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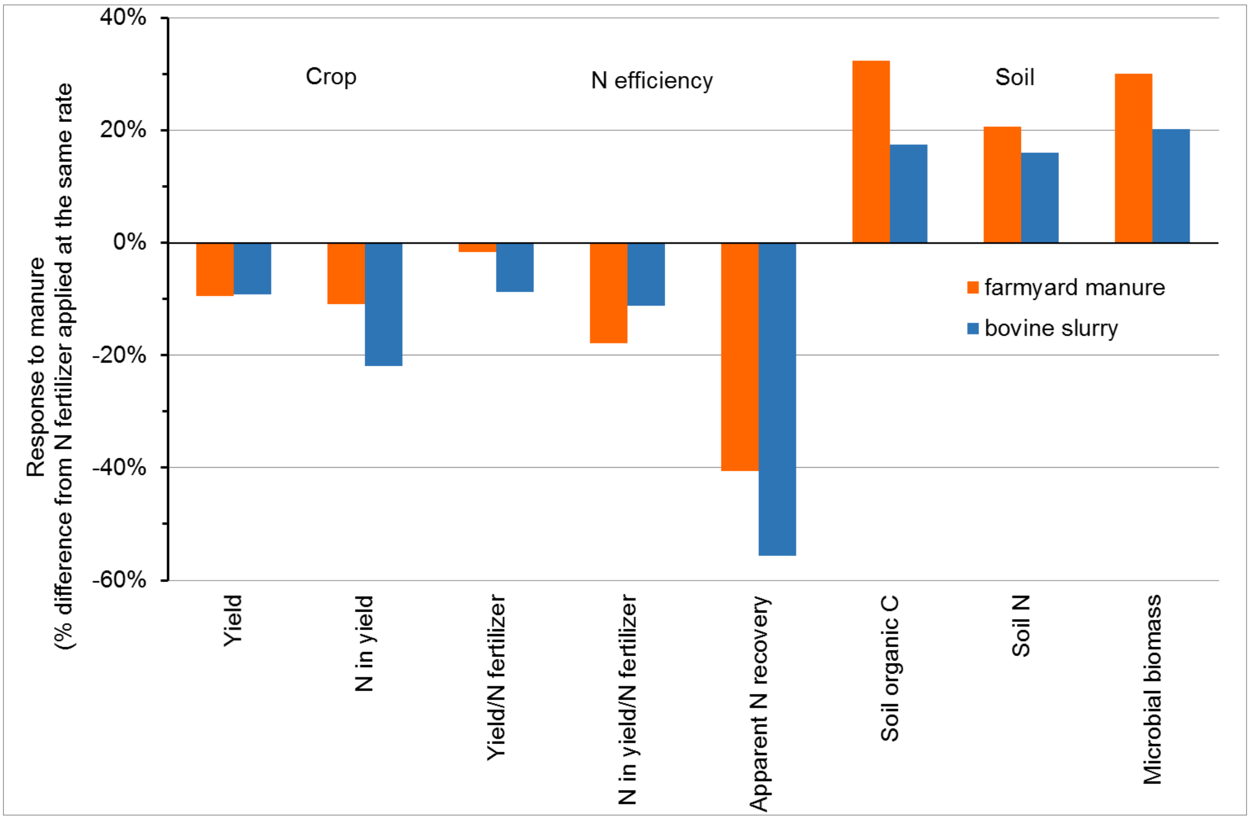
Graphical abstract



Research highlights

- In European long-term experiments, bovine farmyard manure and slurry reduced yields by 9% compared to mineral fertilizers applied at similar nitrogen (N) rates
- Soil organic carbon increased by 33% and 17% due to farmyard manure and slurry applications, respectively, compared to mineral fertilizers applied at similar N rates
- Mineral N integration to farmyard manure improved yield, but reduced N use efficiency and increased soil organic matter to a lesser extent
- Mineral N integration to slurry improved crop and efficiency to the levels of mineral fertilizer only
- Farmyard manure efficiency is higher than European national legislation standards

Agronomic effects of bovine manure: a review of long-term European field experiments

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Abstract

To evaluate the agronomic value of animal manure, we quantified the effects of pedo-climatic, crop and management factors on crop productivity, N use efficiency, and soil organic matter, described with simple indicators that compare manures with mineral fertilizers. We selected 80 European long-term field experiments that used bovine farmyard manure or bovine liquid slurry, alone (FYM and SLU) or combined with mineral fertilizers (FYMm and SLUm), and compared them to mineral fertilizer only reference treatments. We collected 5570 measurements from 107 papers. FYM produced slightly lower crop yields (-9.5%) when used alone and higher (+11.3%) yields when used in combination with N fertilizer (FYMm), compared to those obtained using mineral fertilizers only. Conditions promoting manure-N mineralization (lighter soil texture, warmer temperature, longer growing season, and shallower incorporation depth) significantly increased the effect of FYM/FYMm on crop yield and yield N. The production efficiency of FYM (yield:N applied ratio) was slightly lower than that of mineral fertilizers (-1.6%). The apparent N recoveries of FYM and FYMm were 59.3% and 78.7%, respectively, of mineral fertilizers. Manured soils had significantly higher C (+32.9% on average for FYM and FYMm) and N (+21.5%) concentrations. Compared to mineral fertilizers, yield was reduced by 9.1% with SLU, but not with SLUm. Influencing factors were similar to those of FYM/FYMm. Efficiency indicators indicated SLU (but not SLUm) was less effective than mineral fertilizers. Slurry significantly increased SOC (on average for SLU and SLUm by +17.4%) and soil N (+15.7%) concentrations. In conclusion, compared to mineral N fertilizers, bovine farmyard manure and slurry were slightly less effective on the crop, but determined marked increases to SOC and soil N, and thus, to long-term soil fertility maintenance.

Keywords

Farmyard manure; Slurry; Efficiency; Response ratio; Nitrogen; Soil organic carbon.

1. Introduction

Animal manures are valuable fertilizers. They supply available nutrients to crops, positively affect soil physical properties, activate soil life by providing easily degradable carbon compounds, and help build soil organic matter (Edmeades, 2003). However, if used incorrectly, manure applications can increase soil GHG emissions and nutrient losses (N, P and others) to water bodies. To evaluate the positive and negative effects of manures (Grizzetti et al., 2011; Moldanová et al., 2011; Velthof et al., 2011), their impacts on crop production, nutrient use efficiency and soil status must be assessed by using adequate indicators.

Since the early 1990s, European legislation has regulated animal production, and indirectly the use of animal manure, with a three-pronged objective: protecting human health, preserving environmental quality, and better equilibrating milk and dairy markets (Oenema, 2004). This legislation requires that management criteria, such as the best rate and timing of manure application, are adapted to specific local conditions (soil, climate, crop, manure type, farm organization). Consequently, official ranges of efficiency indicators have been developed in various countries to guide the application of manures and mineral N and P fertilizers. These official values for various European countries are reported by Webb et al. (2013), who list the N fertilizer value of farmyard manure and slurry relative to mineral fertilizers. For bovine farmyard manure, legal N fertilizer value ranges between 10 and 65%, depending on the country. Higher values are used in Italy, the Netherlands, and Denmark, while the UK uses a much lower coefficient. For slurry, N fertilizer values varied within a narrower range (40-70%), with lower values again used in the UK. Values for slurry are always above those of farmyard manure, with the exception of Italy, where the two types of manures are valued the same. Some countries differentiate soil- or season- or crop- or management-specific N fertilizer values. Ideally, official N fertilizer values represent a compendium of scientific knowledge on the crop response to amendments under local conditions.

This scientific knowledge, which can be summarized also using other agronomic performance indicators - such as yield response, nutrient uptake, soil health status, and fertilizer efficiency - is more robust when obtained from long-term field experiments, as the cumulative effects of manure additions only become measurable after several years or decades. Medium- and long-term field experiments (LTEs) are, in fact, widely recognized as essential research infrastructures for environmentally oriented agricultural studies (e.g., Lehtinen et al., 2014; Haddaway et al., 2015; Pikula et al., 2016; Stützel et al., 2016). Their value increases over time (Berti et al., 2016), as global patterns emerge from comprehensive analyses.

The most important animal manures studied in LTEs are bovine farmyard manure (solid; FYM) and bovine slurry (liquid; SLU). Farmyard manure was studied often in LTEs established during the late 19th or early 20th century. Studies using slurries in LTEs are more recent. Manure application rates were typically constant over the years, in terms of fresh mass input, often applied once per rotation cycle to a specific crop, and often without the intention to derive substitution values by direct comparison of manure versus mineral fertilizer. Only recently, LTEs were set up with the purpose of assessing replacement values of amendments at similar N rates. Depending on the study, this equivalency in N rate was either based on total N or only the mineral N fraction in the manure.

Scientific reviews have tried to compile the results of several LTEs to describe the long-term effects of manure. Gutser et al. (2005) summarized various laboratory and field trials in Germany to quantify the short-term and residual effects of manures and other organic fertilizers. The ratio between crop N uptake from manure and from mineral fertilizer ranged from 10 to 20% for farmyard manure, and between 35 and 45% for cattle slurry. Edmeades (2013) collected and analyzed data from 14 LTEs (20 to 120 years) in Europe, the USA, and Canada to compare the effects of fertilizers and manures (farmyard manure, slurry, and green manure) on crop production and soil properties. Körschens et al. (2013) reported mineral and organic fertilizer effects on crop yield and soil carbon from several LTEs (8-135 years), mainly located in Central and Eastern Europe. However, neither Edmeades (2013) nor Körschens et al. (2013) summarized data from the various experiments, or tried to explain variability across trials, or attempted to derive a N fertilizer replacement value of manure. Wei et al. (2016) analyzed 32 LTEs in China where manures and mineral N were compared; however, these experiments neither allowed comparisons at similar N rates, nor was a comprehensive and statistically sound analysis of measured data reported. Diacono and Montemurro (2010) outlined the effects of various amendments on soil chemical, physical, and biological fertility, using long-term trials (3 to 60 years) across the world, but they did not explain variability among LTEs. Similarly, a comprehensive and detailed review by Webb et al. (2013) on short- and long-term crop availability of manure-N in Europe did not report a mean N fertilizer value of manures.

