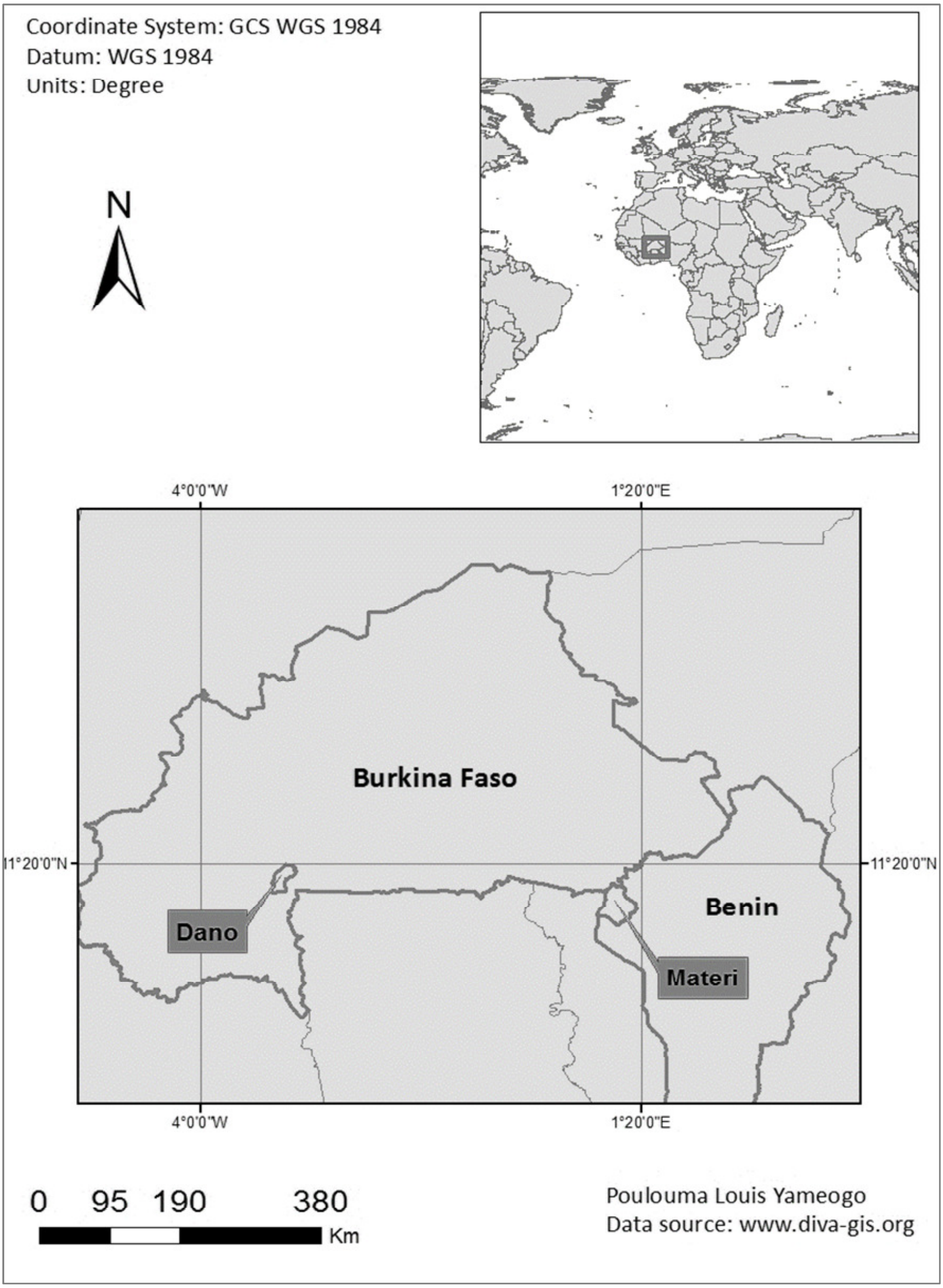

Figure 2.1 Location of the study sites in the Dry Savannah zone of Burkina Faso and Benin

The second site, Dassari (10° 49’ 18’’ Nord, 1° 04’ 3.76’’ EST) is situated in the district of Materi in the sub-humid zone of Benin. The climate is of the Sudano-Guinean type, with a distinct wet seasons from mid-April to mid-October (LGP= 150-160 days) and a dry season from mid-October to mid-April.

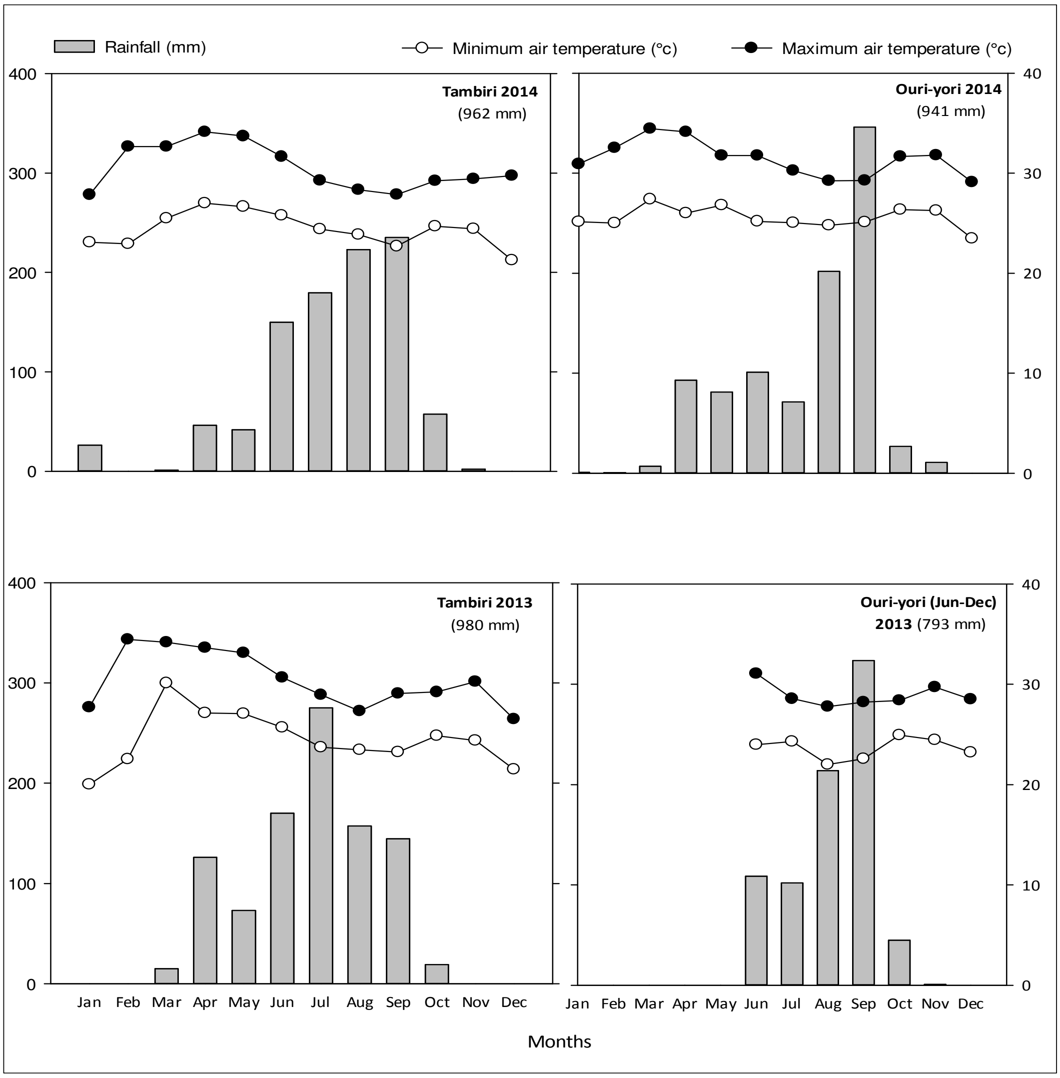

Figure 2.2 Climate conditions (rainfall, mini-max air temperatures) at the experimental sites of Tambiri (Dano, Burkina Faso) and Ouri-yori (Dassari, Benin) in the Dry Savannah zone (2013, 2014)

The rainfall is slightly higher than in Dano with 1 000 to 1 400 mm, with a maximum in August and September. As in Dano, the vegetation is mainly savannah, characterized by trees such as *Vitellaria paradoxa*, *Bombax costatum*, *Ceiba pentandra*, *Borassus aethiopum*, *Hyphaene thebaica*, *Adansonia digitata*, and *Parkia biglobosa.*

The total rainfall and mean air temperature recorded in 2013 and 2014 are presented in Figure 2.2. In Dano, the total rainfall was 981 mm in 2013 and 981 mm in 2014. Air temperatures varied from 19 to 34°c in 2013 and from 21 to 34°c in 2014. As for the Dassari (Ouri-Yori), total rainfall (recorded only from June 2013 onwards) was 793 mm in 2013 with temperatures varying from 22 to 29 °c and 941 mm (whole season) in 2014 with air temperature ranging from 23 to 34°C.

2.2 Soil attributes

According to FAO soil classification, the major soils encountered in the Dano watershed catchment comprise Eutric Cambisols, Plintic Luvisols and Ferric Luvisols on the plateaus and valley slopes (ISRIC, 2013), and Gleyic Fluvisols as well as some Vertisols in the valley bottom lands (Figure 2.3). At the study site in Benin, Ferric Luvisols occupy about half of the upland area at Ouri Yori, with Fluvisols and Gleyic Luvisols dominating the lowlands (Figure 2.4) (ISRIC 2013).

Topsoil samples (0-20 cm) were taken before the implementation of the study in 2013 as composites of 10 individual samples collected along a diagonal transect across the field site. Selected physical and chemical attributes are presented in Table 2.1 and Table 2.2. The soil in the valley bottom at Dano has a clay loam texture, while that at Dassari is clay. At both sites, soils on the slope are mostly loam with an important quantity of gravel (data not presented). Consequently, the bulk density is lower on slope positions compared to the valley bottom soils. The total organic C content at both sites was <1% (2% OM) with resulting N contents ranging from 0.04 to 0.09%.

Soil K is amply available in both soils with 42-79 mg kg^{-1} On the other hand, available soil P (Bray-I extraction) is relatively low in Dano, ranging from 7 to 17 mg kg^{-1}, and is below the critical limit of 3 mg ka-1 at Dassari (0.8-1.6 mg kg^{-1}).

Both soils are slightly acidic with pH (H_2O) of 5-6. However the potential acidity (pH KLC) is only 4.7-5.3. The CEC of the moderately weathered is very low in the wetland soils (about 4 cmol kg^{-1}) with slightly higher values on the upland soils (9 in Dano and 5 in Dassari), but in all cases a very high saturation with aluminum, higher than in the slope position.

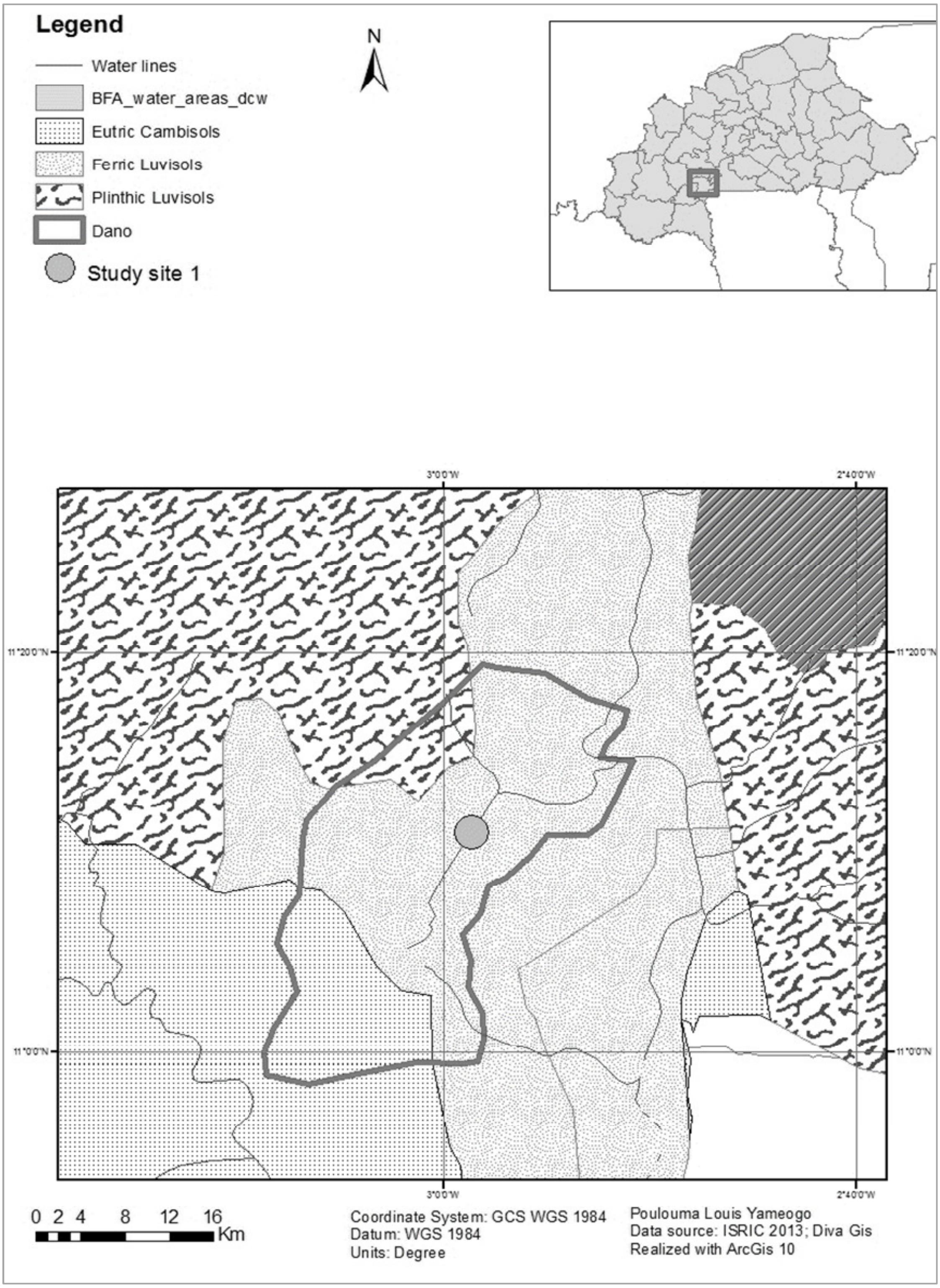

Figure 2.3 Major soil types of the study area in the district of Dano (Burkina Faso). The red marker indicates the study site (Tambiri). Graphic prepared from data obtained from ISRIC (2013) using ArcGIS.

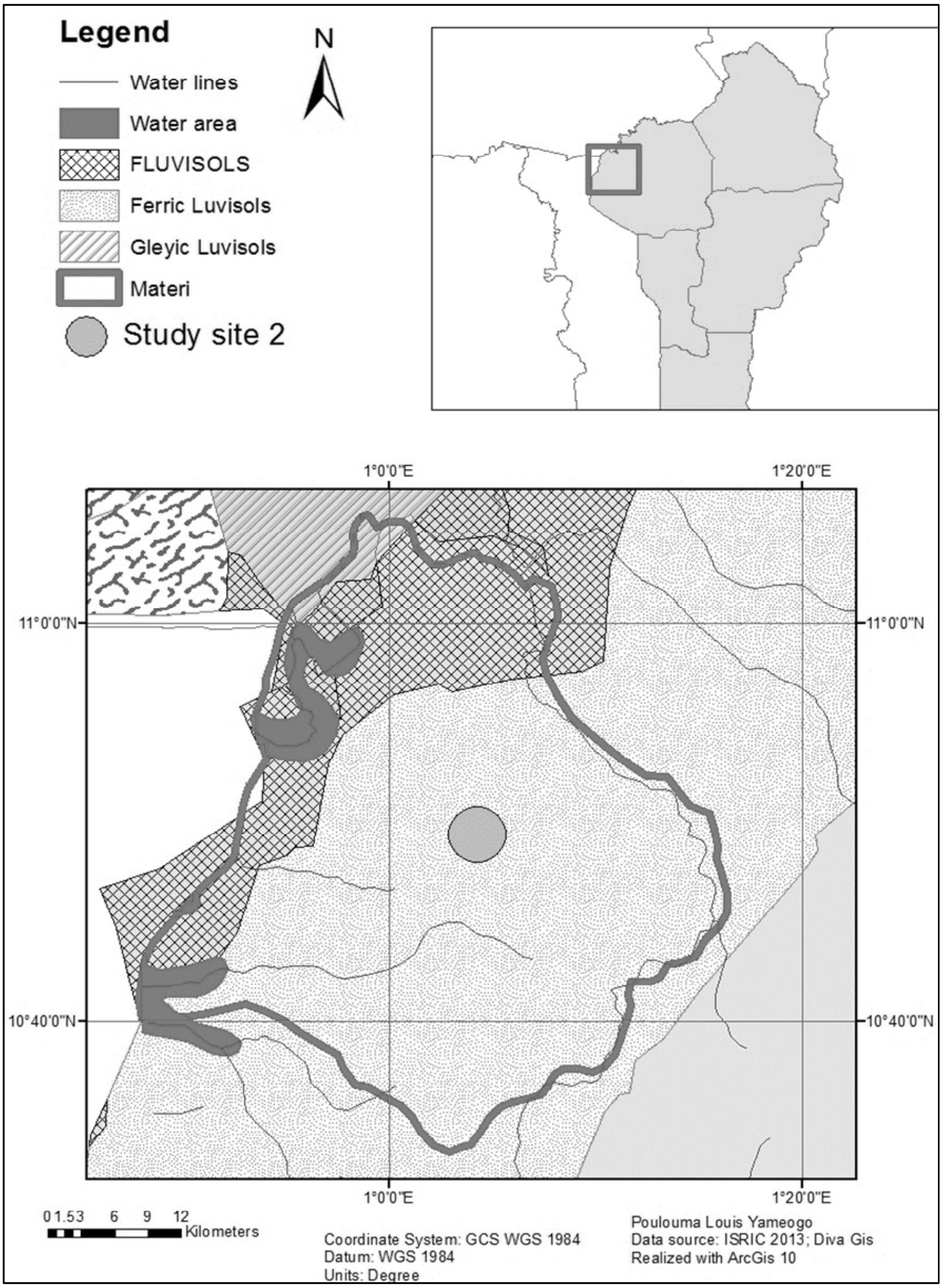

Figure 2.4 Major soil types of the study area in the district of Materi (Benin). Red marker indicates the study site (Ouri Yori). Graphic prepared from data obtained from ISRIC (2013) using ArcGIS.

