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FACTORS MODULATING SOIL NITRATE-N DYNAMICS IN THE WEST AFRICAN SAVANNA ZONE

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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 systems of the dry savanna zone of West Africa. Two field experiments were conducted in 2013 and 2014 with the aim to determine the effect of soil tillage and rainfall intensity on native NO_3-N dynamics during DWT. The study on the effects of soil disturbances on N mineralization compared mechanical tillage with a no-till treatment. The effect of rainfall intensity on nitrate dynamics was assessed by comparing natural rainfall with a simulated 30% increase and a 30% reduction. 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. Reduced rainfall increased the nitrate accumulation in the soil profile with little apparent nitrate losses. With increased rainfall, on the other hand, most nitrate had disappeared once the volumetric soil moisture exceeded 25%. We conclude that tillage and rainfall differentially affect soil-N dynamics during DWT and, there is a need for site-specifically adapted soil-N-conserving management strategies.

Keywords: Burkina Faso, Climate change, N management, Rainfall variability, Tillage.

1. INTRODUCTION

The fertility of most soils in the West African savanna zone is becoming 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 a 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 to success in low- input cropping systems. 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, carbon 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 the root zone and its lateral translocation in inland valleys from the slopes into the wetland are 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.

Tillage accelerates the aeration of the topsoil 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 for trace gas mitigation strategies, reduced tillage systems are becoming increasingly promoted in sub-Saharan Africa. Minimum or no-tillage thereby reduces organic matter mineralization while enhancing soil-C sequestration

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(Lal, 2004). As a side effect, the extent of the Birch effect (Becker et al., 2007) 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 (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 and rainfall intensity on seasonal nitrate dynamics in the dry savanna zone of West Africa in 2013 and 2014.

2. RESEARCH METHODS

2.1 Location and attributes of study site

The study was conducted in the Dry Savanna agro-ecological zone of Burkina Faso, West Africa in 2013 and 2014. The study area is located near the town of Dano (11° 09' 00'' Nord, 03° 04' 00'' West) within a watershed situated in the south-western region of the country. The long-term average rainfall of 900 to 1200 mm annually is distributed in a uni-modal pattern with a dry season from November to April and one rainy season from May to October. Mean temperatures vary from 21 to 32°C. According to FAO soil classification (World Reference Base), the major soils encountered in the Dano catchment comprise Eutric Cambisols, Plintic Luvisols and Ferric Luvisols on the plateaus and valley slopes, and Gleyic Fluvisols as well as some Vertisols in the valley bottom lands (ISRIC, 2013).

2.2 Treatments application

We assessed the spatial-temporal dynamic of soil NO_3-N following soil tillage management in 2013 and 2014. The NO_3-N dynamics were assessed along the toposequence differentiated in an upslope and a footslope sampling position in both tilled and untilled plots (6 m x 4 m). The treatments were distributed following a complete randomized blocs design with four replications. The study focused on the DWT, between the first rainfall event in April until the onset of the main rainy season and crop establishment in July.

Rainfall variability and its effect on soil nitrate-N dynamics was simulated in the lowland in 2014 by modifying the rainfall amounts considering tree scenarios: (1) the normal in-situ rainfall regime of the DWT, (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

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(3) a higher rainfall regime (+30%) achieved by adding 30% of the amount of water received during each week by a watering can on the first day of the following week . The experiment was arranged in a randomized complete block design with 4 replications. The modified rainfall regime plots (1 m x 1 m) were located 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.

Auger samples were taken twice a week and transported to the laboratory within 2 hours for NO_3 determination following the quick on-farm test method (Schmidhalter, 2005). All samples comprised pooled composites of 7 topsoil auger samples (0-15 cm) collected across a diagonal of each plot. Based on soil moisture content (TDR) and bulk density measurements, the nitrate concentrations were transformed into total amount of N per unit area.

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 was applied. Figures were prepared using SigmaPlot, version 12.

3. RESULTS

3.1 Effect of tillage on soil N dynamics

Overall, soil-N mineralization was enhanced by tillage (Fig. 1) However, trends differed between observation years. NO_3-N dynamics are presented for only part of the DWT 2013 due to unavailability of data from Julian days 80-102. 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 day 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 the no-tillage plots, and no N_{min} was detectable at the end of the DWT.