Clearly, a European-wide review of the N fertilizer value of manures is missing. To fill this knowledge gap, our aim is to exploit the large data volume generated by European LTEs, with the purpose of assessing the agronomic value of manures.

To assess the N replacement value by its most common and strict definition (e.g. Schröder et al., 2007), a specific experimental setup is required. Such design should either include manure and mineral fertilizer doses at exactly the same total N rate, or several (stepped) mineral fertilizer N rates in parallel to a manure treatment, allowing for interpolation in between observed outcomes (notably, N offtake) from the stepped mineral N response series, in order to calculate the exact replacement value of the manure. Similarly, the assessment of apparent N recovery of manures (irrespective of an aim to determine replacement values), requires the presence of an unfertilized treatment, or better, one where all nutrients applied in the manure are also given in the fertilizer-only treatment, except nitrogen. All of these conditions are rarely found in LTEs. Nevertheless, LTEs do often include manured and mineral fertilizer treatments, and the attractiveness of such experiments lies in the longer time spans over which treatments can be compared.

Naturally then, because LTEs do not meet the above requirements, we have to resort to other indicators than the N replacement value. Moreover, we intend to clarify how these indicators are affected by factors like soil type, crop type, and climate. Besides aiming to explain variation across LTEs, our review differs from those cited above in its attempt to include all available European LTE literature, to examine impacts of amendments on both crop and soil indicators, and to summarize them with a quantitative method.

2. Materials and methods

2.1. Database

We analyzed prominent literature databases (Scopus®, Web of Science®, Google Scholar®) to find long-term experiments (LTEs) with the following characteristics:

- carried out in Europe;
- scientifically sound (included an experimental design and replicates);
- provided measurements that estimated effects on crops and soil in the long-term;
- included at least one treatment in which farmyard manure or slurry (bovine liquid manure) was applied, as well a reference treatment with mineral N fertilizer only.

Besides literature database searches, we collected papers directly from researchers, and included some technical papers, research reports, and PhD theses as well, when details of an LTE were not reported in mainstream scientific papers. The list of LTEs is reported in Table S1, the list of documents consulted is in Table S2, and a map is in Figure 1. While we aimed to collect data from experiments that lasted a decade or more, we did include a few shorter than 10 years duration, especially in instances of rarely-measured variables (soil microbial biomass) or to expand geographic coverage.

The 80 LTEs considered in this review ensure wide coverage of European climates, soils, and duration (range: three to more than 150 years), with half of the experiments started before 1979. Germany provided the largest number (22) of experiments, Eastern Europe contributed 23 experiments, while Southern Europe was represented by nine LTEs. Light texture soils characterized 53% of the LTEs considered; 38% were of medium texture and only 10% were fine. The eastern European climate was most represented (59% of LTEs), followed by the western (25%), southern (11%), and northern (5%) climates. Section 2.4 and Table 1 report the soil and climate definitions.

Overall, our data set included 5570 measurements. The indicator most available was crop yield, followed in decreasing order by the yield to fertilizer ratio, soil organic carbon content, N offtake in crop yield, N in yield to fertilizer ratio, soil total N, and apparent N recovery (Table S3).

2.2. Treatments

We focused on two manures, bovine farmyard manure (FYM) and bovine slurry (SLU). As several experiments included combinations of manure and mineral fertilizers as single treatments, we included such treatments (FYMm and SLUm) and analyzed them separately from FYM and SLU, where no mineral fertilizer was added. The median of years when the LTEs were initiated was 1979 (FYM and FYMm), 1997 (SLU), and 1995 (SLUm).

Some adjustments were required to handle data differences and special cases that we wished to include in the review. First, in most LTEs, manures were not applied each year; instead, they were applied only to summer crops in a rotation. In such cases, we calculated an average annual input by dividing the applied amount of manure by the number of years in the rotation cycle. Moreover, when N contents in FYM and SLU were lacking (24% of treatments), we used default values of 4.8 (FYM) and 4.0 (SLU) g N per kg fresh weight (Webb et al., 2013).

When available, we included a control without manure or mineral N fertilizer ("0N control"). N offtake in this 0N control was used in calculating apparent N recovery.

2.3. Data analyses

All crop indicators refer to a specific crop (see Section 2.4) and were stored as multi-year averages. We kept separate values for different moments of observation (e.g., after 10 and after 20 years from the start of LTE). Thus, for each LTE we had one value per crop per treatment per moment of observation. We could not use single-year measurements because they were not available for most LTEs. Yield was expressed as dry matter. If only a fresh matter yield was available in the original sourced literature, then dry matter yield was obtained from published dry matter content information (Martin et al., 2006). In a few cases, data from a full rotation were expressed as cereal units or forage units (net energy of a cereal or a forage), and therefore, were not absolute values. We did, however, include them in the dataset to calculate response ratios. Standard yield and biomass N contents were used to calculate N offtake values if not otherwise reported.

Crop indicators were yield (Y), N offtake in yield (NY), yield produced per each kg of N applied, expressed as Y/F (yield to fertilizer ratio), kg of N offtake per kg of total annual N applied, expressed as NY/F (N in yield to fertilizer ratio), and Apparent N Recovery (ANR) (Table 1).

Indicators NY/F and ANR describe fertilizer efficiency differently. ANR represents the fraction of added N that is taken up by the crop, and the 0N treatment serves to estimate the sum of soil N supply and N deposition. NY/F is a widely used indicator for N use efficiency (Zhang et al., 2015). It is, admittedly, a rough expression for N use efficiency because NY/F is larger than ANR as long as the unfertilized soil in the 0N treatment continues to supply N to the crop. In our database, however, there were only few data (16 LTEs) permitting the calculation of ANR, which requires observations on an unfertilized control (0N).

The soil indicators common to most LTEs were: soil organic carbon concentration (SOC), soil total N concentration (SoilN), microbial biomass (often expressed as microbial biomass C, sometimes as microbial biomass N, or as just biomass; MB), and all referred to the tilled layer. Other indicators were reported less often: microbiological indicators, pH, and soil physical indicators (Table S3). Because of their more frequent occurrence in the database, we preferred SOC and SoilN concentrations (g/kg) over SOC and SoilN stocks (g/m^2 or kg/ha). Where we found data expressed as SOC and SoilN stocks, these were converted back to concentrations using reported soil bulk density and sampling depth.

Both crop and soil indicators were standardized against values found in the reference treatment (mineral fertilizer only), and expressed as a Response Ratio (RR): the value in the manured treatment divided by that in the reference treatment. Therefore, an RR value of 1 implies that the manure performed equally well as the reference. For cases where RR indeed reaches a value of 1 or more, performance of the manure can be said to be at least equal to that of mineral fertilizer. There is one obvious caveat here if we wish to apply this approach to N use efficiency indicators: ideally, manures or manure-fertilizer combinations are compared versus their mineral-fertilizer-only reference at the same total N rate. However, N rates in LTEs are usually unequal between manured and reference treatment and thus such direct comparison was not possible. This is why we introduced the variable FR, to indicate by how much the total-N rate in manure (F_{man}) differed from the mineral fertilizer N rate used as reference (F_{min}): FR = F_{man}/F_{min}. We used it to define the subset of data where FR was between 0.8 and 1.2, and will refer to that subset as the “central FR class data”.

The RR was calculated for yield (RR_{Y}), N offtake in yield (RR_{NY}), yield/applied N ($RR_{Y/F}$), N offtake in yield/applied N ($RR_{NY/F}$), apparent N recovery (RR_{ANR}), SOC (RR_{SOC}), SoilN (RR_{SoilN}), MB (RR_{MB}). The indicator RR_{ANR} corresponds to the definition of Nitrogen Fertilizer Replacement Value (NFRV) according to Schröder et al. (2007).

2.4. Statistical analysis

As discussed earlier, each LTE treatment and moment of observation was described by a single RR value per indicator and per crop in our database. After compiling all data on the same treatment (e.g. FYM) across all LTEs, we used a one-sample t-test (two tails) to each of the RR variables, to assess whether its mean differed significantly from 1. To overcome the non-symmetrical distribution of RR means, we tested if natural log-transformed values were different from 0 ($p<0.05$).

We designed a Multiple Linear Regression model (MLR) to identify the conditions that affected most treatment performance. It included seven categorical factors, without interactions. Five of the factors were LTE descriptors: soil texture, crop, practice duration (years from adoption to measurement), climate, tillage depth; two factors indicated RR dependence on total N supplied (FR) and N source type (manure with/without additional mineral fertilizer).

Factor values were grouped for use in the MLR as explained below and in Table 1. Following the climate classification by Metzger et al. (2005), we grouped climate types into four macro-types: northern (BOR, NEM), western (ATN, ATC), eastern (ALS, CON, PAN), and southern (MDM, MDN, MDS). USDA soil texture classes were aggregated into three macro-classes: heavy (clay, silty clay, silty clay loam), medium (clay loam, loam, silty loam), and light (coarse sandy, loamy sand, sand, sandy clay loam, sandy loam, silty sand). Tillage depths, intended as incorporation depths, were grouped into five levels: 0 (no tillage), 0-10 cm, 11- 20 cm, 21 -30 cm, >30 cm. Practice duration was classified in four levels: 1- 5, 6-10, 11-20, > 20 years. Crop types comprised five broader categories, according to growth cycle duration: winter (winter wheat, winter barley, minor winter small grain cereals, rapeseed, winter grain legumes), spring (spring wheat, spring barley, minor spring small grain cereals, maize, potato, sunflower, sugarbeet, fodder beet, spring grain legumes), spring short (vegetables), long duration crops (grass/mixed ley, lucerne, double cropping systems), and combined crops (when the data referred to a rotation as a whole, without reference to a specific crop). Dependent variables were the RRs listed above, that were natural log-transformed to overcome the non-symmetrical distribution of original ratios.

