

**Title: Gross nitrogen transformation rates in shifting cultivation systems in Northern Thailand:
controlling factors and implications for inorganic nitrogen availability**

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Abstract

Slash-and-burn practices and subsequent fallow periods affect soil nitrogen (N) availability. Although extensive studies have examined the global temporal patterns of inorganic N after fire, NO_3^- regulation remains unclear due to ecosystem-dependent responses. Despite inorganic N pool control by NH_4^+ and NO_3^- production and consumption, local-scale patterns and mechanisms of gross N transformations, particularly in tropical regions, remain insufficiently understood. Thus, we aimed to elucidate the controlling factors of inorganic N in the shifting cultivation cycle in Northern Thailand, using a ^{15}N pool dilution method on soil samples at 0–10 cm depth collected across various post-burning stages (1, 4, 6, and 7 years after burning) and forest. We found that gross ammonification was enhanced by high soil organic matter and microbial biomass, while gross nitrification was enhanced by greater soil alkalinity. Ammonium immobilization increased with higher microbial biomass, while NO_3^- immobilization increased with lower NH_4^+ availability. With increasing fallow period, microbial biomass and consequently gross ammonification increased, boosting the NH_4^+ pool. Soil acidity, correlated with soil texture, influenced nitrification: coarser-textured soil intensified acidity and decreased gross nitrification, resulting in NH_4^+ -dominance, while finer-textured soil alleviated acidity, promoting nitrification over NH_4^+ immobilization, leading to NO_3^- -dominance. Our findings confirm that the fallow stage, along with which microbial biomass increases, was an essential driving factor regulating ammonification, while soil acidity, unrelated to fallow but a function of sand/silt content, was an essential driving factor regulating nitrification under shifting cultivation in Northern Thailand.

Keywords: Ultisols; Acrisols; ammonification; nitrification; slash-and-burn; fallow.

1. Introduction

Slash-and-burn agriculture, also known as shifting cultivation, is a prevalent subsistence farming system in the tropical regions among poor ethnic minorities in remote uplands with 300 million to 1 billion people worldwide practicing it (van Vliet et al., 2012; Mertz et al., 2009). Regenerating natural secondary vegetation is a well-known fallow paradigm that restore soil fertility in shifting cultivation systems (Szott et al., 1999). Fallows have various benefits for maintaining the soil productivity (Fachin et al., 2021; Filho et al., 2013; Mukul and Herbohn, 2016), including replenishment of soil organic carbon (C), microbial C (Bruun et al., 2016), and soil nitrogen (N) (Mertz et al., 2008). However, knowledge of the temporal pattern of chemical changes during the fallow period in different soils is still limited, although understanding the resilience of soil chemistry in this agricultural system is essential for defining soil management and recovery strategies of a farm (Fachin et al., 2021).

Shifting cultivation causes N loss from soil through combustion (Caldwell et al., 2002), leading to a decrease in N availability and subsequently limiting crop yields (Bruun et al., 2006; Mertz et al., 2008). Soil N transformation are affected by several factors like soil type (Shibata et al., 2017), microbial communities (Sugihara et al., 2010b), land use (Shibata et al., 2018; Sugihara et al., 2015), management (Sugihara et al., 2012), and fire regimes (Alcaniz et al., 2016; Pellegrini et al., 2020). Previous studies have found that both NH_4^+ and NO_3^- pool increased after fire in tropical ecosystems, with NO_3^- lagging behind NH_4^+ in the first few months, although the trend of NO_3^- was not as clear as NH_4^+ (Jiang et al., 2021; Wan et al., 2001). However, recent meta-analyses have shown that the effect of fire on inorganic N can differ greatly between ecosystem types, and the controls on NO_3^- are not straightforward due to divergent responses reported in different ecosystems (Jiang et al., 2021; Wang et al., 2018). Due to this complexity, it is challenging to generalize the impacts of slash-and-burn on the temporal fluctuation of

soil inorganic N (Mukul and Herbohn, 2016). Hence, as the next step, it is crucial to investigate the factors that regulate the fluctuations in inorganic N, particularly NO_3^- , pools in a particular tropical ecosystem. While site-specific findings are often overlooked, regional investigations into N transformation mechanisms across diverse ecosystems will advance our comprehension of the holistic impact of slash-and-burn practices on tropical ecosystems. Nitrogen transformation is typically measured by net and gross ammonification/nitrification rates. Net rates indicate N availability, while gross rates provide functional relationships with controlling factors of inorganic N pool (Davidson et al., 1991; Li et al., 2020). However, in the tropics, gross N transformation rates during slash-and-burn cycles have not been extensively studied, hindering the comprehensive understanding of the fluctuation of soil inorganic N. Therefore, to bridge this knowledge gap and better understand the factors controlling soil inorganic N, it is essential to measure both inorganic N pool and gross N transformation rates (Norton and Stark, 2011). This approach is likely to provide more precise insights into the impacts of slash-and-burn practices than attempts to make broad generalizations, helping understand variation that global data synthesis cannot explain.

Therefore, the objective of our study was to investigate the controlling factors of soil inorganic N pool under different land-use stages of shifting cultivation in Northern Thailand, quantifying gross N transformation rates to provide insights into the site-specific controls and their underlying mechanisms influencing the fluctuation of available N pool size.

2. Materials and methods

2.1. Study sites

This study was performed in Ban Du La Poe, Mae La Noi District, Mae Hong Song Province,

Northern Thailand (18°24'N, 98°05'E), within a Karen ethnic group farmer's field (Tongkoom et al., 2021). The field lies 1,100–1,300 m above sea level, mostly on steep slopes that usually exceed 20 degrees. Mean annual precipitation and temperature are 1,200 to 1,600 mm and 20°C, respectively, with a rainy season from April to October under a monsoon climate (Funakawa, 2017). Soils, originating from metamorphosed fine-textured sedimentary rocks and granite, are mainly classified as Ustic Haplohumults or Humic/Typic Dystrustepts in the USDA classification system (Soil Survey Staff, 2014). The general description of the soils in this region is given in detail by Funakawa (2017). The villagers follow a 7-year slash-and-burn rotation system, with upland rice cultivated post-March burning, followed by a seven-year fallow.

We utilized a chronosequence approach, examining similar soil types and environment at different shifting cultivation stages: AB0, AB1, AB4, AB6, and AB7 (0, 1, 4, 6, and 7 years after burning), and a long-fallowed forest (F) plot. Soil samples (0–10 cm depth) were taken in May 2015, composited from five sub-samples per replication, with two replications per plot except AB7. Only the AB0 plot was cultivated with upland rice. All samples were sent to Kyoto university for analysis, with part air-dried and sieved through a 2-mm mesh sieve, while the remaining fresh portion was sieved through a 4-mm mesh and refrigerated at 4°C for incubation.

It should be noted that native differences among areas and other factors like pre-fire vegetation, fire regime, or climatic conditions following the burning may cause variation, inaccuracy, and even misjudgment of results in chronosequence studies (Johnson and Miyanishi, 2008). Additionally, only one field of each time point was sampled in our experiment, which constitutes a form of pseudoreplication that is often unavoidable in natural experiments and monitoring studies (Davies and Gray, 2015). However, given that our studied areas had similar elevation, topography, microclimate, and

soil and vegetation type, we still believe that this experimental design could provide valuable information on N transformation during the different stages of the slash-and-burn cycle (Davies and Gray, 2015).

2.2. Air-dried soil analysis

Soil pH was measured with a benchtop pH meter (F-70, Horiba, Kyoto, Japan) using soil to solution (H₂O and 1 M KCl) ratio of 1:5 after shaking for one hour. Total C and N content of the soils were determined using a dry combustion method with a CN analyzer (VarioMax CHN, Elementar, Germany). Exchangeable cations were analyzed by an ammonium acetate (1 M, pH 7.0) batch extraction using atomic absorption spectroscopy (A-A-640-01, Shimadzu, Japan). The cation exchange capacity was then determined using the residual soil after ammonium acetate extraction. Exchangeable Al³⁺ was determined by titration after 1 M KCl extraction. Particle size distribution was determined by a sieve–pipette method (Gee and Or, 2002). For inorganic N extraction, 10 g soil (oven-dried base) was mixed with 30 ml of 1 M KCl for 30 min on an orbital shaker, then centrifuged (2000 rpm, 10 min) and filtered through filter paper (No. 5C, Advantec, Japan). The NH₄⁺ and NO₃[−] in the extract were determined by colorimetric analysis using an automated flow injection analyzer (AQLA-700 Flow Injection Analyzer, Aqualab, Tokyo, Japan). Available phosphorus (P) was extracted from the soil using Bray II solution (Bray and Kurtz, 1945).

