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Abstract

Biotic and abiotic processes controlling nitrogen (N) immobilization in paddy soils may significantly affect nutrient availability for plant uptake during the rice cropping season, as well as the efficiency of applied N fertilizers. Understanding the influence of water and crop residue management practices on N availability, however, requires detailed insight into the mechanisms and factors controlling N immobilization in these soils. We evaluated changes in fertilizer-^{15}N immobilization in a paddy topsoil incubated for 160 d under flooded or non-flooded conditions, with or without rice straw incorporation. The distribution of immobilized N between different soil fractions and interlayer N fixation was assessed by combining aggregate-size, density and chemical fractionation with stable isotope analysis, while compound-specific δ^{15}N analysis of individual amino sugars was used to evaluate microbial utilization of applied N. Fast immobilization of applied N (≈ 48% applied N) was observed in both flooded (Eh = +0.4 to –0.2 V) and non-flooded (Eh = +0.4 to +0.6 V) soils, however in the latter most of this N was released during incubation. The finer soil fractions served as the greatest sink of immobilized N, retaining 5–36% of the added N. Although biotic processes were mainly responsible for N retention, about 4–11% of N applied to flooded soils was weakly fixed within the interlayer of clay minerals, primarily associated with microaggregates. Straw addition further enhanced N immobilization under both oxic and anoxic conditions, with ≈ 12% of total immobilized N (2–4% of applied N) associated with the light organic matter fraction. The increasing incorporation of applied N into microbial residues suggested that addition of rice straw to paddy soils may lead to effective microbial-mediated immobilization and stabilization of significant portions of N inputs.

Keywords

Fertilizer-derived nitrogen; aggregate-size fractionation; interlayer fixation; amino sugars; compound specific δ^{15}N stable isotope mass spectrometry.

1. Introduction

Nitrogen (N) dynamics in paddy soils is perhaps one of the most complex biogeochemical cycles in agriculture, making N the most yield-limiting and difficult nutrient to manage in rice cropping systems worldwide (Eagle et al., 2000; Reddy, 1982). Although N supply drives productivity, poor N fertilizer-use efficiency (30–40% recovery of applied N) is characteristic of irrigated rice agro-ecosystems (Cassman et al., 2002). This has been largely attributed to rapid losses of applied fertilizer-N (Cassman et al., 1998; Ghosh and Bhat, 1998) and a greater degree of immobilization with respect to upland soils (Bird et al., 2001). Although research to reduce N losses through improved fertilizer management has received considerable attention in recent years (Cassman et al., 1998 and references within; Peng et al., 2010), detailed insight into the mechanisms and factors controlling N immobilization in flooded rice soils is still highly required to provide improved understanding of their impact on long-term soil fertility.

Biotic and abiotic processes controlling N immobilization may significantly influence N availability for rice crops as well as affect N losses. Inorganic N added to soil may be immobilized by the soil microbial biomass, primarily as amino and nucleic acids, and amino sugars (Nannipieri and Eldor, 2009). These microbial constituents may be subsequently remineralized or redistributed among more complex heterogeneous and less labile soil organic matter (SOM) fractions (Devêvre and Horwáth, 2001). Devêvre and Horwáth (2000) suggested that the larger and sustained microbial biomass generally found under anaerobic compared to aerobic conditions, may immobilize more N. Moreover, since microbial processes in arable soils are generally constrained by C availability, the incorporation of crop residues (C/N = 50–70) into paddy soils between cropping seasons may possibly result in a further increase in N immobilization (Bird et al., 2001). Various studies have shown that crop residue incorporation into paddy soils may enhance microbial activity and size in both flooded and non-flooded conditions (Devêvre and Horwáth, 2000), and consequently lead to a significant immobilization of applied fertilizer-N into the biomass (Devêvre and Horwáth, 2001). Mineralization and immobilization of N by soil microbes are intimately coupled with the decomposition and stabilization of SOM, and it is the balance between these processes that defines the availability of N for plant uptake (Devêvre and Horwáth, 2001).

Abiotic processes may also contribute to N retention in soils, influencing N availability for plant uptake and feedback to microbial utilization. Relatively stable N-containing compounds may result from chemical reactions between ammonia and SOM (Knicker et al., 1997; Schmidt-Rohr et al., 2004). Olk et al. (2006) suggested that lignin-derived phenols which accumulate under prolonged anaerobic conditions may covalently bind nitrogenous compounds into recalcitrant forms, therefore contributing to the reduction in fertilizer and soil N availability in paddy soils. Ammonium fixation in layer silicates may also result in the immobilization of important amounts of recently applied N, particularly in poorly developed paddy soils that contain appreciable amounts of 2:1 clay minerals such as vermiculite and illite (Nieder et al., 2011; Wang et al., 2001).

Building upon these considerations, this work aims at providing insights into the immobilization of applied fertilizer-N as a function of soil redox conditions and rice straw incorporation. We hypothesize that (i) soil flooding may enhance N immobilization and influence the underlying mechanisms, and (ii) addition of labile OM with rice straw incorporation may influence microbially-mediated processes responsible for the immobilization of applied N.

To test these hypotheses we evaluated changes in fertilizer-^{15}N immobilization in a paddy soil incubated for 160 d under flooded or non-flooded conditions, with or without rice straw incorporation. Certain soil fractions may

have a large potential to selectively retain N by means of both biotic and abiotic processes. This may influence the distribution of immobilized N among fractions having different degrees of aggregation and mineralogical composition, as well as functionally distinct SOM pools with different characteristics and turnover rates (Christensen, 1992; Guggenberger et al., 1994). In order to provide important insights into the mechanisms controlling N immobilization in paddy soils, we quantified the partitioning of immobilized fertilizer N among different soil fractions, as well as interlayer N fixation, by combining aggregate-size, density and chemical fractionation procedures with stable isotope analysis. As plants do not synthesize appreciable amounts of amino sugars, these compounds are assumed to originate from the turnover of the soil microbial community, and therefore their quantification in soil is often adopted to indicate microbial contributions to SOM (Amelung, 2001; Parsons, 1981). These N containing biomarkers represent important constituents of the cell walls of bacteria, fungi and actinomycetes (Amelung, 2001), and as such may serve as a proxy for microbial N immobilization. Coupling amino sugar analysis to $\delta^{15}N$ stable isotope mass spectrometry was therefore employed to evaluate the microbial utilization of applied N.

2. Materials and Methods

2.1 Soil and plant materials

Soil material was collected from the Ap horizon (0–15 cm) of a paddy soil (Haplic Gleysol) within a long-term experimental platform in Vercelli, NW Italy (45°17′47″N, 8°25′51″E). The field has been under continuous single-cropped rice cultivation for the last 30 y, with crop residues incorporation in autumn, and field flooding for most of the cropping period (May–September). After removal of vegetation and bigger roots, the collected soil was passed through a 2-mm sieve without drying, and subsequently stored in cool, dark conditions until use. The main physical, chemical and mineralogical properties of the soil are reported in Table 1. Rice straw (*Oryza sativa* variety Sirio CL) was sampled after grain harvest from the same experimental platform, dried and cut into 1-cm segments. The total C and N contents of the straw were 400 g C kg^{-1} and 6.6 g N kg^{-1}, respectively.

2.2 Microcosm design

The influence of soil redox conditions and rice straw incorporation on N dynamics was studied by means of a laboratory incubation experiment. The experimental design comprised a completely randomized 2×2 factorial arrangement representing (i) soil incubated under non-flooded (NF; moisture content kept at 50% water-holding capacity; Eh values between +0.4 and +0.6 V) or flooded (F; submerged under 5 cm of degassed and deionized water; Eh values from +0.4 to –0.2 V) conditions, (ii) without (NS) or with (S) the addition of rice straw (application dose of 4.3 g kg^{-1} soil equivalent to 10 Mg ha^{-1} d.w.). After a 7 day pre-incubation period, inorganic N was added to the soils as enriched $(NH_4)_2SO_4$ (10 atom% ^{15}N). An application dose of 56 mg N kg^{-1} soil was used, equivalent to 130 kg N ha^{-1} generally applied as mineral fertilizer in the field. A second set of soil samples was treated with natural abundance $(NH_4)_2SO_4$ to account for isotope fractionation. Incubation was carried out in the dark for 160 d at 25°C, and triplicate soil samples destructively sampled after 1, 10, 30, 90 and 160 days from the application of fertilizer.

2.3 Chemical analyses and physical soil fractionation

Inorganic N concentrations in floodwater and 0.5 M K_2SO_4 soil extracts were determined spectrophotometrically, while the amount of immobilized fertilizer-N was calculated from the $\delta^{15}N$ values of soil samples after removal of

K_2SO_4 extractable N. The distribution of immobilized fertilizer-N among soil fractions was assessed by a combination of aggregate-size and density fractionation on samples collected on 1, 10 and 160 d of incubation. This was done using a method adapted from Six et al. (2001; 2000). Briefly, 60 g of soil were submerged in deionized water on a 250 µm sieve for 15 min. Slake-resistant micro- and macroaggregates were separated by moving the sieve up and down 3 cm every 2 seconds for 2 min. The microaggregates (<250 µm) were subsequently dispersed by suspending in 0.1% Na-hexametaphosphate and treating ultrasonically with 440 J ml^{-1} using a probe-type sonicator. Fine sand and coarse silt (250-20 µm), and clay and fine silt (<20 µm) fractions were subsequently isolated by sedimentation. An aliquot (~25 g) of the macroaggregates (>250 µm) was suspended in 1.6 g cm^{-3} Na-polytungstate (1:5 soil:solution ratio) to isolate the light organic matter (OM) fraction. After flotation and removal of the light fraction, the heavy fraction was rinsed in deionized H_2O, dispersed in 0.1% Na-hexametaphosphate and treated ultrasonically with 440 J ml^{-1}. The coarse sand-sized fraction (2000-250 µm) present in the macroaggregate was subsequently separated by sieving, while the fine sand and coarse silt (250-20 µm), and clay and fine silt (<20 µm) fractions were isolated by sedimentation as for the microaggregates. A total of six fractions where thus obtained including: (i) light fraction (LF); (ii) coarse sand-sized fraction (M2000-250); (iii) fine sand and coarse silt-sized fraction of macroaggregates (M250-20); (iv) fine silt and clay-sized fraction of macroaggregates (M<20); (v) fine sand and coarse silt-sized fraction of microaggregates (m250-20); and (vi) fine silt and clay-sized fraction of microaggregates (m<20). All fractions were washed thoroughly with deionized H_2O (electrical conductivity <50 µS cm^{-1}), dried at 40°C, their yield measured and finally ground for analysis.

Total C and N contents and stable N isotope composition of K_2SO_4 treated soils and all soil fractions were determined with an automated elemental analyser – continuous flow isotope ratio mass spectrometer (FlashEA-1112 equipped with a thermal conductivity detector and interfaced via a ConFlo III to a Delta^{Plus} XP system, Thermo Electron Corporation, Bremen, Germany). Since a carbonate-free soil was used, total C content was assumed to be equal to the organic C content. The fraction of fertilizer-derived N (f_{FDN}) was calculated from ^{15}N isotope values by applying a mixing model:

$$f_{\mathrm{FDN}} = \frac{(\text{atom\% } {}^{15}\text{N excess}_{\text{soil fraction}})}{(\text{atom\% } {}^{15}\text{N excess}_{\text{fertilizer}})}$$

Fertilizer-derived N (FDN) was subsequently calculated as the product of f_{FDN} and the total N content, and expressed in mg N kg^{-1} bulk soil.