We applied the MLR model to two subsets of the data: the pooled FYM+FYMm dataset denoted as “FYM/FYMm”, and the pooled SLU+SLUm dataset (“SLU/SLUm”). This allows quantifying the role of factors separately for farmyard manure and slurry, respectively.

We used a Type III Wald Chi-square statistic to test the effect of each factor. To separate individual factor means that were different at a $p<0.05$, we used a pairwise Bonferroni test. Plots of residuals versus fitted values revealed that the variance was generally homogeneous. The linear model was fitted using the GENLIN procedure of SPSS 22.0.

3. Results

Absolute values of crop and soil indicators showed a large variability across crop and soil types and climate classes (Figure S1 and paragraph S1). This is why responses were normalized as Response Ratios, ensuring that each manured treatment was compared with a reference treatment in the same soil, climate, crop, and fertilizer management conditions. This, however, does not resolve that manured treatments on average received higher total N rates than their reference mineral treatments (see FR in Table 2). While FR was fairly near to 1 in FYM, SLUm, and SLU (with total N rates only 7.2 to 9.8% higher in manured than in reference treatments), it deviated strongly from 1 in the FYMm treatment (+68.1%; Table 2). This is why our analyses are reported not only for the total dataset, but also for the "central class data" with 0.8< FR<1.2, where RR should be less prone to distortion by inequality of N rates (Table 2).

The multiple linear model clearly presumes that responses to factors are additive and does not include interactions. In general, for a given level of a given factor, marginal means are estimated (Table 3) by summing the intercept, the regression coefficient of the level, and the average regression coefficients of all the other factors. Marginal means indicate the mean response for each factor level, adjusted for the mean contribution of the other model variables; they are numerically different from sample means (reported in Table 2), especially in unbalanced designs. We discuss sample means, and we use the model to assess significance of factors and factor levels. The regression coefficients estimated by the MLR are reported in Table S4.

The MLR obviously explains only part of the variance; see Table 3 for R^2 values. In general, the fraction of variance explained was large for N in yield (RR_{NY}), small for yield and Y/F, and intermediate for efficiency and soil indicators.

3.1. Farmyard manure (FYM and FYMm)

3.1.1. Crop

For FYM (not supplemented with mineral fertilizer), all crop-based indicators (Y, NY, Y/F, NY/F, and ANR) showed RRs significantly below 1. For FYMm, RR_Y exceeded 1, both in the total data set and in the central class (Table 2).

The MLR model (Table 3a) showed that all factors except duration (so: climate, crop type, soil type, tillage depth, N fertilizer ratio, and supplement with mineral fertilizer) significantly affected RR_Y ($P<0.05$). RR_Y was higher in Southern and Eastern Europe than in Western Europe, and greater in long duration crops than in winter and combined crops. Furthermore, RR_Y was greater on light-textured soils than on medium-textured soils, and greater with shallow (11-20 cm) than with deeper tillage (21-30 cm). Manured treatment yields exceeded the reference yields if N applied in FYM/FYMm exceeded the reference N rate by 20% or more (FR > 1.2), likely a direct effect of a higher N rate. Finally, supplementing FYM with mineral N (FYMm) increased RR_Y significantly (Table 3a).

Nitrogen offtake in the yield was reported for fewer cases than was yield; where available, RR_{NY} corresponded well with RR_Y (Table 2). Influencing factors (Table 3a) were crop type, duration, N fertilizer ratio, and supplement with mineral N.

The $RR_{Y/F}$ was significantly different from 1 (Table 2) for FYM, while it was significantly lower than 1 for FYMm, possibly due to the high N inputs in this treatment. It was influenced by incorporation depth and FR (Table 3a).

The N offtake/fertilizer ratio ($RR_{NY/F}$) and the apparent N recovery ratio (RR_{ANR}) were both significantly lower than 1, for FYM as well as FYMm (Table 2). With values of 0.716 (FYM) and 0.722 (FYMm) in the central class, we consider the RR_{ANR} values relatively high. Factors affecting $RR_{NY/F}$ were soil texture (light > medium), climate type (Southern > Eastern), and crop type (winter > spring short). No significant effects by the respective factors were identified for RR_{ANR}, where only few data were available.

3.1.2. Soil

All soil indicators (SOC, SoilN, MB) were significantly higher in FYM and FYMm treatments than with mineral fertilizer only, as expressed in RR_{SOC} and RR_{SoilN} (Table 2). SOC was higher by 32.4% and 33.4%, and SoilN by 20.6% and +22.4%, for FYM and FYMm, respectively. SOC was significantly affected by climate type (Eastern = Southern > Western), soil type (light > medium = heavy), duration (6-10 years > other classes), and FR (the class >1.2 had higher RR_{SOC} than the others) (Table 3a). For SoilN, tillage depth was the only significant factor, with higher RR_{SoilN} for deeper tillage (21-30 cm), likely due to lower mineralization rates.

Microbial biomass increased significantly with FYM (30.1%) and FYMm (21.1%), as indicated by RR_{MB}. These increases matched those measured for SOC, and were so pronounced that even the first quartile of the RR_{MB} distribution was greater than 1.0. It was influenced by climate type (Southern = Western > Eastern), FR (class ">1.2" = class

"0.8-1.2" > class "<0.8"), and of mineral N supplements (no supplement > with supplement).

The few measurements available for soil physical properties (data not presented in figures or tables) indicated no significant differences between manured and reference treatments. We found only non-significant changes in aggregate stability (*n*=4 measurements) and in soil bulk density (*n*=4), both for FYM. While we registered a significant increase in FYMm of actinomycetes (+16.7%, *n*=5, p = 0.020) and earthworms (+155.5%, *n*=4, p = 0.024), we found a non-significant increase in fungi (*n*=6) .

3.2. Slurry

3.2.1. Crop

As with FYM, we found also for SLU that all crop-based indicators (Y, NY, Y/F, NY/F, ANR) were significantly lower than for the reference (mineral fertilizer) treatment (Table 2). As expected, the fertilizer supplement in SLUm makes the mixed amendment more similar to mineral fertilizer, which is reflected in higher RR values for all these indicators as compared to SLU; RR values for SLUm were not different from 1.

Despite the fairly narrow range in RR_Y, the MLR (Table 3b) again identified influencing factors, and they are similar to those found for FYM/FYMm. Patterns shared with FYM/FYMm are that RR_Y was larger in Southern than in other climates, larger in spring crops than in winter crops, larger in light-textured than other soils. Deep incorporation (>30 cm) resulted in significantly lower RR_Y, an effect not documented for FYM/FYMm for lack of data. While the effect of experiment duration was not significant for FYM/FYMm, it seems erratic in the SLU/SLUm dataset, although the set is admittedly unbalanced with only few data for the short duration. In any case, the RR_Y value for long duration (> 20 years) based on 60 records is very close to 1. Final observations are that high FR (>1.2) had significant positive effect on yield and that, as with farmyard manure, fertilizer supplements in SLUm resulted in increased RR_Y (Table 3b).

$RR_{Y/F}$ was affected by climate, texture, and by mineral N supplements (Table 3b). As with yield, a southern climate, light soil texture and shallow incorporation (11-20cm) rendered SLU/SLUm an efficient N source as reflected by high $RR_{Y/F}$. In contrast, deep incorporation of the slurry, and a high FR value (>1.2) had negative impacts on Y/F, the latter possibly due to excess N. At a value of 0.444, mean RR_{ANR} was significantly below 1 for SLU, but not for SLUm (0.565; Table 2).

3.2.2. Soil

Similar to FYM, slurry increased all three soil indicators significantly relative to the use of mineral fertilizer (Table 2). The high mean RR values for each of these indicators in SLU treatments are matched by exactly the same means for SLUm. Based on an average of SLU and SLUm (Table 2), SOC and SoilN increased by 17.4% and 15.7%, respectively, relative to the mineral fertilizer reference. Very similar values were obtained for the central class of FR. RR_{SOC} and RR_{SoilN} were significantly affected by climate type (Table 3b), but in both cases the contrast relies on a single data pair (n=1) and should therefore be ignored. Significant factors for RR_{SoilN} included crop type (combined crops > spring crops) and FR (but cases are again too few here). Model outcomes (Table 3b) also show that both SOC and SoilN increments from SLU/SLUm were independent of the share of mineral N (which is larger in SLUm). This means that slurry can help build SOC and SoilN pools irrespective of its large fraction of mineral N.

Microbial biomass increased significantly (+20.3%) in both SLU and SLUm (Table 2) relative to the reference. These increases were of about the same size as those for SOC. No significant factors were detected for RR_{MB}.

The few measurements available for soil physical properties (data not presented in figures or tables) did not show important effects in the SLU treatment relative to the reference. We found only a non-significant increase in aggregate stability (*n*=2) and a reduction in soil bulk density (*n*=3). Biological indicators (data not shown) revealed a significant increase of actinomycetes (+16.6%, *n*=5, p = 0.001) for SLU. Non-significant effects (*n*=5) were also found for earthworms (number or biomass) in SLU.