In 2014, different trends between tillage treatments were clearly observed from Julian days 100-130 and from 130-180 (beginning of the rainy season). During the first half of DWT, NO_3- N was significantly higher in tilled than in no-till plots. While amounts remained nearly constant at 20 kg ha^{-1} throughout DWT in the no-till plots, soil tillage increased 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} nitrate

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mineralized in the tilled plots, approximately 78% was no longer present at the onset of rainy season.

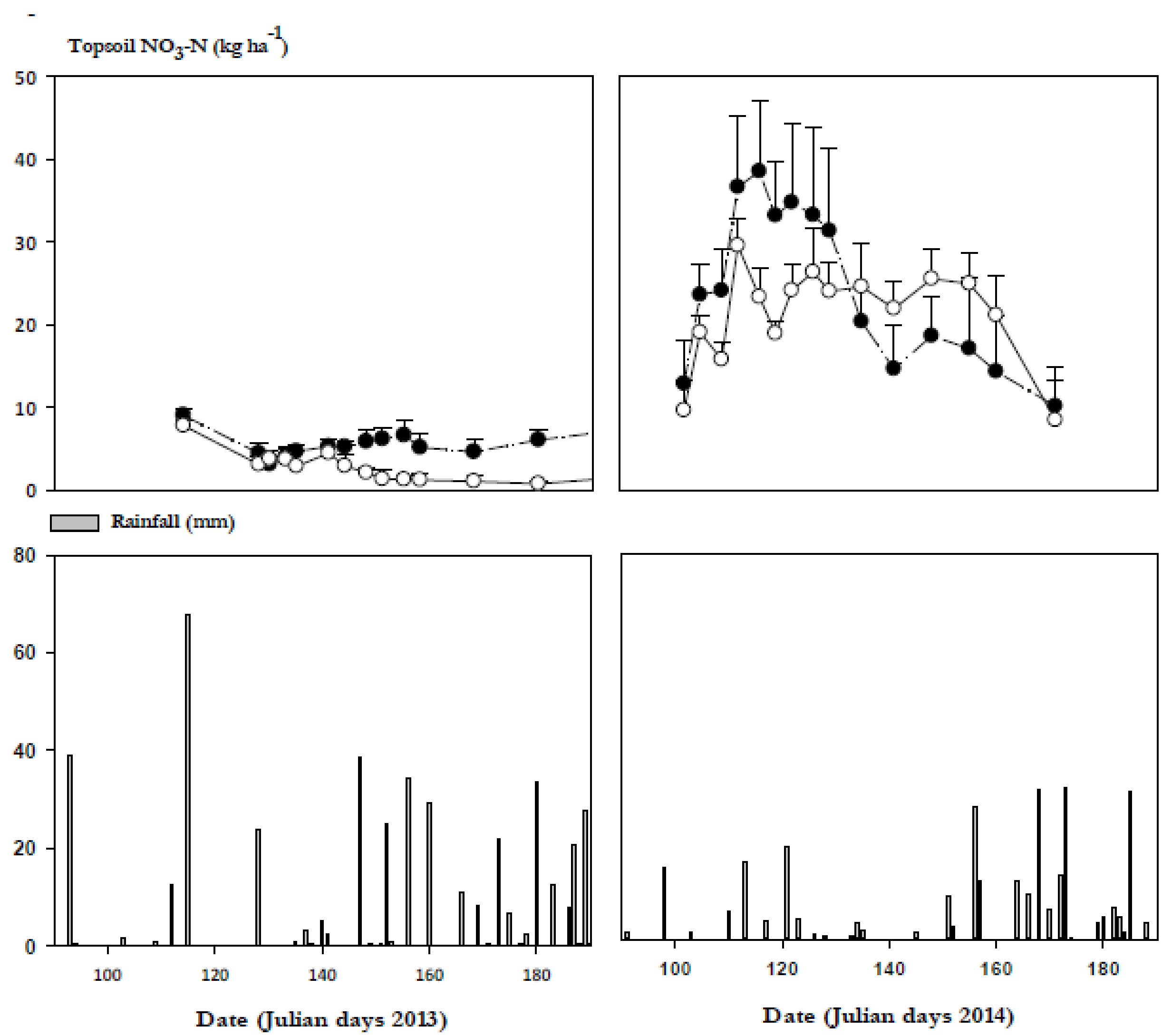

Fig. 1: Seasonal topsoil and soil solution nitrate-N dynamics response to tillage during the dry-to-wet transition season period in an inland valley in Dano (Burkina Faso, 2013-2014). Bars present standard errors of the mean (n=8)

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3.2 Effect of rainfall variability on soil 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 day 165 onwards. In the treatment with a 30% reduced rainfall, soil moisture reached a maximum of only 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 day 170 and remained anaerobic until the end of DWT (Fig. 2).

With normal rainfall, the nitrate dynamics followed the above-described pattern with an increase following the first rainfall event, reaching about 40 kg ha^{-1} at Julian day 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), 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. In the drier soil, we observed first a gradual increase in topsoil nitrate up to 44 kg ha^{-1} at 4% volumetric moisture, followed by a decline to about 20 kg ha^{-1} around Julian day 140.