Table 2.1 Selected physical and chemical characteristics of the soil in Dano, Burkina Faso.

Soil attribute (0-20 cm)		**Lowland**	**Footslope**	**Upslope**
Granulometry	Clay - < 2 µm (%)	38.3	25.0	19.6
	Silts - 2-50 µm (%)	37.3	35.4	43.3
	Sand - 50-2000 µm (%)	24.4	39.6	37.1
	Texture class	Clay loam	Loam	Loam
Bulk density	BD (g cm^{-3})	1.6	1.4	1.2
Organic matter	Total organic C (%)	0.86	0.98	0.77
	Organic matter (%)	1.48	1.7	1.3
	Total N (%)	0.07	0.09	0.07
	C / N ratio	11.3	10.8	11.0
Potassium	Total K (mg kg^{-1})	1403	1334	1130
	Available K (mg kg^{-1})	52.5	79.1	85.4
Phosphorus	Total P (mg kg^{-1})	157	173	132
	Avail. Bray-I P (mg kg^{-1})	7.5	2.4	17.0
Exch. cations	Ca^{2+} (cmol kg^{-1})	7.9	3.7	4.2
	Mg^{2+} (cmol kg^{-1})	1.9	1.0	1.1
	K^{+} (cmol kg^{-1})	0.1	0.2	0.2
	Na^{+} (cmol kg^{-1})	0.14	0.05	0.03
	Sum exch. cations	10.1	4.9	5.5
	CEC (cmol kg^{-1})	9.7	4.7	4.5
	Base saturation (%)	105	105	123
Soil reaction	pH (H_2O)	6.0	5.9	6.1
	pH (KCl)	5.1	5.2	5.3

2.3 Plant material

The lowland rice (*Oryza sativa* L.) variety used in all experiments (TOX 728-1, released in Burkina Faso under the name FKR 19) was obtained from the INERA rice research station at Farakoba. It is a short-cycled improved variety with 100-110 days of growth duration, a yield potential estimated at 6 Mg ha^{-1}, and reportedly adapted to rainfed growing conditions (Sie et al. 2006).

Table 2.2 Selected physical and chemical characteristics of the soil in Dassari, Benin.

Soil attribute (0-20 cm)		**Lowland**	**Footslope**	**Upslope**
Granulo-metry	Clay - < 2 µm (%)	43.2	19.3	15.2
	Silts - 2-50 µm (%)	34.9	31.5	36.9
	Sand - 50-2000 µm (%)	21.9	49.2	47.9
	Texture class	Clay	Loam	Loam
Bulk density	BD (g cm^{-3})	1.6	1.4	1.2
Organic Matter	Total organic C (%)	0.59	0.4	0.49
	Organic matter (%)	1.01	0.69	0.84
	Total N (%)	0.05	0.035	0.04
	C / N ratio	10.3	11.0	10.4
Potassium	Total K (mg kg^{-1})	673	409	663
	Available K (mg kg^{-1})	47.5	74.0	42.0
Phosphorus	Total P (mg kg^{-1})	65.0	41.0	77.0
	Avail. Bray-I P (mg kg^{-1})	0.8	1.3	1.6
Exch. cations	Ca^{2+} (cmol kg^{-1})	2.6	2.1	3.0
	Mg^{2+} (cmol kg^{-1})	0.6	0.5	0.6
	K^+ (cmol kg^{-1})	0.1	0.2	0.1
	Na^+ (cmol kg^{-1})	0.04	0.04	0.03
	Sum exch. cations	3.4	2.9	3.7
	CEC (cmol kg^{-1})	4.73	2.3	4.0
	Base saturation (%)	72	125	94
Soil reaction	pH (H_2O)	5.3	5.2	5.1
	pH (KCl)	4.8	4.7	4.8

Three pre-rice crops have been used, including forage cowpea (*Vigna unguiculata* L.), velvet bean (*Mucuna cochinchinensis* L.), and panicum (*Panicum maximum* L.). The two annual legumes are suited for use as green manures but can also contribute edible grain (Vigna), medicinal products (Mucuna) and forage uses (both). Panicum is mainly used a perennial forage grass. Seeds of all three species were obtained from INERA in Farakoba.

2.4 Soil analyses

Soil sampling involved composites of 7 core samples taken at 0 – 15 cm, with a gravimetric auger. About 20g ±1g field moist soil was extracted with 40 mL of 0.01 M $CaCl_2$. The soil/extractant mixture was shaken for 3 min and filtered through filter paper. A second subsample of soil (20g) was dried at 105°C for 24 h to determine the dry weight of the soil

2.4.1 Nitrate / ammonium sampling and analysis

The nitrate-N concentration was determined by two methods: At concentrations of >5 mg kg L^{-1}, a quick test colorimetric method was applied, using a NitraCheck 404 (range from 5 to 500 ppm NO_3-N) portable photometer, following the method described by Schmidhalter (2005). At nitrate-N concentrations of <5 mg kg L^{-1}, analyses were performed using a PHotoFlex STD (WTW-82360 Weilheim, Germany). A volume of 1 ml of sample was added in a reaction tube. After mixing/reversal of the reaction tube (10 x), one bag of VARIO Nitrate Chromotropic was added. After 5 minutes, the reaction tube is then inserted in the photometer and nitrate concentration is read using program N° 314 (0.2 – 30 mg l^{-1} NO_3-N). The principle of the reaction involves the reduction of nitrate to nitrite and the subsequent formation of red colour complex involving a mixture of n-naphtyl and sulfonile-amid. Vertical translocation of nitrate in the soil profile was assessed along the toposequence using MacroRhizons soil moisture samplers (Seeberg-Elverfeldt et al*.* 2005). Collected solution was analyzed directly in the field for NO_3-N using either the nitrachec test strips (>5 mg kg-1) or the photometry (<5 mg kg-1). Solution samples were collected from 0-15 cm soil depth in the shallow upland soils and from 0-15 as well as 15-30 cm soil depth in the deeper lowland soils.

Cumulative soil NO_3-N and NH_4-N was determined using ion exchange resin capsules (UniBest Inc., Washington, USA). Three capsules each were inserted at soil depths of 10, 20 and 30 cm (three internal replications) at the beginning of the observation seasons (dry-to-wet season transition period - DWT). Capsules were removed at the end of DWT, rinsed with distilled water, and absorbed ions were extracted three consecutive times with 20 mL of 2N HCl. The filtered extract was analyzed for NO_3-N and NH_4-N concentrations using a portable “PHotoFlex STD” (WTW-82360 Weilheim, Germany) photometer. VARIO Nitrate Chromotropic was added for nitrate and VARIO AMMONIA Salicylate F5 and VARIO AMMONIA Cyanurate-F5 for ammonium determination (program N° 313).

The quantity of resin-absorbed nitrogen (RAQN) was expressed as ion-loading:

$$\boldsymbol{RAQN}\ (\mu\boldsymbol{mol/cm}^2) = \frac{\mathbf{C*V}}{\mathbf{M*A}}$$

C = NO_3-N / NH_4-N concentration (mg l^{-1}),
V = Total volume of the extracting solution per capsule (40 ml),
M = Molar weight of nitrogen (14)
A = Surface area of the capsule (11.4 cm^2)

2.4.2 Soil moisture.

Soil moisture at upslope and foot slope has been recorded by an automatic weather station (Camplell Scientific Inc. CR1000) installed by the Hydrology group of WASCAL core research program (Steup, 2016). Soil moisture was measured at 0-20 cm and at 20 – 30 cm). In the lowland, additional Time Domain Reflectometry (TDR) sensors were installed (Figure 2.5) at depths of 10, 20, and 30 cm. Data were recorded via ECH20 EC-5 dielectric sensors connected to a data logger (Em50) and expressed in a daily mean values of volumetric soil moisture. These soil moisture data were used to for translating the nitrate concentrations measured in soil solution to nitrate amounts on a unit area basis.

2.5 Plant analysis

Plant material involved rice as well as pre-rice crops. The above ground biomass was removed and dry matter was estimated after oven-drying at 70° C until constant moisture. Dried material was rough ground and a sub-sample of 50 g were fine-ground for further analyses. Total N uptake by plant material was determined following the Kjeldahl method. Biological nitrogen fixation (*Ndfa*) of the N-fixing cover crops (Cowpea and Mucuna) was determined following ^{15}N natural abundance method described by Peoples et al. (1989), Unkovich and ACIAR (2008), using Panicum as the non-fixing reference plant. The $^{15/14}$N ratios were determined using an ANCA-SL 2020 mass spectrometer at the Institute of Crop Science and Resource Conservation at the University of Bonn. The share of N derived from the atmosphere (%Ndfa) was calculated as follows (Amanuel et al., 2000):

$$\%\text{Ndfa} = \frac{\mathbf{\delta 15N\ of\ reference\ plant - \delta 15N\ of\ N_2\ fixing\ legume}}{\mathbf{\delta 15N\ of\ reference\ plant - B}}\ \mathbf{X\ 100} \qquad (1)$$

$$\text{N fixed} = \frac{\%\text{Ndf}}{100}\ \text{X legume N (kg ha}^{-1}\text{)} \qquad (2)$$

A “B-value” of -3.5‰ ^{15}N (natural isotopic discrimination) was applied for cowpea and -1.5‰ ^{15}N for Mucuna (Peoples et al. 1989).

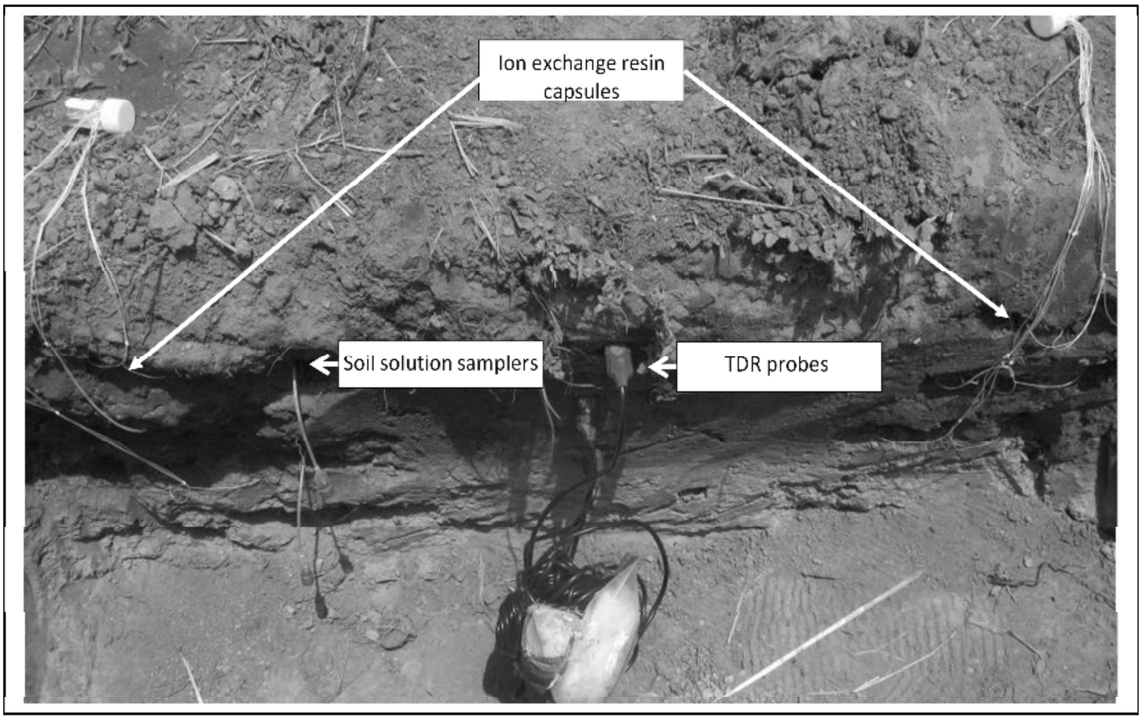

Figure 2.5 Soil instrumentation with sampling devices (ion exchange resin capsules, MicroRhizon moisture samplers and TDR probes).

2.6 Data analysis

All experimental results are based on arithmetic means of three replications. Standard errors of the mean (n=3) were applied in graphical data presentations. Analysis of variance (ANOVA) was performed using Stata/SE 12.1, using Bonferroni method for mean separation ($p<0.05$). Graphics were prepared using SigmaPlot, version 12.

3 SEASONAL SOIL N DYNAMICS AND THEIR EFFECT ON LOWLAND RICE IN AN INLAND VALLEY OF BURKINA FASO

ABSTRACT

Rainfed lowland rice farmers in the inland valleys of the Dry Savanna zone of Burkina Faso are challenged with N deficiency as a major production constraint. With extremely low use of external inputs, there is a need to efficiently use systems' internal resources such as native soil N. Organic matter starts to mineralize with the onset of the rains after a prolonged dry season, leading to transient peaks of nitrate in the soil. Substantial amounts of this nitrate may be translocated to the lowlands by (sub) surface flow from adjacent valley slopes. Largest soil nitrate-N losses are expected to occur in lowlands when the soil aeration status changes from aerobic to anaerobic conditions. We quantified seasonal soil N dynamics along the toposequence of an inland valley and assessed the effect of slope N contribution to the yield of lowland rice near Dano in Burkina Faso during the transition period between the dry and the wet season (DWT) of 2013 and 2014. Soil N mineralization and nitrate accumulation and translocation (both vertical and horizontal) were determined in soils solution sampled 3 times per week and by ion exchange resin capsules (cumulative N mineralization during DWT). The biomass and yield of rice were determined in both the absence and the presence of nitrate fluxes. With the onset of the first rains, soil nitrate accumulated, reaching peaks of 20-45 kg N ha^{-1} after about 25 days. Some 10-15 kg of the nitrate in lowland soils was contributed via interflow from the slope, corresponding to an addition of 11 and 13 µmol cm^{-2} RAQ-N in 2013 and 2014, respectively. Subsequently, nitrate gradually decreased in the upland soil and 77-80% disappeared in the lowland upon reaching soil saturation around day 60. Despite substantial nitrate-N losses, N contribution from the slope increased the N uptake of rice by 11 kg ha^{-1} and the grain yield by 0.4 Mg ha^{-1}. We conclude that intense N dynamics occur during DWT and that rice benefits from nitrate losses from the valley slope into the lowland. Given the substantial amounts of unaccounted nitrate, appropriate options for soil N management are required to minimize native soil N losses and to enhance rice productivity in the low-input production systems in inland valleys of West Africa's dry savanna zone.

Keywords: Dry Savanna zone, Ion exchange resin, Nitrate, *Oryza sativa*, West Africa.

3.1 Introduction

In Burkina Faso, rice (*Oryza sativa* L.) is one of the most important cereal crops and the main crop produced in inland valleys of the Dry Savanna zone. In the predominant smallholder rainfed production systems, N deficiency is widespread and a major production constraint. Besides soil N limitations (0.07-0.09 mg N kg^{-1}), soils are also generally low in soil organic C (1.3-1.7%). The return of crop residues is limited by the low overall production of biomass and its competitive uses as fodder, construction material and cooking fuel (Erenstein 2002). The continuous removal of crop residues results in a further decline in SOC (Hammerbeck et al. 2012) and hence the reduction of soil N supplying capacity (Gami et al. 2001). In the absence of residue return and the prevailing low application of external inputs, there is a need to more efficiently use systems' internal resources such as native soil N reserves.

In the seasonal savanna climate, the transitional period between the dry and the wet season (DWT) is subjected to intense change processes. With the onset of the first rains, soil microbial activity results in soil N mineralization (Birch 1960) and the accumulation of nitrate in the profile, particularly in the absence of a vegetation cover (Pande and Becker 2003). With the filling of the pore space at the onset of the main rains, the nitrate-N fraction is prone to leaching, but also to being used as a terminal electron acceptor for microbial respiration (denitrification). Thus, DWT experiences in the first place a large accumulation of N in the profile and subsequent nitrate fluxed and N losses (Becker et al. 2007).

This seasonal dynamics of soil moisture and native soil N are further exacerbated in the inland valley landscape. With soil saturation, rainwater is not only vertically translocated in the soil profile. Water and dissolved ions can also move horizontally, once reaching the largely impermeable saprolyte layer in the profile (Windmeijer and Andriesse 1993). Thus, nitrate-N is leached from the light-textured upland and slope soils into deeper soil layers and eventually into the lowland. There, lateral influxes of water and nitrate increase both the extent of the Birch effect (nitrate peak) and the speed of change in soil aeration status in the lowland (Bognonkpe and Becker 2009), with resulting effects on denitrification losses (George et al. 1998).

This study aimed to assess the extent and the dynamics of native soil nitrate-N, to quantify the vertical and lateral translocation of nitrate-N along the toposequence and to evaluate the effect of N translocation on the performance of lowland rice in an inland valley of the semi-arid zone of Burkina Faso.

3.2 Material and methods

3.2.1 Study site

The present study has been conducted in the watershed catchment of Dano (Burkina Faso) from 2013 to 2014. Characteristics of the study site have been presented in Chapter 2.