4. Discussion

4.1. Farmyard manure

Crop yields obtained using FYM were 9.5% smaller than yields obtained using mineral fertilizers applied at similar N rate. Significant factors affecting crop yield in FYM treatment were conditions that can promote manure N mineralization and crop N uptake - lighter soil texture, warmer temperature, longer mineralization season, and shallower incorporation depth. Using laboratory incubations of uncropped soils amended with FYM, some authors have found that the effect of soil texture on FYM N mineralization was not significant (Sørensen and Jensen, 1995; Thomsen and Olesen, 2000; Thomsen et al., 2003). On the contrary, Sørensen et al. (1994), in a cropped lysimeter experiment with sheep manure, found that soils with a higher clay content (16% vs. 4%) tended to decrease barley uptake of applied manure N due to immobilization, while gross N mineralization was not influenced by texture. Therefore, soil texture might have influenced crop N uptake to a larger extent than N mineralization in the absence of a crop.

We expected the yield reduction to decrease with duration of practice, due to the increasing contribution, in the medium and long term, of the mineralization of recalcitrant manure organic components to crop nutrition. Indeed, with repeated manure applications the annual mineralization increases compared to single applications (Dilz et al., 1990; Whalen et al., 2001; Muñoz et al., 2003; Cusick et al., 2006). Contrary to our expectation, duration was not identified as a significant factor influencing yield (Table 3a), probably because most of the dataset experiments lasted more than 11 years, a moment after which N release from previous manure applications has almost stabilized at a constant value

(Cusick et al., 2006; Schröder et al., 2013). Another possible explanation is that duration of FYM application could influence crop productivity to an extent that is too variable with experimental conditions to emerge as statistically significant. When all N was supplied using FYM, crop productivity was decreased, while when some supplied N came from mineral fertilizers, as in the FYMm treatment, it was instead increased to a larger extent than when all N was given as mineral, as evidenced by $RR_Y = 1.113$ (Table 2). Our results for FYM/FYMm are in line with Edmeades (2003), who analyzed various experiments in which FYM or FYMm was used and who reported an average RR_Y of 0.95. The increased yield response to manure + mineral fertilizer compared to mineral fertilizer only is frequently observed in field experiments (e.g. Kong et al., 2007; Pan et al., 2009; Shah et al., 2009; Liang et al., 2013; Pincus et al., 2016) and the reason could be due to other positive effects of manure other than N supply, such as other nutrients, soil organic matter increase, improvement of soil physical and chemical properties, stimulation of soil microorganism activities, and minor losses (Singh et al., 2001; Sanz-Cobena et al., 2017). In fact, Abbasi and Khaliq (2016) in an incubation study observed that mineral N release from fertilizer was slowed down in the presence of organic sources because soil microbes immobilized mineral N to decompose the organic compounds, and this resulted in a longer persistence and retention of N in the soil mineral pool.

The production efficiency of FYM was similar to that of mineral fertilizers, as testified by a $RR_{Y/F}$ which was not significantly different from 1 (Table 2). We hypothesized that the markedly higher standard deviation of $RR_{Y/F}$ *versus* RR_Y was due to Y/F decrease as the fertilizer rate increased, compared to crop yield that did not respond strongly to fertilizer rates at the tested levels. The MLR confirmed this hypothesis by identifying N fertilizer ratio (FR) as one of the most influential factors to explain $RR_{Y/F}$ variability (Table 3a). Whether mineral fertilizer was added or not did not significantly affect the $RR_{Y/F}$ (Table 3a), but the reason for this remains unclear.

For FYM, nitrogen in yield was reduced by 10.9% in a comparison to the reference treatment (RR_{NY} in Table 2), while N in soil (+20.6%) showed a greater positive response. Crop type, duration, N fertilizer rate, and addition of mineral N influenced N in yield (Table 3). The winter crops category stood out as significantly different from the spring short category, a result likely related to its longer growth period that benefits from prolonged mineralization. Integration of FYM with mineral N had a significant positive effect on N offtake. This effect is distinct from the effect of FR as the statistical procedure deals with the two factors separately.

The crop uptake efficiency of manure N was significantly lower than that of mineral N in the reference treatment, as indicated by $RR_{NY/F}$ and RR_{ANR} (Table 2). The difference between NY/F and ANR lies in the fact that NY/F does not take into account the unfertilized control, while ANR does. The crop N offtake in the unfertilized control (Figure S1b) was high due to high N availability derived from soil mineralization and to a lesser extent from atmospheric deposition (Tipping et al., 2012). High soil N mineralization is consistent with factors that increase NY/F and ANR of FYM: southern climate and light soil texture (Table 3a). In addition, the same conditions are associated with higher microbial biomass in FYM/FYMm than in the reference treatment (Table 3a). As for yield, we expected that experiment duration would affect ANR, which normally increases over time because of residual effects. However, in this case also we found a lack of significance for duration on ANR (Table 3a), probably for the same reason as that outlined for yield – stabilization of manure effects after the first 10 years (Schröder et al., 2013). Following repeated FYM applications to soil, indeed, recalcitrant compounds not mineralized in the short term are gradually and slowly decomposed in the long term (Muñoz et al., 2003). This gives rise to an increase of N mineralization and thus of crop N availability over time (Indraratne et al., 2009). Gutser et al. (2005) reported mineral fertilizer equivalents (same as RR_{ANR}) of 10-20% for solid manure in the first year of application, and of 40-50% for the longer term, which is roughly consistent with our value of 59.3% for FYM, that includes short and long term effects. Webb et al. (2013) indicated that the sum of N availability in the short term (application year) and long term (residual effects between one and 10 years) averages 50-80% for all manure types (solid and liquid). All these findings are in contrast with officially recommended N fertilizer replacement values of 30% to 60% (first-year and residual effects combined) (Webb et al., 2013; Schröder et al., 2013).

A SOC increase in the manured treatment, as opposed to the reference treatment (Table 2), was expected because C was applied in the manured treatments, but not in the reference treatment with mineral fertilizers. Even if part of manure C is decomposed by soil microorganisms, part of it remains in the soil and thus contributes to long-term C storage. For SoilN we have a different situation, because similar amounts of this element are supplied in both manured and reference treatments. The increase of SoilN in manured treatments compared to reference (Table 2) is thus due to the fact that part of supplied N is recalcitrant to decomposition. Indeed, the fraction of applied manure N not utilized by the crop was greater in FYM and in FYMm than in the reference treatment, as shown by RR_{NY} <1 (at equal N supplied; Table 2). Evidence from the literature confirms that manure C and N can partially remain in the soil after the year of application. Edmeades (2003) analyzed experiments in which FYM was used; for nine experiments, the RR_{SOC} averaged 1.48 and RR_{SoilN} for seven experiments averaged 1.51. Manure incubation studies, too, indicate that a fraction of applied manure C is not easily mineralized. For example, Thomsen and Olesen (2000) indicated that (on average for six farmyard manures) only 14% of manure C was in pools having relatively high relative mineralization rates of 0.0693 to 0.00693 d^{-1} (these values indicate that manure C was totally or almost totally mineralized in one year), while the rest had slower turnover rates. This is probably due to the presence in the manure of lignified compounds originating both from the bedding material (generally winter cereal straw) and from recalcitrant compounds in the feed (van Kessel et al., 2000), which are still undecomposed after the passage of the forage in the digestive tract and the storage of feces and urine to produce FYM.

4.2. Slurry

Crop productivity is slightly reduced (Table 2; RR_Y) when N is provided with cattle slurry compared to when it is provided with mineral fertilizer. We hypothesize that the reduction of crop yield with cattle slurry compared to mineral fertilizer is due to a more prompt effect of the latter; our hypothesis is at least partly confirmed by the yield obtained when slurry is supplied without extra mineral fertilization, similarly to what was observed in FYM/FYMm. Spring crops performed better than other types of crops, probably because of more favourable conditions for mineralization that led to a better synchrony of N release and crop N uptake. The dry mass produced per unit of applied slurry-N equaled the dry mass produced per unit of applied mineral N (Table 2; $RR_{Y/F}$). Similarly to what was observed for FYM/FYMm, for SLU/SLUm the conditions enhancing crop yield (RR_Y) and the production of dry mass per unit of applied N ($RR_{Y/F}$) are: southern climate, light soil texture, and shallow incorporation depth – a set of conditions where N mineralization is faster (Table 3b). We interpret these findings to mean that favorable conditions cause faster mineral N release and higher crop N uptake that result in higher crop yields (Table 3b).

The effect of SLU on N offtake was less evident than that on crop yield. When slurry is integrated with mineral N, yield and N offtake reach levels obtained using mineral fertilizers alone at the same total N applied (Table 2). The few data on apparent N recovery were characterized by high standard deviations that may derive from the high inter-annual variability that characterizes N use efficiency (e.g., Cavalli et al., 2016a, Zavattaro et al., 2016). The dataset contained just 22 data points from three LTEs (Tetto Frati, El Encín, and Foulum) with a high standard deviation; as such, no significant effects were identified for RR_{ANR}, with the exception of the addition of mineral N (Table 3b).

Laboratory experiments confirm (Cavalli et al., 2014 and 2016b) and help to explain the increase of SOC and SoilN after the application of slurry. Firstly, incubation experiments show that part of the slurry ammonium-N is quickly immobilized by microbial biomass that decomposes slurry organic matter, in particular compounds – like volatile fatty acids, VFAs – with high C/N ratio (Sørensen, 1998). Part of this N remains immobilized for several years (Sørensen, 2004) and explains the SOC and SoilN increase that we have registered in the LTEs. Secondly, slurries contain organic compounds that are chemically recalcitrant to microbial decomposition (van Kessel et al., 2000) and that remain in the soil longer than the N applied with mineral fertilizers ($RR_{SoilN} > 1$) (Spiegel et al., 2010). Thirdly, the rapid fixation of slurry ammonium in non-exchangeable form by clay minerals may also contribute to soil N retention (Nieder et al., 2011), because normally the release of fixed ammonium is slow (Cavalli et al., 2015). The fact that C and N increased quite similarly in the LTEs might indicate that the first two mechanisms (microbial immobilization and chemical recalcitrance) were more important than the third one (ammonium fixation by clay minerals).