2.4 Interlayer ammonium fixation

The extent of interlayer NH_4^+ fixation within clay minerals was evaluated by HF:HCl treatment followed by microdiffusion of the released NH_4^+ as described by Eudoxie and Gouveia (2008). After removal of exchangeable NH_4^+, this procedure allows for the quantitative determination of fixed NH_4^+ including that fixed weakly near the edges of clay minerals. Aliquots of fine silt and clay-sized fractions of micro- (m<20) and macro-aggregates (M<20) were treated with 5 M HF: 1 M HCl mixture at a solid/solution ratio of 1:20 (w/v) for 24 h at 25°C. The samples were subsequently centrifuged at 3000×*g* for 15 min and the supernatants subsequently analysed by microdiffusion. An aliquot of each acid digest (~100 µg N) was dispensed into plastic diffusion tubes containing 32 ml of 2 M KOH and an acid trap prepared as described by Schleppi et al. (2006), immediately sealed and

allowed to diffuse for 7 days at 25°C. Filter packs were then transferred to Sn capsules, dried and analysed for total N and stable N isotope composition as described above. The amount of fixed fertilizer-N was calculated from the $\delta^{15}N$ values after correcting for blanks.

2.5 Amino sugar analysis

2.5.1 Extraction and quantification

Amino sugars were extracted and purified from soil samples as described by Zhang and Amelung (1996). Air-dried, ground (<0.5 mm) soil samples containing about 0.5 mg N were spiked with 100 µg *myo*-inositol (internal standard) and subsequently hydrolysed with 10 mL of 6 M HCl for 8 h at 105°C. Amino sugar extracts were purified from interfering iron by pH adjustment (pH 6.6-6.8) and centrifugation, while salts were removed by dissolution of the previously freeze-dried supernatant in methanol. After addition of 100 µg of *N*-methylglucamine as recovery standard, amino sugars were converted to their aldononitrile acetate derivatives as described by Guerrant and Moss (1984). The purified soil hydrolysates were dissolved in 0.3 ml derivatization reagent containing 32 mg hydroxylamine hydrochloride ml^{-1} and 40 mg 4-(dimethylamino)pyridine ml^{-1} in pyridine/methanol (4:1 v/v), and heated to 75-80°C for 30 min. Acetylation was carried out by adding 1 ml acetic anhydride and heating to 75-80°C for another 20 min. After allowing to cool, 2 ml of dichloromethane were added and excess reagents were removed from the organic phase by repeated washing steps (1 ml) with 1 M HCl and deionized water. The final organic phase was dried under a gentle stream of N_2 and finally dissolved in 300 µl of ethyl acetate-hexane (1:1). Aldononitrile acetate derivatives of glucosamine, galactosamine, mannosamine and muramic acid were separated and quantified by GC-FID (Shimadzu GC-2010, Tokyo, Japan) equipped with a split/splitless injector and a 30 m × 0.25 mm i.d. fused silica capillary column coated with 5% diphenyl- and 95% dimethyl-polysiloxane stationary phase (Supelco SPB-5, 0.25 µm film thickness). The oven temperature was held at 120°C for 1 min, increased to 250°C at 10°C min^{-1}, held at 250°C for 2.5 min, increased to 270°C at 20°C min^{-1}, held at 270°C for 2 min and finally ramped to 300°C at 50°C min^{-1} and kept there for 5 min. Quantification and recovery determination were carried out against the internal standards *myo*-inositol and *N*-methylglucamine, respectively.

2.5.2 Compound-specific $\delta^{15}N$ analysis

Compound-specific $\delta^{15}N$ analysis of individual amino sugars was performed using a gas chromatograph-combustion-isotope ratio mass spectrometer (GC-C-IRMS) system consisting of a Thermo GC Ultra interfaced via a GC Combustion Interface III to a Delta V Advantage continuous flow IRMS (Thermo Electron Corporation). The GC was equipped with a split/splitless injector kept at 250°C and with a gooseneck liner for splitless injection (length 10.5 cm, 5 mm i.d. for 9.2 cm, without glass wool packing), which was previously deactivated with 5% dimethylchlorosilane in toluene for at least one week. A constant sample volume of 2 µl (~2-8 nmol of each amino sugar) was injected splitless for 1 min, with an autosampler (TriPlus, Thermo Finnigan MAT, Bremen, Germany) equipped with a 50-mm needle length. Injector liner, needle length and splitless time are known to influence isotope ratios of individual compounds, and this setup was previously shown to be most appropriate for correcting injection-dependent isotope fractionation (Schmitt et al., 2003). Chromatographic separation of aldononitrile acetate derivatives was performed on a 60 m × 0.25 mm i.d. fused silica capillary column coated with 5% diphenyl- and 95% dimethyl-polysiloxane stationary phase (Agilent DB-5ms, 0.25 µm film thickness) adopting a temperature programme starting at 120°C for 1 min, increased to 230°C at 20°C min^{-1}, held at 230°C

for 22 min, increased to 260°C at 20°C min^{-1}, held at 260°C for 8 min and finally ramped to 300°C at 60°C min^{-1} and kept there for 5 min. The connection to the Combustion Interface III (Thermo Finnigan MAT) was through a borosilicate press-fit Y-splitter that, together with a backflush valve supplying He, allowed for the removal of solvent peaks from the effluent of the GC column. When the backflush valve is closed the column effluent passes through an oxidation furnace composed of braided nichrome/copper oxide wire kept at 950°C and a reduction furnace of braided copper wire kept at 650°C, followed by a H_2O/CO_2 trap at liquid N_2 temperature before reaching the IRMS.

During all measurements, six pulses of N_2 gas were directly discharged into the IRMS for 20 s via the open split, as a reference gas for the calculation of relative $\delta^{15}N$ values and drift correction during measurements. $\delta^{15}N$ values of individual amino sugar derivatives, calculated from five replicate measurements were calibrated against internal standard *N*-methylglucamine and corrected for the N added during derivatization and amount dependence using the $\delta^{15}N$ values of standard amino sugars determined by EA-IRMS as described in detail by Glaser and Amelung (2002).

2.6 Spectroscopic characterization of light fractions

Solid state ^{15}N nuclear magnetic resonance (NMR) spectroscopy with cross polarization/magic angle spinning (CPMAS) was adopted to investigate the composition of fertilizer-derived ^{15}N in the light fractions. NMR spectra were acquired on a Bruker Avance II 400 MHz spectrometer with a frequency of 40.55 MHz for ^{15}N and 400.23 MHz for ^{1}H, while CPMAS acquisition parameters as described by DiCosty et al. (2003) were adopted. These involved a 90° pulse to ^{1}H applied for 3.05 µs, a contact time of 800 µs, 10 ms acquisition time with a decoupling frequency of 75 kHz, 1 s delay time and 100 Hz line-broadening. LF samples (85 mg) were spiked with 40 mg of $(NH_4)_2SO_4$ as an internal standard, packed into a 4 mm diameter rotor and spun at a frequency of 9 kHz. About 244,000 scans were acquired for each sample.

3. Results and Discussion

3.1 Available and immobilized N

Soil redox conditions and the application of rice straw influenced N availability in soils (Table 2). Incubation of soils under non-flooded conditions in the absence of straw resulted in a rapid decrease in available N with respect to initial contents (64.9 ± 0.9 mg N kg^{-1}). However, after only 10 d, available N was equal to or greater than initial contents. These results suggest that after an initial fast net immobilization, the degradation of SOM eventually led to a net N mineralization. The addition of rice straw (C/N = 61) resulted in lower available N concentrations with respect to the initial inorganic N content throughout the incubation. In fact, available N concentrations in samples receiving straw were always lower than those in samples without straw suggesting a greater net N immobilization in the presence of labile OM.

Under flooded soil conditions contrasting trends in available N contents were observed. Flooded soils without straw showed unchanged contents of available N over the first 30 d of incubation, followed by a drastic decrease thereafter. N availability in these soils was lower than in non-flooded soils without straw. This is in contrast with the widely held notion that net ammonification is generally greater under anaerobic than aerobic conditions because of the low metabolic N requirement of anaerobic bacteria (Reddy and deLaune, 2008). This suggests that N immobilization could nevertheless play an important role under anaerobic conditions, although loss of fertilizer-N through nitrification-denitrification reactions could not be excluded (Devêvre and Horwáth, 2001). In

their study on N mineralization and immobilization in different soils, Wang et al. (2001) reported that net N mineralization was not always higher under waterlogged with respect to aerobic conditions since it depends on the balance of processes including mineralization, immobilization, clay fixation, and losses by nitrification–denitrification and volatilization. The addition of straw to flooded soils enhanced N availability with incubation time, suggesting that the rate of release of inorganic N during the mineralization of straw-derived OM was faster than the rate of immobilization and loss.

$\delta^{15}N$ values of K_2SO_4 treated soils allowed for the calculation of the amount of immobilized FDN (Table 2). In all cases, approximately 48% of the applied N was immediately immobilized at the beginning of the incubation irrespective of redox conditions or addition of rice straw. Many studies have documented a rapid immobilization of applied NH_4^+ into non-exchangeable pools via abiotic processes and microbial immobilization in both upland (e.g. Compton and Boone, 2002; Morier et al., 2008) and lowland (e.g. Green et al., 1994; Zhang and Scherer, 2000) soils. Except for flooded soils receiving straw, the amount of immobilized fertilizer-N tended to decrease with incubation time, and after 160 d of incubation immobilized N followed the order NF-NS < NF-S ≤ F-NS < F-S with 8, 23, 27 and 49% of the applied N being immobilized, respectively. These results suggest that both lower soil redox conditions and the addition of labile OM may enhance the immobilization of applied fertilizer-N in paddy soils.

3.2 Distribution of immobilized N among different soil fractions

Physical fractionation of soil samples allowed for the evaluation of the distribution of immobilized N between different soil fractions, thus providing an insight into the importance of different N immobilization mechanisms involved. Grouped results obtained from the analyses of all soil samples show that the C/N ratio of the different fractions was largest in the LF and decreased with both aggregate- and particle-size in all treatments (Fig. 1). Larger C/N ratios were obtained for the <20 and 250-20 μm size fractions in macroaggregates (M<20 and M250-20) with respect to the corresponding fractions in microaggregates (m<20 and m250-20). This suggests that macroaggregates contained more recent, partially stabilized OM, while OM associated with microaggregates was enriched in microbial products and showed a higher degree of decomposition. The application of rice straw to flooded and non-flooded soils contributed recent material to the LF resulting in an increase in the mean C/N ratio with respect to soils without straw. Moreover, in soils that received straw both the C content and C/N ratio of the LF decreased with incubation time (from a mean C content of 1.1 to 0.6 mg C g^{-1} and a C/N of 26 to 18 on days 1 and 160, respectively) reaching final values similar to those obtained for soils without straw (0.5 mg C g^{-1} and C/N = 17). This confirmed the rapid turnover of this fraction under both aerobic and anaerobic conditions. On the other hand, C contents and C/N ratios of the other fractions were neither influenced by straw addition nor flooding, and did not show any variations with incubation time.

Although across all treatments the LF had the largest C (110.5–253.5 mg C g^{-1} fraction) and N (6.7–25.3 mg N g^{-1} fraction) contents, this fraction represented only 3.5–11.9% and 2.0–4.8% of total soil C and N, respectively. On the other hand, the finer soil fractions (M<20 and m<20) together represented 68-79% and 78-85% of the total C and N, respectively. Non-flooded soils had more C associated with the fine soil fractions present within the slake-resistant macroaggregates (M<20) with respect to microaggregates (m<20), while the opposite was true for flooded soils. In fact, in the latter mean yields as well as C and N contents of m<20 size fractions were generally greater than those obtained for M<20 size fractions, both in the presence or absence of straw (Fig. 1). These results suggest that the predominant mechanism of SOM stabilization may be ascribed to the close associations

between OM and mineral phase in the finer soil fractions. Moreover, macroaggregate stability may be somewhat compromised in flooded soils possibly due to the disruptive energy occurring upon slaking (Six et al., 2000; Zanini et al., 1998), reductive dissolution of Fe oxides (Kögel-Knabner et al., 2010), reduced growth of fungal mycelia under anaerobic conditions (Polyanskaya et al., 2010), or soil compaction during the preparation of the trials.