3.2.2 Treatments application

We assessed the spatial-temporal dynamics of soil nitrate along a toposequence. The upland was differentiated into an up-slope and a foot-slope sampling position in each of which three bare fallow plots of 6 x 4m were randomly distributed following a complete randomized design. Assessing nitrate contribution from the slope to the valley bottom required two sub-treatments at the hydromorphic valley fringe, where the subsurface flow water is welling up (intercept vs. open). On half of the area, horizontal fluxes of water and nitrate were blocked by digging a 15m long interception trench down to the saprolyte layer and quantifying and subsequently laterally deviating the flows towards the center of the lowland (“intercepted”). The neighboring “open” area (no interflow interception) served as reference. The difference in soil moisture/water, nitrate content and N amounts between the “intercepted” and the “open” areas allowed determining the slope contribution to the lowland. Rice was grown and N uptake and yields were assessed in the lowland, both the “intercepted” and the “open” areas during the wet season. In each of the two main treatments in the hydromorphic fringe, rice was established at 20 cm x 20 cm spacing in 4 x 3m subplots, representing three replications. Direct seeding was used in 2014 with 2 grains/hill. In 2014, rice was transplanted using two 25-day-old seedling/hill.

3.2.3 Soil and nutrient sampling

Before the onset of the experiment, reference soil samples were taken for soil attributes. Additionally, biweekly samples were taken during DWT between mid-April and early July and transported to the laboratory for within 2 hours for N_{min} extraction and nitrate determination as described in Chapter 2. All samples were pooled composites of seven topsoil auger samples (0-15 cm), collected across a diagonal of each plot. Soil solution was sampled in each treatment at weekly intervals at 0-15 cm depth in both upslope and foot slope and at 0-15 cm and 15-30 cm in the lowland positions. Concentrations of nitrate in soil solution were measured by a colorimetric quick-test or by photometric methods as described before. Based on soil moisture content (TDR) and bulk density, the nitrate concentrations were transformed into total amounts of N per unit area. The cumulative total nitrate and ammonium (N_{min}) mineralized during DWT was assessed using ion exchange resin capsules. At each position and profile depth, and in both “open” and “intercepted” lowland sites, three capsules were inserted (internal replications) before the first rain and removed before the establishment of the rice crop after 12 weeks. NO_3-N and NH_4-N were extracted and analyzed as described in Chapter 3.

3.2.4 Rice biomass and yield

The contributing effect of subsurface nitrate flows on rice performances was determined (1) as sequential biomass accumulation at 28, 56 and 84 days after transplanting (based on 5 hills cut at ground level), (2) as grain yield based on a $4m^2$ harvest area and reported at 14% moisture, and (3) as total N uptake by grain and straw. After oven-drying and weighing, biomass samples were analyzed following the micro-Kjeldahl procedure.

3.2.5 Data analysis

Results are expressed as arithmetic means of 3 replications. Analysis of variance (ANOVA) was performed using Stata 12. For mean comparison, Bonferroni method was used. Regression analyses were performed using R. Results are presented in figures realized with SigmaPlot, version 12.

3.3 Results

This section presents the key findings on (1) the temporal dynamics of soil NO_3-N along the toposequence, (2) the vertical translocation of NO_3-N, and (3) the effect of nitrate contributed from the slope on the performance of lowland rice.

3.3.1 Soil moisture and nitrate-N dynamics

The dynamics of topsoil NO_3-N along the toposequence during the dry-to-wet season transition periods of 2013 and 2014 and its relation to rainfall and soil water content is presented in Figure 3.1. During the dry season, starting in November and lasting until the first rainfall event in April of the following year, soils are generally dry. With the onset of the rain, soil water content increases after each rainfall event during DWT, and more so in the lowland than the foot slope or the up-slope positions. Volumetric soil water varied between 2-20% on the upslope, between 4-19% in the foot-slope, and between 8-32% in the valley bottom in 2013 (174mm during Julian days 60-147). Lower soil water and less spatial-temporal variability (4-20%, irrespective of the toposequence position) was observed in the relatively dry year of 2014 (88mm during Julian days 90-155).

Nitrate-N dynamics can only be presented for part of the DWT in 2013 (no data available from Julian date 80 to 102). Nevertheless, initial soil nitrate was <5 kg ha^{-1} at the end of the dry season. Towards the end of DWT, 20 kg N ha^{-1} were recorded. Upon reaching 30% volumetric moisture on Julian date 115 or soil saturation at the onset of the main rainy season on Julian date 145, nitrate was <5 kg N ha^{-1} in upland soils and non-detectable in the lowland soil. In 2014, we observed a gradual increase in nitrate up to 45 kg N ha^{-1} three weeks after the first rain, and a subsequent gradual decline to about 15 kg N ha^{-1} when soil moisture exceeded 18%. At the onset of the main rains and with the associated saturation of the lowland positions, no more nitrate was detectable. Out of a cumulative mineralization of 23 kg N ha^{-1} in the foot-slope and 45 kg ha^{-1} in the up-slope positions, 60-80% was no longer present at the end of DWT. In the lowland, some 67 kg of cumulative soil nitrate-N ha^{-1} mineralized during DWT had disappeared completely from the soil at rice transplanting and can be assumed lost.

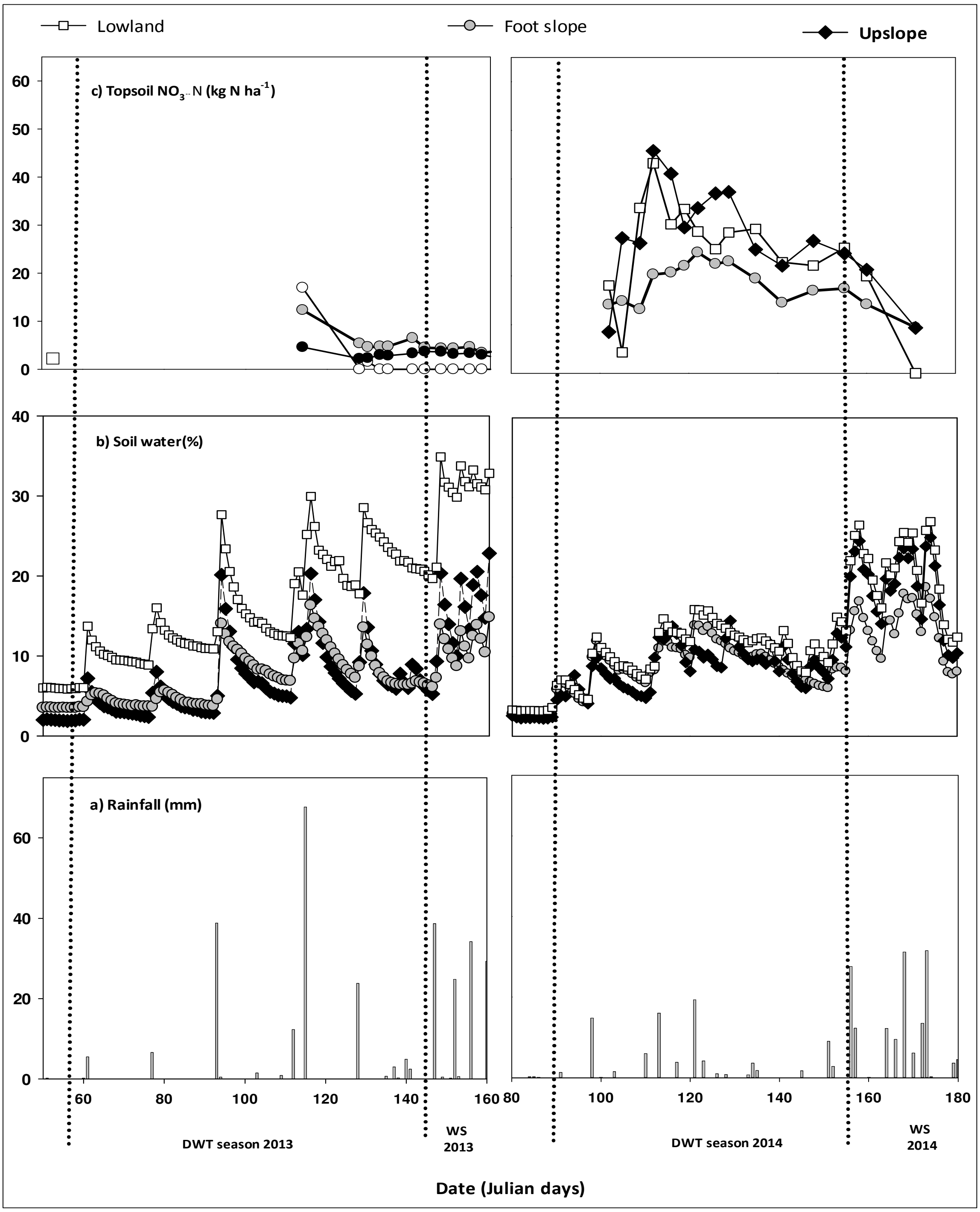

Figure 3.1 Rainfall-related dynamics of soil water and nitrate-N in the topsoil (0 – 15 cm) during the dry-to-wet transition season at three toposequence positions in an inland valley of Burkina Faso (Dano, 2013-2014)

In general, amounts of solution nitrate confirm the trends and the nitrate dynamics observed from soil extracts, being again significantly higher in 2014 than 2013 (P=0.001), but presenting only about 50-60% of the nitrate detected by soil extraction. Data presented in Figure 3.2 show only Julian dates 130-180 for 2013 and 145-188 for 2014. As with soil extract, solution nitrate was highest in the lowland, reaching 21 kg ha^{-1} and being significantly higher than in the upland positions with 7-11 kg N ha^{-1}.

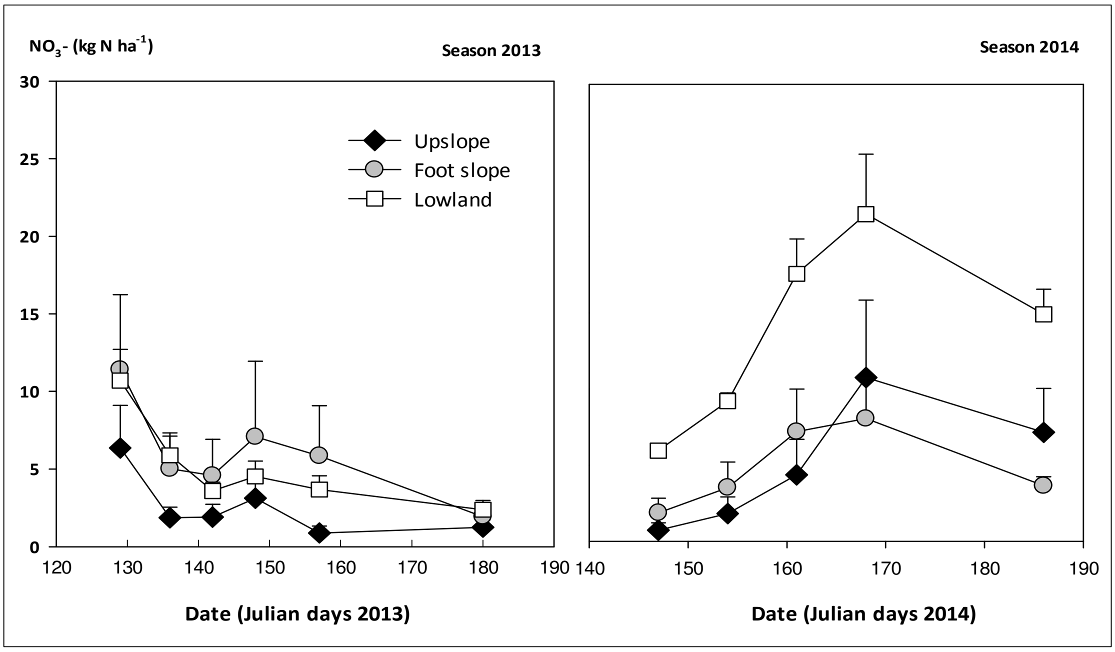

Figure 3.2 Seasonal dynamics of soil solution nitrate during the dry-to-wet season transition at three toposequence positions in an inland valley of Burkina Faso (Dano, 2013-2014). Bars present standard errors of the mean (*n=3*)

3.3.2 Cumulative N_{min} and lateral nitrate fluxes

Cumulative N_{min} mineralization during DWT was assessed using ion exchange resin capsules. They were installed in the lowland position, both in open and intercepted sub-area to determine horizontal N fluxes or the contribution of subsurface flows of N_{min} (NO_3-N; NH_4-N) from the slope to the valley bottom. The Resin-Adsorbed Quantities (RAQ) of N_{min} during the DWTs of 2013 and 2014 are presented in Figure 3.3. Regardless of the year or the profile depth, the nitrate fraction dominated the soil N_{min}, particularly in areas open to subsurface interflow. The ammonium content was similar across years with 2-3 µmol NH_4-N cm^{-2}, irrespective of the soil layer. Nitrate, on the other hand, tended to be higher in the deeper soil layer and across the soil profile (0-40 cm) exceeded the nitrate absorption in open by 11-12 µmol NO_3-N cm^{-2} over the intercepted areas.

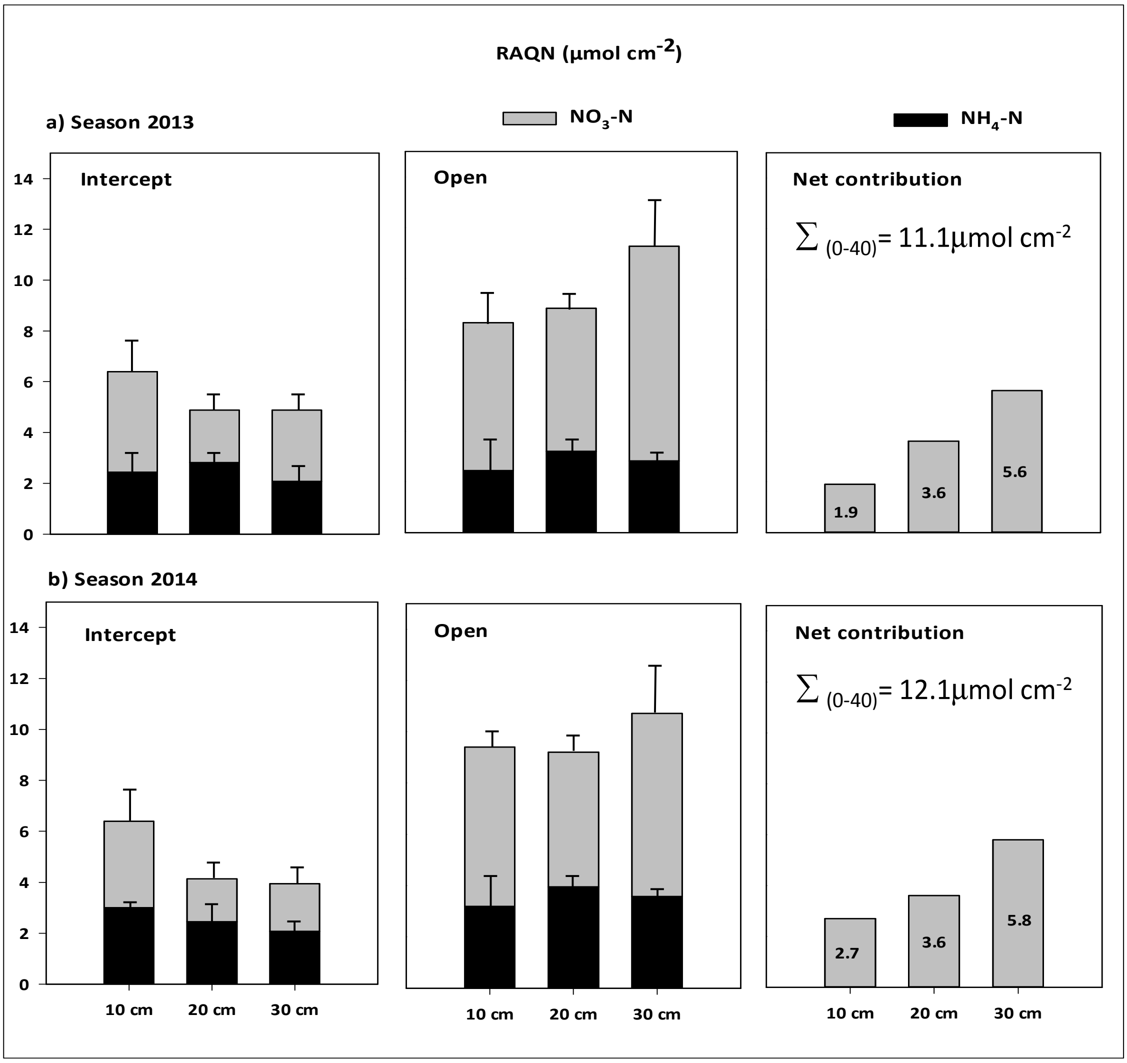

Figure 3.3 Cumulative soil N_{min} quantities absorbed by ion exchange resin (RAQ-N) during the dry-to-wet transition season period in an inland valley of Dano, Burkina Faso (transition season 2013, 2014)

3.3.3 Rice crop response to soil nitrate interflow

Rice biomass accumulation, grain yield, and total N uptake were assessed in the lowland in 2013 and 2014, both in absence and the presence of interflow contribution. Results of these parameters during the vegetative phase and at maturity are presented in Figure 3.4. Cumulative NO_3-N translocated into the valley bottom was similar in both years, and rice tended to respond to this N influx. Sequential biomass accumulation at 28, 56 and 84 days after seeding (DAS) and at harvest tended to be more in areas open to subsurface interflow and was significantly higher at 84 days after crop establishment in 2013 and at harvest in both 2013 and 2014. At harvest, the total biomass reached 4.6 t ha^{-1} in open areas in 2013 and 4.3 t ha^{-1} in 2014. Particularly the biomass of the rice straw was significantly lower ($P < 0.05$) in areas with interflow interception with 1.9 Mg ha^{-1} in 2013 and 1.4 Mg ha^{-1} in 2014. The rice grain yield followed the same trend with 2.0 and 2.3 t ha^{-1} in open areas and only 1.6 and 1.8 t ha^{-1} in interception areas in 2013 and 2014, respectively (not significant in 2013). The total N uptake (grain + straw) ranged from 62 to 90 kg ha^{-1} in open and from 45-62 kg ha^{-1} in interception areas and differences were significant in 2014. A multiple linear regression between rice grain yields and interflow attributes showed no effect of soil water, while interflow N and crop N uptake were significantly related to grain yield (Table 3.1). The model explained 99% of the variance and indicates that 4 kg of nitrate interflow result in 1 kg additional crop absorbed N (25% use efficiency) and a rice yield increase of 52 kg grain.