Even if our statistical approach does not allow a rigorous comparison between farmyard manure and slurry, we observed that farmyard manure had a stronger positive effect, both on the crop (yield and N offtake) and on the soil (soil total N and soil organic C) compared to slurry. Caution should be used when commenting on the effects on soil C. Indeed, as shown by Thomsen and Olesen (2000), if the comparison of farmyard manure and slurry is carried out at equal C application rates, it is obvious that more C will be stored in the soil with farmyard manure, due to its more recalcitrant nature (more C is stored in the soil per unit of farmyard manure-C applied than for slurry-C applied). However, if the comparison is made at equal C excreted from livestock, then farmyard manure and slurry are far more similar, because similar amounts of C are stored in the soil per unit C emitted from the livestock, as either farmyard manure or slurry.

In conclusion, the potential of farmyard manure and slurry to substitute mineral fertilizers is high. Given a manure-N production of 5,729,308 t (Eurostat, data referred to year

2013), and an average N fertilizer replacement value of the four treatments (referred to the central class of FR) of 0.754, European livestock produces in the manure 4,317,033 t of fertilizer-equivalent N annually, capable of supplying 170 kg of N ha^{-1} to more than 25,000,000 ha. This illustration shows the importance of properly accounting for the manure fertilizer value; if this is underestimated, it could result in calculation of an excessive need for mineral N integration to crops, with consequent increases in farmer costs, environmental pollution risks, and GHG emissions.

4.3. Issues and recommendations

This study exposed that even though the number of experiments in Europe on bovine farmyard manure and cattle slurry is rather high, long-term data on manures different from bovine excreta are very limited and insufficient to support comprehensive statistical analysis. In fact, European geographic, pedological, and climatic coverage of non-bovine manures was incomplete, which made it impossible to derive useful information about the conditions that make a particular practice perform best in terms of manure use efficiency. Similarly, the experiments surveyed in this study also reported few measurements of soil properties beyond SOC and SoilN. Soil chemistry variables, such as pH, soil physical properties, soil biological properties, and greenhouse gas emissions were lacking and should receive more attention in future research.

Not all available experiments provided data that were easily usable. Several decades-long experiments did not permit direct comparison of manured and mineral fertilizer treatments. Moreover, supplied amounts of organic amendments in some experiments were based on a fixed total fresh mass, whereas N and P contents may have varied by year. This data should have been reported in publications.

LTEs are expensive to manage and provide information that becomes relevant only when combined with that derived from other LTEs. Difficult as it is to start and maintain new long-term trials, it remains important to preserve those that are ongoing at the very least. In addition to compile meta-analyses and reviews, it is important to establish networks of existing LTEs to coordinate research projects, study processes, and to provide a forum for researchers to exchange and share measurement protocols. Some attempts have been made in this direction (e.g., IC-FAR, ExpeER, AnaEE, ESFRI, ICOS), but others should be promoted as proposed by Stützel et al. (2016).

5. Conclusions

The positive long-term effects of bovine farmyard manure and bovine slurry were strong, both on crop and soil. Indeed, when we compared manures to mineral fertilizers, their capacity to sustain crop yield and N uptake was very similar (yield reduction of 9%). A clear pedo-climatic effect also emerged; light-textured soils and warm climates performed better than medium-textured soils and cool climates provided the most favourable conditions for crop performance and soil organic C increase. Among crop types, the best results were obtained by long-duration crops with farmyard manure, and by spring crops with slurry. Integration of farmyard manure and slurry with mineral N fertilizers resulted in significantly higher crop yield and N offtake than without integration; differences with pure mineral fertilization did not exceed 4%. Conversely, soil C and N increased at least 14% when manures were used in combination with mineral N fertilizers, similar to what was obtained using manures only. These findings are important because the integration of manure with mineral N is a practice frequently adopted by farmers. In conclusion, this review has highlighted that the potential of farmyard manure and slurry to substitute mineral fertilizers is high.

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References

Abalos, D., Sanz-Cobena, A., García-Torres, L., van Groenigen, J.W., Vallejo, A., 2013. Role of maize stover incorporation on nitrogen oxide emissions in a non-irrigated Mediterranean barley field. Plant and Soil 364, 357–371.

Abaye, D.A., Lawlor, K., Hirsch, P.R., Brookes, P.C., 2005. Changes in the microbial community of an arable soil caused by long-term metal contamination. European Journal of Soil Science 56, 93–102.

Abbasi M.K. and Khaliq A., 2016. Nitrogen mineralization of a loam soil supplemented with organic–inorganic amendments under laboratory incubation. Front Plant Sci. 7: 1038.

Ailincăi, D., Ailincăi, C., 2012. The Evolution of Soil Fertility Under Longterm Experiments in The Moldavian Plateau. Cercetari agronomice in Moldova 45, 41–52.

Albert, E., Grunert, M., 2013. Wirkung einer langjährig differenzierten mineralisch-organischen Düngung auf Ertrag, Humusgehalt, N-Bilanz und Nährstoffgehalte des Bodens. Archives of Agronomy and Soil Science 59, 1073–1098.

Barkusky, D.; Baumecker, M.; Chmielewski, F.-M.; Ellmer, F.; Gagern, W. von; Hierold, W.; Käding, H.; Köhn, W.; Rühlmann, J.; Zimmer, J., 2009. Dauerfeldversuche in Brandenburg und Berlin. Beiträge für eine nachhaltige landwirtschaftliche Bodennutzung. MLUV Brandenburg und LVLF (Eds.), Schriftenreihe des Landesamtes für Verbraucherschutz, Landwirtschaft und Flurneuordnung, Abteilung Landwirtschaft und Gartenbau. Reihe Landwirtschaft, 10 , IV, 216 pages. http://www.mil.brandenburg.de/sixcms/media.php/4055/Dauerfeldversuche%20f%C3%BCr%20nachhaltige%20Landwirtschafte%20Bodennutzung.pdf (last verified 22/02/2016).

Berner, A., Hildermann, I., Fließbach, A., Pfiffner, L., Niggli, U., Mäder, P., 2008. Crop yield and soil fertility response to reduced tillage under organic management. Soil and Tillage Research 101, 89–96.

Berti, A., Dalla Marta, A., Mazzoncini, M. Tei, F., 2016. An overview on long-term agro-ecosystem experiments: Present situation and future potential. European Journal of Agronomy 77, 236-241. doi:10.1016/j.eja.2016.01.004

Biau, A., Santiveri, F., Lloveras, J., 2013. Stover Management and Nitrogen Fertilization Effects on Corn Production. Agron. J. 105, 1264–1270.

Birkhofer, K. et al., 2008. Long-term farming fosters below and aboveground biota: Implications for soil quality, biological control and productivity. Soil Biology and Biochemistry 40, 2297–2308.

Bischoff, R., Emmerling, R., 2001. Einfluss Kombinierter organischer und mineralischer Düngung auf den Ertrag und Rohproteingehalt von Winterweizen und Wintergerste sowie die Rübenqualität im IOSDV Speyer. Archives of Agronomy and Soil Science 47, 445–457.

Blair, N., Faulkner, R.D., Till, A.R., Poulton, P.R., 2006. Long-term management impacts on soil C, N and physical fertility. Soil and Tillage Research 91, 30–38.

Blecharczyk, A., Piechota, T., Malecka, I., 2005. Changes of effect chemical soil properties under long-term cropping systems and fertilization. Fragmenta Agronomica XXII Nr 2, 30–38.

Borda, T., Celi, L., Zavattaro, L., Sacco, D., Barberis, E., 2011. Effect of Agronomic Management on Risk of Suspended Solids and Phosphorus Losses from Soil to Waters. Journal of Soils and Sediments 11, 440–451.

Borjesson, G., Menichetti, L., Kirchmann, H., Katterer, T., 2012. Soil microbial community structure affected by 53 years of nitrogen fertilisation and different organic amendments. Biol. Fertil. Soils 48, 245–257.

Borrelli, L., Tomasoni, C., 2010. Effetti di Reflui Zootecnici su Sostanza Organica, pH, Densità Apparente e Infiltrazione dell'Acqua nel Suolo, in: Atti Convegno Società Italiana Di Agronomia 2010. Presented at the Convegno Società Italiana di Agronomia 2010, Società Italiana di Agronomia, Roma, Italy.

Borrelli, L., Tomasoni, C., Degano, L., 2011. Impiego di Reflui Zootecnici Bovini su Erba Medica, in: Convegno Società Italiana Di Agronomia. Presented at the Convegno Società Italiana di Agronomia, Società Italiana di Agronomia, Teramo (Italy), pp. 254–255.

Carter, M.S., Hauggaard-Nielsen, H., Heiske, S., Jensen, M., Thomsen, S.T., Schmidt, J.E., Johansen, A., Ambus, P., 2012. Consequences of field N2O emissions for the environmental sustainability of plant-based biofuels produced within an organic farming system. Global Change Biology Bioenergy 4, 435–452.

Cavalli, D., Bechini, L., Marino, P., 2014. Measuring and modeling soil carbon respiration following repeated dairy slurry application. Soil Science Society of America Journal 78, 1414–1425. doi:10.2136/sssaj2013.08.0343

Cavalli, D., Cabassi, G., Borrelli, L., Geromel, G., Bechini, L., Degano, L., Marino Gallina, P., 2016a. Nitrogen fertilizer replacement value of undigested liquid cattle manure and digestates. European Journal of Agronomy 73, 34–41.