2.3. Fresh soil analysis

Microbial biomass carbon (MBC) and nitrogen (MBN) were measured immediately after coming back to Kyoto university in triplicate using the fumigation–extraction method (Brookes et al.,

1985; Vance et al., 1987). Briefly, soil samples (8.0 g dry base) were fumigated with ethanol-free CHCl_3 for 24 h at 25°C. The soluble C and N were then extracted from both the fumigated and non-fumigated samples with 32 ml of 0.5 M K_2SO_4 for 30 min on an orbital shaker. Total organic C and extractable N in the filtered extract were determined using a TOC-N auto-analyzer (TOC-V carbon analyzer with an IN unit, Shimadzu, Japan). The difference between extractable C from fumigated and non-fumigated samples were used to calculate the microbial C flush, which was converted to MBC using a K_{EC} factor of 0.45 (Vance et al., 1987). Similarly, microbial N flush was converted to MBN using a K_{EN} factor of 0.54 (Brookes et al., 1985).

Gross ammonification, nitrification, and microbial immobilization rates were measured by the ^{15}N isotope dilution technique (Hart et al., 1994; Kirkham and Bartholomew, 1954). Four fresh subsamples (15 g oven-dried basis) with three replicates were placed into 100 mL of glass vials covered with parafilm with several small holes for each soil sample. The soil moisture was adjusted to 60% of field capacity by adding deionized water. After pre-incubation at 25 °C for one week for stabilizing microbial activity, each sample was applied with 1 mL of either ^{15}N -enriched K^{15}NO_3 (30.3 mg N L^{-1} ; 99 atom% ^{15}N in excess) or $^{15}\text{NH}_4\text{Cl}$ (30.6 mg N L^{-1} ; 98 atom% ^{15}N in excess) by pipetting solutions uniformly over the soil surface, resulting in an equivalent addition of 2 mg of $^{15}\text{NO}_3^-$ -N or $^{15}\text{NH}_4^+$ -N kg^{-1} soil. Each sample was incubated in the lab at 25°C. After 0.5 h and 24.5 h incubation, a part of the sample in the bottles was extracted with 2 M KCl solution with soil to solution ration of 1:5, reciprocally shaken for one hour, filtered, and stored at 4°C until later measurement. Within a few days from extraction, the concentration of inorganic N in the extract was measured.

2.4. Analysis of ^{15}N

The diffusion method was used for measuring the enriched N isotopic ratio of NH_4^+ or NO_3^- (Brooks et al., 1989). To measure NH_4^+ -N, first, 500 μgN of NH_4Cl or KNO_3 was added to a 15 ml aliquot of extract so that the amount of ^{15}N was sufficient to be detected in the following analysis mass spectrometry. Second, approximately 2 g of KCl was added to a 15 ml aliquot of extract to promote diffusion. Third, 200 mg of heated MgO was added to increase solution pH to 10.5 for converting NH_4^+ to gaseous NH_3 . In 6 days, generated NH_3 was trapped into acidified filter disks (ADVANTEC No. 6), already pipetted 10 μL of 2.5 M KHSO_4 , and then, analyzed ^{15}N of acidified filter disks using a stable isotope ratio mass spectrometer (IsoPrime100, Elementar UK Ltd, Cheadle, UK) operating in continuous flow mode, coupled with a CN analyzer (Vario MAX, Elementar, Hanau, Germany). To measure NO_3^- -N, first, NH_4^+ was removed by adding MgO as described above. Second, approximately 200 mg of Devarda's alloy was added to the extracts, and reduced NO_3^- into NH_4^+ , which was immediately converted to NH_3 . After six days, ^{15}N of trapped NH_3 -N in acidified filter disks was analyzed as described above.

2.5. Calculation of gross transformation rates

The gross nitrification and ammonification rate and gross nitrate and ammonium consumption rate were calculated from the following equations (Kirkham and Bartholomew, 1954; Norton and Stark, 2011):

$$G = ((M_0 - M_t) / t) \times (\log(H_0 M_t / H_t M_0)) / (\log(M_0 / M_t))$$

$$F = G - (M_t - M_0) / t$$

where G is the gross rate of nitrification or ammonification, M is the concentration of soil $^{14+15}\text{NO}_3^-$ -N or $^{14+15}\text{NH}_4^+$ -N ($^{14+15}\text{N}$ pool), H is the concentration of soil $^{15}\text{NO}_3^-$ -N or $^{15}\text{NH}_4^+$ -N (^{15}N pool), t is the

length of the incubation (24 h in the present study), and 0 and t indicate whether the measurement is made at time 0 or time t . F is the gross consumption rate of NO_3^- -N or NH_4^+ -N. The gross NH_4^+ -N immobilization (heterotrophic assimilation) rate was determined by subtracting the gross nitrification rate from the gross consumption rate of NH_4^+ -N. The gross consumption rate of NO_3^- -N was assumed to be equivalent to the gross immobilization (heterotrophic assimilation) rate of NO_3^- -N in this study as it was measured in the absence of both plant root uptake and leaching, and under aerobic conditions, the denitrification rate was expected to be minimized (Bahr et al., 2014).

2.6. Data analysis

The results are expressed on an oven-dried weight basis for soil samples (105°C, 24 h). The normality of samples was verified by the Shapiro-Wilk test at $p < 0.05$, and if necessary, the variance was normalized using logarithmic transformations. Pearson correlation coefficient analysis examined relationships among N transformation rates and soil properties. All statistical analyses were performed with Sigmaplot 11.0 (Systat Software, San Jose, CA).

3. Results

3.1. Physico-chemical and biological properties of the studied soils

Sand contents of the soils ranged from 22 to 46%, with an average of $36 \pm 9\%$ ($\pm$ S.D; Table A.1), and the texture of most soils was classified as clay loam (Fig. A1). Total C contents ranged from 30 to 61 g kg^{-1} , with an average C/N ratio of 15 ± 2 . The soils in all the plots were moderately acidic, with the pH (H_2O) values ranging from 5.0 to 5.9, with an average base saturation of $18 \pm 3\%$. Considerable variability was observed in the ratio of NO_3^- pool to inorganic N ($\text{NH}_4^+ + \text{NO}_3^-$) pool,

which ranged from 3 to 93%, with an average of $63 \pm 35\%$ (Fig. 1a). The size of soil NH_4^+ pool decreased in the first year of fallow and increased after the six years of fallow, while that of NO_3^- pool increased just after slash-and-burn and decreased after the six years of fallow. At the F plots, the soil NO_3^- pool size was much larger than the soil NH_4^+ pool. Microbial biomass C and N tended to increase along with the fallow stage (Fig. 1b).

3.2. Gross N transformation rates

The gross ammonification rate was $9.3 \pm 2.3 \text{ mg N kg}^{-1} \text{ day}^{-1}$, which did not fluctuate during the fallow period and was the highest at the F plots (Fig. 2a). Ammonium consumption rate, which is the sum of NH_4^+ immobilization rate and gross nitrification rate, ranged from 2.1 to $9.7 \text{ mg N kg}^{-1} \text{ day}^{-1}$, with an average of $4.6 \pm 2.3 \text{ mg N kg}^{-1} \text{ day}^{-1}$ (Fig. 2a). The gross nitrification rate ranged from 0.0 to $5.4 \text{ mg N kg}^{-1} \text{ day}^{-1}$, with an average of $1.9 \pm 1.9 \text{ mg N kg}^{-1} \text{ day}^{-1}$ (Fig. 2b). It increased at AB1 and decreased later, though high at one of F. Nitrate consumption rate ranged from -0.9 to $4.3 \text{ mg N kg}^{-1} \text{ day}^{-1}$, with an average of $0.9 \pm 1.4 \text{ mg N kg}^{-1} \text{ day}^{-1}$ (Fig. 2b). It increased at AB1 and decreased later on.

3.3. Correlations among variables

In the relationships among N transformation rates and soil properties (Table 1), the gross ammonification rate had significant positive correlations with TC, TN, MBC, and MBN. Gross nitrification rate and NH_4^+ consumption rate had significant positive correlations with pH (KCl), total exchangeable bases, base saturation, and silt content. Nitrate consumption rate had significant negative correlations with gross ammonification rate and MBN. In the relationships among variables of soil

properties, sand content had significant negative correlations with silt content, pH (KCl), total exchangeable bases, and base saturation.

4. Discussion

The present study provides a site-specific variation of soil inorganic N and quantifies controlling factors of it, by measuring gross N transformation rates with soil physicochemical properties, in the slash-and-burn cycle of Northern Thailand, where moderately fine-textured and moderately acid soil distributes. Gross N transformation rates observed in this study were within the range reported globally (Booth et al., 2005; Elrys et al., 2021a; Elrys et al., 2021b). The main finding of this study is that soil microbial biomass and organic matter content, which could increase along with the fallow period, in combination with soil acidity, enhanced with higher sand content, mainly control the variations of inorganic N pool in the studied area.

4.1. Soil texture and acidity in the studied area

Despite the uniform distribution of soil texture within the clay loam category in the studied area, we found a negative correlation between sand content and pH (KCl), total exchangeable bases, and base saturation, while silt content showed a positive correlation with these parameters (Fig. 3; Table 1). This suggests that higher sand content contributes to soil acidity, while higher silt content enhances soil alkalinity. The underlying factor regulating this relationship is currently unknown and requires further investigation. We acknowledge that this finding is irregular, and there may be several possible explanations for it. However, at this point, any attempt to explain the cause of this relationship would be speculative.