Table 3.1 Relationship between rice grain yield and interflow attributes on (1) crop N uptake, (2) soil water content, and (3) N fluxes into the lowland of an inland valley in Burkina Faso

	Estimate	Std. Error	Pr (>|t|)	Probability
Intercept	479	629	0.475	
N uptake	58	8	0.000	0.001
Interflow nitrogen	400	152	0.039	0.05
Interflow water	- 0.271	0.874	0.766	
	$R^2 = 0.9935$; P value = 1.07 e^{-06}			

3.4 Discussion

3.4.1 Soil nitrate-N dynamics

As shown is several previous studies and confirming the concept of the “Birch Effect”, the onset of the rains after a prologued dry season results in the accumulation of N_{min}

(mainly nitrate) in the soil profile. The onset of the main rainy season entail changes in soil aeration status with associated risks of nitrate-N losses by leaching and/or denitrification (Pande and Becker 2003; Logah et al. 2011, Cacciotti et al. 2011; Unger et al. 2012). In the first place, nitrate is vertically translocated (leached) in the soil profile as indicated by higher nitrate concentrations in the sub- than in the topsoil as reported before (Smethurst et al. 2014). However, and in contrast to previous work, this study highlights the additional importance of landscape effects in inland valleys.

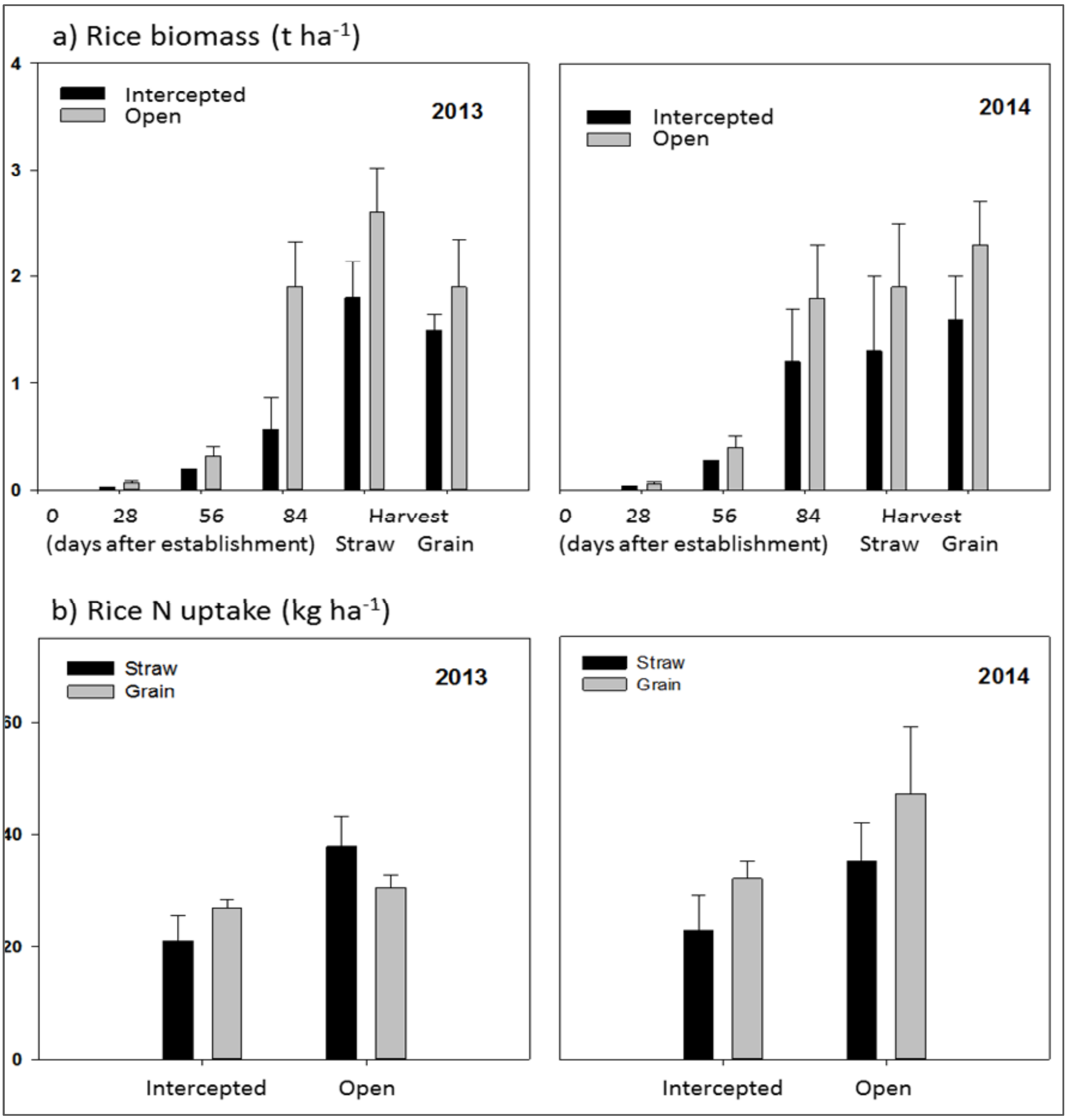

Figure 3.4 Rice N uptake, biomass accumulation and grain yield response to native soil and inflow nitrogen in an inland valley of Burkina Faso (Dano, 2013, 2014). Bars present standard errors of the mean (*n=3*).

Thus, in addition to the reported *in-situ* mineralization dynamics, our work could show a substantial contribution of the soil N_{min} in the lowland by addition from adjacent slopes. This assertion is confirmed by the difference of RAQ-N between the treatments with and without interflow interception. Indeed, regardless of the year, RAQ-N indicate some 11-12 µmol cm^{-2} of nitrate being translocated from the slope into the valley bottom. As the wetland is more prone to rapid changes in soil aeration status than the well-drained upland or slope soils (George et al. 1998), the risk of nitrate N losses is exacerbated but such interflow effects. Such seasonal movements of the soil nitrate along the toposequence are reportedly responsible for stream nitrate export in agricultural headwater catchments (Molenat et al. 2008). The complete disappearance of soil nitrate upon soil saturation combined with the presence of an impermeable layer in the soil at around 40 cm depth points towards a high likelihood of N losses by denitrification as shown in a rice-wheat rotation system in Nepal.

While the trends observed were similar in both years, the dryer conditions in 2014 and the later onset of the main rains compared to 2013 extended the length of DWT and hence the period where soil N mineralization takes place. The rainfall-related extension of DWT duration can increase the amount of nitrate accumulated in the soil as indicated by George et al (1993). Such an increased length of the period of soil N mineralization also offers possibilities of managing soil nitrate and preventing its losses, i.e. by absorbance in a growing “nitrate catching” crop (George et al. 1998; Becker et al. 2007). On the other hand, wet years or rapid changes in soil aeration status by heavy precipitation will not only shorten DWT and hence the amount of soil N mineralized, it may also prevent the application of such nitrate-conserving agronomic options (too short growing period) and hence making nitrate N losses unavoidable. Depending on the model used and on the assumptions made, both drier and wetter scenarios are forecast for the near future in West Africa (IPCC 2014). These futures of precipitation will determine both the magnitude of N mineralization, the intensity of soil N dynamics, the nitrate N losses and possible opportunities to manage and save native soil N.

3.4.2 Rice crop response

While lateral flow of water from the slope reportedly increases the performance of rainfed lowland rice (Toure et al. 2009), curbing this inflow by physical interception in the present study did not negatively affect rice, and the observed positive effects related to N inputs outweighed any possible induced water deficit. Despite the apparent substantial loss of soil nitrate upon soil saturation or flooding, lowland rice did benefit from both native (*in-situ* mineralized) and interflow N, responding with increased N uptake and higher yield. Similar observations have been reported from Ivory Coast where rice yields declined in the presence of a physical barrier that deviated subsurface water flows from a valley slope (Bognonkpe 2004). Thus increased N influxes stimulated rice N uptake and increased grain yield as reported before (Yameogo et al. 2013). These findings suggest that against evidence, not all nitrate is lost from the soil. It is conceivable that substantial amounts of native soil nitrate (both *in-situ* mineralized and laterally translocated) have been temporarily immobilized, possibly, in the soil microbial biomass (Becker et al. 2007) or in the biomass of weeds associated with rice (George et al. 1993). However, the rice yield observed was far below the reported yield potential of the variety used (Sie et al. 2006) or the yield responses suggested by the amounts of soil N mineralized during DWT and/or those translocated into the wetland (i.e. 50 kg grain yield per kg of N), indicating that improved management of native soil N may significantly improve rice performances and contribute to closing the large yield gap reported for rainfed rice in West Africa (Becker et al. 2003; Haefele et al. 2013).

3.5 Conclusion

With the onset of the first rains and the rewetting of dry soil, mineralization processes start and result in a transient peak of soil nitrate during DWT. In a valley landscape, lateral subsurface water flows contribute further nitrate from the slope to the valley bottom wetland. While much of this nitrate is unaccounted for upon soil saturation or flooding, lowland rice benefits from both *in-situ*-mineralized and inflow contributed nitrate-N. An improved management of this nitrate is likely to further increase rice productivity in inland valley of the dry savanna zone of West Africa.

4 MANAGEMENT OF SEASONAL SOIL NITROGEN DYNAMICS AND ITS EFFECT ON LOWLAND RICE YIELD

ABSTRACT

Rice (*Oryza sativa* L.) in low-input systems of West Africa generally depends on nutrient supply from the soil. This is particularly true for nitrogen (N), which often unavailable or costly in its mineral forms. Associated with non-adapted cropping practices, rice yields are far below the ago-ecological and genetic potentials of the used varieties with nitrogen being most limiting production factor. During the dry-to-wet transition season (DWT) in rainfed lowlands of the savanna zone, soil N is mineralized *in-situ* following the rewetting of the dry soil after the onset of the rains. In addition, in inland valley landscapes, some nitrate is also translocated from the adjacent slopes into the valley wetland. In the absence of a vegetation cover or conservation measures, much of the nitrate fraction in the lowland soils is prone to losses by leaching and/or denitrification. Management interventions are urgently required to improve soil N use efficiency and consequently reduce the wide gap between potential and actual yields. A field experiment was conducted to assess the effect of pre-rice vegetation or “nitrate catch crops” on soil N dynamics and on the agronomic performance of lowland rice in Dano (Burkina Faso). Vegetation cover acted as a “nitrate catch crop”, significantly reducing the build-up of soil N_{min} during DWT from 50-75 kg N ha^{-1} in the bare fallow to 8-25 kg N ha^{-1}. Nitrogen accumulation by the biomass of transition season vegetation ranged from 41-56 kg N ha^{-1} in the absence of subsurface interflow from the slope. In the presence of interflow, panicum (*Panicum maximum* L.) accumulated 73, velvet bean (*Mucuna cochinchinensis* L.) accumulated 79, and cowpea (*Vigna unguiculata* L.) accumulated 86 kg N ha^{-1}, and during DWT. The contribution of biological N_2 fixation in the legumes ranged from 30-50% Ndfa. Rice agronomic performance improved following the incorporation of this transition season vegetation. Thus, non-fixing panicum increased rice grain yield by 1.0 t ha^{-1} compared to the bare fallow control. Yields further increased with N_2-fixing transitions season crops to 2.9 and 3.8 t ha^{-1} with mucuna and cowpea, respectively. Thus, integrating transition season crops in the prevailing low-input lowland rice-based systems in inland valleys of the dry savanna zone of West Africa can immobilize and conserve substantial amounts of soil nitrate, add biologically-fixed N in case of legumes, and contribute to increasing rice yields in the short-term and maintaining soil fertility in the long-term.

Keywords: Burkina Faso, nitrate catch crops, *Oryza sativa*, transition season, yield gap.

4.1 Introduction

Rice consumption steadily increases in West Africa due demographic growth, recent changes in consumer preferences, and increasing rates of urbanization (Africa Rice Center 2011). In Burkina Faso, rice constitutes the fourth cereal cultivated after sorghum, millet and maize (CEFCOD 2013). After the food crisis in 2008, the national production increased significantly but still covers only 47% of the demand (SNDR 2011). Importing the shortfall in production entails costs of an estimated US$ 82 million (SNDR 2011). Bridging the gap between supply and demand appears to be a critical challenge to cope with undernutrition in rural area. Potentially highly productive irrigated system cover only 23% of the total rice production area (INERA and DGPER 2010), and most rice is produced under rainfed conditions. Recent increases in national rice production largely stem from irrigated environments (Guissou and Ilboudo 2012; FAO 2014), while rainfed production stagnates at yield levels of around 1.3 t ha^{-1} (Bazié et al. 2014). Thus, rainfed lowland systems cover 62% of the rice production area, but contribute only 46% of the national production (Ouedraogo et al. 2011).

Small-scale farming predominates in the rainfed lowlands in inland valleys of the savanna zone and is characterized by low or no use of external inputs such as fertilizers (Africa Rice Center 2011). The nutrition in rainfed rice thus relies largely on native soil nutrient supply. Nitrogen deficiency is particularly wide-spread, affecting crop yields (Henao and Baanante 1999; Segda et al. 2014). While mineral or organic N applications enhance crop N uptake and grain yield (Dobermann and Fairhurst 2000; Segda 2006, Yameogo et al. 2013), current fertilizer use is below 12 kg ha^{-1} (Saito et al. 2013) and farmers' yields are far below the climatic and genetic potential (Saito et al. 2012; Haefele et al. 2013). Increasing the rice yields in rainfed environments requires thus options aimed at an improved management of system-internal N resources such as native soil and biologically-fixed N (Becker et al. 2007).

Particularly during the dry-to-wet season transition period (DWT) when the soil aeration status changes from aerobic to anaerobic, and before rice establishment, substantial amounts of native soil N are lost by nitrate leaching and denitrification

(Bognonkpe and Becker 2009), leading to N deficiency in rice and low and declining yields (Becker et al. 2007). Management of soil native N by the avoidance of losses during DWT appear to be of a particular importance in low-input systems to enhance grain yields in the short-term and to maintain soil fertility in the longer term (Becker et al. 2007). Such management options aim at avoiding the build-up of mineralized N_{min} in the soil, either by temporary immobilization in the soil microbial biomass (Liu et al., 2006; Lou et al., 2011) or by nitrate uptake in growing vegetation (Buresh and DeDatta 1991). Thus, the return of straw in rice-wheat rotations of Nepal could temporarily immobilize native soil N in the microbial biomass (Pande et al. 2009) and half N losses by denitrification (Becker et al. 2007).

Another option includes the uptake and hence conservation of nitrate-N in the biomass of growing vegetation of such called “nitrate catch crops” (George et al. 1994; Baldwin and Creamer 2006) during DWT. Besides the conservation of soil N, such strategies may add biologically-fixed N when legumes are grown (George et al. 1998; Sullivan et al. 2012) and incorporated as green manure into the soil before rice establishment (Ro et al. 2016). Benefits of applying such N conservation and cycling strategies on the yield of rice have been reported from a wide range of rainfed production systems in South and Southeast Asia but are so far not documented for West Africa. While straw management strategies are limited by competing demands for fuel, feed or bedding (Eherenstein 2002), pre-rice nitrate catch crops appear promising for the rainfed production systems of the dry savanna zone of West Africa.

Particularly in the inland valley landscape, with the additional lateral translocation of nitrate by subsurface flow from valley slopes into the valley bottom lands, soil N conservation by vegetation during DWT and N addition by biological N_2 fixation during the pre-rice niche may contribute to maintain soil fertility and increase rice grain yield. The objectives of this study were to assess the effect of non-fixing and N_2-fixing pre-rice crops on native soil N dynamics during DWT and on the yield of subsequent rice, both in the absence and in the presence of lateral N fluxes from the valley slope in the dry savanna zone of Burkina Faso.

4.2 Material and methods

4.2.1 Study site

A field experiment was conducted in a rainfed lowland close to the town of Dano in Burkina Faso in 2014. The characteristics of the study site are presented in chapter 2 on general material and methods.

4.2.2 Plant material

The lowland rice (*O sativa* L.) variety TOX 728-1, released in Burkina Faso under the name FKR-19, was used. Seeds were obtained from the INERA rice research station at Farakoba. The short-cycled improved 105-day variety has a yield potential of 6 Mg ha^{-1}, and is reportedly adapted to rainfed conditions (Sie et al. 2006). Three pre-rice crops were compared with the traditional practice of a bare fallow, including forage cowpea (*Vigna unguiculata* L.), velvet bean (*Mucuna cochinchinensis* L.), and panicum (*Panicum maximum* L.) (Figure 4.1). The two annual legumes are suited for use as green manures but can also contribute edible grain (Vigna), medicinal products (Mucuna) and forage uses (both). Panicum is mainly used as perennial forage grass. Seeds of all three species were obtained from INERA in Farakoba, Burkina Faso.

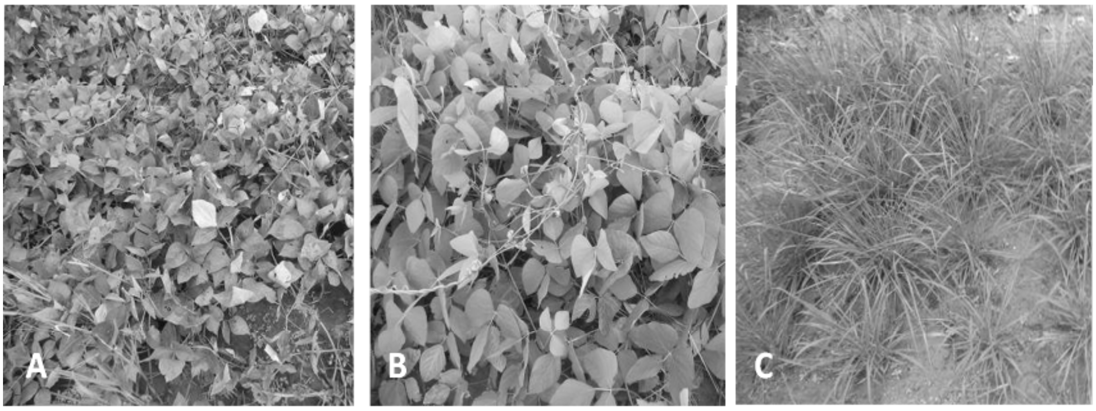

Figure 4.1 Pre-rice crops after 75 days of development during the dry-to-wet season transition period in an inland valley of Dano in Burkina Faso (2014). A = *Vigna*, B = *Mucuna*, C = *Panicum*

4.2.3 Experimental design and crop management

Management options were compared in two main treatments in the hydromorphic valley fringe, where the subsurface flow water is welling up (intercept vs. open). On half of the area, horizontal fluxes of water and nitrate were blocked by a 15m long interception trench down to the saprolyte layer and subsequently laterally drain the flows towards the center of the lowland (“intercepted”). The neighboring “open” area (no interflow interception) received the interflow contribution from a 100 m long valley slope and served as reference.