Cavalli, D., Consolati, G., Marino, P., Bechini, L., 2015. Measurement and simulation of soluble, exchangeable, and non-exchangeable ammonium in three soils. Geoderma 259–260, 116–125. doi:10.1016/j.geoderma.2015.05.011

Cavalli, D., Marino Gallina, P., Sacco, D., Bechini, L., 2016b. Soil mineral nitrogen dynamics following repeated application of dairy slurry. European Journal of Soil Science 67, 804–815. doi:10.1111/ejss.12391

Ceotto, E., Borrelli, L., Tomasoni, C., 2010. Farmyard manure versus slurry: is it worthwhile to remove crop residues from the field to increase soil carbon stock elsewhere?, in: Proceedings of the 14th Ramiran International Conference, of the FAO ESCORENA Network on the Recycling of Agricultural, Municipal and Industrial Residues in Agriculture. Presented at the Treatment and use of organic residues in agriculture: challenges and opportunities towards sustainable management, Cláudia S.C. Marques dos Santos Cordovil, Luís Ferreira, Lisbon, Portugal.

Chirinda, N., Carter, M.S., Albert, K.R., Ambus, P., Olesen, J.E., Porter, J.R., Petersen, S.O., 2010. Emissions of nitrous oxide from arable organic and conventional cropping systems on two soil types. Agriculture, Ecosystems and Environment 136, 199–208.

Chirinda, N., Olesen, J.E., Porter, J.R., Schjonning, P., 2010. Soil properties, crop production and greenhouse gas emissions from organic and inorganic fertilizer-based arable cropping systems. Agric. Ecosyst. Environ. 139, 584–594.

Clark, I.M., Buchkina, N., Jhurreea, D., Goulding, K.W.T., Hirsch, P.R., 2012. Impacts of nitrogen application rates on the activity and diversity of denitrifying bacteria in the Broadbalk Wheat Experiment. Philosophical Transactions of the Royal Society B: Biological Sciences 367, 1235–1244.

Cvetkov, M., Santavec, I., Kocjan Acko, D., Tajnšek, A., 2010 Soil organic matter content according to different management system within long-term experiment. Acta agriculturae Slovenica 95(1), 79–88.

Cvetkov, M., Tajnšek, A., 2009. Soil organic matter changes according to the application of organic and mineral fertilizers within long-term experiments. Acta agriculturae Slovenica 93(3), 311–320.

Cusick, P.R., Kelling, K.A., Powell, J.M., Muñoz, G.R., 2006. Estimates of residual dairy manure nitrogen availability using various techniques. Journal of Environment Quality 35, 2170–2177. doi:10.2134/jeq2005.0287

D'Hose, T., Cougnon, M., De Vliegher, A., Willekens, K., Van Bockstaele, E., Reheul, D., 2012. Farm Compost Application: Effects on Crop Performance. Compost Science & Utilization 20, 49–56.

Dambreville, C., Morvan, T., Germon, J.-C., 2008. N2O emission in maize-crops fertilized with pig slurry, matured pig manure or ammonium nitrate in Brittany. Agriculture, Ecosystems and Environment 123, 201–210.

Diacono, M., Montemurro, F., 2010. Long-term effects of organic amendments on soil fertility. A review. Agronomy for Sustainable Development 30, 401–422. doi:10.1051/agro/2009040

Dilz, K., Postmus, J., Prins, W.H., 1990. Residual effect of long-term applications of farmyard manure to silage maize. Fertilizer Research 26, 249–252. doi:10.1007/BF01048763

Edmeades, D.C., 2003. The long-term effects of manures and fertilisers on soil productivity and quality: a review. Nutrient Cycling in Agroecosystems 66, 165–180.

Elfstrand, S., Hedlund, K., Martensson, A., 2007. Soil enzyme activities, microbial community composition and function after 47 years of continuous green manuring. Appl. Soil Ecol. 35, 610–621.

Ellmer, F., Baumecker, M., 2005. Der statische Nährstoffmangelversuch Thyrow. Ergebnisse nach 65 Versuchsjahren (Static nutrient depletion experiment Thyrow. Results after 65 experimental years). Archives of Agronomy and Soil Science 51, 151–161.

Ellmer, F., Peschke, H., Köhn, W., Chmielewski, F.-M., Baumecker, M., 2000. Tillage and fertilizing effects on sandy soils. Review and selected results of long-term experiments at Humboldt-University Berlin. Journal of Plant Nutrition and Soil Science 163, 267–272.

Esperschütz, J., Gattinger, A., Mäder, P., Schloter, M., Fliessbach, A., 2007. Response of soil microbial biomass and community structures to conventional and organic farming systems under identical crop rotations. FEMS Microbiology Ecology 61, 26–37.

García-Gil, J., Plaza, C., Soler-Rovira, P., Polo, A., 2000. Long-term effects of municipal solid waste compost application on soil enzyme activities and microbial biomass. Soil Biology and Biochemistry 32, 1907–1913.

Giardini, L., Borin, M., Berti, A., 1999. Effetti del letame e del liquame bovino in avvicendamenti colturali a diverso livello di concimazione. Rivista di Agronomia 33, 118–129.

Giardini, L., Borin, M., Berti, A., Giupponi, C., 1995. Confronto tra avvicendamenti colturali con diversi tipi di concimazione minerale ed organica. Rivista di Agronomia 29, 403–408.

Grizzetti, B., Bouraoui, F., Billen, G., van Grinsven, H., Cardoso, A.C., Thieu, V., Garnier, J., Curtis, C., Howarth, R., Johnes, P., 2011. Nitrogen as a threat to European water quality. In: Sutton, M.A., Howard, C.M., Erisman, J.W., Billen, G., Bleeker, A., Grennfelt, P., van Grinsven, H., Grizzetti, B. (Eds.), The European Nitrogen Assessment, Cambridge University Press, UK, pp. 379–404.

Gutser, R., Ebertseder, T., Weber, A., Schraml, M., Schmidhalter, U., 2005. Short-term and residual availability of nitrogen after long-term application of organic fertilizers on arable land. Journal of Plant Nutrition and Soil Science 168, 439–446.

Haddaway, N.R., Hedlund, K., Jackson, L.E., Kätterer, T., Lugato, E., Thomsen, I.K., Jørgensen, H.B., Söderström, B., 2015. What are the effects of agricultural management on soil organic carbon in boreo - temperate systems? Environ Evid 4:23 . DOI 10.1186/s13750-015-0049-0.

Haneklaus S., Schick J., Kratz S., Rückamp D., Schnug E., 2016. Variable rate application of manure-Gain or pain? Landbauforschung Volkenrode, 66 (1): 11-19.

Hege, U., Offenberger, K., 2006. Effect of differentiated mineral fertilization and organic manuring on yield, product quality and N balances in the international permanent organic nitrogen experiment (IOSDV) Puch. Archives of Agronomy and Soil Science 52, 535–550.

Heitkamp, F., Raupp, J., Ludwig, B., 2009. Impact of fertilizer type and rate on carbon and nitrogen pools in a sandy Cambisol. Plant and Soil 319, 259–275.

Heitkamp, F., Raupp, J., Ludwig, B., 2011. Soil organic matter pools and crop yields as affected by the rate of farmyard manure and use of biodynamic preparations in a sandy soil. Org. Agr. 1, 111–124.

Hoffmann, S., Csitári, G., Hegedüs, L., 2002. The Humus Content and Soil Biological Properties as a Function of Organic and Mineral Fertilization. Archives of Agronomy and Soil Science 48, 141–146.

Houot, S., Chaussod, R., 1995. Impact of agricultural practices on the size and activity of the microbial biomass in a long-term field experiment. Biology and Fertility of Soils 19, 309–316.

Indraratne, S.P., Hao, X., Chang, C., Godlinski, F., 2009. Rate of soil recovery following termination of long-term cattle manure applications. Geoderma 150, 415–423. doi:10.1016/j.geoderma.2009.03.002

Jäger, N., Stange, C.F., Ludwig, B., Flessa, H., 2011. Emission rates of N2O and CO2 from soils with different organic matter content from three long-term fertilization experiments - a laboratory study. Biol Fertil Soils 47, 483–494.

Janowiak J. 1995. Wpływ nawożenia obornikiem z dodatkiem słomy i zróżnicowanych dawek azotu na właściwości materii organicznej. (The influence of fertilization with manure plus straw and different nitrogen doses on the properties of organic matter). Zeszyty Problemowe Postępów Nauk Rolniczych 421a, 145-150.

Johnston, A.E., Poulton, P.R., Coleman, K., 2009. Chapter 1 Soil Organic Matter, in: Advances in Agronomy. Elsevier, pp. 1–57.

Jones, S.K., Rees, R.M., Kosmas, D., Ball, B.C., Skiba, U.M., 2006. Carbon sequestration in a temperate grassland; management and climatic controls. Soil Use and Management 22, 132–142.

Jones, S.K., Rees, R.M., Skiba, U.M., Ball, B.C., 2005. Greenhouse gas emissions from a managed grassland. Global and planetary change 47, 201–211.

Kautz, T., Wirth, S., Ellmer, F., 2004. Microbial activity in a sandy arable soil is governed by the fertilization regime. Eur. J. Soil Biol. 40, 87–94.

Kismányoky, T., Tóth, Z., 2010. Effect of mineral and organic fertilization on soil fertility as well as on the biomass production and N utilization of winter wheat (Triticum aestivum L.) in a long-term cereal crop rotation experiment (IOSDV). Archives of Agronomy and Soil Science 56, 473–479.