Recovery of immobilized FDN, calculated as the ratio of the sum of fertilizer-N immobilized in the different fractions (Fig. 2) to the total immobilized N (Table 2), ranged from 71–90% suggesting that the amount of immobilized N lost during the fractionation procedure was limited. Only 1–4% of applied fertilizer-N (8–16% of total immobilized FDN) was associated with the coarser mineral fractions (M2000-250, M250-20 and m250-20) with no differences between treatments. In contrast, the finer soil fractions in both macro- and microaggregates (M<20 and m<20) served as the greatest sink of applied N in all treatments, together retaining 62–91% of the total immobilized FDN. Similar findings were reported by Hagedorn et al. (2005) who showed that about 50–60% of the immobilized ^{15}N applied to forest soils occurred in the finer soil fractions with small C/N ratios. Rapid transfer of added N onto such soil fractions is often attributed to microbial immobilization (Hagedorn et al., 2005), since most of the soil microbial biomass is associated with small-sized separates (Kandeler et al., 2000; Kögel-Knabner et al., 2008) that are also dominated by products of microbial resynthesis (Guggenberger et al., 1994). However, considering that the soil used in this experiment contained a vermiculite- and illite-dominated clay fraction (Table 1), fast, diffusion controlled, abiotic fixation of NH_4^+ may be also responsible for significant immobilization of applied N on finer soil fractions, particularly under flooded soil conditions (Nieder et al., 2011). Trends in FDN immobilized on the finer soil fractions during incubation for each treatment were similar to those observed for total immobilized FDN. With time, the sum of FDN in M<20 and m<20 fractions decreased more rapidly in non-flooded than flooded soils, while straw addition generally enhanced FDN retention in these fractions, especially under flooded conditions.

Moreover, results evidenced that in non-flooded soils more immobilized FDN was associated with the fine soil fractions present within macroaggregates with respect to microaggregates, while in flooded soils the opposite was true. Aggregate ratios were generally <1 in non-flooded and >1 in flooded soils (Table 3) suggesting that the lower degree of aggregation in the latter could be responsible for the greater amount of applied N immobilized on microaggregates. However, the different ^{15}N isotope ratios and f_{FDN} values obtained for the m<20 and M>20 fractions also suggest that aggregation may nonetheless influence N immobilization processes. In fact, in flooded soils enrichment ratios evidenced a preferential immobilization of applied N on microaggregates (values >1; Table 3). With time these ratios tended to decrease both with and without straw incorporation, reaching values close to unity in the former. In contrast, in non-flooded soils N immobilization on microaggregates was favoured at the beginning of the incubation but strongly shifted towards a preference for macroaggregates after 10 d of incubation (values <1; Table 3). These results seem to suggest that preferential and rapid immobilization of FDN on the finer soil fraction within microaggregates could be due to their greater surface area or lower diffusive inhibition with respect to macroaggregates. These properties could strongly influence abiotic N immobilization mechanisms. Scherer and Zhang (1999) previously reported that coating of the surface of clay minerals by Fe oxides may limit the diffusion of NH_4^+ into or out of the interlayer of clay minerals. Moreover, the major processes determining aggregate stability under flooded soil conditions often involve iron bridging and formation of iron cutans (Kögel-Knabner et al., 2010). Thus, it is plausible to hypothesize that aggregation could significantly limit interlayer NH_4^+ fixation and release when 2:1 clays are present. On the other hand, since

water-stable macroaggregates are generally considered to be "hotspots" of microbial activity (Bronick and Lal, 2005; Jiang et al., 2011), the decreasing trend in enrichment ratios with incubation time (Table 3) could have also possibly resulted from an enhanced biotic immobilization of N in macroaggregates, particularly under oxic soil conditions. However, the expected influence of substrate addition in samples receiving straw was not observed.

Nevertheless, in both non-flooded and flooded treatments, straw addition resulted in enhanced FDN immobilization on the light fraction (≈ 12% of total immobilized FDN) with respect to soils not receiving straw (Fig. 2). Although the LF was rapidly decomposed during incubation under both oxic and anoxic soil conditions (as described above), FDN associated with this fraction tended to increase with time. This suggests that applied N was actually immobilized during degradation of the LF, although it was not possible to distinguish between microbially-mediated uptake of applied N or abiotic reactions between added N and lignin-derived phenols present in the decomposing rice straw. The smaller values of f_{FDN} observed for the LF in flooded with respect to non-flooded samples nonetheless agrees well with the widely held notion that less mineral-N is assimilated into microbial biomass during the anaerobic decomposition of organic substrate in contrast to aerobic conditions which are generally characterized by higher microbial N requirements (Wang et al., 2001). The significant role of the LF pool in cycling recently added N was also reported by Bird et al. (2002) who showed rapid enrichment of this fraction in straw incorporated plots after application of ^{15}N fertilizer. Similarly, findings from the short-term incubations with forest soils presented by Compton and Boone (2002) suggest that a large portion of the rapid NH_4^+ sink (35-55% of added NH_4^+) involves the LF. In both cases, however, the authors were not able to discern between microbial and abiotic mechanisms although they hypothesized that, since the specific surface area of the relatively undecomposed LF organic matter is expected to be small, sorption reactions may be less important than microbial activity as a mechanism for N incorporation into this fraction.

3.3 Abiotic N immobilization on clay minerals

The soil used in this work had a mean fixed NH_4^+ content of 51 mg N kg^{-1}, approximately 4.6% of the total N, but over 15 times the amount of exchangeable NH_4^+ before application of fertilizer-N (Table 1). Moreover, the presence of vermiculite and illite (Table 1), as well as the low percentage K^+ saturation (≈ 2.8%), suggest that interlayer NH_4^+ fixation may strongly influence N availability in this soil (Wang et al., 2001). The amount of FDN fixed within the clay minerals present in the finer soil fractions (Fig. 3) evidence that clay fixation was responsible for the rapid immobilization of 10-13% of applied N in all treatments. This explained about 34% of the total immobilized FDN after only 1 d of incubation, irrespective of redox conditions or addition of rice straw. In fact, NH_4^+ fixation in vermiculite is known to be a fast reaction occurring at a similar rate to the NH_4^+ exchange reaction on surface sites (Shen et al., 1997). However, under aerobic soil conditions most of the fixed fertilizer-derived NH_4^+ was rapidly released within 10 d of incubation both in the presence or absence of straw, reaching values as low as 0.9 mg N kg^{-1}, barely 1% of the applied N. These results suggest that under oxic conditions nitrification may promote the release of NH_4^+ from the clay mineral interlayers (Green et al., 1994). This lends support to the notion that recently fixed NH_4^+ may nonetheless be weakly retained along the edges of clay mineral interlayers, and thus prone to release and subsequent utilization by plants or microorganisms (Nieder et al., 2011 and references therein).

In contrast, in flooded soils fixed fertilizer-N was released to a lesser extent with respect to non-flooded soils. After 160 d of incubation, fixed FDN explained approximately 16 and 20% of total immobilized FDN equivalent

to about 7 and 4% of applied fertilizer-N in flooded soils with and without straw addition, respectively. Similar results were obtained by Devêvre and Horwáth (2001) who estimated that 1 to 5% of fertilizer-derived N was immobilized by abiotic clay fixation. Since the release of fixed NH_4^+ is generally assumed to be diffusion controlled, the inhibition of nitrification under anaerobic conditions, responsible for greater exchangeable NH_4^+ concentrations, probably resulted in a slower release of fixed FDN with respect to oxic soils. However, we cannot exclude that this process was underestimated with respect to field conditions where plant uptake would further contribute to reducing available NH_4^+ concentrations. Moreover, NH_4^+ fixation in flooded paddy soils was also found to be closely related to the declining redox potential (Schneiders and Scherer, 1998). The decreasing E_h (from +350 to +10 mV) and increasing pH (from 5.9 to 7.1) measured during the first 90 d of incubation under flooded conditions could have brought about the reductive dissolution of Fe (hydr)oxides coated on the surface of clay minerals, favouring the diffusion of NH_4^+ ions into the interlayers (Nieder et al., 2011).
The addition of straw to flooded soils resulted in significant increase in available N with incubation time (Table 2), probably due to the mineralization of the added labile OM. This increase in exchangeable NH_4^+ could have further limited the diffusion of NH_4^+ out of the clay mineral interlayers, thus explaining the higher amounts of fixed FDN in these soils. Moreover, the low Eh values measured during incubation (as low as –180 mV after only 30 d with pH values around 7) suggest that the supply of readily oxidizable OM (i.e. electron donors) with the incorporation of crop residues could have further stimulated the microbially-catalyzed reductive dissolution of Fe (hydr)oxides (Katoh et al., 2005; Kögel-Knabner et al., 2010), possibly promoting NH_4^+ fixation (Matsuoka and Moritsuka, 2011). Results also evidenced that under flooded conditions (F-NS and F-S) more applied N was fixed into the finer soil fraction within microaggregates (m<20) with respect to macroaggregates (M<20) confirming our previous interpretation that the preferential and rapid immobilization of FDN on microaggregates was abiotically driven.

3.4 Biotic N immobilization

Various studies have highlighted the importance of biotic factors and the active role of the soil microbial biomass in the immobilization and cycling of added fertilizer-N in paddy soils, as a function of redox soil conditions (Devêvre and Horwáth, 2001) and rice straw incorporation (Bird et al., 2001). It is well known that during the mineralization of OM, amino sugars are rapidly synthesized (Liang et al., 2007) and are therefore ideal biomarkers to represent biotic N immobilization processes. Total amino sugar-N expressed as the sum of glucosamine, galactosamine, mannosamine and muramic acid-N contents (Fig. 4), ranged between 47–57 mg N kg^{-1}. These values were similar to those reported by Roth et al. (2011) for topsoil samples collected from rice fields subjected to prolonged paddy management. Under non-flooded conditions, soil samples without straw had relatively constant amino sugar contents except for a slight initial reduction in the first 30 d. Mean contents over the incubation period were 690 ± 12 mg kg^{-1} equivalent to 52.8 ± 0.9 mg N kg^{-1}, about 4.6% of total N. On the other hand, the addition of rice straw resulted in a steady increase in amino sugar contents during the first 30 d, from values of 653 ± 14 to 741 ± 22 mg kg^{-1} equivalent to an increase in the amino sugar N pool of 6.8 mg N kg^{-1}. Soil amino sugar contents remained relatively higher in oxic soils receiving straw with respect to those without straw throughout most of the incubation period, although similar values were obtained towards the end of the incubation. These results are in line with the transient increase in amino sugar contents after incorporation of plant materials in different soils observed by various authors (Ding et al., 2010; Liang et al., 2007). We rationalized these observations by noting that amino sugar contents depend on the rates of amino sugar

synthesis and degradation, since these cell wall constituents are preferentially decomposed by soil microorganisms when available nutrients and energy become limiting (Liang et al., 2007).

Although amino sugars may constitute an important part of the newly immobilised N (He et al., 2006) and may adequately represent the degree of N sequestered within soil microbial residues (Amelung, 2003; Decock et al., 2009), recent investigations have shown that a significant portion may be present as microbial residues stabilized in soil and not part of living microbial cells (Amelung, 2001; Glaser et al., 2004; Liang et al., 2007). Since the turnover time of these cell wall constituents in soil is suggested to be much longer than that of living microorganisms (Glaser et al., 2006), variations in their total concentrations may not necessarily reflect actual microbial activity. The application of compound-specific $\delta^{15}N$ isotope analysis of amino sugars, therefore allowed not only for differentiation between old and new bacterial and fungal residues, but also to trace and quantify the incorporation of enriched fertilizer-N into the active microbial biomass. Incorporation of applied N into the amino sugar-N pool (Fig. 4) was calculated from the ^{15}N isotopic enrichment of glucosamine and galactosamine, since mannosamine and muramic acid contents were generally below the limits of quantification for GC-C-IRMS analysis.