One possible explanation is that the coarser-textured soil could intensify the leaching, which causes greater soil acidity in the studied area within the range of clay loam texture (Fig. A.1). Evaporation and infiltration are a function of soil texture (Grote et al., 2010; Li et al., 2014), and the vertical soil water movement in the soil profile is especially variable within the range of clay loam, sandy clay loam, silty clay loam and silty clay soils (Yetbarek et al., 2020). As the soil texture of the present study is close to this range, and actual evapotranspiration is almost balanced with precipitation (Fisher and van Velthuisen, 2016), the soil texture might determine soil acidity in the studied area. Leaching intensity might be marginal for finer-textured soil, mitigating soil acidity.

Another possibility is the effect of dust, desert loess, defined as aeolian silt generated in and derived from low- to mid-latitude (10°N to 40°N) arid or semiarid regions that were not glaciated (Lancaster, 2020; Muhs, 2013). Indeed, silt-sized loess-like sediments have been observed in Chiang Mai, a town 100km straight from the studied area (Ying, 2018). Silty aeolian dust contains a certain amount of carbonate (Pécsi, 1990), which can ameliorate soil acidity. Hence, the higher silt content could increase soil pH (Fig. 3b, 3d).

We believe that either mechanism or a combination of them, works, although further studies are needed for the relationship of soil texture with soil acidity within a relatively narrow range of variation at a local scale to confirm its underlying mechanism.

4.2. Drivers of gross N transformation rates

A positive correlation of gross ammonification rates and TC, TN, MBC, and MBN (Fig. 4) suggests that organic matter contents and microbial biomass are mainly responsible for gross ammonification (Booth et al., 2005; Elrys et al., 2021a). This finding highlights the importance of

substrate availability (quantity), which is a source of energy for soil microbes (Schimel and Bennett, 2004), in regulating inorganic N production (Booth et al., 2005). This is well following the global pattern that the higher total N accelerates ammonification via increasing microbes (Elrys et al., 2021a). Although organic matter content did not seem to increase along with the fallow period in the studied area, microbial biomass, reacting fast to land-use change and sensitive C pools (Pabst et al., 2013), gradually increased (Fig. 1b). Therefore, gross ammonification rates increase as the fallow stage proceeds. The lack of clear correlations between fallow length and the stock of organic matter may indicate that the intensity of land use is sufficiently low for C levels not to be significantly affected, and spatial heterogeneity might be more significant than changes in organic matter due to land use in this region (Bruun et al., 2006; Bruun et al., 2021).

A positive correlation of gross nitrification rates and pH (KCl), base saturation, and total exchangeable bases (Fig. 5) suggests that soil alkalinity, but not NH_4^+ pool size, could enhance gross nitrification by acid-sensitive nitrifiers (Elrys et al., 2021b). There is a general understanding that higher soil pH enhances nitrification, primarily through its effect on NH_3 availability (Cheng et al., 2013; Nugroho et al., 2007). Nitrification capacity (presented as the ratio of gross nitrification rate to gross ammonification rate; (Zhang et al., 2013)) was positively correlated with pH (KCl) and base saturation (Fig. 6), suggesting that the fate of NH_4^+ is to turn into NO_3^- for less acid soil. As discussed above, soil texture, but not the fallow stage, probably controls soil acidity, affecting gross nitrification rates in the studied area.

Ammonium consumption rate, which is the sum of gross nitrification and microbial NH_4^+ immobilization, positively correlated with base saturation (Table 1). If we compare the contribution of each process to the ammonium consumption, i.e., the fate of NH_4^+ , gross nitrification increased in

proportion with soil alkalinity (Fig. 7). Ammonium immobilization rate increased in proportion with MBC and MBN (Fig. 8). The finding in this study suggests that under greater soil alkalinity, nitrifiers were more successful in competing for NH_4^+ with immobilizing microbes, as already shown by nitrification capacity, while higher microbial biomass may increase NH_4^+ immobilization. Microbial populations are responsible for the immobilization of nutrients (Booth et al., 2005).

Nitrate consumption rate, i.e., microbial NO_3^- immobilization rate, had a weak but negative correlation with gross ammonification rate and MBN (Table 1). We conducted stepwise multiple regression analysis to examine the contribution of other factors to NO_3^- immobilization rate, and the following equation was obtained:

NO_3^- immobilization rates ($\text{mg N kg}^{-1} \text{ day}^{-1}$.)

$= 3.90 + 0.34 \times (\text{Gross nitrification rate}) - 0.39 \times (\text{Gross ammonification rate})$

$R_{adj}^2 = 0.55 \quad p < 0.05$

This equation indicates that gross nitrification positively contributes and gross ammonification negatively contributes to NO_3^- immobilization, implying that the decrease of NH_4^+ availability may increase the microbial use of NO_3^- in the soil. Microbes prefer uptake of NH_4^+ over NO_3^- because NO_3^- immobilization requires more energy than NH_4^+ immobilization, and microbes have higher affinity and maximum uptake capacity for soil NH_4^+ over soil NO_3^- (Kuzuyakov and Xu, 2013). NO_3^- immobilization may be suppressed by NH_4^+ even at low concentrations (Templer et al., 2008).

4.3. Controls on the pool size of inorganic N

The balance of inorganic N can be controlled by the factors governing NH_4^+ and NO_3^- production and consumption. Both substrate quantity (soil C and N content) and soil quality (soil acidity)

are highlighted for controlling N cycling rates and the relative importance of soil inorganic N economy in the slash-and-burn cycle of Northern Thailand (Fig. 9). The fallow period controls the gross ammonification rate, along with which microbial biomass, possibly with soil organic matter content (Arunrat et al., 2022), could increase. Higher MBC and MBN also increase microbial NH_4^+ immobilization. Then, if the soil texture is coarser, ranging from sandy clay to sandy clay loam, the soil becomes more acidic, and therefore nitrification is inhibited, resulting in the dominance of NH_4^+ for soil inorganic nitrogen (Fig. 9a). On the other hand, if the soil texture is finer, ranging from clay to clay loam, the soil acidity is alleviated, and therefore nitrification is promoted over microbial NH_4^+ immobilization, resulting in the dominance of NO_3^- for soil inorganic N (Fig. 9b). For an NH_4^+ -dominant type environment, if the microbial biomass is large, N will be retained in the soil by microbial NH_4^+ immobilization, and even if not, N will be less susceptible to leaching as NH_4^+ is a cation. For NO_3^- -dominant type environment, due to the low NH_4^+ availability, microbial NO_3^- immobilization is enhanced, and N will be retained in the soil. Although NO_3^- is an anion, leaching intensity may be only marginal due to its finer soil texture in the studied area. As a result, for both NH_4^+ - and NO_3^- -types of soil, soil N cycles could be tight with a minimal loss of N, although seasonal fluctuations of N dynamics also should be considered (Sugihara et al., 2010a).

5. Conclusion

Our study provides significant insights into the site-specific variation of soil inorganic N in the slash-and-burn cycle of Northern Thailand, with soil microbial biomass, organic matter content, and soil acidity being the principal controlling factors. Our results indicate that the fallow stage in this region mainly enhances soil fertility by boosting soil microbial biomass, rather than mitigating soil acidity.

Interestingly, soil alkalinity emerges as a significant contributor to gross nitrification, irrespective of the NH_4^+ pool size. An unusual correlation was observed between soil texture—specifically sand content—and soil acidity, which requires further investigation. These region-specific conditions shed light on the challenge of generalizing the controlling factors of temporal patterns of soil inorganic N after fire, despite extensive meta-analyses conducted (Jiang et al., 2021). As diverse ecosystems have different mechanisms and capacities to replenish N after a fire (Wan et al., 2001), the primary function of fallow can differ based on region-specific environmental factors. Although the limited sample size inherent to chronosequence studies restricts making broad generalizations of our findings (Davies and Gray, 2015), we assert their importance in highlighting the intricate interplay of local environmental factors in controlling N cycles. While the conclusions drawn provide valuable regional understanding, they illuminate the necessity for more extensive studies across broader ecological ranges.

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Table captions

Table 1 Pearson correlation coefficient among N transformation rates and soil properties

Table A.1 Physico-chemical properties of the studied soils

Figure captions

Fig. 1 (a) Inorganic nitrogen pool and (b) microbial biomass carbon (MBC), nitrogen (MBN), and their ratio (MBC/MBN) at each plot.

Fig. 2 (a) Gross production rates of NH_4^+ (as a positive value), consisting of gross ammonification rates (blue bar), and gross consumption rates of NH_4^+ (as a negative value), consisting of gross NH_4^+ immobilization rate (light blue dashed bar) and gross nitrification rates (red bar), and (b) gross production rates of NO_3^- (as a positive value), consisting of gross nitrification rates (red bar), and gross consumption rates of NO_3^- (as a negative value), consisting of gross NO_3^- immobilization rate (light orange dashed bar).