Kismányoky, T., Tóth, Z., 2013. Effect of mineral and organic fertilization on soil organic carbon content as well as on grain production of cereals in the IOSDV (ILTE) long-term field experiment, Keszthely, Hungary. Archives of Agronomy and Soil Science 59, 1121–1131.

Kondratowicz-Maciejewska K., 2007 Susceptibility of organic matter to oxidation and soil microbiological activity under conditions of varied crop rotation systems and fertilization. Polish Journal of soil science 15(1), 89 98.

Kong, A.Y.Y., Fonte, S.J., Van Kessel, C., Six, J., 2007. Soil aggregates control N cycling efficiency in long-term conventional and alternative cropping systems. Nutr. Cycl. in Agroecosys. 79 (1), 45-58.

Korsaeth, A., Eltun, R., 2000. Nitrogen mass balances in conventional, integrated and ecological cropping systems and the relationship between balance calculations and nitrogen runoff in an 8-year field experiment in Norway. Agriculture, Ecosystems & Environment 79, 199–214.

Körschens, M., Albert, E., Armbruster, M., Barkusky, D., Baumecker, M., Behle-Schalk, L., Bischoff, R., Čergan, Z., Ellmer, F., Herbst, F., Hoffmann, S., Hofmann, B., Kismanyoky, T., Kubat, J., Kunzova, E., Lopez-Fando, C., Merbach, I., Merbach, W., Pardor, M.T., Rogasik, J., Rühlmann, J., Spiegel, H., Schulz, E., Tajnsek, A., Toth, Z., Wegener, H., Zorn, W., 2013. Effect of mineral and organic fertilization on crop yield, nitrogen uptake, carbon and nitrogen balances, as well as soil organic carbon content and dynamics: results from 20 European long-term field experiments of the twenty-first century. Archives of Agronomy and Soil Science 59, 1017–1040.

Krauss, M., Berner, A., Burger, D., Wiemken, A., Niggli, U., Mäder, P., 2010. Reduced tillage in temperate organic farming: implications for crop management and forage production. Soil Use and Management 26, 12–20.

Langer, U., Klimanek, E.-M., 2006. Soil microbial diversity of four German long-term field experiments. Archives of Agronomy and Soil Science 52, 507–523.

Lehtinen, T., Schlatter, N., Baumgarten, A., Bechini, L., Krüger, J., Grignani, C., Zavattaro, L., Costamagna, C., Spiegel, H., 2014. Effect of crop residue incorporation on soil organic carbon and greenhouse gas emissions in European agricultural soils. Soil Use Manage 30, 524–538.

Leidel, S., Augustin, J., Köppen, D., Merbach, W., 2000. Einfluss Unterschiedlicher Organisch-Mineralischer N-Düngung auf die Lachgas- und Methanemission eines ackerbaulich genutzten standortes Norddeutschlands. Archives of Agronomy and Soil Science 45, 453–469.

Leifeld, J., Reiser, R., Oberholzer, H.R., 2009. Consequences of conventional versus organic farming on soil carbon: results from a 27-year field experiment. Agronomy Journal 101, 1204–1218.

Leinweber, P., Reuter, G., 1992. The influence of different fertilization practices on concentrations of organic carbon and total nitrogen in particle-size fractions during 34 years of a soil formation experiment in loamy marl. Biol. Fertil. Soils 13, 119–124.

Leroy, B., 2008. Soil food web, C and N transformations and soil structure : interactions and feedback mechanisms as a function of the quality exogenous organic matter. PhD thesis, Ghent University, Gent, pp. 246.

Leroy, B.L.M., De Sutter, N., Ferris, H., Moens, M., Reheul, D., 2009. Short-term nematode population dynamics as influenced by the quality of exogenous organic matter. Nematology 11, 23–38.

Leroy, B.L.M., Herath, H.M.S.K., De Neve, S., Gabriels, D., Bommele, L., Reheul, D., Moens, M., 2008. Effect of vegetable, fruit and garden (VFG) waste compost on soil physical properties. Compost Science & Utilization 16, 43–51.

Leroy, B.L.M., Schmidt, O., Van den Bossche, A., Reheul, D., Moens, M., 2008. Earthworm population dynamics as influenced by the quality of exogenous organic matter. Pedobiologia 52, 139–150.

Leroy, B.L.M.M., Bommele, L., Reheul, D., Moens, M., De Neve, S., 2007. The application of vegetable, fruit and garden waste (VFG) compost in addition to cattle slurry in a silage maize monoculture: Effects on soil fauna and yield. European Journal of Soil Biology 43, 91–100.

Liang, B., Zhao, W., Yang, X., Zhou, J., 2013. Fate of nitrogen-15 as influenced by soil and nutrient management history in a 19-year wheat-maize experiment. Field Crops Res. 144, 126-134.

Ludwig, B., Geisseler, D., Michel, K., Joergensen, R.G., Schulz, E., Merbach, I., Raupp, J., Rauber, R., Hu, K., Niu, L., Liu, X., 2010. Effects of fertilization and soil management on crop yields and carbon stabilization in soils. A review. Agronomy Sust. Developm. 31, 361–372.

Mäder, P., Fließbach, A., Dubois, D., Gunst, L., Fried, P. und Niggli, U., 2002 : Soil fertility and biodiversity in organic farming. Science 296, 1694-1697.

Marschner, P., Kandeler, E., Marschner, B., 2003. Structure and function of the soil microbial community in a long-term fertilizer experiment. Soil Biol. Biochem. 35, 453–461.

Martin, J.H., Waldren, R.P., Stamp, D.L., 2006. Principles of field crop production, 4. ed. ed. Pearson/Prentice Hall, Upper Saddle River, NJ.

Maxfield, P.J., Brennand, E.L., Powlson, D.S., Evershed, R.P., 2011. Impact of land management practices on high-affinity methanotrophic bacterial populations: evidence from long-term sites at Rothamsted. European Journal of Soil Science 62, 56–68.

Merbach, I., Schulz, E., 2013. Long-term fertilization effects on crop yields, soil fertility and sustainability in the Static Fertilization Experiment Bad Lauchstädt under climatic conditions 2001–2010. Archives of Agronomy and Soil Science 59, 1–17.

Metzger, M.J., Bunce, R.G.H., Jongman, R.H.G., Mücher, C.A., Watkins, J.W., 2005. A climatic stratification of the environment of Europe. Global Ecology and Biogeography 14, 549–563. doi:10.1111/j.1466-822X.2005.00190.x.

Moldanová, J., Grennfelt, P., Jonsson, A., Simpson, D., Spranger, T., Aas, W., Munthe, J., Rabl, A., 2011. Nitrogen as a threat to European air quality. In: Sutton, M.A., Howard, C.M., Erisman, J.W., Billen, G., Bleeker, A., Grennfelt, P., van Grinsven, H., Grizzetti, B. (Eds.), The European Nitrogen Assessment, Cambridge University Press, UK, pp. 99–125.

Monaco, S., Hatch, D.J., Sacco, D., Bertora, C., Grignani, C., 2008. Changes in chemical and biochemical soil properties induced by 11-yr repeated additions of different organic materials in maize-based forage systems. Soil Biol. Biochem. 40, 608–615.

Muñoz, G.R., Powell, J.M., Kelling, K.A., 2003. Nitrogen budget and soil N dynamics after multiple applications of unlabeled or ^{15}nitrogen-enriched dairy manure. Soil Science Society of America Journal 67, 817–825. doi:10.2136/sssaj2003.8170

Murphy, D.V., Stockdale, E.A., Poulton, P.R., Willison, T.W., Goulding, K.W.T., 2007. Seasonal dynamics of carbon and nitrogen pools and fluxes under continuous arable and ley-arable rotations in a temperate environment. European Journal of Soil Science 58, 1410–1424.

Nedvěd, V., Balìk, J., Černý, J., Kulhánek, M., Balíková, M., 2008. The changes of soil nitrogen and carbon contents in a long-term field experiment under different systems of nitrogen fertilization. Plant, Soil and Environment 11, 463–470.

Nevens, F., Reheul, D., 2003. The application of vegetable, fruit and garden waste (VFG) compost in addition to cattle slurry in a silage maize monoculture: nitrogen availability and use. European Journal of Agronomy 19, 189–203.

Nevens, F., Reheul, D., 2005. Agronomical and environmental evaluation of a long-term experiment with cattle slurry and supplemental inorganic N applications in silage maize. European Journal of Agronomy 22, 349–361.

Nieder, R., Benbi, D.K., Scherer, H.W., 2011. Fixation and defixation of ammonium in soils: a review. Biology and Fertility of Soils 47, 1–14. doi:10.1007/s00374-010-0506-4

Oenema, O, 2004. Governmental policies and measures regulating nitrogen and phosphorus from animal manure in European agriculture. Journal of Animal Science 82, 196-206.

Ogilvie, L.A., Hirsch, P.R., Johnston, A.W.B., 2008. Bacterial Diversity of the Broadbalk “Classical” Winter Wheat Experiment in Relation to Long-Term Fertilizer Inputs. Microbial Ecology 56, 525–537.

Olesen, J.E., Askegaard, M., Rasmussen, I.A., 2000. Design of an Organic Farming Crop-Rotation Experiment. Acta Agriculturae Scandinavica, Section B - Soil & Plant Science 50, 13–21.

Olesen, J.E., Askegaard, M., Rasmussen, I.A., 2009. Winter cereal yields as affected by animal manure and green manure in organic arable farming. European Journal of Agronomy 30, 119–128.