Under non-flooded conditions, isotopic enrichment of the amino sugars increased with incubation time, particularly in soils receiving straw (Fig. 4). Incorporation of FDN into the amino sugar pool was from 6.5 to 10 times greater in soils receiving straw with respect to those not receiving straw, even though fertilizer-derived amino sugar-N accounted for only a minor portion (0.6–1.3%) of the total amino sugar-N pool. After 30 d of incubation about 0.6 mg FDN kg^{-1} were incorporated into the amino sugars in non-flooded soils with straw. This accounted for about 9% of the increase in total amino sugar-N calculated for this treatment over the same period of time, assuming that this increase was totally due to microbial growth. These results suggest that under aerobic soil conditions, application of rice straw stimulated microbial growth due to the presence of labile substrate, that in turn resulted in significant biotic N immobilization. However, only a small portion of the N utilized for microbial growth actually accounted for the applied N, with most of the incorporated N probably originating from the degrading straw.

Under flooded soil conditions, variations in total amino sugar contents showed different trends with respect to non-flooded conditions (Fig. 4). In fact, in both flooded treatments without or with straw, amino sugar contents tended to decrease with time resulting in a loss of ~9 mg N kg^{-1} over the incubation period. This loss was more rapid in the soil samples with straw compared to those without straw, particularly in the first 90 d of incubation. This is in contrast with the findings of Devêvre and Horwáth (2001) that report that the incorporation of a significant amount of C substrate in the form of rice straw increased microbial activity and size dramatically, and led to an increase in biomass-N under flooded soil conditions. Moreover, the depletion in amino sugar-N proportions generally attributed to conditions of substrate limitations (Amelung et al., 1999; Roth et al., 2011) was not expected to be responsible for the observed trend, particularly in the soils that received both straw and inorganic N. Therefore, we suggest that the decrease in total amino sugars under flooded soil conditions could be attributed to a net loss possibly due to substantial desorption of previously stabilized microbial residues and subsequent mineralization or loss to floodwaters. Previous studies have suggested that free amino sugars may only weakly sorb to the soil solid phase (Roberts et al., 2007), whereas the strong sorption and stabilization of these N-containing compounds onto clay-sized mineral fractions (Glaser et al., 2006; Kandeler et al., 2000; Zhang et al., 1998) is mainly attributable to the presence of acidic functional groups present on the peptidoglycan microbial residues (Kaiser and Zech, 2000). This binding mechanism would probably explain the rapid

desorption of these microbial residues with increasing pH and decreasing E_h observed during the incubation of flooded soils receiving straw, and to a lesser extent those not receiving straw. We further speculate that the release of microbial residue-N under anoxic conditions and consequent loss of organic N (and C) previously stabilized on the mineral phase, could partly explain the lower amino sugar-N stocks in paddy subsoils with respect to non-paddy soils, observed by Roth et al. (2011).

Although total amino sugar-N contents decreased under anoxic conditions, their isotopic enrichment tended to increase during incubation (Fig. 4), confirming that applied fertilizer-N was nonetheless incorporated into these N-containing microbial constituents. Amino sugar FDN was from 2 to 2.7 times greater in soils receiving straw with respect to those not receiving straw, although the incorporation of applied N was limited with respect to non-flooded soils, particularly in the first 90 d of incubation. However, after 90 d both treatments with or without straw showed a significant increase in amino sugar FDN values. This could have been due to a shift in the microbial community structure leading to the establishment of a biomass with higher N requirements. Various authors report that upon flooding, changing environmental conditions resulting from the decreasing availability of electron acceptors and simple C sources for growth, could lead to a shift from copiotrophic to oligotrophic bacterial populations (Bai et al., 2000; Noll et al., 2005). Similarly, the proliferation of gram-positive bacteria with thicker cell walls as the major decomposers of rice straw incorporated into a paddy soil under submerged conditions, has been widely reported (Kimura et al., 2001; Nakamura et al., 2003), and can possibly explain the increase in fertilizer-N immobilization under anoxic conditions.

Due to their specific occurrence in cell wall structures of fungi and bacteria, the GluN:GalN ratio has been frequently used to cautiously estimate the relative contributions of these microbial groups to SOM turnover and accumulation (Amelung, 2001; Liang et al., 2007; Zhang and Amelung, 1996). A mean value of 1.9 was obtained for the total amino sugar GluN:GalN ratio, with no differences between treatments (Fig. 5). Moreover, ratios failed to show any temporal variations in any of the treatments investigated. Considering that cultivated bacteria and fungi were reported to have GluN:GalN ratios of about 1.9 and 4.6, respectively (Glaser et al., 2004), the relatively low measured ratios were probably indicative of a dominance of bacterial over fungal microbial residues in the paddy soil used for the experiment. This agrees with the well known fact that anoxic soil conditions established during the flooding of rice paddies tend to inhibit fungal proliferation (Bossio and Scow, 1998; Reddy and deLaune, 2008). However, the higher GluN:GalN ratios for fertilizer-derived amino sugar-N observed for non-flooded soils receiving straw (Fig. 6), suggested that the fungal biomass present in these soils could have been partly responsible for the biotic immobilization of applied N under oxic conditions, although this had no effect on total GluN:GalN ratios. On the other hand, addition of straw to flooded soils did not have a clear effect on fertilizer-derived GluN:GalN ratios, although it resulted in a greater variability with values ranging from 1.6–2.8. This increased variability might well result from changes in the composition of the bacterial community since even gram-positive and gram-negative bacteria may have different amino sugar contents (Amelung, 2001).

Biotic immobilization of applied N and distribution among different soil fractions was evaluated by correlating amino sugar FDN to soil fraction FDN. Among all the soil fractions analysed only fertilizer-N immobilized on the LF was significantly correlated to the amino sugar FDN (r=0.896, P<0.001; Fig. 6). It could be therefore concluded that the transfer of applied N onto the LF was strictly related to biotic N immobilization mechanisms as a result of microbial growth during the decomposition of labile substrates. Although the maximum amino sugar contents generally occur in the clay fractions (Glaser et al., 2006; Guggenberger et al., 1999), these results suggest that the labile OM pool serve as important “hotspots” for microbial N transformations and play a

significant role in determining N availability. The degree of decomposition and disintegration of incorporated rice straw was previously reported to be correlated to the microbial colonization of the leaf sheaths (Kimura and Tun, 1999). Moreover, scanning electron microscopy and transmission electron microscopy of soil sections have evidenced that bacteria are often largely confined to the periphery of degrading plant residues (Nannipieri and Eldor, 2009). The biotic immobilization of applied N onto decomposing plant residues was also confirmed by ^{15}N CPMAS NMR spectra of natural abundance rice straw and the ^{15}N-enriched light fractions separated from non-flooded and flooded soils receiving straw (Fig. 7). In fact, during incubation under both redox conditions, spectra evidenced an increase in intensity of the signal between 73 and 108 ppm with maximum intensity at 96 ppm attributable to amide N of proteins (Knicker et al., 1997). The predominance of NMR signals from products of biological origin, particularly N in peptide linkages, suggests that microbial activity on the LF could have been responsible for the immobilization of applied N. These results are in line with the findings of Knicker et al. (1997) that report the uptake of applied NH_4^+ and synthesis of microbial proteins and biological N-containing structures as the major pathway of N metabolism during the incubation of organic residues under flooded and non-flooded conditions. These results suggest that biotic immobilization of fertilizer-N may play an important role in controlling N availability in paddy soils when crop residues are incorporated. Nevertheless, we cannot exclude that abiotic reactions between ammonia and lignin-phenols in the LF could have led to the formation of amide N directly bonded to aromatic rings (i.e. anilides) as reported by Schmidt-Rohr et al. (2004) and Olk et al. (2006) for humic acid fractions extracted from paddy soils. However, this mechanism is not expected to contribute significantly to N immobilization on the LF since this SOM fraction contains predominantly intact lignin biopolymers with less phenolic hydroxyl functionalities with respect to lignin-derived constituents in the humic fractions. No significant amount of heterocyclic N structures, such as indoles, pyrroles and imidazoles, were detected in any of the LF samples analysed on the low field side of the main amide-peptide peak (between 120 and 213 ppm; Fig. 8), suggesting that their formation and contribution to immobilized N forms was limited within the experimental time frame.

4. Conclusions

The extent and mechanisms of N immobilization in paddy soils strongly depend on redox conditions and presence of labile OM. In fact, under flooded conditions 27–50% of applied N may be immobilized, with enhanced immobilization when rice straw is incorporated into the soil. This suggests that crop residue and water management practices adopted in rice cropping systems may strongly influence N immobilization and availability for the crop. In particular, the results obtained in this work give rise to the following implications:

1) Microbially-mediated processes were mainly responsible for the immobilization of applied N in both flooded and non-flooded paddy soils, particularly in the presence of labile OM. Most of the immobilized fertilizer-N was found to be associated with finer soil fractions, although significant amounts of applied N were also retained by the light fraction in those soils receiving straw. Microbial growth on decomposing straw seems to be mainly responsible for the transfer of applied N into particulate OM fractions. This provides further evidence that immobilization of applied N by soil microbes is intimately coupled with OM decomposition.
2) Under flooded conditions, the effective abiotic immobilization of applied N by interlayer NH_4^+ fixation may also play an important role in controlling N availability in relatively young, lowland rice paddies having a mineralogical composition rich in 2:1 clay minerals. We showed that under these conditions, NH_4^+ fixation may be responsible for the immobilization of 4–11% of applied N. Nevertheless, weakly fixed fertilizer-N

may be made available during the cropping season, although its release is mainly regulated by biotic processes. Re-establishing oxic soil conditions during field drainage as well as N assimilation by the crop may influence the equilibria and release of fixed fertilizer-N. However, understanding the magnitude and dynamics of these processes as a function of plant N uptake during the cropping season still requires further research.

3) Soil redox conditions were shown to have a strong influence on aggregate stability. Moreover, results have evidenced that, apart from implications on OM stabilization, changes in aggregate stability with flooding may also affect biotic and abiotic processes controlling the immobilization and release of applied N.

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References

Amelung, W., 2001. Methods using amino sugars as markers for microbial residues in soil. In: R. Lal, J.M. Kimble, R.F. Follett, B.A. Stewart (Eds.), Assessment methods for soil carbon. Lewis Publishers, Boca Raton, FL, pp. 233-272.

Amelung, W., 2003. Nitrogen biomarkers and their fate in soil. J. Plant Nutr. Soil Sci. 166(6), 677-686.

Amelung, W., Zhang, X., Flach, K.W., Zech, W., 1999. Amino sugars in native grassland soils along a climosequence in North America. Soil Sci. Soc. Am. J. 63(1), 86-92.

Bai, Q., Gattinger, A., Zelles, L., 2000. Characterization of microbial consortia in paddy rice soil by phospholipid analysis. Microb. Ecol. 39(4), 273-281.

Bird, J.A., Horwáth, W.R., Eagle, A.J., van Kessel, C., 2001. Immobilization of fertilizer nitrogen in rice: Effects of straw management practices. Soil Sci. Soc. Am. J. 65(4), 1143-1152.

Bird, J.A., van Kessel, C., Horwáth, W.R., 2002. Nitrogen dynamics in humic fractions under alternative straw management in temperate rice. Soil Sci. Soc. Am. J. 66(2), 478-488.