Fig. 3 Relationship between soil pH (KCl) and (a) sand content and (b) silt content, and base saturation and (c) sand content and (d) silt content.

Fig. 4 Relationship between gross ammonification rate and (a) total carbon (TC) content, (b) total nitrogen (TN) content, (c) microbial biomass carbon (MBC), and (d) microbial biomass nitrogen (MBN).

Fig. 5 Relationship between gross nitrification rate and (a) soil pH (KCl) and (b) base saturation.

Fig. 6 Relationship between nitrification capacity and (a) soil pH (KCl) and (b) base saturation.

Nitrification capacity is presented as the ratio of gross nitrification rate to gross ammonification rate.

Fig. 7 Relationship between the proportion of gross nitrification rate (GNR) to NH_4^+ consumption rate and (a) soil pH (KCl) and (b) base saturation.

Fig. 8 Relationship between NH_4^+ immobilization rate and microbial biomass nitrogen (MBN).

Fig. 9 Schematic showing regulation of soil inorganic N pool (a) for coarser-textured soil and (b) for finer-textured soil during slash-and-burn cycle in Northern Thailand. C, carbon; N, nitrogen; MBC, Microbial biomass carbon; MBN, Microbial biomass nitrogen; Org-N, Soil organic nitrogen. Elevated MBC and MBN during the fallow period stimulate ammonification and microbial NH_4^+ immobilization. Ammonification is also accelerated by TC and TN (substrate quantity). (a) Soil acidity induced by coarser-textured soil suppresses nitrification and increases NH_4^+ availability. High NH_4^+ availability, in turn, decreases microbial NO_3^- immobilization. (b) Soil alkalinity induced by finer-textured soil stimulates nitrification but reduces NH_4^+ availability. Decreased NH_4^+ availability, in turn, increases microbial NO_3^- immobilization.

Fig. A.1 Ternary diagram of the USDA soil texture classification for studied plots.

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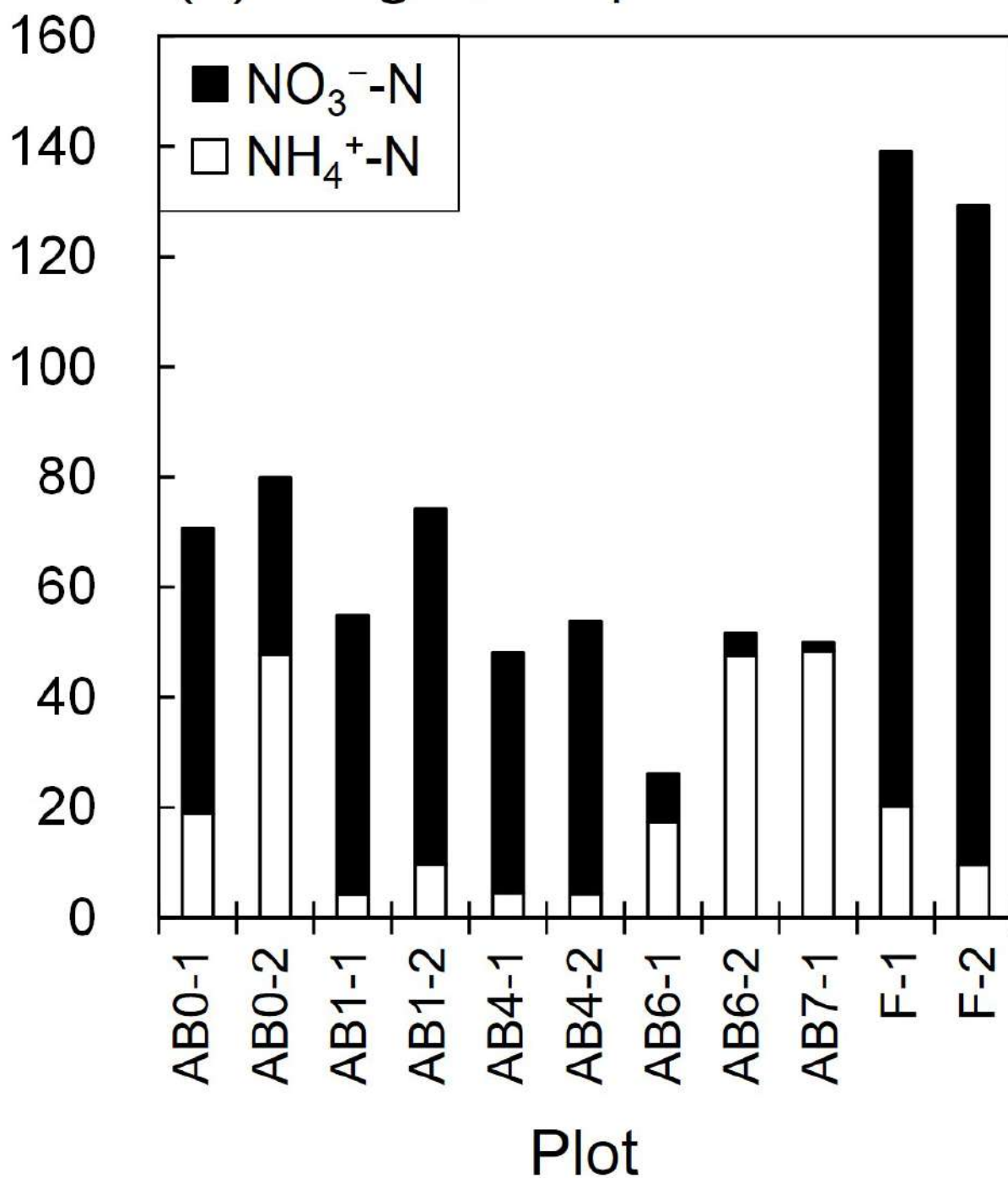
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Soil $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$
(mg kg^{-1})