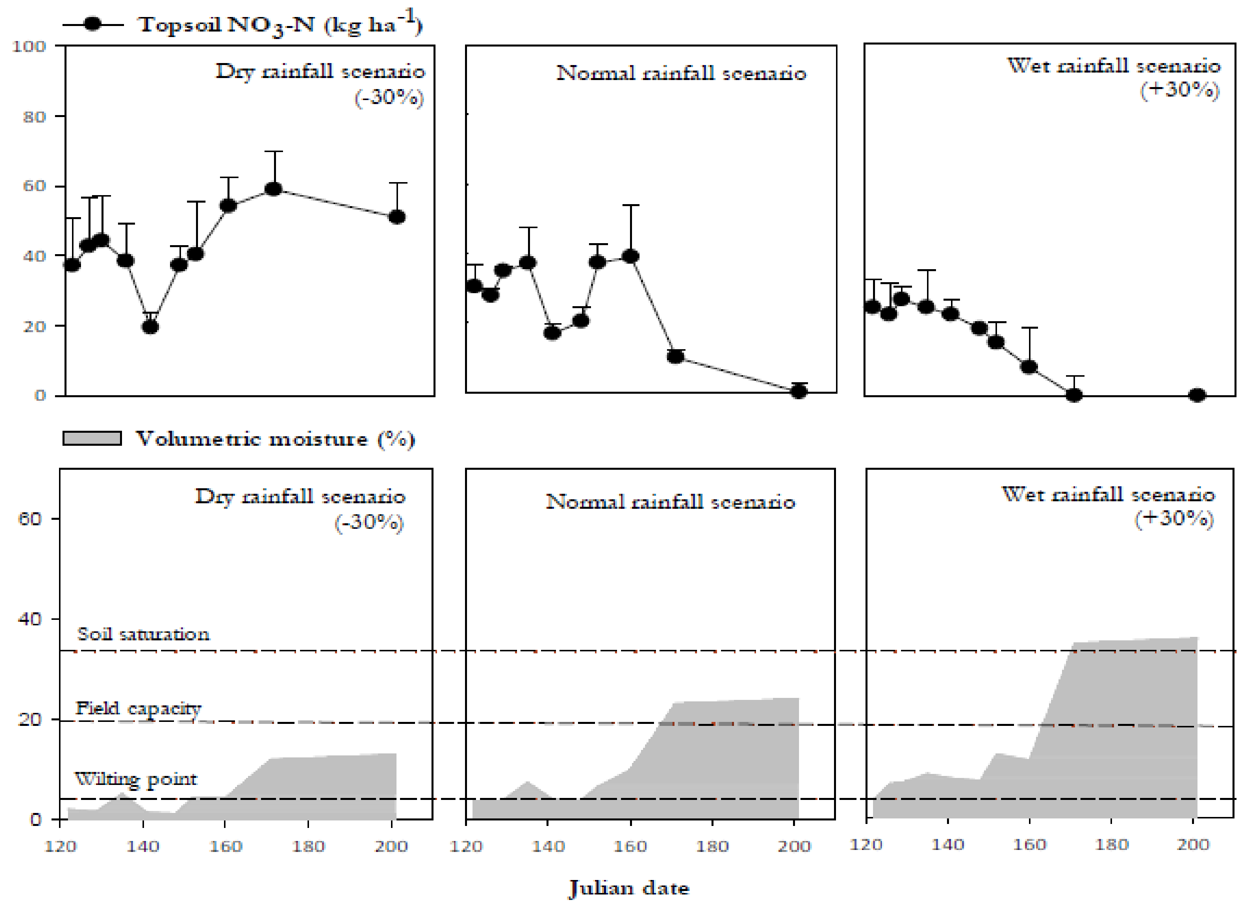

Fig. 2: Effect of rainfall regime (normal, dry and wet scenarios) on soil moisture, and extracted topsoil and soil solution nitrate-N dynamics during the dry-to-wet transition season period in an inland valley in Dano (Burkina Faso, 2014). Bars present standard errors of the mean (n=4)

4. DISCUSSION

4.1 Soil tillage and nitrate-N dynamics

The general trend of enhanced soil-N mineralization with mechanical tillage is neither surprising nor new, as it has already been reported that frequent disturbances of soil accelerate the breakdown of organic matter (Calegari et al., 2008; Aurora and Avelino, 2010; Kenneth et al., 2014). Tillage at the onset of the rainy season is commonly practiced around the world 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 plowing additionally contributes to enhancing soil roughness for increased water infiltration (Thierfelder and Wall, 2009). Such

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benefits of tillage are in contrast to the generally observed trend of mechanical tillage for enhancing soil-N mineralization and possibly N losses. Thus, frequent disturbances of soil accelerate the breakdown of organic matter with the released Nmin after its microbial oxidation to nitrate being prone to losses by leaching and denitrification (Becker et al., 2007; Kenneth et al., 2014). Moreover, conventional tillage is responsible for the disruption of the life cycle of beneficial microorganisms reducing soil organic matter (NRC, 2010) and for increasing 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 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). However, such reports related to enhanced C sequestration with reduced tillage are contested by some authors, who assume 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 Nmin 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 environments (Giller et al., 2009), and when crop residues are not returned to the soil surface (Ouedraogo et al., 2007). The findings in the present study are also not conclusive. While tillage increased soil-nitrate accumulation in the topsoil in 2013, it resulted in lower accumulation in 2014. The more favorable soil moisture conditions after tillage, resulting from improved water infiltration attributes, possibly favored 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 curbing soil-N mineralization and nitrate-N losses, particularly in wet years.