Figure 4.2 Application of green manure biomass at the end of the dry-to-wet season transition period and before rice transplanting an inland valley bottom at Dano, Burkina Faso (2014)

Nitrogen management treatments involved growing nitrate catch crops during DWT and their incorporation into the soil before rice transplantation. We compared two N_2-fixing green manure legumes and a non-fixing forage grass. The pre-rice crops were sown at a 40x40 cm spacing with 2 (legumes) or 4 gains/hill (*Panicum*). The traditional bare fallow during DWT served as reference treatment. The four treatments were applied in both the “open” and “intercepted” valley fringe in randomized complete blocks following a lattice design with three replications and using a sub-plot size of 2x2 m. The treatments were imposed during DWT between May and July (145th to 190th Julian day). The biomass was chopped into 20 cm long segments and incorporated by hand into the soil before transplanting 25-day-old seedling at a 20 x 20 cm spacing at two seedlings per hill (Figure 4.2). Throughout DWT and the rice-growing season, weeds were manually controlled as required and no mineral fertilizer was applied.

4.2.4 Soil and nutrient sampling

Before the onset of the experiment, reference soil samples were taken for soil attributes. For assessing soil nitrate dynamics, biweekly samples were taken during DWT between the establishment of the pre-rice crop in May and their incorporation in July and transported to the laboratory within 2 hours for N_{min} extraction and nitrate determination as described in Chapter 2 (general material and methods). All samples were pooled composites of seven topsoil auger samples (0-15 cm), collected across a diagonal of each plot. Based on the volumetric soil moisture content (TDR) the bulk density, and the nitrate concentration in soil solution or extracts, the amount of nitrate N per unit area was calculated.

4.2.5 Plant sampling and analyses

Aboveground biomass of the 10-week-old pre-rice crops was determined at the end of DWT based on $1m^2$ harvest areas in the centre of each plot. Sub-samples of 100 g fresh matter were oven-dried for dry matter determination and subsequently ground for chemical analyses. Biological nitrogen fixation (*Ndfa*) of the N-fixing cover crops (Cowpea and Mucuna) was determined following ^{15}N natural abundance method described by Peoples et al. (1989), Unkovich and ACIAR (2008), using Panicum as the non-fixing reference plant. The $^{15/14}N$ ratios were determined using an ANCA-SL 2020 mass spectrometer at the Institute of Crop Science and Resource Conservation at the University of Bonn. The share of N derived from the atmosphere (%Ndfa) was calculated as follows (Amanuel et al. 2000):

$$\%\text{Ndfa} = \frac{\boldsymbol{\delta 15N\ of\ reference\ plant - \delta 15N\ of\ N_2\ fixing\ legume}}{\boldsymbol{\delta 15N\ of\ reference\ plant - B}}\ \mathbf{X\ 100} \qquad (1)$$

$$\text{N fixed} = \frac{\%\text{Ndf}}{100}\ \text{X legume N (kg ha}^{-1}\text{)} \qquad (2)$$

A “B-value” of -3.5‰ ^{15}N (natural isotopic discrimination) was applied for cowpea and -1.5‰ ^{15}N for Mucuna (Peoples et al. 1989).

Rice tiller and panicle numbers were assessed based on 1m² harvest areas at the end of vegetative and the reproductive phases, respectively. The rice cycle (sowing-harvest) was recorded for all treatments. At harvest, straw and grain yield were assessed based on 4m^2 harvest areas (*edge effects were not considered*) and reported at 14% grain moisture. N uptake by grain and straw was analyzed in 100 g sub-samples after oven-drying and grinding, following the micro-Kjeldahl procedure (Page et al. 1982). The share of applied N used was computed from the difference in rice N uptake in DWT vegetation treatments and the bare fallow control, divided by the amount of N cycled (soil N uptake) plus the amount of N derived from N_2 fixation. The agronomic N use efficiency was computed as kg grain yield increase above the bare fallow control divided by the amount of N cycled and/or added.

4.2.6 Data analysis

Results are based on arithmetic means of three replications. Standard errors of the mean (n=3) were applied in graphical data presentations. Analysis of variance (ANOVA) was performed using Stata/SE 12.1, using Bonferroni method for mean separation ($p<0.05$). Graphics were prepared using SigmaPlot, version 12.

4.3 Results

This section presents the major findings on (1) the dynamics of soil NO_3-N in response to development of pre-rice crops during DWT, (2) the accumulation of N in the biomass of pre-rice crops both from soil N uptake and biological nitrogen fixation, and (3) the response of lowland rice to transition season treatments (bare fallow and incorporation of different pre-rice crops).

4.3.1 Soil NO_3- dynamics

The dynamics of soil NO_3-N during DWT differed between transition season treatments and interflow contribution from the slope. While the volumetric water content of the lowland soil showed near-identical trends, the water content tended to be slightly higher in plots open to interflow than in those with interflow interception (Figure 4.3, lower graphs). This trend was also reflected in the nitrate content of the topsoil which was significantly higher in bare fallow plots with than in those without interflow contribution from the adjacent valley slope (Figure 4.3, upper graphs). In both cases, growing vegetation during DWT reduced soil nitrate from maxima of 50 (interflow interception) and 75 (open plots) kg ha^{-1} in bare fallow at around the 170th Julian day to 8-25 kg N ha^{-1} in vegetation plots, irrespective of the species. With vigorous plant growth and associated soil N uptake, nitrate in the topsoil was close to the detection limit of 5 kg ha^{-1} at the end of DWT.

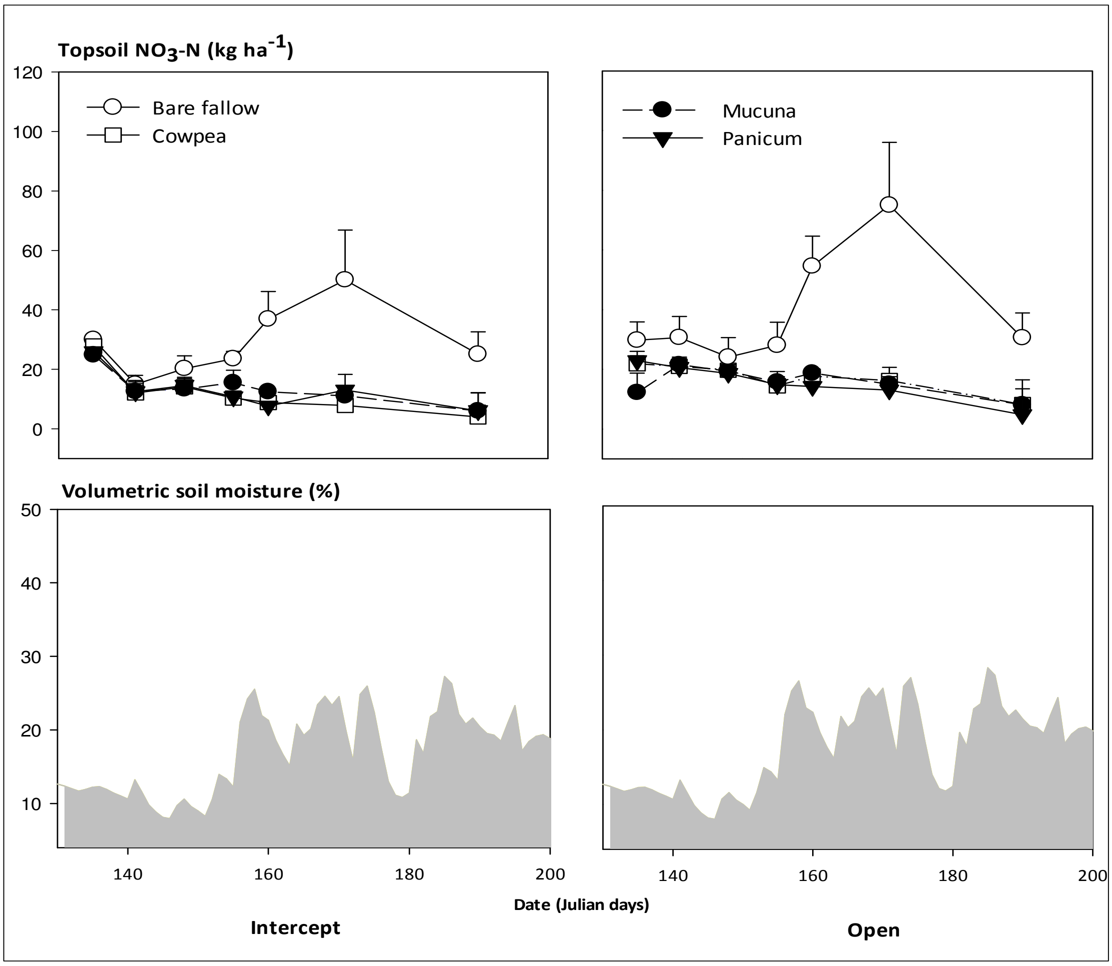

Figure 4.3 Effect of transition season management (bare fallow vs. different pre-rice cops) on soil nitrate-N dynamics in an inland valley of Dano in Burkina Faso. Bars present standard errors of mean (*n = 3*).

Weekly increases in soil nitrate during DWT provided a cumulative net-mineralization of 31 kg NO_3-N ha^{-1} in the bare fallow plots open to interflow, only 6 kg N ha^{-1} in the case of panicum and 3 kg ha^{-1} in the cases of mucuna and cowpea. Little nitrate was detectable at the end of DWT and above amounts can be assumed having been lost from the soil.

4.3.2 Biomass and N accumulation

The accumulations of biomass and N by pre-rice crops during DWT are presented for both open and interception plots in Figure 4.4. There was no biomass in the bare fallow, while transition season crops accumulated between 2 and 4 t dry matter ha^{-1} (no significant difference between crop species and interception treatments).

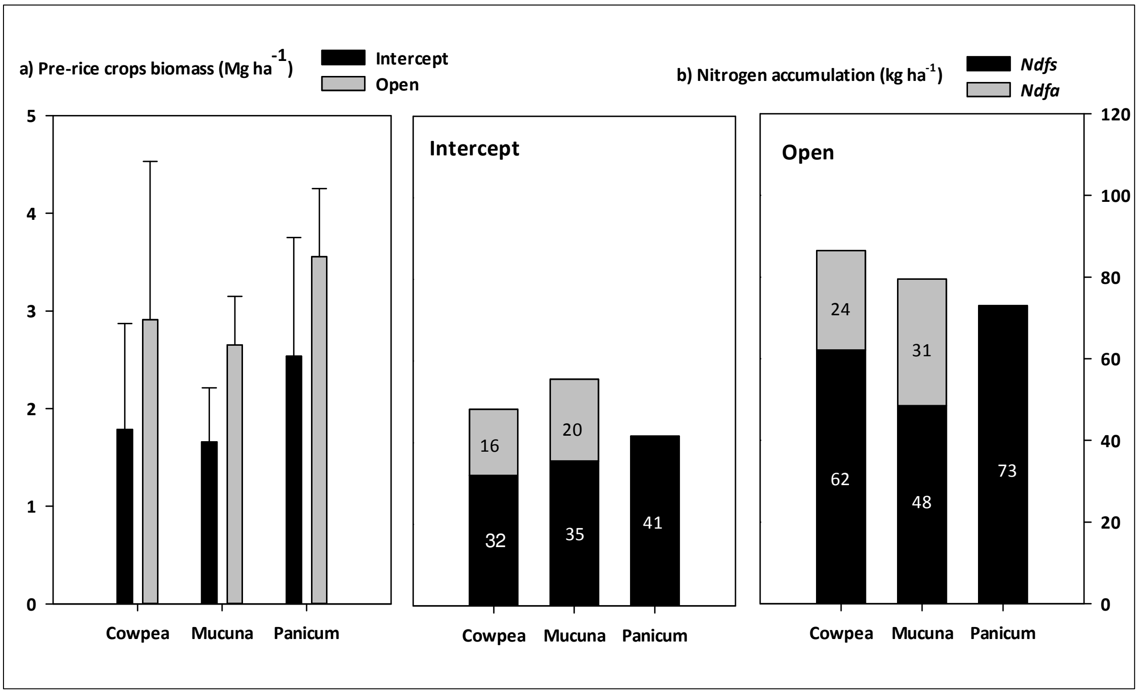

Figure 4.4 Biomass and N accumulation by crops during the dry-to-wet season transition in an inland valley of Dano (Burkina Faso 2014). Bars present standard errors of the mean (*n=3*). *Ndfs* = nitrogen derived from the soil, *Ndfa* = nitrogen derived from the atmosphere.

The accumulation by non-fixing panicum increased from 41 to 73 kg ha^{-1} of soil derived mineral N in interception and open plots, respectively. In addition to soil N uptake of about 34 (32-35) kg N ha^{-1} in interception and of about 54 (47-62) kg N ha^{-1} in open plots, biological N_2 fixation contributed an additional 16-24 kg ha^{-1} in cowpea and 20-31 kg N ha^{-1} in mucuna. Irrespective of the main plot treatment and the legume species, the share of N derived from biological N_2 fixation (Ndfa = N derived from the atmosphere) was relatively low with 33-49%.

4.3.3 N balances and rice response

Nitrogen balances and rice performance attributes following the bare fallow control and the incorporation of different transition season vegetation types as green manure are presented in Table 4.1 and Table 4.2.

In the absence of transition season vegetation, no N was neither cycled (uptake from the soil) nor added (biological N_2 fixation) and the N uptake by rice during the wet season of 32-38 kg ha^{-1} originated from native soil N mineralization during the wet season and possibly some N contributed by interflow from the slope in open plots. Panicum absorbed 41 and 73 kg N ha^{-1} from the soil during DWT in interception and open plots respectively, which was returned upon biomass incorporation. This cycled N together with N mineralization during the wet season resulted in a rice N uptake of 48-58 kg with an about 38% use of the cycled N and an agronomic N use efficiency of 14-24 kg grain increase per kg N added in interception and open plots, respectively. The addition of biologically-fixed N by the legumes resulted in total N inputs of 55 (interception) and 86 (open) kg N ha^{-1} in cowpea and of 55 (interception) and 79 (open) kg N ha^{-1} in mucuna. The resulting rice N uptake of 51-66 kg ha^{-1} provides calculated efficiencies of 28-34% in the case of mucuna and of 36-68% in the case of cowpea. The resulting agronomic N use efficiencies were consequently also higher with cowpea (22-28 kg grain kg^{-1} N applied) than with mucuna (16-19 kg grain kg^{-1} N applied). In contrast to the bare fallow control, treatments involving the return / incorporation of transition season crops tended to provide similar or higher amounts of N than those removed by rice uptake. Grain yields, tiller and panicle numbers, crop phenology and harvest index of rice did not respond to flow interception from the slope (Table 4.2).

Table 4.1 Effect of pre-rice crop management during the dry-to-wet transition season on the N balance in an inland valley of Dano (Burkina Faso, 2014).

Tansition season treatments		N cycled (kg ha^{-1})	N added (kg ha^{-1})	N uptake by rice (kg ha^{-1})	N use efficiency (kg grain kg^{-1} N)
Interception	Bare fallow	0	0	32	-
	Cowpea	32	16	65	28
	Mucuna	35	20	51	19
	Panicum	41	0	48	21
Open	Bare fallow	0	0	38	-
	Cowpea	62	24	66	22
	Mucuna	48	31	60	16
	Panicum	73	0	58	14

Consequently, the effects of transition season crop management on rice performance attributes are presented as mean values from the open and the flow inception plots (n=6).

Grain yields responded strongly and highly significantly to the incorporation of the biomass of pre-rice crops and the cycling of soil and/or the addition of biologically-fixed N. The highest grain yield was observed with rice grown after cowpea (3.8 t ha^{-1}), followed by mucuna (2.9 t ha^{-1}) and the non-fixing panicum (2.7 t ha^{-1}). These yields were in all cases significantly higher than those following the bare fallow treatment (1.7 t ha^{-1}).

Grain yield increases were explained mainly by the number of panicles or effective tillers. Thus, compared to 125 tillers and only 86 panicles m^{-2} (<70% of effective tillers) in the control treatment (bare fallow), rice grown after cowpea, mucuna and panicum produced 171, 159 and 145 tillers and 127, 106, and 103 panicles m^{-2} (75% effective tillers), respectively. Also rice phenology was affected by applied treatments and in the bare fallow control, apparent N deficiency accelerated grain maturation, reducing the 105-day growth cycle of FKR-19 by about one week to 95 days.

Table 4.2 Effect of flow interception and pre-rice crop management during the dry-to-wet transition season on rice agronomic performance (means from inflow interception and open plots) in an inland valley of Dano (Burkina Faso, 2014).