Bossio, D.A., Scow, K.M., 1998. Impacts of carbon and flooding on soil microbial communities: Phospholipid fatty acid profiles and substrate utilization patterns. Microb. Ecol. 35(3), 265-278.

Bronick, C.J., Lal, R., 2005. Soil structure and management: a review. Geoderma 124(1-2), 3-22.

Cassman, K.G., Peng, S., Olk, D.C., Ladha, J.K., Reichardt, W., Dobermann, A., Singh, U., 1998. Opportunities for increased nitrogen-use efficiency from improved resource management in irrigated rice systems. Field Crop. Res. 56(1-2), 7-39.

Cassman, K.G., Dobermann, A., Walters, D.T., 2002. Agroecosystems, nitrogen-use efficiency, and nitrogen management. Ambio 31, 132-140.

Christensen, B.T., 1992. Physical fractionation of soil and organic matter in primary particle size and density separates. In: B.A. Stewart (Ed.), Advances in Soil Science. Springer-Verlag, New York, pp. 1-89.

Compton, J.E., Boone, R.D., 2002. Soil nitrogen transformations and the role of light fraction organic matter in forest soils. Soil Biol. Biochem. 34(7), 933-943.

Decock, C., Denef, K., Bode, S., Six, J., Boeckx, P., 2009. Critical assessment of the applicability of gas chromatography-combustion-isotope ratio mass spectrometry to determine amino sugar dynamics in soil. Rapid Commun. Mass Spectrom. 23(8), 1201-1211.

Devêvre, O.C., Horwáth, W.R., 2000. Decomposition of rice straw and microbial carbon use efficiency under different soil temperatures and moistures. Soil Biol. Biochem. 32, 1773-1785.

Devêvre, O.C., Horwáth, W.R., 2001. Stabilization of fertilizer nitrogen-15 into humic substances in aerobic vs. waterlogged soil following straw incorporation. Soil Sci. Soc. Am. J. 65(2), 499-510.

DiCosty, R.J., Weliky, D.P., Anderson, S.J., Paul, E.A., 2003. N-15-CPMAS nuclear magnetic resonance spectroscopy and biological stability of soil organic nitrogen in whole soil and particle-size fractions. Org. Geochem. 34(12), 1635-1650.

Ding, X.L., Zhang, X.D., He, H.B., Xie, H.T., 2010. Dynamics of soil amino sugar pools during decomposition processes of corn residues as affected by inorganic N addition. J. Soils Sediments 10(4), 758-766.

Eagle, A.J., Bird, J.A., Horwáth, W.R., Linquist, B.A., Brouder, S.M., Hill, J.E., van Kessel, C., 2000. Rice yield and nitrogen utilization efficiency under alternative straw management practices. Agron. J. 92(6), 1096-1103.

Eudoxie, G.D., Gouveia, G.A., 2008. Distillation and microdiffusion modifications for total NH_{4f} quantification and ^{15}N recovery. Am. J. Agri. & Biol. Sci. 3(4), 689-698.

Ghosh, B.C., Bhat, R., 1998. Environmental hazards of nitrogen loading in wetland rice fields. Environ. Pollut. 102, 123-126.

Glaser, B., Amelung, W., 2002. Determination of C-13 natural abundance of amino acid enantiomers in soil: methodological considerations and first results. Rapid Commun. Mass Spectrom. 16(9), 891-898.

Glaser, B., Millar, N., Blum, H., 2006. Sequestration and turnover of bacterial- and fungal-derived carbon in a temperate grassland soil under long-term elevated atmospheric pCO_2. Glob. Change Biol. 12(8), 1521-1531.

Glaser, B., Turrion, M.B., Alef, K., 2004. Amino sugars and muramic acid - biomarkers for soil microbial community structure analysis. Soil Biol. Biochem. 36(3), 399-407.

Green, C.J., Blackmer, A.M., Yang, N.C., 1994. Release of fixed ammonium during nitrification in soils. Soil Sci. Soc. Am. J. 58(5), 1411-1415.

Guerrant, G.O., Moss, C.W., 1984. Determination of monosaccharides as aldonitrile, O-methyloxime, alditol, and cyclitol acetate derivatives by gas chromatography. Anal. Chem. 56, 633-638.

Guggenberger, G., Christensen, B.T., Zech, W., 1994. Land-use effects on the composition of organic-matter in particle-size separates of soil. 1. Lignin and carbohydrate signature. Eur. J. Soil Sci. 45(4), 449-458.

Guggenberger, G., Frey, S.D., Six, J., Paustian, K., Elliott, E.T., 1999. Bacterial and fungal cell-wall residues in conventional and no-tillage agroecosystems. Soil Sci. Soc. Am. J. 63(5), 1188-1198.

Hagedorn, F., Maurer, S., Bucher, J.B., Siegwolf, R.T.W., 2005. Immobilization, stabilization and remobilization of nitrogen in forest soils at elevated CO_2: a N-15 and C-13 tracer study. Glob. Change Biol. 11(10), 1816-1827.

He, H.B., Xie, H.T., Zhang, X.D., 2006. A novel GC/MS technique to assess N-15 and C-13 incorporation into soil amino sugars. Soil Biol. Biochem. 38(5), 1083-1091.

Jiang, X., Wright, A.L., Wang, J., Li, Z., 2011. Long-term tillage effects on the distribution patterns of microbial biomass and activities within soil aggregates. Catena 87(2), 276-280.

Kaiser, K., Zech, W., 2000. Sorption of dissolved organic nitrogen by acid subsoil horizons and individual mineral phases. Eur. J. Soil Sci. 51(3), 403-411.

Kandeler, E., Tscherko, D., Bruce, K.D., Stemmer, M., Hobbs, P.J., Bardgett, R.D., Amelung, W., 2000. Structure and function of the soil microbial community in microhabitats of a heavy metal polluted soil. Biol. Fertil. Soils 32(5), 390-400.

Katoh, M., Murase, J., Sugimoto, A., Kimura, M., 2005. Effect of rice straw amendment on dissolved organic and inorganic carbon and cationic nutrients in percolating water from a flooded paddy soil: A microcosm experiment using C-13-enriched rice straw. Org. Geochem. 36(5), 803-811.

Kimura, M., Miyaki, M., Fujinaka, K.I., Maie, N., 2001. Microbiota responsible for the decomposition of rice straw in a submerged paddy soil estimated from phospholipid fatty acid composition. Soil Sci. Plant Nutr. 47(3), 569-578.

Kimura, M., Tun, C.C., 1999. Microscopic observation of the decomposition process of leaf sheath of rice straw and colonizing microorganisms during the cultivation period of paddy rice. Soil Sci. Plant Nutr. 45(2), 427-437.

Knicker, H., Ludemann, H.D., Haider, K., 1997. Incorporation studies of NH_4^+ during incubation of organic residues by N-15-CPMAS-NMR-spectroscopy. Eur. J. Soil Sci. 48(3), 431-441.

Kögel-Knabner, I., Amelung, W., Cao, Z., Fiedler, S., Frenzel, P., Jahn, R., Kalbitz, K., Kölbl, A., Schloter, M., 2010. Biogeochemistry of paddy soils. Geoderma 157(1-2), 1-14.

Kögel-Knabner, I., Guggenberger, G., Kleber, M., Kandeler, E., Kalbitz, K., Scheu, S., Eusterhues, K., Leinweber, P., 2008. Organo-mineral associations in temperate soils: Integrating biology, mineralogy, and organic matter chemistry. J. Plant Nutr. Soil Sci. 171(1), 61-82.

Liang, C., Zhang, X.D., Rubert, K.F., Balser, T.C., 2007. Effect of plant materials on microbial transformation of amino sugars in three soil microcosms. Biol. Fertil. Soils 43(6), 631-639.

Matsuoka, K., Moritsuka, N., 2011. Dynamics of clay-fixed ammonium as a sink or source of exchangeable ammonium in a paddy soil. Soil Sci. Plant Nutr. 57(6), 751-758.

Morier, I., Schleppi, P., Siegwolf, R., Knicker, H., Guenat, C., 2008. N-15 immobilization in forest soil: a sterilization experiment coupled with ^{15}CPMAS NMR spectroscopy. Eur. J. Soil Sci. 59(3), 467-475.

Nakamura, A., Tun, C.C., Asakawa, S., Kimura, M., 2003. Microbial community responsible for the decomposition of rice straw in a paddy field: estimation by phospholipid fatty acid analysis. Biol. Fertil. Soils 38(5), 288-295.

Nannipieri, P., Eldor, P., 2009. The chemical and functional characterization of soil N and its biotic components. Soil Biol. Biochem. 41(12), 2357-2369.

Nieder, R., Benbi, D.K., Scherer, H.W., 2011. Fixation and defixation of ammonium in soils: a review. Biol. Fertil. Soils 47(1), 1-14.

Noll, M., Matthies, D., Frenzel, P., Derakshani, M., Liesack, W., 2005. Succession of bacterial community structure and diversity in a paddy soil oxygen gradient. Environ. Microbiol. 7(3), 382-395.

Olk, D.C., Cassman, K.G., Schmidt-Rohr, K., Anders, M.M., Mao, J.D., Deenik, J.L., 2006. Chemical stabilization of soil organic nitrogen by phenolic lignin residues in anaerobic agroecosystems. Soil Biol. Biochem. 38, 3303-3312.

Parsons, J.W., 1981. Chemistry and distribution of amino sugars in soils and soil organisms. In: E.A. Paul, J.N. Ladd (Eds.), Soil Biochemistry. Marcel Dekker, New York, pp. 197-227.

Peng, S.B., Buresh, R.J., Huang, J.L., Zhong, X.H., Zou, Y.B., Yang, J.C., Wang, G.H., Liu, Y.Y., Hu, R.F., Tang, Q.Y., Cui, K.H., Zhang, F.S., Dobermann, A., 2010. Improving nitrogen fertilization in rice by site-specific N management. A review. Agron. Sustain. Dev. 30(3), 649-656.

Polyanskaya, L.M., Gorbacheva, M.A., Milanovskii, E.Y., Zvyagintsev, D.G., 2010. Development of microorganisms in the chernozem under aerobic and anaerobic conditions. Eurasian Soil Sci. 43(3), 328-332.

Reddy, K.R., 1982. Nitrogen cycling in a flooded-soil ecosystem planted to rice (Oryza sativa L.). Plant Soil 67, 209-220.

Reddy, K.R., deLaune, R.D., 2008. Biogeochemistry of wetlands: science and applications. Taylor and Francis Group.

Roberts, P., Bol, R., Jones, D.L., 2007. Free amino sugar reactions in soil in relation to soil carbon and nitrogen cycling. Soil Biol. Biochem. 39(12), 3081-3092.

Roth, P.J., Lehndorff, E., Cao, Z.H., Zhuang, S.Y., Bannert, A., Wissing, L., Schloter, M., Kögel-Knabner, I., Amelung, W., 2011. Accumulation of nitrogen and microbial residues during 2000 years of rice paddy and non-paddy soil development in the Yangtze River Delta, China. Glob. Change Biol. 17(11), 3405-3417.

Scherer, H.W., Zhang, Y.S., 1999. Studies on the mechanisms of fixation and release of ammonium in paddy soils after flooding. I. Effect of iron oxides on ammonium fixation. J. Plant Nutr. Soil Sci. 162(6), 593-597.

Schleppi, P., Bucher-Wallin, I., Saurer, M., Jaggi, M., Landolt, W., 2006. Citric acid traps to replace sulphuric acid in the ammonia diffusion of dilute water samples for N-15 analysis. Rapid Commun. Mass Spectrom. 20(4), 629-634.