4.2 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 to chemo-lithotrophic organisms spending more energy on their maintenance than on ammonium oxidation (Wong and Nortcliff, 1995). The findings of the present study, however, indicate a higher nitrate accumulation under dry (30% reduced precipitation) than under wet (30% increased precipitation) conditions. White et al. (2004) suggested that an extreme soil water deficit may be responsible for the death of nitrifying bacteria that, upon decomposition, release even more inorganic N to the soil. In the present study, dry conditions were created 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). Even more than drought, soil flooding or anoxic conditions reduce nitrification (Haynes, 1986). In the present study, little nitrate accumulated in soils under the wet scenario, and this rapidly disappeared upon the soil reaching 25% moisture. This observation is consistent with findings by Cregger et al. (2014) who manipulated precipitation in the semi-arid climate of the USA, 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 decreases with volumetric moisture content. The disappearance of nitrate is reportedly related to leaching where values increased up to 12-fold in a wet compared to a baseline rainfall condition (Gu and Riley, 2010) and to denitrification, whereby N_2O emissions peaked after the onset of the rains 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 in this study, 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. CONCLUSION

We conclude that tillage affects soil-N dynamics during DWT but, depending on environmental conditions, the extent is controlled by the soil moisture regime. Soil moisture differs by toposequence position and is determined by rainfall. The projected reduced rainfall during DWT will lead to higher 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.

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