Treatments	Tillers (number m^{-2})	Panicle (number m^{-2})	Rice cycle (DAS)	Harvest index	Grain yield (t ha^{-1})
Interception	152	104	101	0.47	2.7
Open	157	107	102	0.45	2.9
	ns	ns	ns	ns	ns
Bare fallow	125^{a}	86^{a}	95^{a}	0.50	1.7^{a}
Cowpea	171^{b}	127^{b}	105^{b}	0.48	3.8^{bc}
Mucuna	149^{b}	106^{ab}	101^{b}	0.42	2.9^{b}
Panicum	145^{b}	103^{ab}	101^{b}	0.47	2.7^{ab}

Harvest index: grain / total biomass weight; DAS: days after seeding.
Interaction between treatments is not significant (P > 0.05)
Means affected by the same letter within the same column do not differ significantly (P < 0.05, Bonferroni's method)

4.4 Discussion

4.4.1 Soil nitrate-N dynamics

Maintaining soil cover has been shown to significantly impact the dynamics of soil N in rice-based cropping systems of Asia (George et al. 1995; Pande and Becker 2003). Thus, provided the environmental conditions permit it, growing pre-rice green manures were efficient in avoiding the build-up of soil nitrate-N in rice-wheat rotations of Nepal and to improve systems N balances (Becker et al. 2007). While grass crops have been reported to be more effective in trapping and recovering soil N than legumes (Baldwin and Creamer 2006), up to 60 kg N ha^{-1} can be provided additionally every year by biological N_2 fixation when integrating adapted legumes instead of nitrate-catching grasses into a rainfed rice rotation (Ladha et al. 2000). Amounts of native soil N saved by transition season legumes or by a temporary N immobilization following the application of straw have been estimated to range from 10 to over 60 kg N ha^{-1} (George et al. 1998; Becker et al. 2007; Yu et al. 2014).

However, in most rainfed rice production systems of Asia, the pre-rice niche is not used to grow green manures. Under the prevailing bare fallow conditions, the change in soil redox or aeration status during DWT leads not only to a temporary build-up of nitrate in the soil profile (Buresh and DeDatta 1991); depending on edaphic and climatic conditions, this nitrate is prone to subsequent losses by leaching and/or denitrification. These N losses have been estimated to range from 20 to over 80 kg of nitrate N ha^{-1} (Becker et al. 1990; George et al. 1998; Pande and Becker 2003; Becker et al. 2007; Pande et al. 2009; Yu et al. 2014). The present work provides the first evidence that similar nitrate N dynamics and comparable amounts of N mineralization, nitrate accumulation and N losses can be expected from rice-based systems in West Africa. Compared to most systems in Asia, the low-input production orientation and the prevailing wide-spread N deficiency in rice further enhances the negative implications of massive N losses for regional rice production and food security in West Africa. In addition, the lateral contribution of nitrate by sub-surface flow from the slopes in the inland valley landscape of the savanna zone adds an additional dimension of need to improve native soil N management. Such strategies become even more important in production environments where farmyard manure is scarce or has competing uses, and where mineral N fertilizers are either unavailable or not affordable by small-scale farmers. The dry savanna zone of West Africa represents such conditions and may thus become a prime target for the suggested native soil N management options.

4.4.2 Rice response to applied green manure

The use of green manures in lowland rice-based systems has been intensively researched, mainly in South and South East Asia and comprehensive literature reviews are available (i.e., Becker 2003). No similar work is available from the African continent except for fallow rotations in upland rice systems of West Africa (Becker and Johnson 1998; 1999; 2001). However, overall trends and key limiting factors are likely to be similar in both rainfed rice production regions. Thus the need for site- and soil-specifically adapted legume species as a key factor to high N_2 fixation and successful green manures (Becker and Ladha 1996) will likely be highly relevant for the adverse environmental conditions widely encountered throughout the West Africa savanna. Another critical factor for green manure performance can be rhizobial inoculation (Mfilinge et al. 2014) and available soil P (Engels et al. 1995; Carsky et al. 1998; Becker 2003). While soil P deficiency is a widely reported production constraint in Africa (Sanchez 2002), was no constraint at the study in Dano, and appears generally to less critical in the dry savanna than in the more humid environments of the continent (Bationo et al. 2005). Green manure-derived N is reportedly used more efficiently by rice than mineral N in coarse-textured soils in rainfed environments with unreliable precipitation (Becker et al. 1995). Such conditions apply to much to rice production sites in the inland valley landscape of West Africa's dry savanna zone.

The incorporation of fast-growing legumes grown as bio-fertilizers in the cropping niche before lowland rice reportedly improves rice grain yield, particularly in rainfed production systems on sandy soils (Becker et al. 1995; Nascente et al. 2013; Yu et al. 2014). As in the present study, Latt et al. (2009) and Islam et al. (2015) showed that the incorporation of green manure legumes can not only fully replace mineral N fertilizers at current application rates in Asia, but may well do so in West Africa. In addition, green manures can have various additional benefits on soil nutrient mobilization and uptake (Mandal et al. 2003), on nutrient recovery (Dobermann and Fairhurst 2000; Segda 2006), on soil physical attributes (Becker et al. 1995) and on pest control (Sullivan et al. 2012). Despite such positive reports, adoption of green manure technology by farmers in Asia is low, mainly due to the unreliability in the outcome of such investments and to high labor demand for seed production, crop establishment and the incorporation of green manure biomass (Ali 1999). Such draw-backs may not apply to the same extent to the situation in West Africa, where mineral fertilizers are no alternative to low-cost organic sources in the prevailing low-input systems (Seck et al. 2013), where soil fertility is generally poor (Sanchez 2002) and where the lateral influx of nutrients with the subsurface flow in the inland valley landscape provides additional opportunities and accrued benefits for N-saving technologies (Windmeijer and Andriesse 1993).

4.5 Conclusion

Cultivation of crops in the pre-rice niche in rainfed lowlands contributes to avoid the build-up of nitrate in the soil profile, originating both from *in-situ* mineralization and from lateral influx by subsurface flow from adjacent valley slopes, and its subsequent losses related to the change in soil aeration status during DWT. Returning this recycled native soil and addition of biologically-fixed N following the incorporation of the biomass before the establishment of the wet season crop enhances the performance of lowland rice and may in the long-run contribute to sustain soil fertility in inland valleys of the West African savanna zone.

5 FACTORS MODULATING SOIL N DYNAMICS IN THE WEST AFRICAN SAVANNA ZONE

ABSTRACT

Soil nitrate-N dynamics during the dry-to-wet transition (DWT) season and its management are key determinants of soil productivity in low-input rice-based systems in the inland valley landscape of West Africa. The extent of nitrate mineralization but also of lateral nitrate translocation from valley slopes is likely to be affected tillage operations (stimulation of microbial mineralization), by rainfall intensity (vertical movement of water and nitrate in the soil profile and speed of change in soil aeration status and microbial respiration), and by site attributes (mainly soil type, texture and CN content). A set of experiment was conducted in the dry savanna zone of West Africa in 2013 and 2014 with the aim to determine the effect of such modulating factors (soil tillage, rainfall intensity and location) on native soil NO_3-N dynamics during DWT. The study on effects of soil disturbances on N mineralization compared mechanical tillage with a no-till treament of the upland adjacent to the study lowland. The effect of rainfall intensity on nitrate dynamics was assessed by comparing natural rainfall during DWT in 2014 with a simulated 30% increase (additional irrigation) and a 30% reduction (soil cover). Location effects involved a comparison of lowland sites in Dano (Burkina Faso) and Dassari (Benin) with similar climatic conditions but contrasting soil attributes.

Mechanical soil tillage increased N mineralization in 2013 and during the initial phase of DWT in 2014. Towards the end of DWT, most nitrate from wetland soils adjacent to a tilled upland had disappeared, while N mineralization continued in the lowland below the reduced tillage treatment. However, no differences in grain yield of rice were apparent between tillage treatments. Reduced rainfall increased the nitrate accumulation in the soil profile with little apparent nitrate losses occurring during DWT. With increased rainfall, on the other hand, most nitrate had disappeared once the volumetric soil moisture exceeded 25%. Finally, the soil nitrate-N accumulation during DWT stood in no apparent relation to rice agronomic performances. Thus, soil nitrate accumulation during DWT was higher in Dano, while grain yields of rice were lower (1.6 – 2.1 t ha^{-1}) in Dano than in Dassari (1.8 – 2.5 t ha^{-1}). These relations indicate that nitrate mineralized during DWT had apparently been lost from the soil before wet season rice was able to take it up. We conclude that soil types, tillage and rainfall differentially affect soil N dynamics during DWT but, in the absence of soil N management strategies, not necessarily the grain yield of rice. Particularly under conditions favouring nitrate accumulation during DWT, there is a need for site-specifically adapted soil N-conserving management strategies.

Keywords: climate change, dry-to-wet season, nitrate, rainfall variability, tillage.

5.1 Introduction

The fertility of most soils in the West African savanna zone is increasingly depleted due the low biomass accumulation by crops and natural vegetation (Bationo et al. 2007), little residue cycling due to competing use of organic matter for fuel, feed and animal bedding (Giller et al. 2009), and a hot climate causing a rapid turnover of organic matter (Henao and Baanante 2006). This is associated with inherently low organic carbon content and light-textured soils (Bationo et al. 1998), and with low cation exchange capacities due to kaolinite dominating the clay mineral fraction (Vanlauwe et al. 2015). Nutrient depletion is further exacerbated by environmental conditions such wind and water erosion, constituting further cause of productivity decline in low-input systems of West Africa (Zougmore et al. 2003). However, smallholder farmers heavily depend on soil nutrient supply for their food production (Giller et al. 2011).

Nitrogen is the most limiting factor and its management is, therefore key of the success in low-input cropping system (Segda 2006). In the savanna environment, a surge of soil nitrate occurs with the onset of the rains after a prolonged dry period (Birch 1960). Being a biological process, nitrification is affected by edaphic properties (soil N supply, C content, texture, aeration status) and climatic conditions (temperature and rainfall) but also by management interventions (residue return, soil tillage) that affect the microbial dynamics in the soil (Sahrawat 2008). Upon soil saturation at the onset of the main rains, and in the absence of a vegetation cover, this native soil nitrate-N is prone to losses by leaching and/or microbial respiration or denitrification (Pande and Becker 2003; Becker et al. 2007; Blackmer et al. 2008). The extent and speed of disappearance of nitrate-N from root zone and its lateral translocation in inland valleys from the slopes into the wetland is determined by the geomorphology of the landscape (length and steepness of valley slopes, soil texture, and presence of an impermeable saprolyte layer in the profile (Windmeijer and Andriesse 1993) and the amount and intensity of the rainfall (Bognonkpe 2004). Consequently, both site attributes (soil and climate) and management factors (tillage, soil cover) will differentially affect native soil N dynamics in savanna production systems, particularly during DWT when the soil aeration changes from dry aerobic to saturated anaerobic conditions.

Within the dry savanna zone, different soil type and rainfall environments are encountered, leading to different pre-conditions for N mineralization and changes in soil aeration status. Thus, the areas around the town of Dano in Burkina Faso and Dassari in Benin are dominated by soils developed on acidic metamorphic rock with low kaolinitic clay content (Callo-Concha et al. 2012). However, soils in Dassari are slightly acid and finer textured in the lowland than those in Dassari. Rainfall is characterized by high variations both within and between sites and recurrent changes between years (Forkuor 2014).

Tillage accelerates the aeration of the top soil and hence favors microbial mineralization processes (Balesdent et al. 2000). In the dry savanna zone of West Africa tillage is usually done during DWT either by hand hoe or animal traction. However, with growing awareness of climate change phenomena and the need not only for adaptation but also trace gas mitigation strategies, reduced tillage systems are increasingly promoted in sub-Saharan Africa (Milder et al. 2016). Minimum or no-tillage thereby reduces organic matter mineralization while enhancing soil C sequestration (Lal 2004). As a side-effect, the extent of the “Birch effect” and the likelihood of N losses during DWT may be reduced. The region is also characterized by increasingly variable rainfall (van Wesenbeeck et al. 2016). Recurrent droughts (Nicholson 2001) coexist with more intense but erratic rainfall events (IPCC 2007), mostly at the onset of the wet season. Model predictions are however often conflicting, and depending on “representative concentration pathway” (RCP) scenarios, both drier and wetter futures are predicted for West Africa (Cooper et al. 2008; Regelj et al. 2012). It is, therefore, urgent to understand the effect of these modulating factors (site/soil, tillage and rainfall variability) on the seasonal dynamics of soil nitrate-N in view of estimating expected N losses and targeting soil N management strategies to specific environments. We assessed the effects of tillage, of rainfall and of site attributes on seasonal nitrate dynamics and rice performance in the dry savanna zone of West Africa in 2013 and 2014.

5.2 Material and methods

5.2.1 Study sites

We conducted field experiments during the dry-to-wet transition (DWT) seasons of 2013 and 2014. Studies comparing soil tillage methods (2013 and 2014) and varying rainfall intensities (2014 only) were carried out at the Dano study site in Burkina Faso, while the comparison of site conditions on N dynamic and rice performance attributes (N uptake and yield) included both Dano in Burkina Faso and Dassari in Benin (2013 and 2014). Geographic characteristics and climatic as well as edaphic attributes of the study sites are presented in Chapter 2 on general material and methods.

5.2.2 Treatment application

We assessed the spatial-temporal dynamic of soil nitrate following soil tillage management in Dano in 2013 and 2014. The NO_3-N dynamics were assessed:

a) in a lowland adjacent to a slope which had either been left untilled or tilled (0-10 cm) using an animal-drawn plow four weeks after the first rainfall event following farmer's practice. Plots of 6x4 m were established in the lowland (valley fringe) directly adjacent and perpendicular to the tillage treatments in 4 replications

b) along the toposequence differentiated in an upslope and a foot-slope sampling position in both tilled untilled plots of 6 x 4m, with four replications distributed following a complete randomized design.

The study focused on the DWT seasons of 2013 and 2014, between the first rainfall event in April until the onset of the main rainy season and rice establishment in July. To assess site-effects on N mineralization during DWT and on crop performance, rice was grown in the lowland in Dano and Dassari. At each site, rice was established at 20 cm x 20 cm spacing in 4 x 3 m subplots in four replications. Direct seeding was used in 2013 with 2 grains/hill. In 2014, rice was transplanted, using two 25 day-old seedling per hill. Straw biomass and grain yield of rice were assessed at maturity, based on a $4m^2$ harvest areas. Grain yield was reported at 14% moisture. After oven-drying and weighing, total N uptake by grain and straw was analysed following the micro-Kjeldahl procedure.

Rainfall variability and its effect on soil nitrate-N dynamics was simulated in the lowland by modifying the rainfall amounts*,* considering *t*ree scenarios : (1) the normal *in-situ* rainfall regime of the DWT 2014, (2) a lower rainfall regime (-30%) achieved by covering part of the plot area with plastic sheets until a cumulative DWT rainfall of 30% less than "normal" was reached, and (3) a higher rainfall regime (+30%) achieved by adding 30% of the amount of water having been received during each week, the first day of the following week by watering can on the soil surface. The experiment was arranged to a randomized complete blocks design with four replications. The size of the modified rainfall regime plots was 1x1 m situated 1 m apart. Volumetric moisture was monitored continuously in each experimental plot using EC-5 TDR soil moisture sensors (Decagon Devices) at a depth of 10, 20 and 30 cm. Soil moisture readings were recorded two-hourly and stored in an EM-50 data logger.

Before the onset of the experiment, reference soil samples were taken for soil attributes. Additionally, auger samples were taken during DWT between mid-April and early July twice per week and transported to the laboratory within 2 hours for N_{min} extraction and nitrate determination as described in Chapter 2. All samples comprised pooled composites of seven topsoil auger samples (0-15 cm), collected across a diagonal of each plot. In addition, in each treatment soil solution was sampled at weekly intervals by suction cups installed at 10 cm (0-20 cm soil layer) at the foot slope position, and at 10cm (0-20 cm) and 30 cm (20-40 cm) depth in the lowland positions. The NO_3-N was extracted and analyzed as described in Chapter 2, and concentrations of nitrate in solution were measured by photometric method. Based on soil moisture content (TDR) and bulk density measurements, the nitrate concentrations were transformed into total amounts of N per unit area.

5.2.3 Data analysis

Results are based on arithmetic means of three replications. Analysis of variance (ANOVA) was performed using Stata/SE version 12.1. For mean comparison, Bonferroni correction pairwise multiple comparison post-hoc were applied. Figures were prepared using SigmaPlot, version 12.

5.3 Results

This chapter presents the findings on effects of selected modulating factors on topsoil and soil solution N dynamics in three sections: (1) the soil N response to tillage, (2) the effect of rainfall variability, and (3) the soil N and rice yield trends by location.

5.3.1 Effect of soil tillage

The dynamics of topsoil and solution NO_3-N following tillage operations during DWT of 2013 and 2014 and its relation to rainfall are presented in Figure 5.1. Overall, soil N mineralization was enhanced by tillage. However, trends differed between observation years. As indicated in chapter 3, nitrate-N dynamics is presented for only part of DWT 2013 due to unavailability of data from Julian date 80 to 102. At the onset of the sampling period, topsoil nitrate was similar in tilled and non-tilled plots (about 10 kg ha^{-1}), and was followed by a gradual decrease. After soil tillage around Julian date 130 and with the occurrence of 24 mm rainfall, nitrate increased gradually to about 8 kg ha^{-1} and remained almost constant until the onset of the main rainy season. At the same time, nitrate continued to decline in no-tillage plots and no N_{min} was detectable at the end of the DWT. Amounts of nitrate in soil solution were much lower than those extracted from auger samples and were close to or below the detection limit in 2013.

In 2014, different trends between tillage treatments were clearly observed from Julian date 100 - 130 and from 130 – 180 (beginning of the rainy season). During the first half of DWT, NO_3^- was significantly higher in tilled than in no-till plots. While soil nitrate amounts remained nearly constant at 20 kg ha^{-1} throughout DWT in no-till plots, soil tillage increase soil nitrate to 30-40 kg ha^{-1} after the first rain, and only 20-25% of this nitrate was detectable once the volumetric soil moisture content exceeded 25% (data not shown). Out of a maximum of 46 kg ha^{-1} of nitrate mineralized in tilled plots, approximately 78% was no longer present at the onset of rainy season and can be assumed to have been lost. Such presumed N losses during DWT were only about one half in the case of no-tillage.