Schmidt-Rohr, K., Mao, J.D., Olk, D.C., 2004. Nitrogen-bonded aromatics in soil organic matter and their implications for a yield decline in intensive rice cropping. Proc. Natl. Acad. Sci. U.S.A. 101(17), 6351-6354.

Schmitt, J., Glaser, B., Zech, W., 2003. Amount-dependent isotopic fractionation during compound-specific isotope analysis. Rapid Commun. Mass Spectrom. 17(9), 970-977.

Schneiders, M., Scherer, H.W., 1998. Fixation and release of ammonium in flooded rice soils as affected by redox potential. Eur. J. Agron. 8(3-4), 181-189.

Shen, S.Y., Tu, S.I., Kemper, W.D., 1997. Equilibrium and kinetic study of ammonium adsorption and fixation in sodium-treated vermiculite. Soil Sci. Soc. Am. J. 61(6), 1611-1618.

Six, J., Guggenberger, G., Paustian, K., Haumaier, L., Elliott, E.T., Zech, W., 2001. Sources and composition of soil organic matter fractions between and within soil aggregates. Eur. J. Soil Sci. 52(4), 607-618.

Six, J., Paustian, K., Elliott, E.T., Combrink, C., 2000. Soil structure and organic matter: I. Distribution of aggregate-size classes and aggregate-associated carbon. Soil Sci. Soc. Am. J. 64(2), 681-689.

Wang, W.J., Chalk, P.M., Chen, D., Smith, C.J., 2001. Nitrogen mineralisation, immobilisation and loss, and their role in determining differences in net nitrogen production during waterlogged and aerobic incubation of soils. Soil Biol. Biochem. 33(10), 1305-1315.

Zanini, E., Bonifacio, E., Albertson, J.D., Nielsen, D.R., 1998. Topsoil aggregate breakdown under water-saturated conditions. Soil Sci. 163(4), 288-298.

Zhang, X.D., Amelung, W., 1996. Gas chromatographic determination of muramic acid, glucosamine, mannosamine, and galactosamine in soils. Soil Biol. Biochem. 28(9), 1201-1206.

Zhang, X.D., Amelung, W., Ying, Y.A., Zech, W., 1998. Amino sugar signature of particle-size fractions in soils of the native prairie as affected by climate. Soil Sci. 163(3), 220-229.

Zhang, Y.S., Scherer, H.W., 2000. Mechanisms of fixation and release of ammonium in paddy soils after flooding - II. Effect of transformation of nitrogen forms on ammonium fixation. Biol. Fertil. Soils 31(6), 517-521.

Figure captions

Figure 1: Distribution of organic C (box plots) among different soil fractions and their C/N ratio (filled symbols) in soils incubated under non-flooded (NF) or flooded (F) conditions, without (NS) or with (S) straw addition. For box-plots, the line within the box marks the median (n = 18), the box boundary marks the 25th and 75th percentile and whiskers above and below the box indicate the 90th and 10th percentiles, while the filled symbols represent the mean (n = 18). LF, light fraction; M, macroaggregates; m, microaggregates.

Figure 2: Variations in the distribution of fertilizer-derived N among different soil fractions with time in soils incubated under non-flooded (NF) or flooded (F) conditions, without (NS) or with (S) straw addition. Error bars represent the standard error. Labels above bars represent the sum of fertilizer-derived N in all fractions expressed as a percentage of applied N. LF, light fraction; M, macroaggregates; m, microaggregates.

Figure 3: Variations in the total contents of interlayer fixed fertilizer-derived N and its distribution between the fine fractions of macro- (M<20) and microaggregates (m<20) with time in soils incubated under non-flooded (NF) or flooded (F) conditions, without (NS) or with (S) straw addition.

Figure 4: Variations in total (sum of glucosamine, galactosamine, mannosamine and muramic acid) and fertilizer-derived (sum of glucosamine and galactosamine) amino sugar N with time in soils incubated under non-flooded (NF) or flooded (F) conditions, without (NS) or with (S) straw addition. Error bars represent the standard error.

Figure 5: Total and fertilizer-derived (FDN) glucosamine-to-galactosamine N ratios for soils incubated under non-flooded (NF) or flooded (F) conditions, without (NS) or with (S) straw addition. The line within the box marks the median, the box boundary marks the 25th and 75th percentile, whiskers above and below the box indicate the 90th and 10th percentiles.

Figure 6: Linear regression between fertilizer-derived N in the light fraction and amino sugar pools for samples without (open circles) or with (closed circles) straw addition. Error bars represent the standard error while dotted line represents 95% confidence intervals.

Figure 7: ^{15}N-NMR spectra of added rice straw (natural abundance), and the ^{15}N-enriched light fractions separated from straw-amended, non-flooded and flooded soils at the beginning (1 d) and end (160 d) of the incubation period. ^{15}N chemical shifts were referenced to $(NH_4)_2SO_4$ added to the samples as internal standard (*), while shaded area represents chemical shifts of amide-N of proteins.

Table 1
Soil physical, chemical and mineralogical properties.

OC (g kg^{-1})[a]	11.6
TN (g kg^{-1})[b]	1.1
NO_3^- (mg N kg^{-1})	5.5
NH_4^+ (mg N kg^{-1})	3.3
pH	6.3
CEC ($cmol_c$ kg^{-1})[c]	6.7
K^+ exchangeable (meq kg^{-1})	1.9
Fe_{d-o} (g kg^{-1})[d]	3.8
Fe_o (g kg^{-1})[e]	3.2
Al_o (g kg^{-1})[e]	0.6
Sand (g kg^{-1})	524
Silt (g kg^{-1})	411
Clay (g kg^{-1})	65
WHC (g kg^{-1})[f]	405
Clay mineral composition[g]	vermiculite, illite, chlorite, mixed layer phases

[a] Organic carbon;
[b] Total nitrogen;
[c] Cation exchange capacity determined by $BaCl_2$ (pH 8.1);
[d] Dithionite-citrate-bicarbonate minus oxalate extractable Fe;
[e] NH_4-oxalate-extractable Fe and Al;
[f] WHC: water-holding capacity determined gravimetrically;
[g] Determined by XRD analysis.

Table 2
Variations in total available N and immobilized fertilizer-derived N (mg N kg^{-1} soil) with time in soils incubated under non-flooded (NF) or flooded (F) conditions, without (NS) or with (S) straw addition.

Treatment	Incubation time (d)					
	1 d	10 d	30 d	90 d	160 d	$LSD_{0.05}$[c]
Non-flooded, without straw (NF-NS)						
Total available N[a]	52.7	77.1	70.0	78.7	60.6	5.7
Immobilized FDN[b]	29.4	6.9	5.2	4.4	4.6	1.1
Non-flooded, with straw (NF-S)						
Total available N	39.3	59.8	43.6	55.4	55.2	8.1
Immobilized FDN	25.3	14.9	13.7	11.9	12.7	1.5
Flooded, without straw (F-NS)						
Total available N	51.8	55.3	56.5	21.3	23.4	4.6
Immobilized FDN	25.6	20.3	20.0	16.5	15.3	2.0
Flooded, with straw (F-S)						
Total available N	38.5	52.6	45.8	56.6	71.9	6.0
Immobilized FDN	25.9	24.8	25.8	27.9	27.2	2.3

[a] Determined as the sum of NH_4^+ and NO_3^- in soil extracts and floodwater (in flooded soils).
[b] Fertilizer derived N determined after removal of K_2SO_4 extractable N.
[c] Least significant difference for $P < 0.05$.

Table 3
Variations in aggregate yield and enrichment ratios for the fine silt and clay-sized fraction (<20 μm) in micro- to macroaggregates with time in soils incubated under non-flooded (NF) or flooded (F) conditions, without (NS) or with (S) straw addition.

Treatment	Yield ratio[a]			Enrichment ratio[b]		
	1 d	10 d	160 d	1 d	10 d	160 d
Non-flooded, without straw (NF-NS)	0.64	0.60	0.69	1.22	0.64	0.88
Non-flooded, with straw (NF-S)	0.49	0.67	0.77	1.43	0.87	0.90
Flooded, without straw (F-NS)	0.85	1.56	1.79	1.29	1.12	1.13
Flooded, with straw (F-S)	1.66	1.66	1.53	1.32	1.26	1.02

[a] Calculated as the ratio of mass yields (in g fraction kg^{-1} soil) of m<20 to M<20 fractions;
[b] Calculated as the ratio of f_{FDN} of m<20 to M<20 fractions.

FIGURE 1

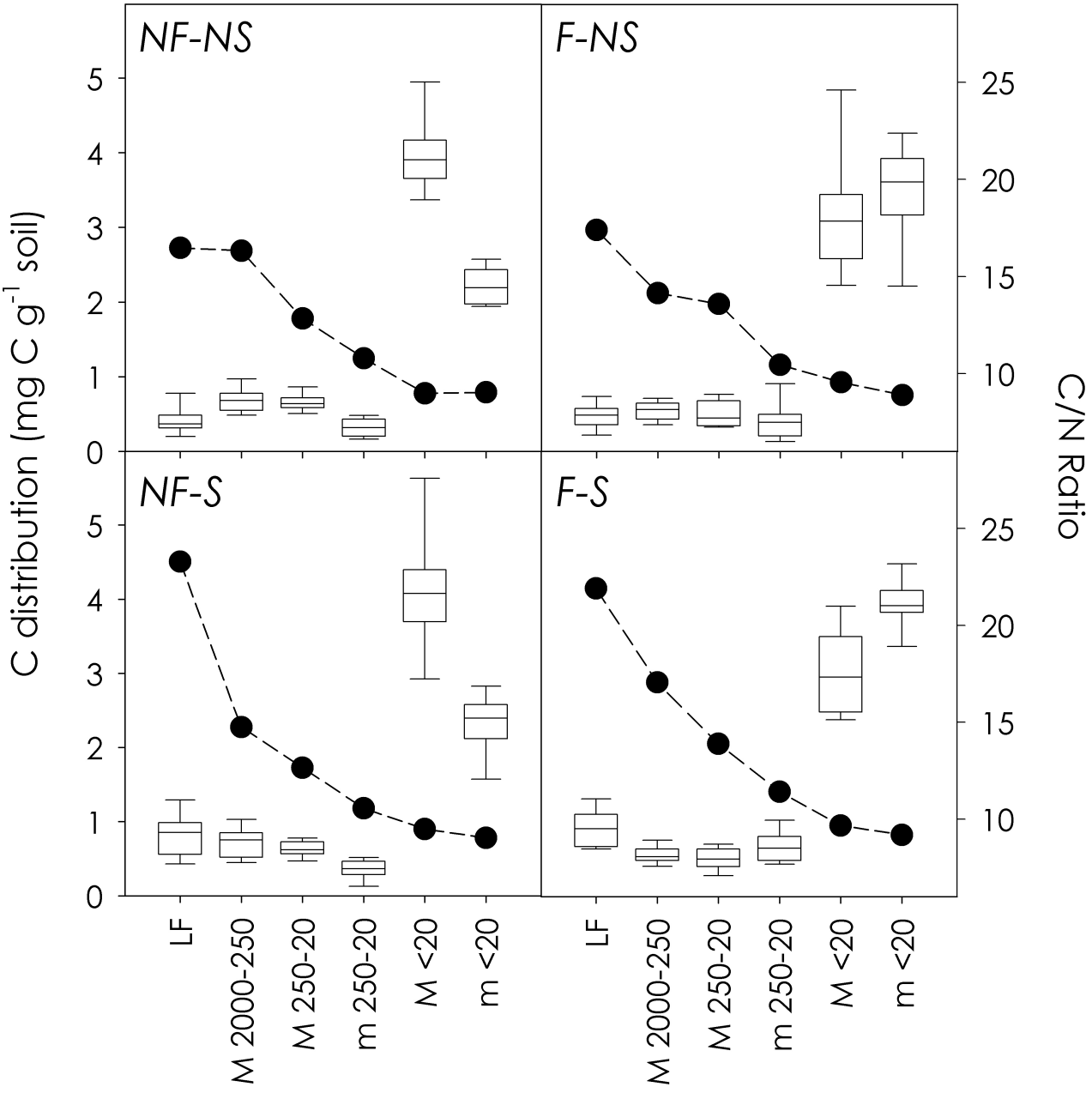

NF-NS
F-NS
NF-S
F-S
C distribution (mg C g-1 soil)
C/N Ratio
0
1
2
3
4
5
10
15
20
25
LF
M 2000-250
M 250-20
m 250-20
M <20
m <20