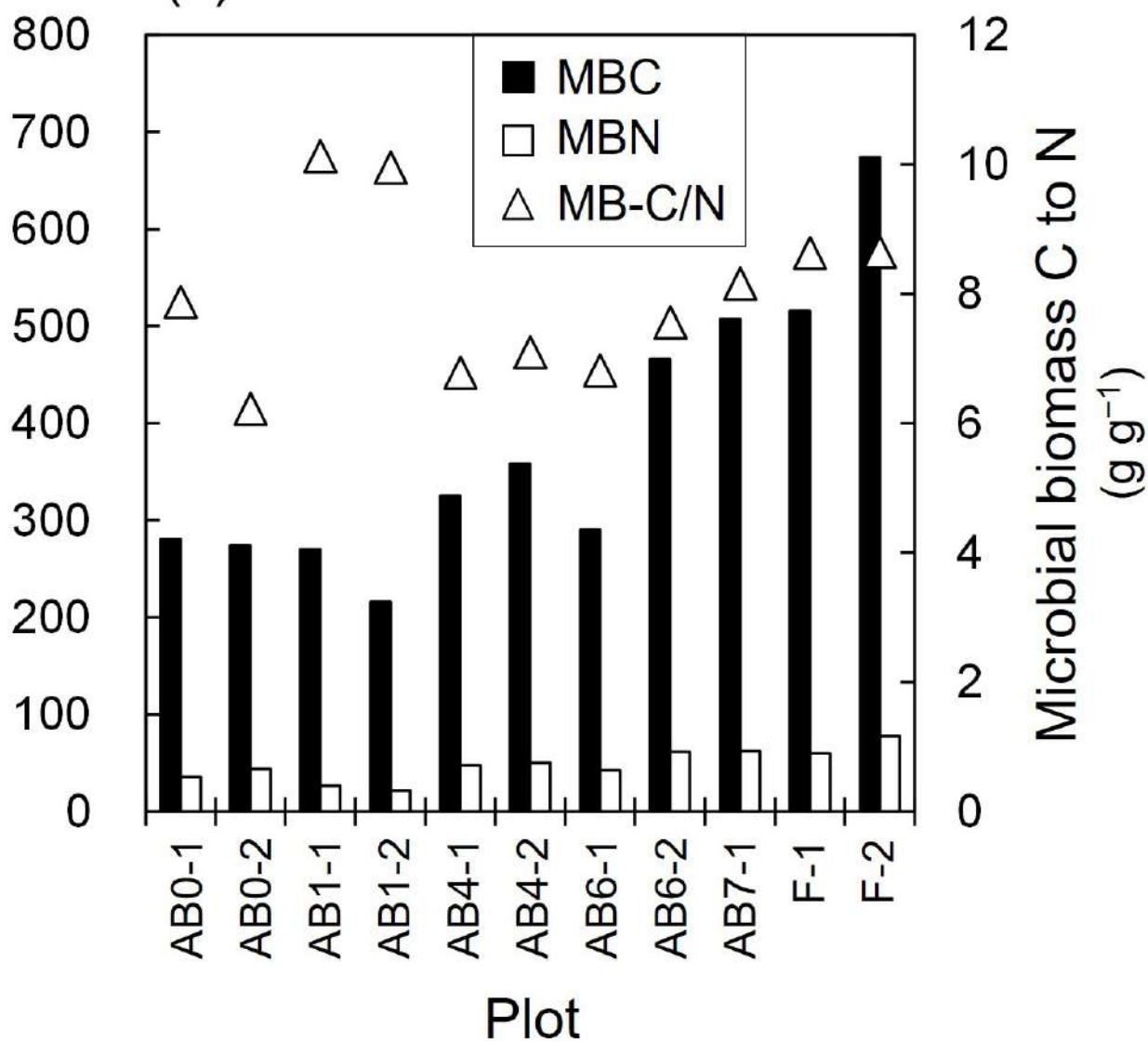
(a) Inorganic N pool



Microbial biomass C and N

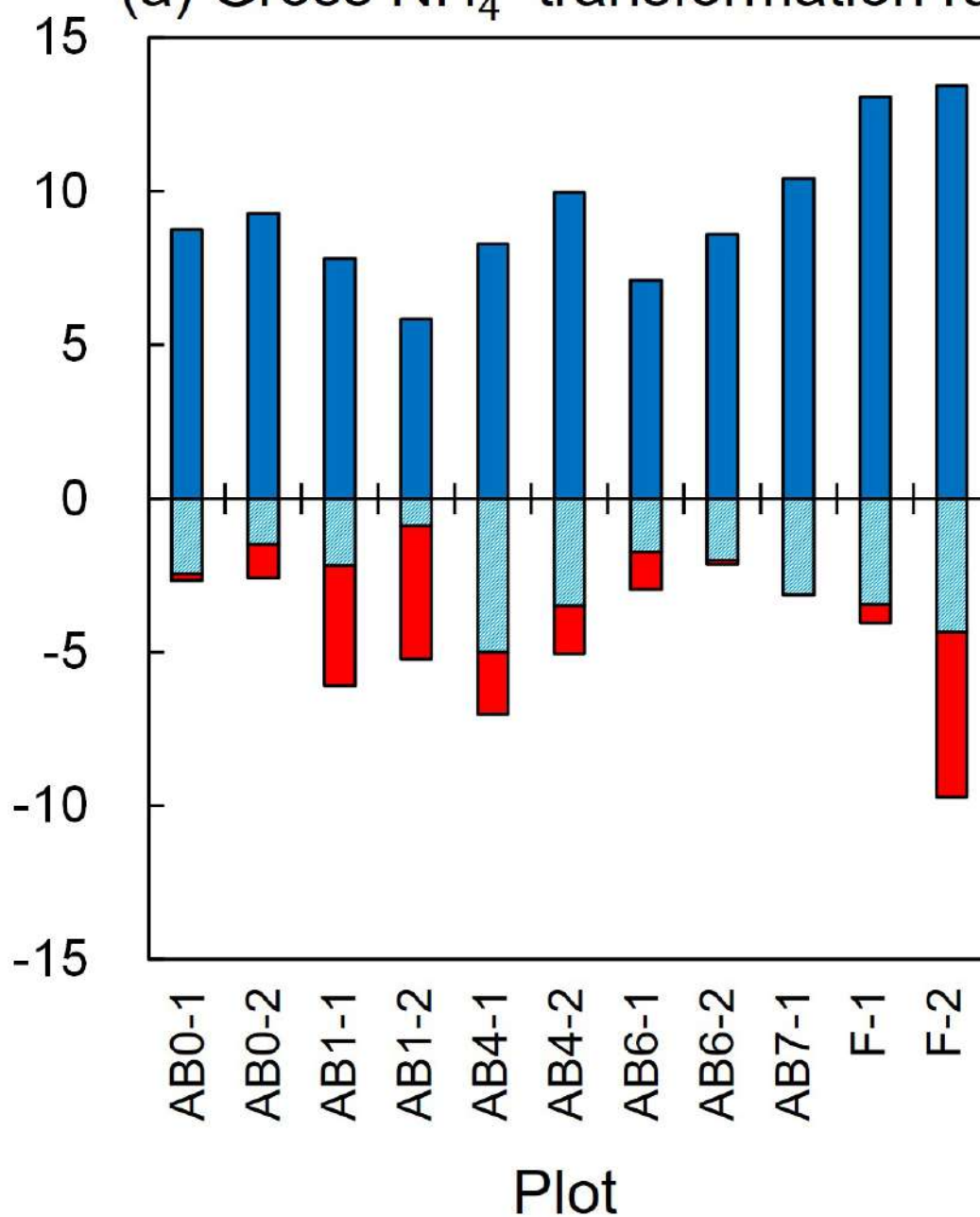
(mg kg⁻¹)

(b) MBC and MBN



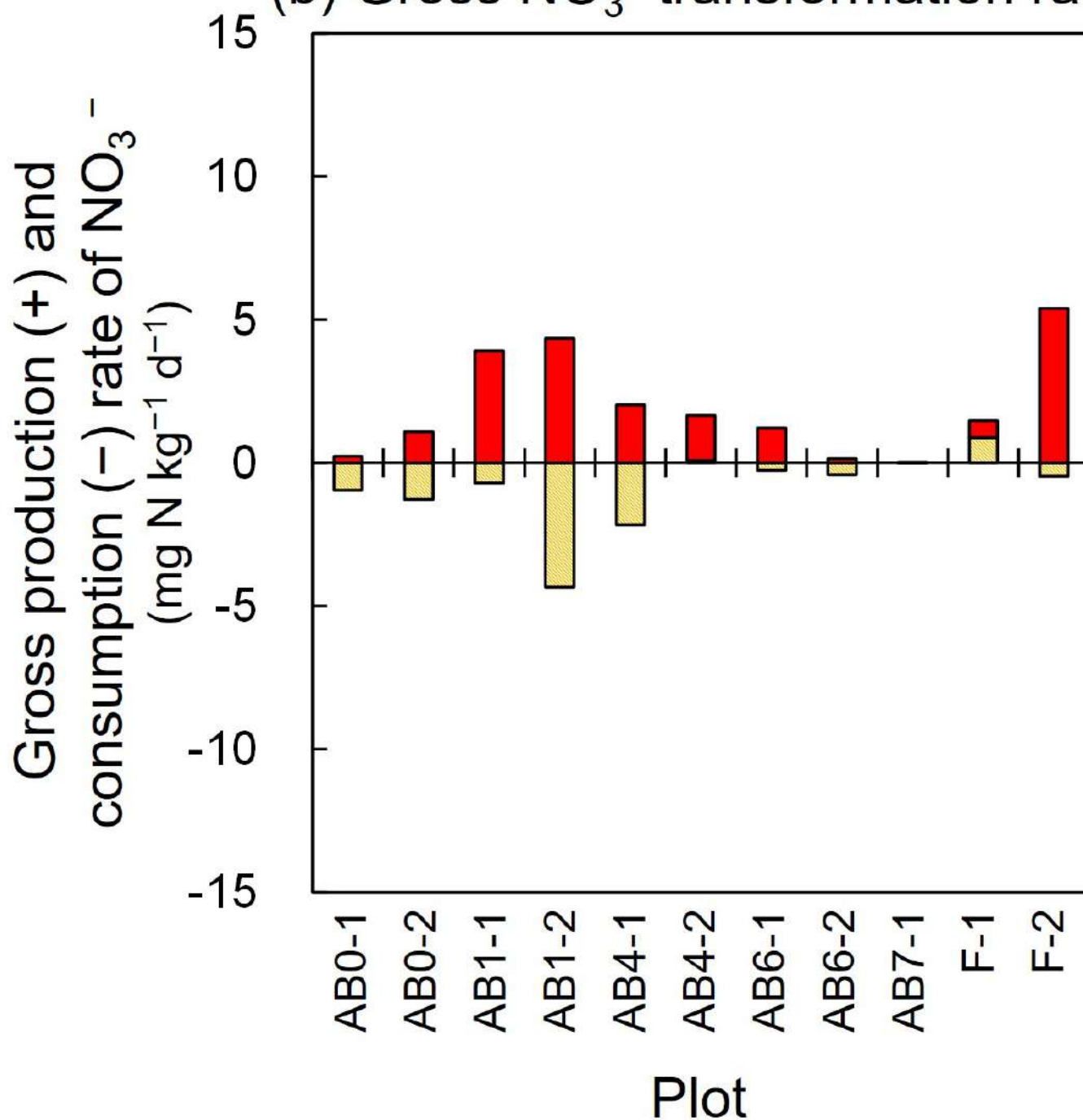
Gross production (+) and
consumption (-) rate of NH_4^+
($\text{mg N kg}^{-1} \text{ d}^{-1}$)