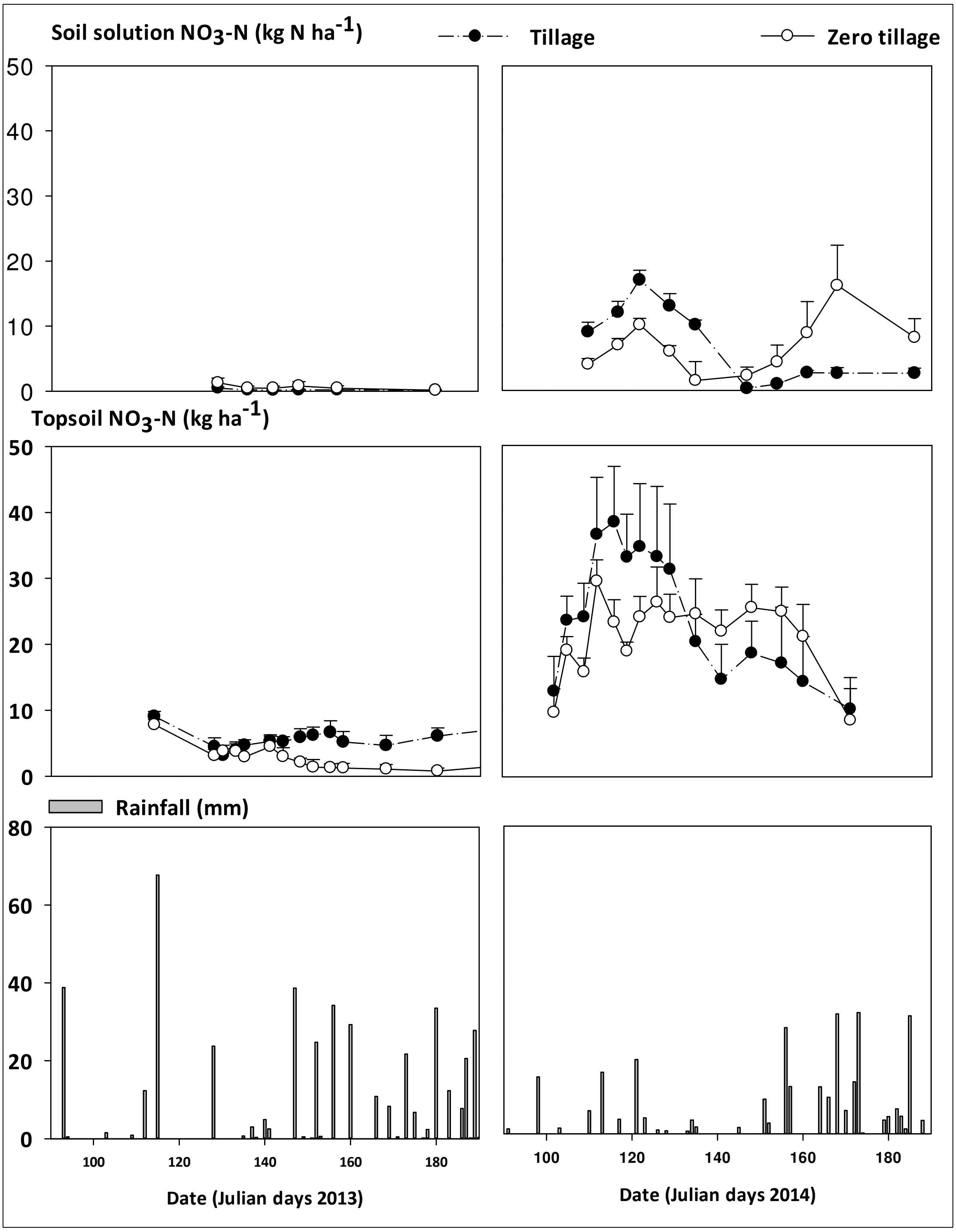

Figure 5.1 Seasonal topsoil and soil solution nitrate-N dynamics response to tillage during the dry-to-wet transition season period in an inland valley in Dano (Burkina Faso, 2013-2014). Bars present standard errors of the mean (*n=8*)

5.3.2 Rainfall variability on soil nitrate-N dynamics

The dynamics of soil NO_3-N during DWT responded to the amount of rainfall. With "normal" rainfall, volumetric soil moisture increased gradually until reaching 25% from Julian date 165 onwards. In the treatment with a 30% reduced rainfall, soil moisture reached a maximum of 18%, thus remaining below the field capacity level of 20%. In the wet scenario with 30% higher rainfall, the soil reached saturation levels (35% moisture) at Julian date 170 and remained anaerobic until the end of DWT (Figure 5.2).

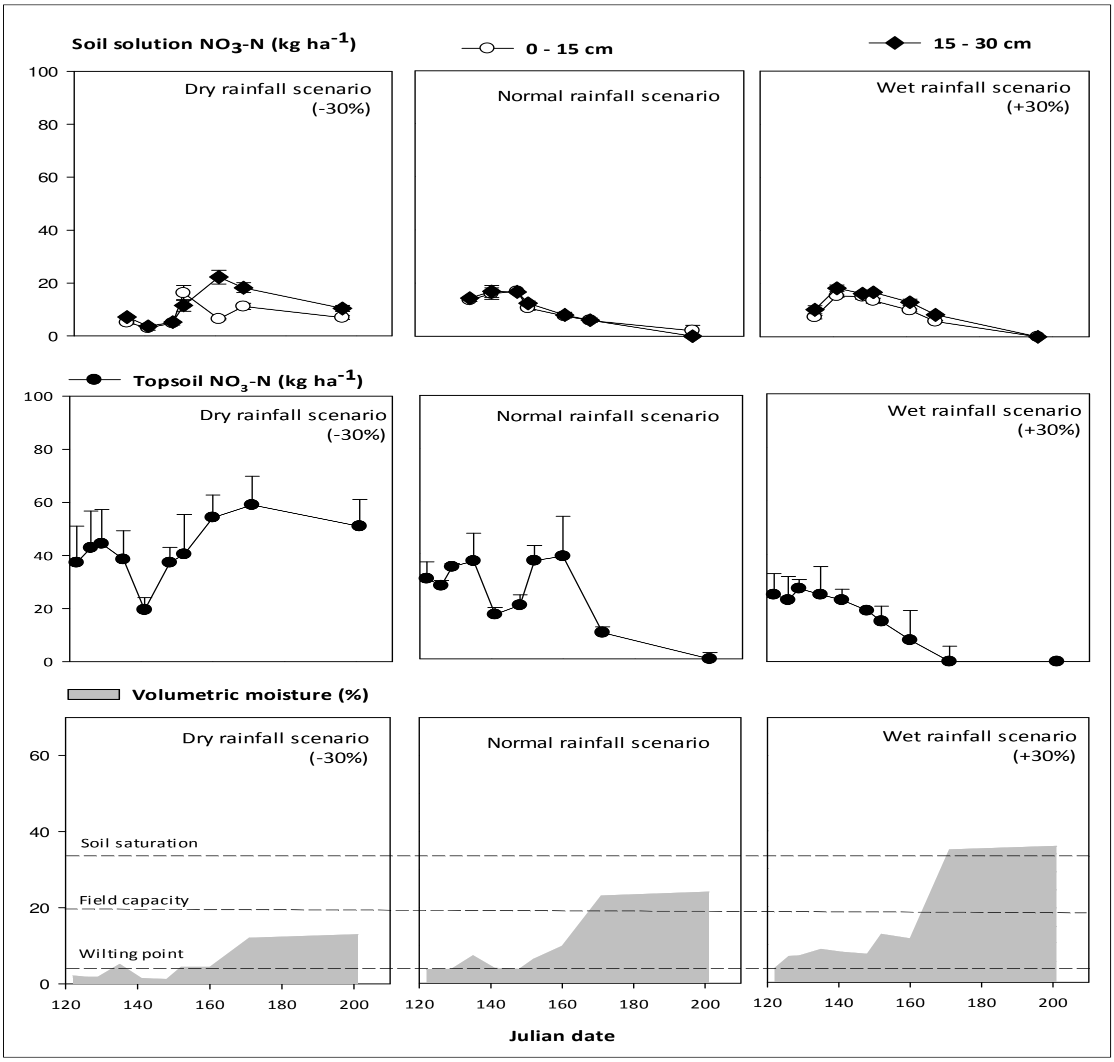

Figure 5.2 Effect of rainfall regime (normal, dry and wet scenarios) on soil moisture, and extracted topsoil and soil solution nitrate-N dynamics during the dry-to-wet transition season period in an inland valley in Dano (Burkina Faso, 2013-2014). Bars present standard errors of the mean (n=4)

With “normal” rainfall, the nitrate dynamics followed the pattern described before with an increase following the first rainfall event, reaching about 40 kg ha^{-1} at Julian date 160. This nitrate disappeared once the soil moisture exceeded field capacity and no nitrate was detectable at the time of rice establishment. In case of the dry scenario (30% less rainfall during DWT), the nitrate mineralization continued throughout DWT, reaching peak values of 50-60 kg ha^{-1} in the still aerobic topsoil at the time of rice establishment. In the wet scenario (30% more rainfall during DWT) soil nitrate continuously declined from initially 25 kg ha^{-1} with the increase in soil moisture and no nitrate was detectable once soil saturation was reached. to In the drier soil, we observed first, a gradual increase of topsoil nitrate up to 44 kg ha^{-1} at 4% volumetric moisture, following by a subsequent decline to about 20 kg ha^{-1} around Julian day 140. Similar trends but at a much lower level were observed from the soil solution samples (on average only about 20% of the nitrate determined by soil extraction).

5.3.3 Variability by location

The relevance of location attributes (here mainly soil type) on soil N dynamics during DWT and on the grain yield of rainfed lowland rice has been comparatively studied in Dano (Burkina Faso) and Dassari (Benin) in 2013 and 2014.

Rainfall and soil NO_3-N dynamics

Rainfall distribution can only be presented for 2014 (no data available during the DWT of 2013 in Dassari). Figure 5.3 (below graphs) shows the distribution of rainfall in Dano and Dassari during the DWT in 2014. Units are measured on daily-basis in mm. Overall, total amount rainfall of Dassari was higher than that of Dano. In Dassari, the first 30 days of the DWT received around 20 mm of rains as opposed to twofold in Dano. During the following 30 days, up to 250 mm which account around 65% of the total rainfall of the DWT or 25% or the yearly rainfall was observed in Dassari. On the other hand, a period of drought was observed in Dano with only 30 mm of rainfall in one month time. From the Julian day 150 to 170, rainfall was higher in Dano than in Dassari (about 100 mm and 80 mm, respectively).

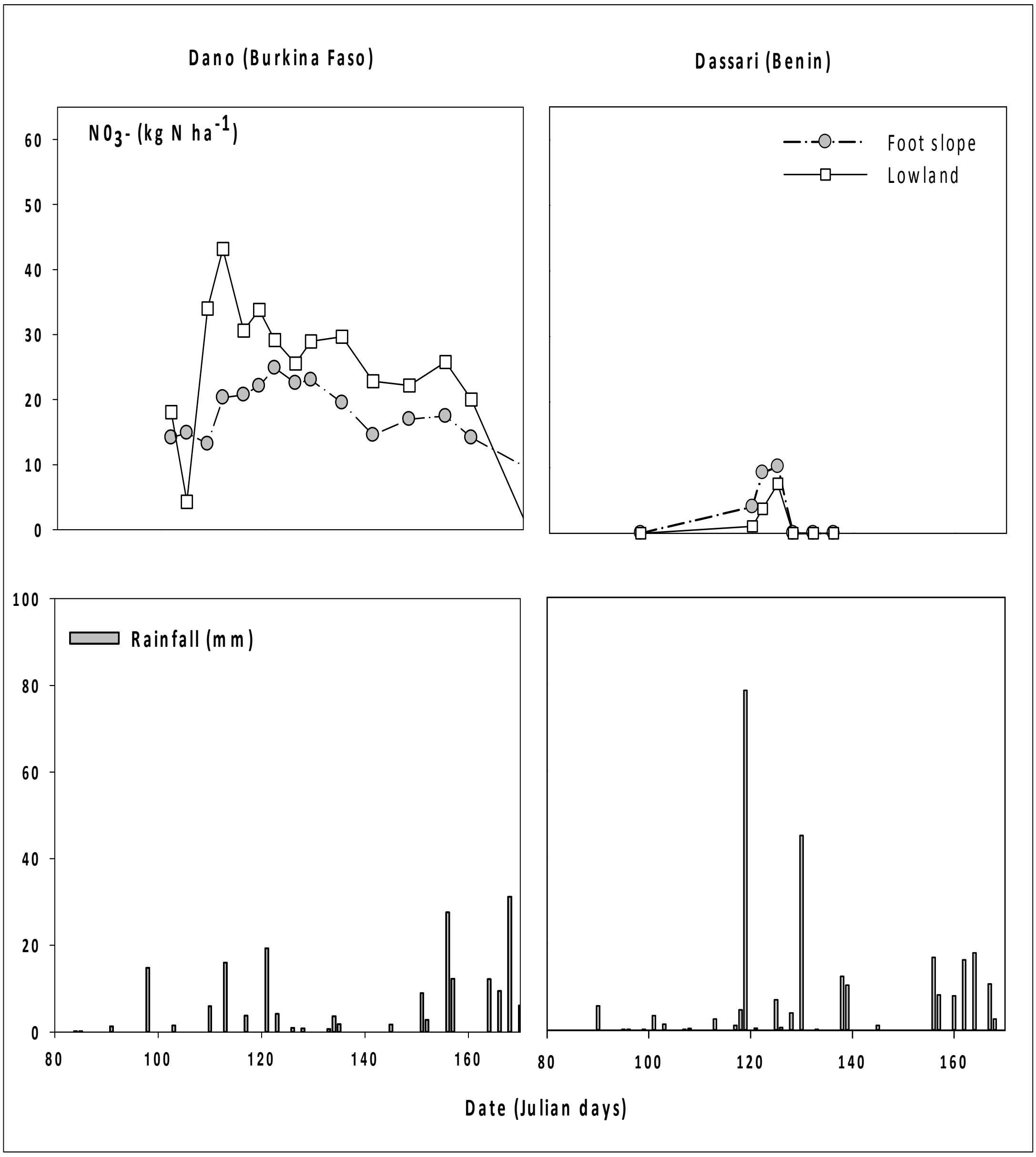

Figure 5.3 Seasonal topsoil nitrate-N dynamics during the dry-to-wet transition season period at two toposequence positions in two inland valleys in Dano and Dassari (Burkina Faso, Benin, 2014).

Figure 5.3 presents the dynamics of soil NO_3-N in footslope upland and valley bottom lowland soils at Dano and Dassari during DWT of 2014. At both sites, the mineralization was triggered by the first rainfall around Julian date 120, with considerably more nitrate accumulating in the lowland than the upland (foot slope) soils. However, total amounts of nitrate formed and subsequently lost were much higher in Dano (45 kg ha^{-1}) than in Dassari (10 kg N ha^{-1}), despite similar soil texture (clay vs. clay loam) and C and N contents (1% C, 0.04-0.09%N).

Rice response

Rice biomass, grain yield and rice N uptake in Dano and Dassari (2013 and 2014) are presented in Figure 5.4. The rate of nitrogen mineralization and nitrate accumulation during DWT had no apparent relation with the performance of rainfed lowland rice. Thus, N uptake by rice was similar between sites and years with 63-95 kg N ha^{-1} in Dassari and 59 to 64 kg N ha^{-1} in Dano. The grain yields, however, were lower (1.6 – 2.1 t ha^{-1}) in Dano than in Dassari (1.8 – 2.5 t ha^{-1}). These relations indicate that nitrate mineralized during DWT had apparently been lost from the soil before wet season rice was able to take it up.

5.4 Discussion

Overall, the results indicated that strong mineralization kinetics of native soil nitrate can be observed during DWT, and that their extent appears to be related to soil tillage, rainfall regime and site/soil attributes. However, the nitrate accumulation the top soil shows no apparent relationship to the N uptake and yield of rice during the wet season. This disconnection of N mineralization from rice performance points towards nitrate N being lost before rice can take it up and transform it into biomass and yield.

5.4.1 Soil tillage and N dynamic

The general trend of enhances soil N mineralization with mechanical tillage is neither surprising nor new , as was reported before that frequent disturbances of soil accelerate the breakdown of organic matter (West and Post 2002; Mahdi et al. 2004; Grandy and Robertson 2007; Calegari et al. 2008; Aurora and Avelino 2010; Kenneth et al. 2014; IPNI 2014). Tillage at the onset of the rainy season is commonly practiced around the word to remove crop residues from the soil surface, to prepare the seed bed and to control the growth of weeds (Buhler 1994). In the dry savanna zone of West Africa contour ploughing additionally contributes to enhance soil roughness for increased water infiltration (Thierfelder and Wall 2009). Such benefits of tillage stand in contrast to the generally observed trend of mechanical tillage to enhance soil N mineralization and possibly N losses.