FIGURE 2

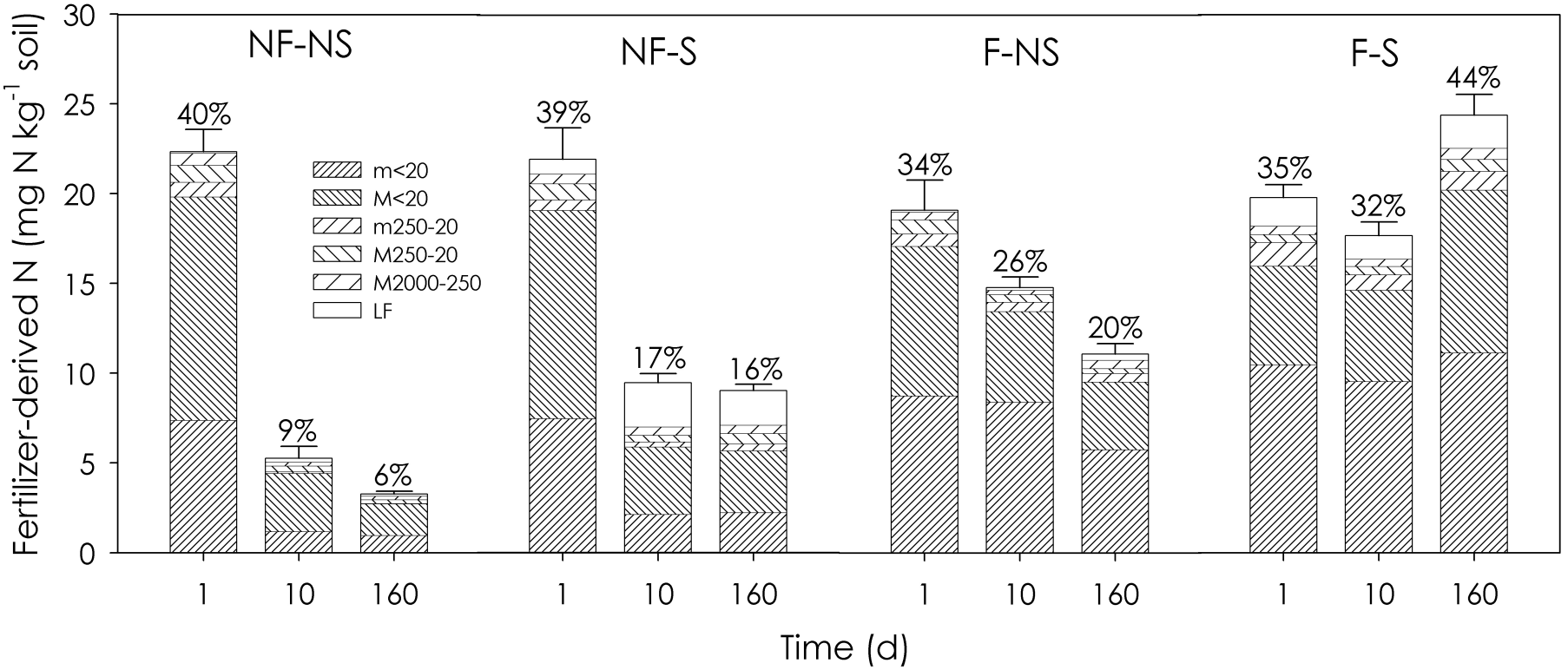

NF-NS
NF-S
F-NS
F-S
m<20
M<20
m250-20
M250-20
M2000-250
LF
40%
9%
6%
39%
17%
16%
34%
26%
20%
35%
32%
44%
Fertilizer-derived N (mg N kg-1 soil)
Time (d)
0
5
10
15
20
25
30
1
10
160

FIGURE 3

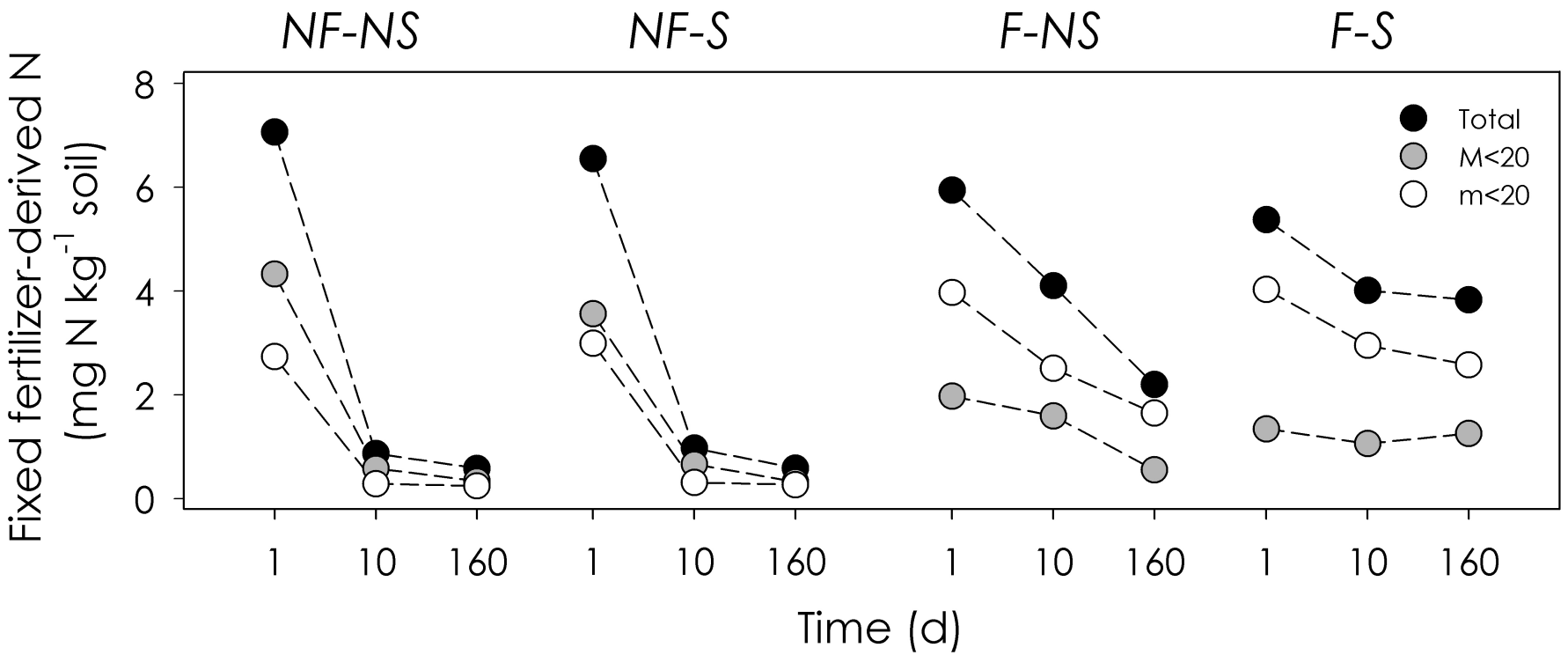

NF-NS
NF-S
F-NS
F-S
Fixed fertilizer-derived N
(mg N kg-1 soil)
0
2
4
6
8
1
10
160
Time (d)
Total
M<20
m<20

FIGURE 4

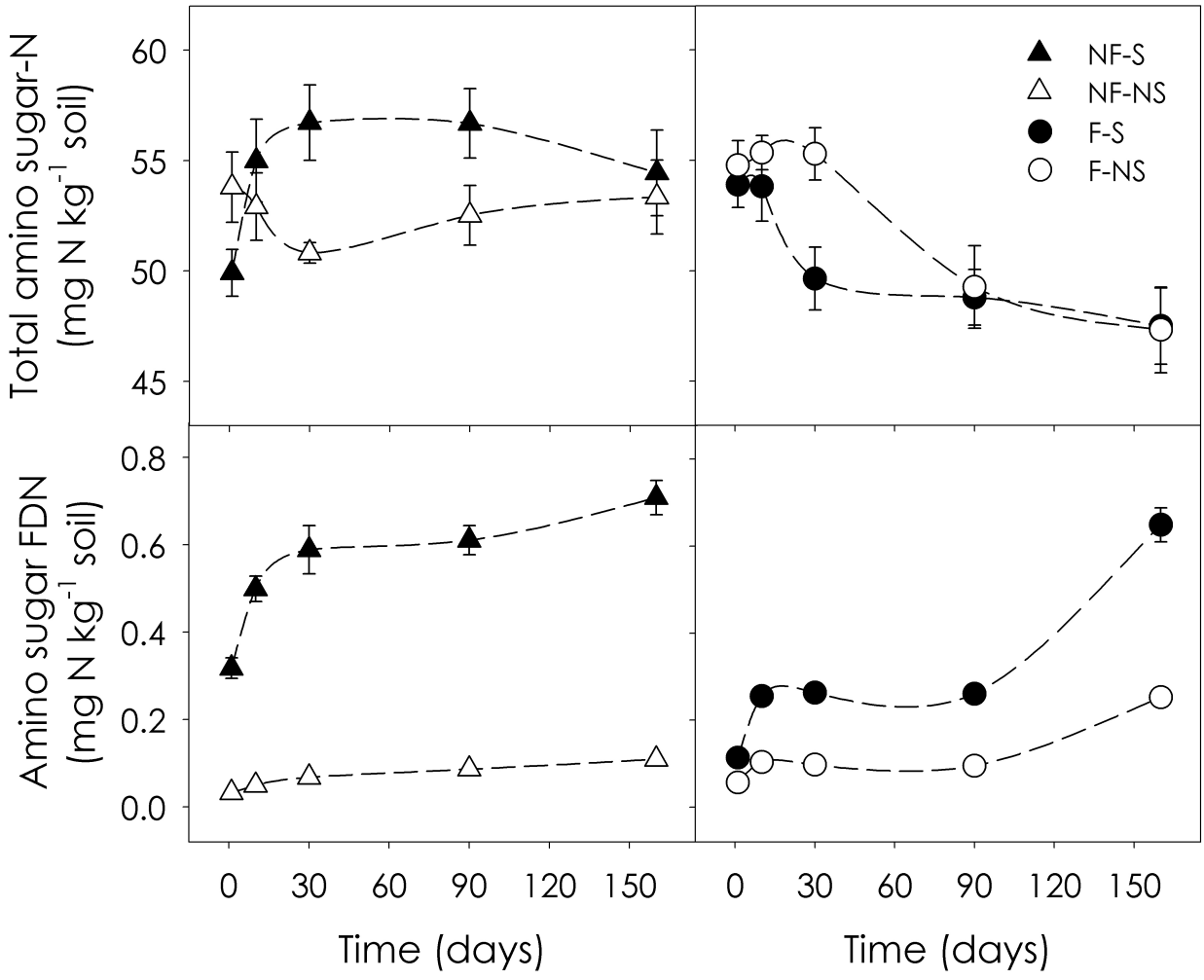

Total amino sugar-N (mg N kg-1 soil)
60
55
50
45
NF-S
NF-NS
F-S
F-NS
Amino sugar FDN (mg N kg-1 soil)
0.8
0.6
0.4
0.2
0.0
0
30
60
90
120
150
Time (days)
Time (days)