(a) Gross NH_4^+ transformation rate



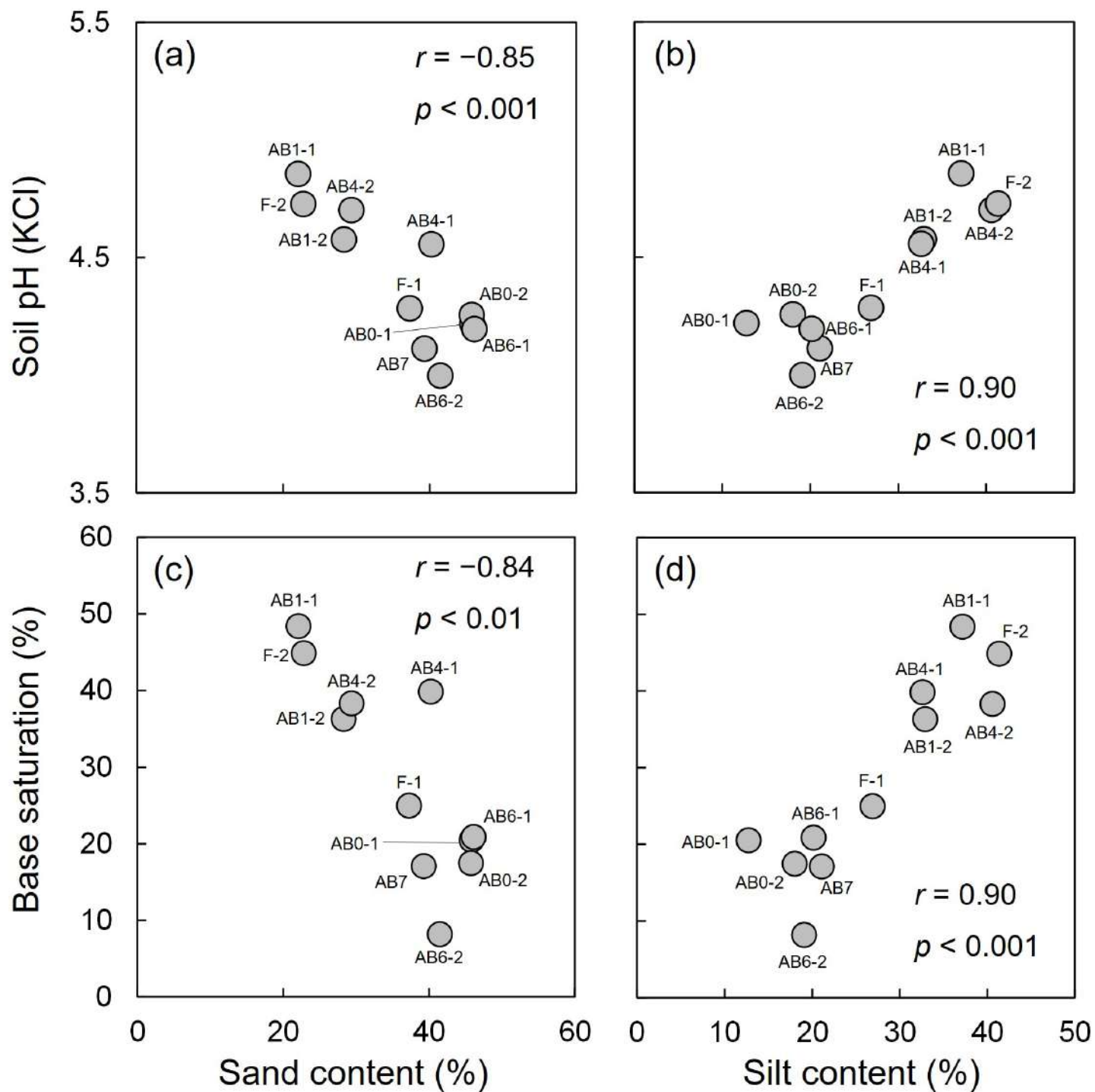
- Gross ammonification rate
- Gross NH_4^+ immobilization rate
- Gross nitrification rate

(b) Gross NO_3^- transformation rate



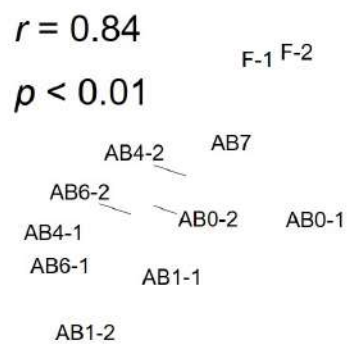
■ Gross nitrification rate

▨ Gross NO_3^- immobilization rate

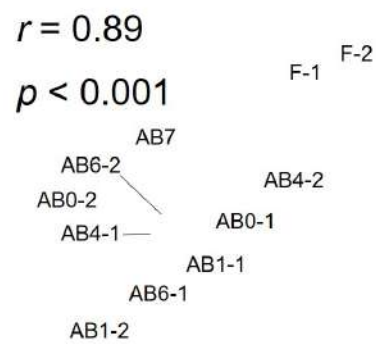


Gross ammonification rate
($\text{mg kg}^{-1} \text{ d}^{-1}$)

(a)

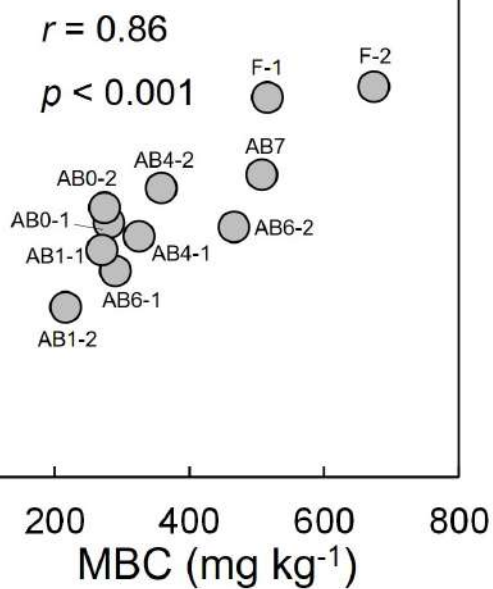


(b)