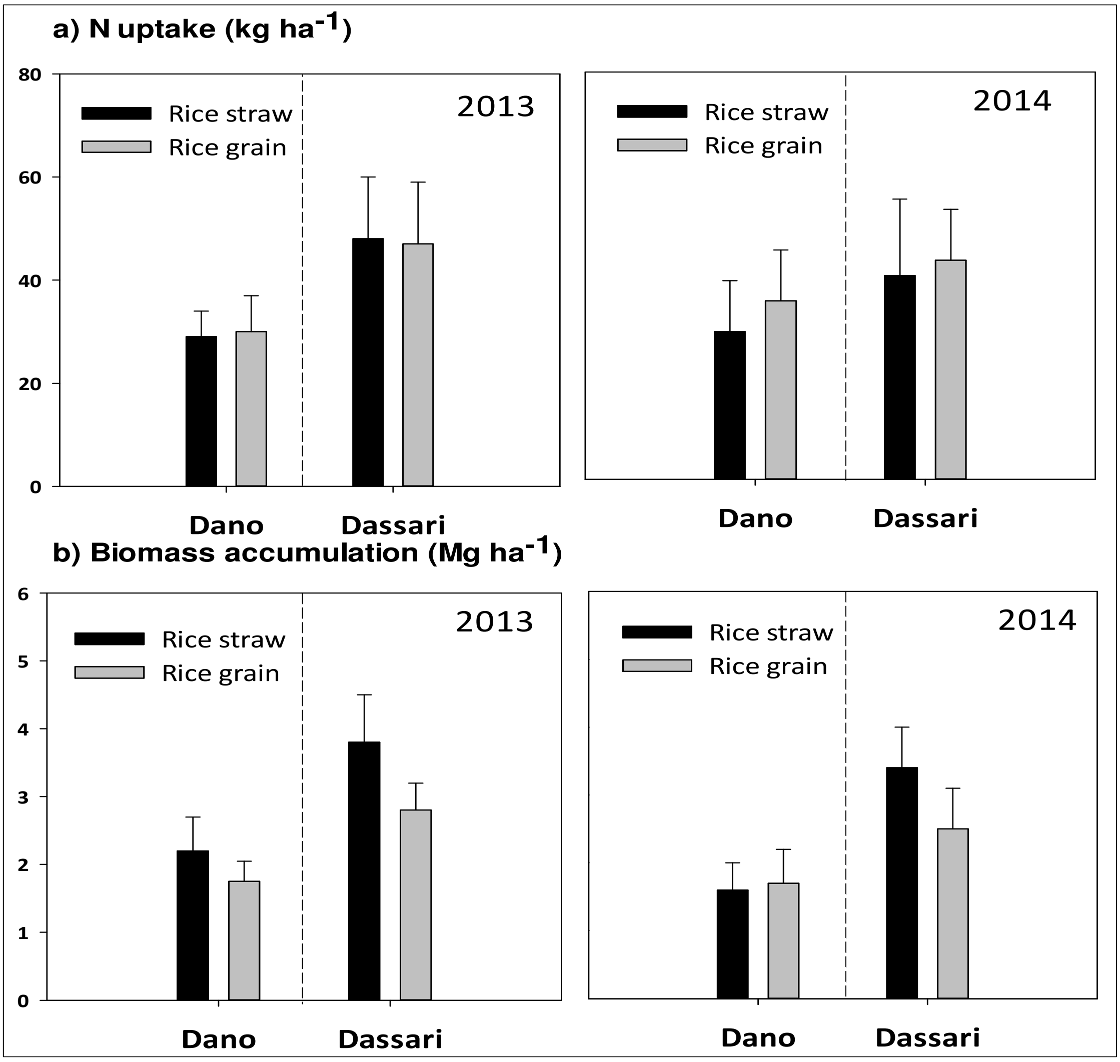

Figure 5.4 Rice N uptake, biomass accumulation and grain yield response to native soil mineralization during the dry-to-wet season transition in two inland valleys of Burkina Faso (Dano) and Benin (Dassari) (2013, 2014). Bars present standard errors of the mean (*n=4*).

Thus, it was reported before that frequent disturbances of soil accelerate the breakdown of organic matter (Grandy and Robertson 2007; Calegari et al. 2008; Aurora and Avelino 2010; IPNI 2014), with the released N_{min} after its microbial oxidation to nitrate being prone to losses by leaching and denitrification (Becker et al. 2007;

Kenneth et al. 2014). Additionally, conventional tillage is responsible for the disruption of the life cycle of some beneficial microorganisms to reduce soil organic matter (NRC 2010) and to increase soil compaction (Badalikova 2010). On the other hand, no-till systems increase the soil organic C content by up to 40% (Salinas-Garcia et al. 1997) and with long-term reduced tillage, the soil microbial biomass increases, at least in the warm sub-humid climates. Associated with a lower mineralization of carbon substrates under no-till conditions is a reduced N mineralization as shown by Li et al. (2015) from long-term experiments in rice-based systems of China. Such a reduction in the soil N supplying capacity does not necessarily require compensation by higher N fertilizer inputs to maintain crop productivity (Angas et al. 2006). In the contrary, tillage even reduced the use efficiency of applied mineral N by 17%.

However, such reports related to enhanced C sequestration with reduced tillage are contested by some authors who surmise that apparent soil C gains are the result of a redistribution of soil C near the surface, rather than a real increase in total soil C (Baker et al. 2007; Blanco-Canqui and Lal 2008; Christopher and Mishra 2009). Supporting such observations, Yagioka et al. (2014) reported significant increases in soil N and N_{min} in the top 2.5 cm with reduced tillage. Irrespective of possible C sequestration or N distribution effects, reduced tillage does reduce soil erosion (Maqsood et al. 2013; Premov et al. 2014) and increase the share of water-stable soil aggregates (Brye et al. 2012). Such no-till associated changes are reported not to affect crop productivity, at least after several years of no-till use, while other authors report declining crop productivity, particularly in dry environment (Giller et al. 2009), and when crop residues are nor returned to the soil surface (Ouedraogo et al. 2007).

Findings in the present study are also not conclusive. While tillage increased soil nitrate accumulation in the topsoil in 2013, it resulted in lower soil nitrate accumulation in 2014. Possibly, the more favorable soil moisture conditions after tillage, resulting from improved water infiltration attributes, favoured the rapid development of vegetation cover and associated absorption of soil N (El-Haris et al. 1983), while no-till plots remained bare and weed-free throughout most of DWT and showed continued high nitrate levels in the soil. Considering these findings, we suggest that depending on climatic conditions, no-tillage systems can contribute to curb soil N mineralization and nitrate-N losses, particularly in wet years.

5.4.2 Effect of rainfall regimes on soil nitrate-N dynamics

It is commonly acknowledged that nitrification is limited by dry conditions, when dissolved C in the soil solution becomes increasingly concentrated, leading chemo-lithotrophic organisms to spend more energy for their maintenance than for ammonium oxidation (Wong and Nortcliff 1995). The present work, however, indicated a higher nitrate accumulation under dry (30% reduced precipitation) than under wet (30% increased precipitation) conditions. White et al. (2004) suggested that extreme soil water deficit may be responsible for the death of nitrifying bacteria, which upon decomposition release even more inorganic N to the soil. Also, in the present study dry conditions were obtained by temporarily covering the soil surface with plastic sheets, thus possibly increasing soil temperature and stimulating soil microbial activity (Russell et al. 2002); Ma et al. 2014; Walley 2016).

Even more than drought, soil flooding or anoxic conditions reduce nitrification (Haynes 1986). According to IPNI (2014), microbial ammonium oxidation ceases when 60% of the soil pore space is filled with water. In the present study, little nitrate accumulated in soils under the wet scenario and rapidly disappeared upon reaching 25% soil moisture. This observation is consistent with findings by Cregger et al. (2014) who manipulated precipitation in the semi-arid climate of the US, and those of D'odorico et al. (2003) who modelled soil moisture effects on the N cycle in the dry savanna of South Africa. Both concur that nitrate accumulates more in soils of drier than of wetter conditions and that NO_3-N decreased with volumetric moisture content. The disappearance of nitrate is reportedly related to leaching that increased up to 12-fold in a wet compared to a baseline scenario (Gu and Riley 2010) and to denitrification, whereby N_2O emissions peaked after the onset of the rain in a semi-arid grassland (Liu et al. 2014). Besides such rainfall manipulation and simulation studies, other authors exploited natural gradients to investigate the effect of rainfall variability on soil C and N dynamics. In a study from the USA, Groffman et al. (2009) reported that both mineralization and nitrification decrease towards the drier side of a rainfall gradient. On the other hand, no effect of rainfall on either soil respiration or native soil N mineralization was apparent along a precipitation gradient in Mediterranean woodland (Jongen et al. 2013). However, most authors agree that in the semi-arid tropics, changes in soil moisture regimes induced by rainfall variability affect soil N mineralization dynamics at field level, and that the reported 10% yield reduction in the past decade is related to changing precipitation patterns and associated changes in soil N mineralization and N cycling (van Wesenbeeck et al. 2016). The observed increase in soil N mineralization during DWT under drier conditions, and the absence of wet season rice yield response to N mineralization during DWT will negatively affect soil fertility and increase the vulnerability of low-input farmers in West Africa, if soil N conservation measures are not implemented.

5.4.3 Location effects on soil N mineralization dynamics and its effect on rice

Soil N mineralization is a biological process involving several groups of micro-organisms that is governed by climatic and edaphic factors (Ward 2015). Carbon and N mineralization is generally lower in fine than in course-textured soils (Walley 2016). While ammonification is an unspecific process occurring under a wide range of conditions, nitrification occurs only in aerobic soils and at an optimum range of pH 6-8 (IPNI 2014). Thus, in the acid clay soil in Dassari, nitrification was much less than at Dano. However, because of the complexity of relationship between different soil attributes (pH, texture, dissolved organic C, nutrient availability, etc.) and nitrification, these factors cannot simply explain the potential of nitrification (Rudebeck and Persson 1998; Walley 2016). Mineralization potential and soil N supplying capacity are general measures of soil quality, fertility and productivity (Deenik 2006). However, due to the high mobility of nitrate in the soil system, the lateral fluxes in inland valleys and the temporal disconnect between mineralization/nitrification during DWT and N uptake during the wet season, direct effects of mineralization on productivity could not be shown in the present study. In fact, high soil N mineralization and nitrate accumulation was not related to wet season yield, indicating the likelihood of nitrate having been lost towards the end of DWT. Such N losses are likely to affect long-term soil fertility (Ward 2015) and to affect the production levels in small-scale low-input production systems of West Africa. These findings suggest the need to improve native soil N management during DWT and to implement N- conserving options for long-term benefits on systems productivity.

5.4.4 Conclusion

We conclude that tillage affects soil N dynamics during DWT, but depending on environmental conditions, the extent of which depending on the soil moisture regime. Soil moisture differs by toposequence position and is determined by rainfall. Reduced projected rainfall during DWT will lead to more nitrate accumulation in aerobic soils, while increased rainfall will stimulate lateral translocation of nitrate, accelerate changes in soil aeration status and enhance nitrate losses. Both scenarios will require N management options that conserve native soil N, mainly by temporary immobilization in the biomass of growing vegetation during DWT and its return to the soil upon incorporation / land preparation for wet season lowland rice.

6 GENERAL DISCUSSION

Inland valleys in West Africa occur abundantly and constitute an important potential for staple food crops and their production by small-scales farmers (Windmeijer and Andriesse 1993). Due to favorable hydrological conditions, rice is widely grown in the valley bottoms, benefitting from the lateral inflow of water, but also of nutrients and sediments from adjacent slopes. Combined with recent advances in rice breeding and the release of new rainfed genotypes, adapted to variable hydrologically conditions in inland valley bottom lands and that efficiently using limited nutrients, such lowland environments provide opportunities for increasing yields and regional production of rice in the inland valley landscape of West Africa. However, grain yields remain low and are far below the ecological and genetic potential of rice (Becker et al. 2003; Haefele et al. 2013; Saito et al. 2012; Saito et al. 2013). One of the main culprits of low productivity is inherently low fertility of the soils (Windmeijer and Andriesse 1993). Mineral and organic fertilizers can increase crop productivity. However financial limit their use by small-scale farmers who continue to depend largely on the native supply of nutrients, mostly N, from the soil. However, the soil nutrient reservoir is increasingly depleted by intensified land use combined with inappropriate management practices and a lack of residue cycling. Extreme climatic conditions further deteriorate the soil resource base, particularly in semi-arid environments. The research questions addressed in this thesis relate to the fact that low crop productivity in inland valleys of the dry savanna zone are closely related to soil N dynamics and N losses during the dry-to-wet transition season period (DWT), calling for improved management strategies that are geared to a more effective use of native soil N to enhance crop productivity in the short-term and sustain soil fertility in longer-term. Such strategies need to consider both the temporal (seasonality of element dynamics) as well as the spatial dimension (fluxes along toposequence) of processes occurring in the soil. The following sections discuss first the process of seasonal soil N dynamics along a valley toposequence and its implications for the N nutrition and yield of lowland rice. Subsequently, it discusses strategies aimed at avoiding soil nitrate-N build-up and N cycling and conservation. Finally, the importance of selected factors modulating the extent of seasonal N dynamics and determining the effectiveness of technical options for soil N conservation are presented in view of regionalizing and upscaling our process understanding to the dry savanna zone of West Africa.

6.1 Seasonal soil N dynamics along the toposequence and its effect on lowland rice

We hypothesized that nitrate-N is not only formed by *in-situ* mineralization after the onset of the rains, it is also vertically leached and horizontally translocated along the valley toposequence, contributing to large nitrate peaks occurring during DWT in lowland soils and potentially increasing rice agronomic performance during the wet season. Chapter 3 provided the evidence of the Birch-effect (transient nitrate mineralization peak) to occur during DWT at all levels of the toposequence, following the rewetting of the soil after a prolonged dry season (Figure 3.1) and represents a significant share of the total N balance (Table 4.1). Larger nitrate amounts in lowland than in slope soils point to the presence of lateral nitrate fluxes that are highest once the rains have established as shown before from humid forest environments of West Africa (Bognonkpe and Becker 2000; Bognonkpe 2004). We suggest that nitrate translocation to the valley bottom is mainly the result of subsurface inflow which will contribute to deplete soil N on the slopes and thus, contribute the widely reported nutrient mining of African upland soils (Smalling et al. 1997). The present study showed that 9- 40 kg ha^{-1} of NO_3-N having been translocated from some 100 m of slope length into the valley bottom lands during DWT. Considering the whole Dano watershed covering an area of some 600 km² and with 60-90 km² of valley bottoms, a total amount of 54-81,000 kg of native soil N are "stolen" every year from the uplands/slopes simply owing to the fact that the rains have started at a time when the landscape is largely bare of vegetation cover.

The transient nature of the nitrate peak in the lowland during DWT and before the establishment of rice suggests that this nitrate is lost and does not or only to a low extent contribute to rice production. This assumption is strengthened by previous reports from Asia and the humid zone of West Africa (Bognonkpe and Becker 2000; Pande et al. 2009).

6.2 Soil nitrogen management during DWT and its effects on rice.

The combined processes of large *in-situ* N mineralization, its lateral translocation into the wetland with reduced soil aeration status, and the resulting losses by microbial respiration (denitrification), and the absence of significant effects of N mineralization and /or translocation on lowland rice performance attributes, motivated our studies on assessing the effects of soil N conservation and/or N addition by system-inherent N sources. As shown in chapter 4, soil N can be managed in different ways by cultivating fast growing cover crops, either N-fixing legume or non-N-fixing grasses (Table 4.1). The absorption of nitrate by the growing biomass of such pre-rice vegetation types can lead to a temporary immobilization of nitrate that is otherwise prone to losses. Upon incorporation of the biomass into the soil in the process of land preparation for rice establishment, this “saved” as well as the ”added” N are restituted in organic form to the soil where it can benefit the rice crop after its decomposition (Table 4.2). Similarly to these findings, Logah et al. (2011) showed that organic amendments were able to immobilize soil N in Ghana. In a rice-wheat rotation system in Nepal, Pande et al. (2009) reported grain yield gains varying from 1 to 2 Mg ha^{-1}, depending of the type of the pre-rice crop, its capacity to absorb soil N and its N addition by biological N_2 fixation. Our findings support that up to 2 t ha^{-1} of additional rice grain can be produced with an appropriate soil N management during DWT.

In Burkina Faso, as in many parts of the West African savanna, demographic pressure has led to a near complete disappearance of fallow period that traditionally contributed to restore soil fertility between crop cycles (Becker and Johnson 2001). With the continuous cropping and in the absence of replacing the removed nutrients, soil fertility tends to rapidly decline with associated effects on the grain yield of rice (Becker et al. 2003; Saito et al. 2013; Haefele et al. 2013). Considering the potential of inland valley in the country and the present findings, we conclude that pre-rice cover crops can play a key role in sustaining soil fertility and increasing regional production in low-input systems. However, growing crops during the DWT may not be possible in very dry environments or in years when the rains start suddenly and DWT becomes too short to accumulate sufficient biomass and absorb sufficient quantities of soil N. Also the N contribution by biological N_2 fixation in pre-rice green manure legumes is often limited by low soil P availability (Ro et al. 2016). Finally, the investment of labor for establishing and incorporating green manure crops can be limiting adoption in labor-strapped situations (Ali et al. 2000), and unsecure land tenure has been shown to be a general disincentive for farmers to invest in soil fertility capital-building (Hamadou et al. 2005). Thus, technology options are available and have proven to be effective in managing native soil N for increased wet season rice yields, but their actual use in West Africa will require defining target environments and appropriate social-ecological niches for larger-scale adoption.

6.3 Effects of modulating factors and its improved management

Soil mineralization potential and related N dynamics show complex relationship with a number of factors that may modulate the extent of these processes. Such factors may comprise site effects (soil type and climate) as well as management effects (tillage, vegetation cover of valley slopes). We therefore hypothesized that soil disturbance via tillage, rainfall variability and soil type will differentially influence native soil N dynamics during the DWT and hence lowland rice performance. We have shown that tillage could enhance soil N mineralization but the trend was highly variable across years, depending on environmental conditions. Although tillage can create favorable conditions to soil microbial activity, it is not a key to accumulation of inorganic N in the soil. Several earlier studies could show that apparent C gains associated with reduced tillage are rather the result of a redistribution of C near soil surface (Maqsood et al. 2013; Premov et al. 2014) or associated with organic inputs (Yagioka et al. 2014).

We have showed that reduced rainfall will increase the nitrate accumulation in the soil with little apparent nitrate losses occurring during DWT. One the other hand, increased rainfall leads to a rapid and near complete disappearance of nitrate from lowland soils. The findings largely agree with previous studies suggesting that low

N accumulation in soils of wet environments is likely related to massive leaching (Gu and Riley 2010) and denitrification from the saturated soils Cregger et al. 2014). Models predict both dryer and wetter futures for West Africa. The dry scenario is likely to result in important accumulation of NO_3-N in the soil but rather poor use by the lowland vegetation. On the other hand, the wet scenario is likely to result in high nitrate translocation of rapid denitrification and hence poor availability to the wetland vegetation.

Finally, the high site variable of mineralization and fluxes of nitrate are likely due to combined effects of climatic differences between sites, to different geo-morphological settings (i.e., length and steepness of valley slopes) as well as to soil physical and chemical characteristics. Despite large site – related differences in mineralization, translocation and the fate of soil nitrate, the yield of season rice responded only slightly to N dynamics during DWT. This fact points to the need for management approaches that contribute to conserving native soil N for enhancing rice production. The use of such-called “nitrate catch crops” in the pre-rice niche appears a most promising approach, but necessitates the definition of niches and extrapolation domains.

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