FIGURE 5

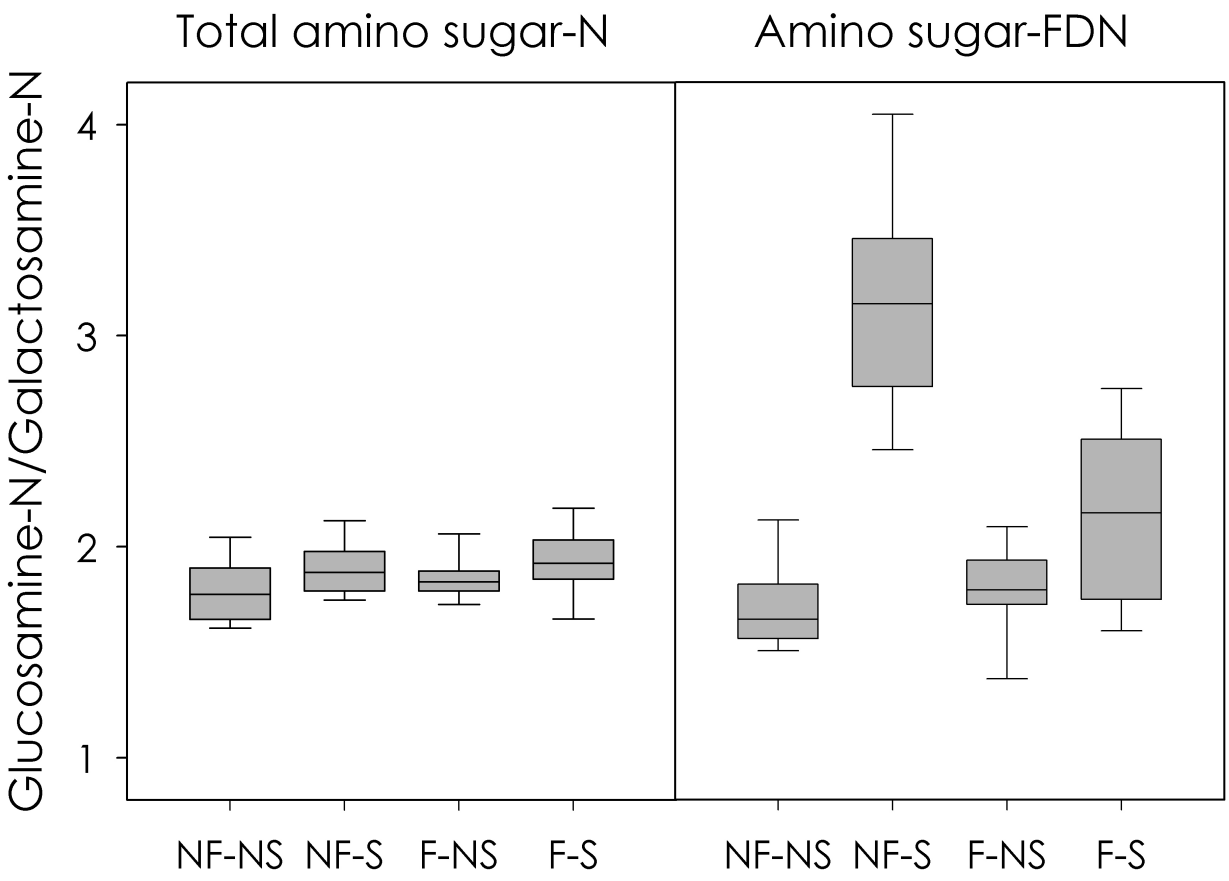

Total amino sugar-N
Amino sugar-FDN
Glucosamine-N/Galactosamine-N
4
3
2
1
NF-NS
NF-S
F-NS
F-S
NF-NS
NF-S
F-NS
F-S

FIGURE 6

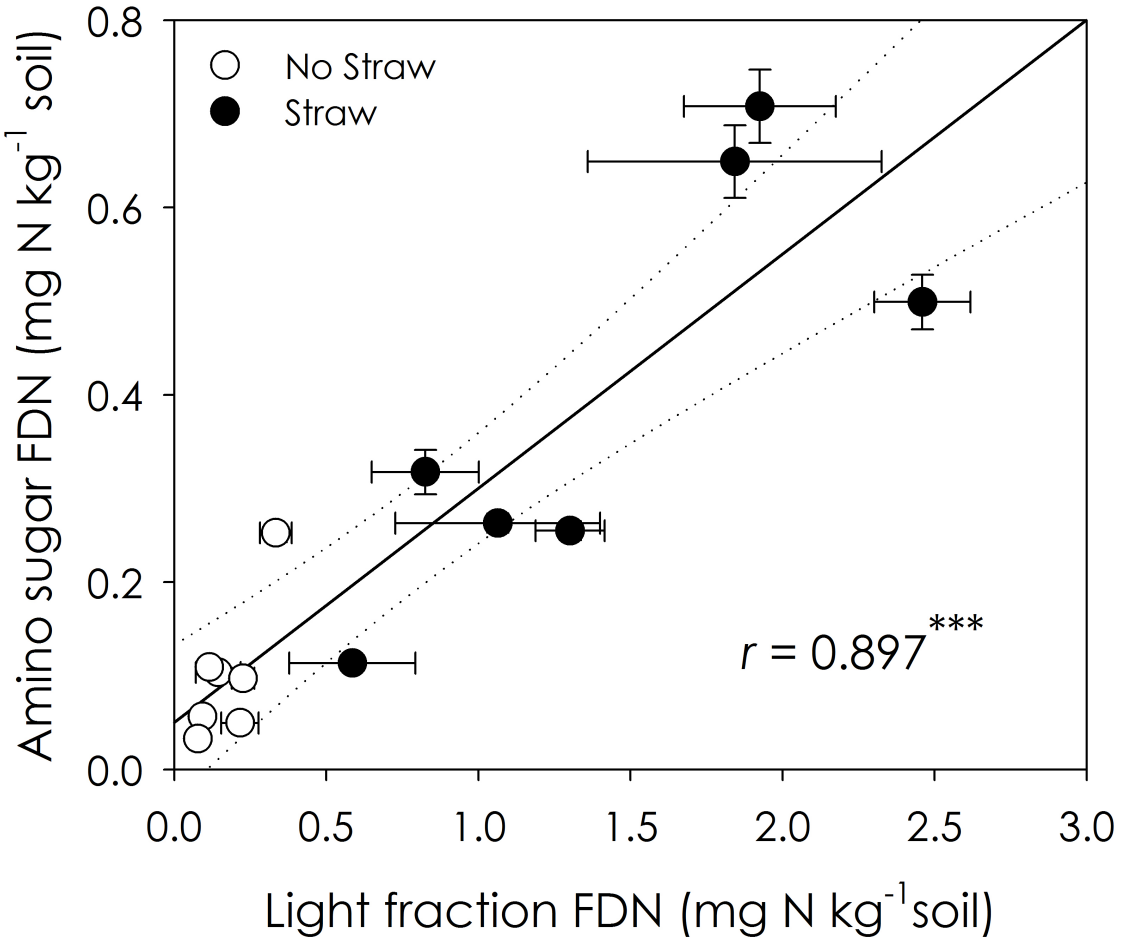
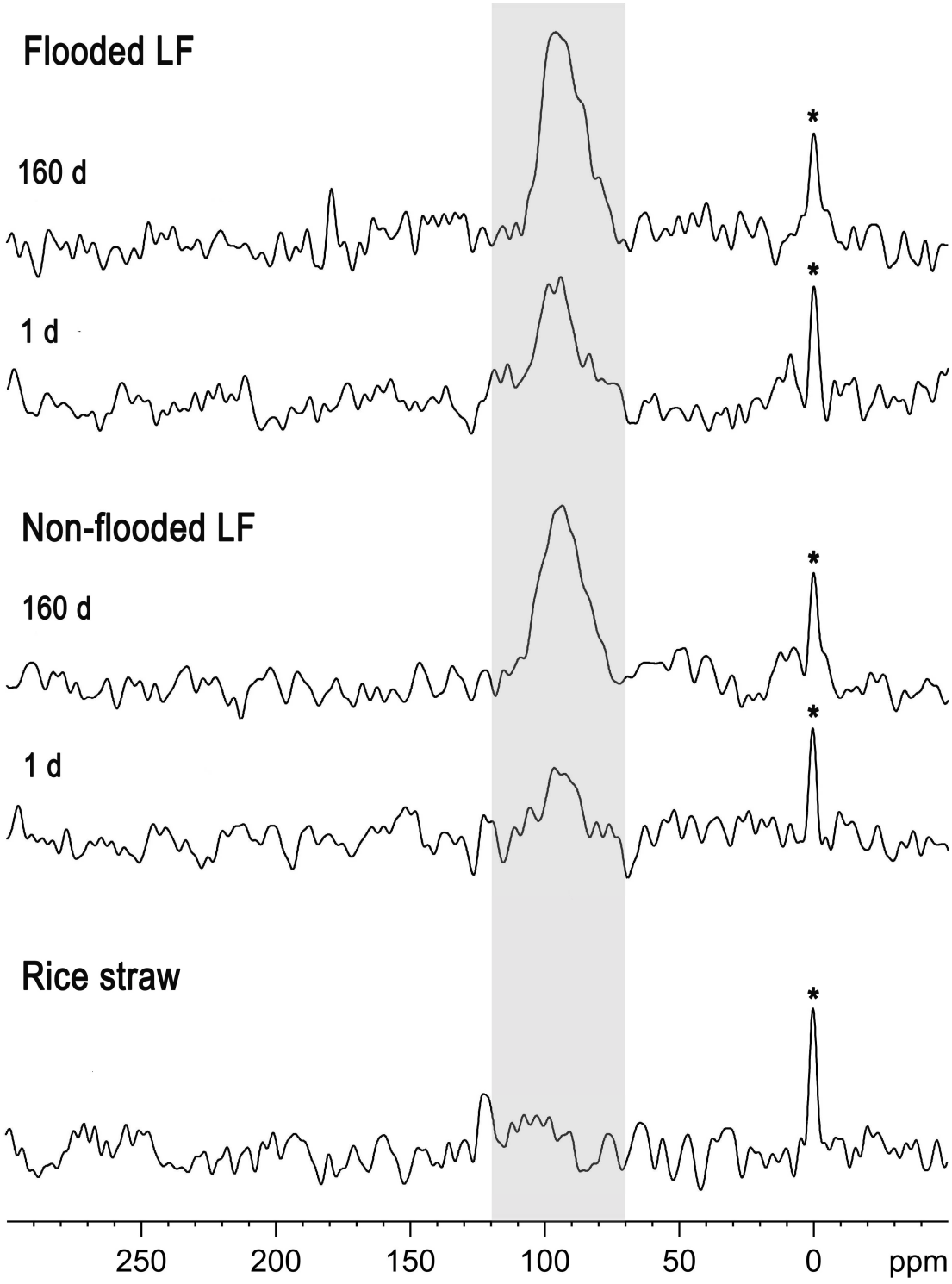

No Straw
Straw
r = 0.897***
Amino sugar FDN (mg N kg-1 soil)
Light fraction FDN (mg N kg-1soil)
0.0
0.2
0.4
0.6
0.8
0.0
0.5
1.0
1.5
2.0
2.5
3.0

FIGURE 7


Flooded LF
160 d
1 d
Non-flooded LF
160 d
1 d
Rice straw
250
200
150
100
50
0
ppm