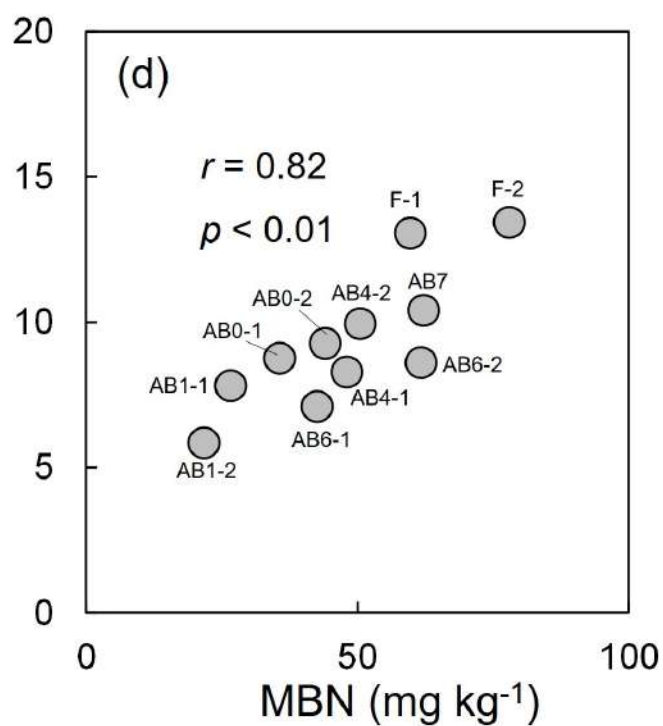


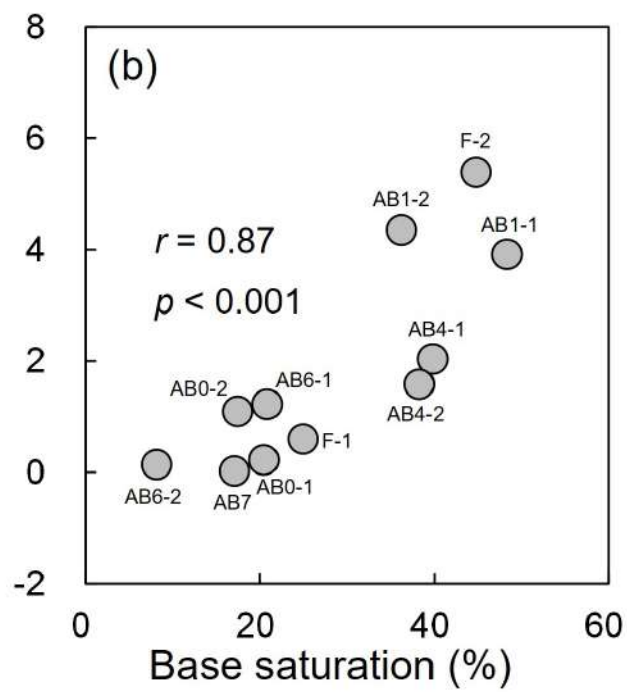
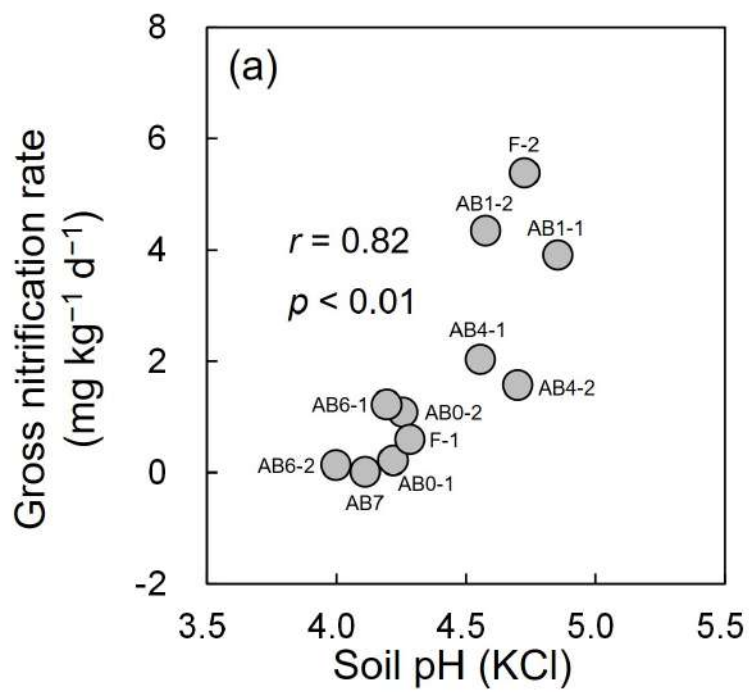
Gross ammonification rate
($\text{mg kg}^{-1} \text{ d}^{-1}$)

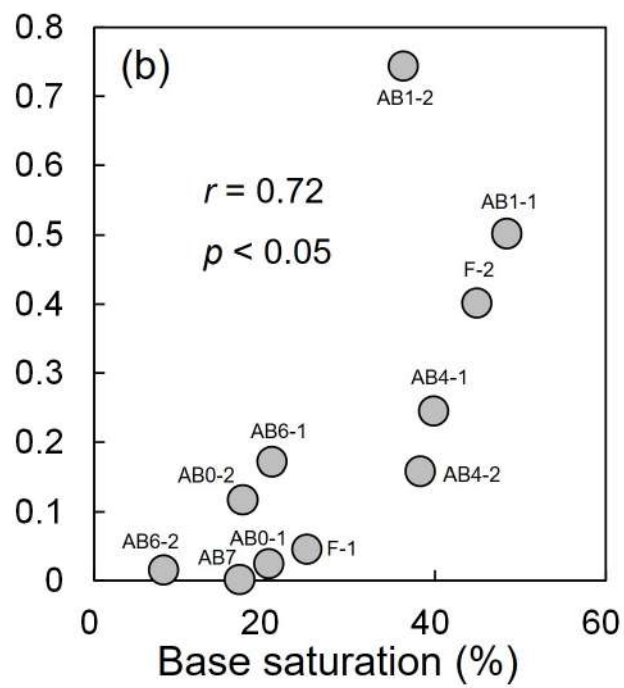
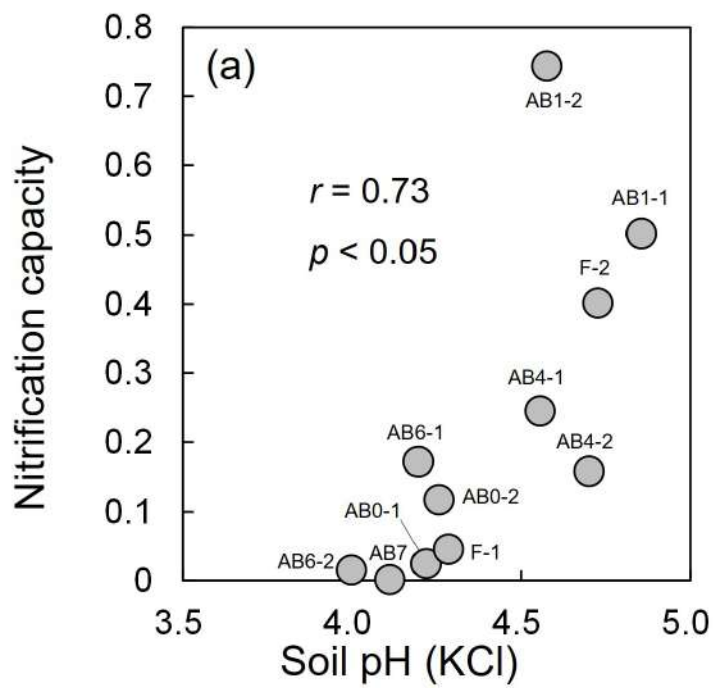
(c)

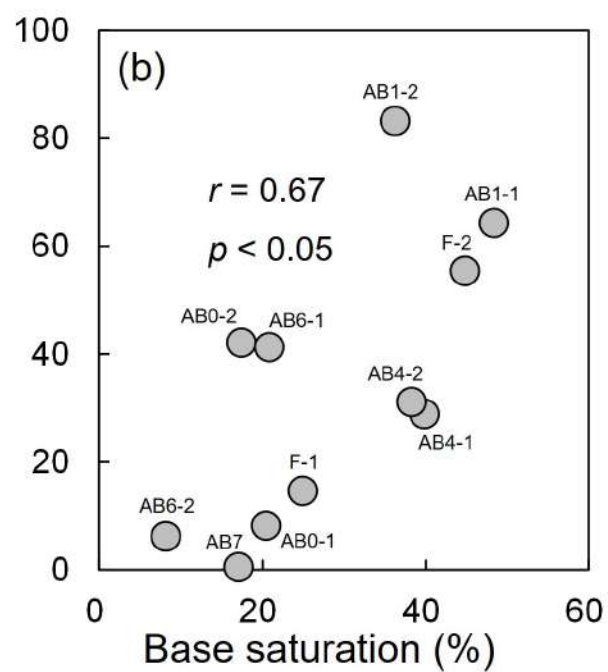
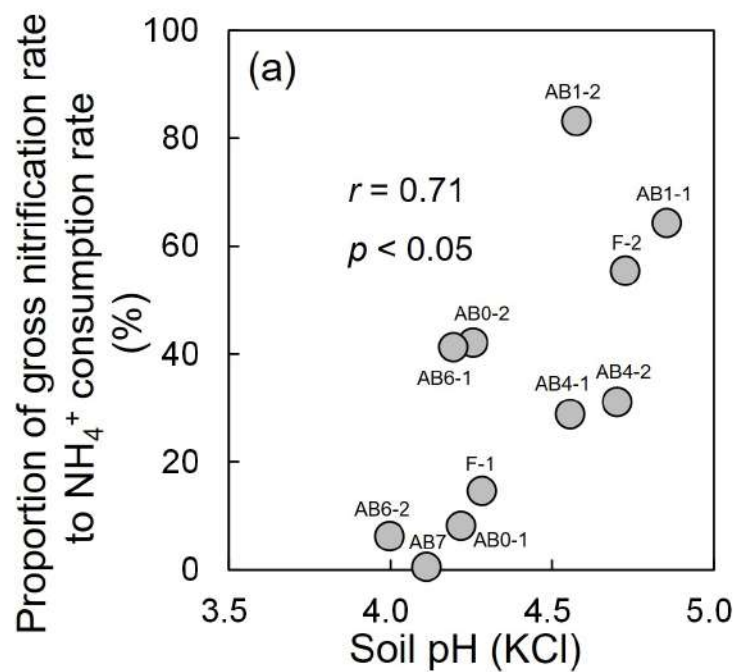


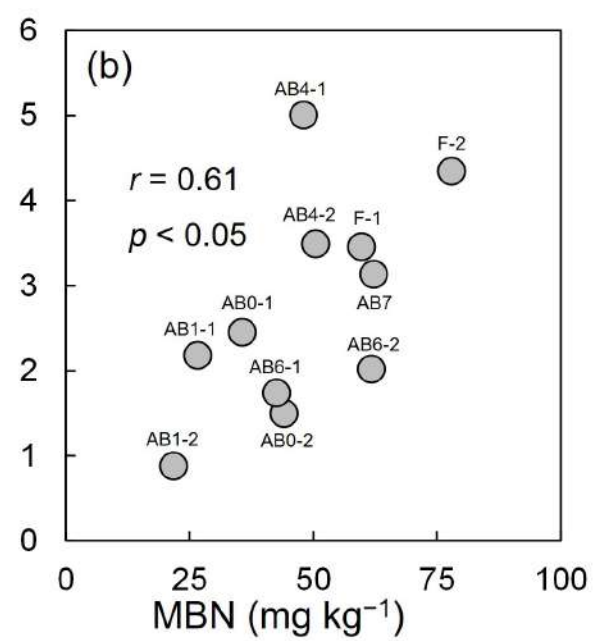
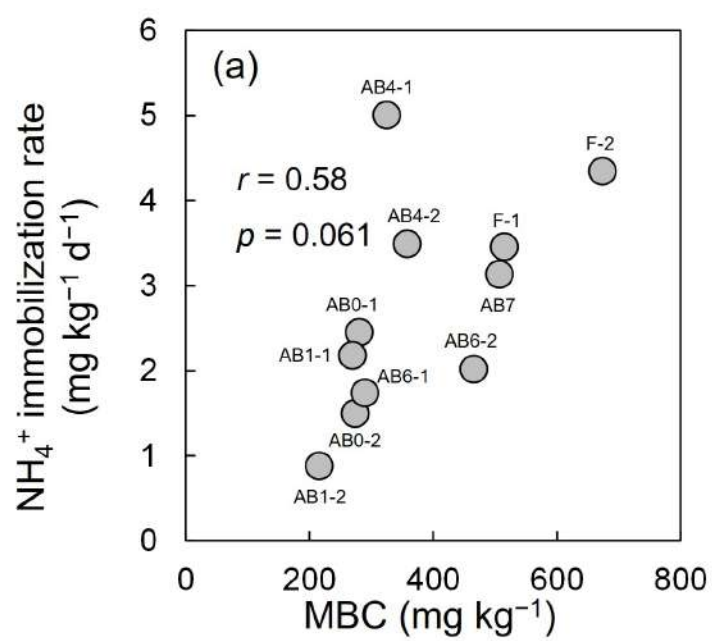
(d)



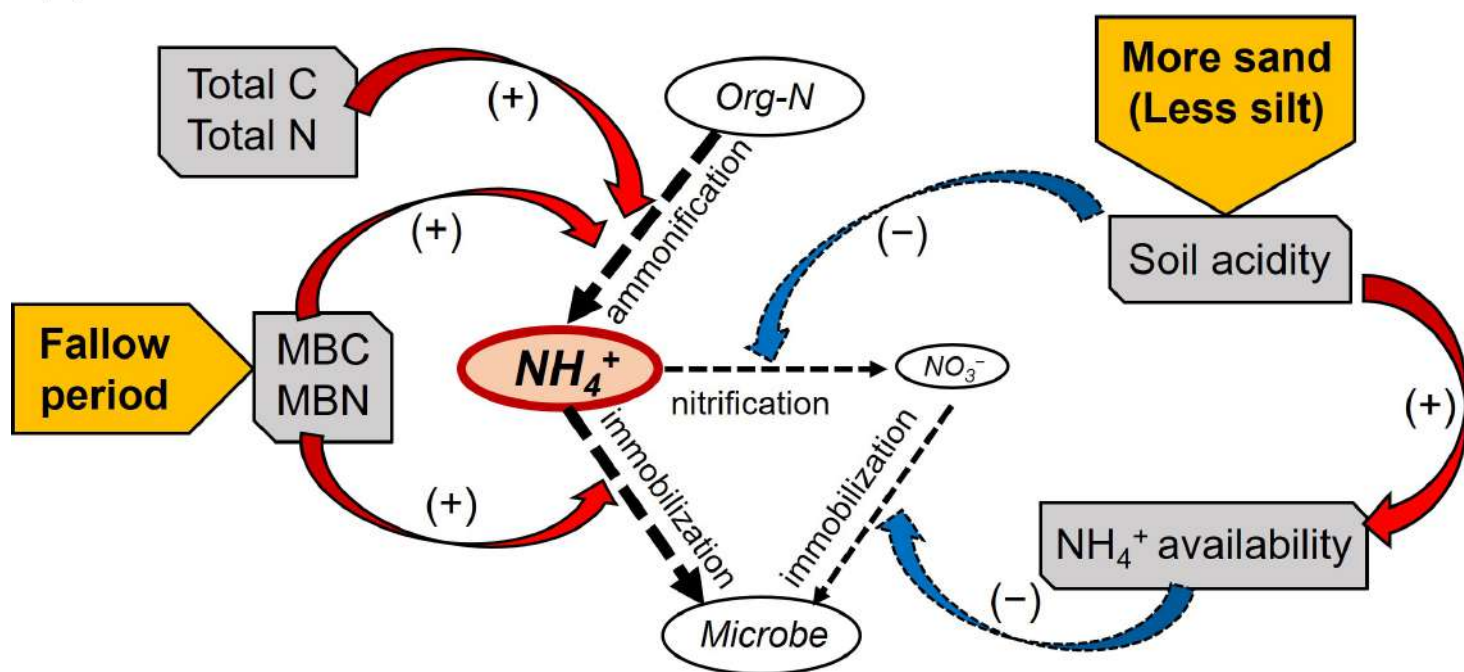








(a) Coarser-textured soil



(b) Finer-textured soil

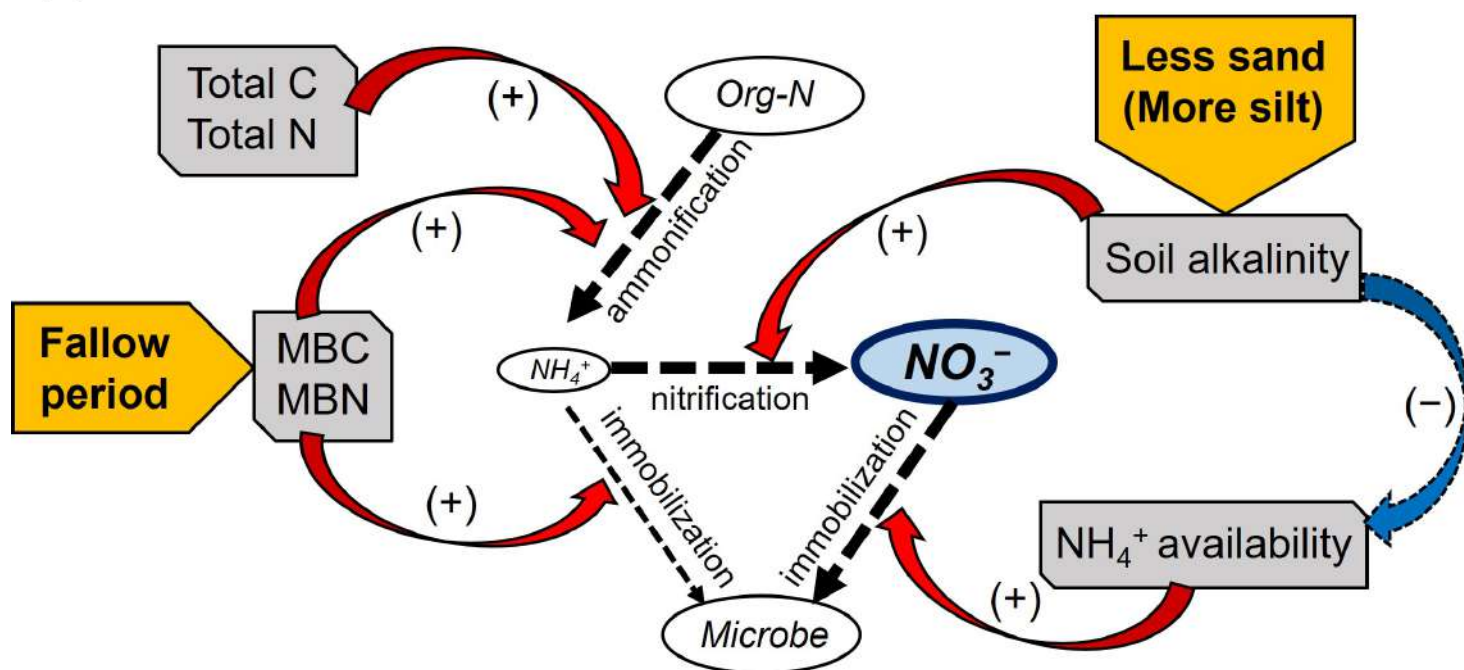


Table 1. Pearson correlation coefficients among N transformation rates and soil properties

Variables		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Nitrogen transformation rates	1 Gross ammonification rate	1																
	2 NH_4^+ consumption rate		1															
	3 NH_4^+ immobilization rate	0.62*		1														
	4 Gross nitrification rate		0.84**		1													
	5 NO_3^- consumption rate	-0.66*				1												
Soil properties	6 pH (H_2O)						1											
	7 pH (KCl)		0.82**		0.82**			1										
	8 Exchangeable Al								1									
	9 Total exchangeable bases		0.92***		0.84**			0.86***		1								
	10 Base saturation		0.93***		0.87***			0.97***		0.94***	1							
	11 Total C	0.84**										1						
	12 Total N	0.89***		0.61*								0.83**	1					
	13 Available P													1				
	14 MBC	0.86***										0.66*	0.76**		1			
	15 MBN	0.82**		0.61*		-0.61*							0.64*		0.94***	1		
	16 Sand		-0.76**		-0.82**			-0.85**		-0.85***	-0.84**						1	
	17 Silt		0.86***		0.77**			0.90***		0.84**	0.90***						-0.89***	1
	18 Clay																	

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$