Pan, G., Zhou, P., Li, Z., Smith, P., Li, L., Qiu, D., Zhang, X., Xu, X., Shen, S., Chen, X., 2009. Combined inorganic/organic fertilization enhances N efficiency and increases rice productivity through organic carbon accumulation in a rice paddy from the Tai Lake region, China. Agric, Ecosyst. Environ 131, 274-280.

Pikula D., Berge ten H.F.M., Goethart P.W., Schröder J.J. 2016. Apparent nitrogen fertilizer replacement value of grass-clover leys and of farmyard manure in an arable rotation. Part II: farmyard manure. Soil Use and Management 32, 20-31.

Pincus L., Margenot A, Six J., Scow L., 2016. On-farm trial assessing combined organic and mineral fertilizer amendments on vegetable yields in central Uganda. Agric., Ecosys. & Environ. 225: 62-71.

Riley, H., Pommeresche, R., Eltun, R., Hansen, S., Korsaeth, A., 2008. Soil structure, organic matter and earthworm activity in a comparison of cropping systems with contrasting tillage, rotations, fertilizer levels and manure use. Agriculture, Ecosystems & Environment 124, 275–284.

Rodhe, L., Pell, M., Yamulki, S., 2006. Nitrous oxide, methane and ammonia emissions following slurry spreading on grassland. Soil Use and Management 22, 229–237.

Rogasik, J., Schroetter, S., Funder, U., Schnug, E., Kurtinecz, P., 2004. Long-term fertilizer experiments as a data base for calculating the carbon sink potential of arable soils. Archives of Agronomy and Soil Science 50, 11–19.

Rogasik, J., Schroetter, S., Schnug, E., Kundler, P., 2001. Langzeiteffekte ackerbaulicher massnahmen auf die bodenfruchtbarkeit. Archives of Agronomy and Soil Science 47, 3–17.

Ros, M., Klammer, S., Knapp, B., Aichberger, K., Insam, H., 2006. Long-term effects of compost amendment of soil on functional and structural diversity and microbial activity. Soil Use and Management 22, 209–218.

Ros, M., Pascual, J.A., Garcia, C., Hernandez, M.T., Insam, H., 2006. Hydrolase activities, microbial biomass and bacterial community in a soil after long-term amendment with different composts. Soil Biology & Biochemistry 38, 3443–3452.

Ruehlmann, J., 2013. The Box Plot Experiment in Grossbeeren after eight rotations: nitrogen, carbon and energy balances. Archives of Agronomy and Soil Science 59, 1159–1176.

Rühlmann, J., 2003. Der kastenparzellenversuch grossbeeren nach sechs rotationen: C- und n-bilanzen des dauerversuchs mit gemüsebaulicher bodennutzung. Archives of Agronomy and Soil Science 49, 511–536.

Rühlmann, J., 2006. The Box Plot Experiment in Grossbeeren after six rotations: Effect of fertilization on crop yield. Archives of Agronomy and Soil Science 52, 313–319.

Rühlmann, J., Ruppel, S., 2005. Effects of organic amendments on soil carbon content and microbial biomass – results of the long-term box plot experiment in Grossbeeren. Archives of Agronomy and Soil Science 51, 163–170.

Sánchez-Martín, L., Meijide, A., García-Torres, L., Vallejo, A., 2010. Combination of drip irrigation and organic fertilizer for mitigating emissions of nitrogen oxides in semiarid climate. Agriculture, Ecosystems and Environment 137, 99–107.

Sanz-Cobena, A., García-Marco, S., Quemada, M., Gabriel, J.L., Almendros, P., Vallejo, A., 2014. Do cover crops enhance N_2O, CO_2 or CH_4 emissions from soil in Mediterranean arable systems? Science of the Total Environment 466-467, 164–174.

Sanz-Cobena, A., Sánchez-Martín, L., García-Torres, L., Vallejo, A., 2012. Gaseous emissions of N_2O and NO and NO_3^- leaching from urea applied with urease and nitrification inhibitors to a maize (*Zea mays*) crop. Agriculture, Ecosystems and Environment 149, 64–73.

Sanz-Cobena, A., Lassaletta, L., Aguilera, E., Prado, A.D., Garnier, J., Billen, G., Iglesias, A., Sánchez, B., Guardia, G., Abalos, D., Plaza-Bonilla, D., Puigdueta-Bartolomé, I., Moral, R., Galán, E., Arriaga, H., Merino, P., Infante-Amate, J., Meijide, A., Pardo, G., Álvaro-Fuentes, J., Gilsanz, C., Báez, D., Doltra, J., González-Ubierna, S., Cayuela, M.L., Menéndez, S., Díaz-Pinés, E., Le-Noë, J., Quemada, M., Estellés, F., Calvet, S., van Grinsven, H.J.M., Westhoek, H., Sanz, M.J., Gimeno, B.S., Vallejo, A., Smith, P., 2017. Strategies for greenhouse gas emissions mitigation in Mediterranean agriculture: A review. Agric., Ecosys. and Environ. 238, 5-24.

Schjønning, P., Christensen, B., Carstensen, B., 1994. Physical and Chemical-Properties of a Sandy Loam Receiving Animal Manure, Mineral Fertilizer or No Fertilizer for 90 Years. Eur. J. Soil Sci. 45, 257–268.

Schjønning, P., Elmholt, S., Munkholm, L.J., Debosz, K., 2002. Soil quality aspects of humid sandy loams as influenced by organic and conventional long-term management. Agriculture, Ecosystems & Environment 88, 195–214.

Schjønning, P., Iversen, B.V., Munkholm, L.J., Labouriau, R., Jacobsen, O.H., 2005. Pore characteristics and hydraulic properties of a sandy loam supplied for a century with either animal manure or mineral fertilizers. Soil Use Manage. 21, 265–275.

Schröder, J.J., Uenk, D., Hilhorst, G.J., 2007. Long-term nitrogen fertilizer replacement value of cattle manures applied to cut grassland. Plant and Soil 299, 83–99.

Schröder, J.J.; Bechini, L.; Bittman, S.; Brito, M.P.; Delin, S.; Lalor, S.T.J.; Morvan, T.; Chambers, B.J.; Sakrabani, R.; Sørensen, P.B., 2013. Residual N effects from livestock manure inputs to soils. Proceedings of the 15th International RAMIRAN conference, 3-5 June 2013, Versailles, France, S10.04 http://www.ramiran.net/doc13/Proceeding_2013/documents/S10.04.pdf (accessed 3.22.16).

Shah, S.A., Shah, S.M. Mohammad, W. Shafi, M., Nawaz, H., 2009. N uptake and yield of wheat as influenced by integrated use of organic and mineral nitrogen. Int. J. Plant Prod. 3, 45-55.

Šimon, T., Cerhanova, D., Mikanova, O., 2011. The effect of site characteristics and farming practices on soil organic matter in long-term field experiments in the Czech Republic. Archiver of Agronomy and Soil Science 57, 693–704.

Šimon, T., Mikanová, O., Cerhanová, D., 2013. Long-term effect of straw and farmyard manure on soil organic matter in field experiment in the Czech Republic. Archives of Agronomy and Soil Science 59, 1193–1205.

Singh U., Giller K.E., Palm C.A., Ladha J.K., Breman H., 2001. Synchronizing N release from organic residues: opportunities for integrated management of N. The Scientific World Journal 1(Suppl. 2): 880-886.

Sørensen, P., 1998. Carbon mineralization, nitrogen immobilization and pH change in soil after adding volatile fatty acids. European Journal of Soil Science 49, 457–462.

Sørensen, P., 2004. Immobilisation, remineralisation and residual effects in subsequent crops of dairy cattle slurry nitrogen compared to mineral fertiliser nitrogen. Plant and Soil 267, 285–296.

Sørensen, P., and Jensen E.S., 1995. Mineralization of carbon and nitrogen from fresh and anaerobically stored sheep manure in soils of different texture. Biol. Fertil. Soils 19, 29–35.

Sørensen, P., Jensen, E.S., Nielsen, N.E., 1994. The fate of ^{15}N-labelled organic nitrogen in sheep manure applied to soils of different texture under field conditions. Plant and Soil 162, 39–47.

Spiegel, H., Dersch, G., Baumgarten, A., Hösch, J., 2010. The International Organic Nitrogen Long-term Fertilisation Experiment (IOSDV) at Vienna after 21 years. Archives of Agronomy and Soil Science 56(4): 405-420.

Stützel, H., Brüggemann, N., Inzé, D., 2016. The future of field trials in Europe: establishing a network beyond boundaries. Trends in Plant Science 21(2): 92-95.

Sümer, M.R., 2012. Auswirkungen verschiedener Bodennutzungssysteme auf ausgewählte physiko-chemische Bodeneigenschaften und pflanzenbauliche Parameter in Berlin-Dahlem und Dedelow. PhD thesis, Humboldt-Universität zu Berlin.

Tajnsek, A., Cergan, Z., Ceh, B., 2013. Results of the long-term field experiment IOSDV Jable at the beginning of the 21st century. Arch. Agron. Soil Sci. 59, 1099–1108.

Tajnšek, A., Čergan, Z., Čeh, B., 2013. Results of the long-term field experiment IOSDV Rakičan at the beginning of the 21st century. Archives of Agronomy and Soil Science 59, 1109–1119.

Tatzber, M., Stemmer, M., Spiegel, H., Katzlberger, C., Zehetner, F., Haberhauer, G., Roth, K., Garcia-Garcia, E., Gerzabek, M.H., 2009. Decomposition of Carbon-14-Labeled Organic Amendments and Humic Acids in a Long-Term Field Experiment. Soil Sci. Soc. Am. J. 73, 744–750.

Thomsen, I.K., Olesen, J.E., 2000. C and N mineralization of composted and anaerobically stored ruminant manure in differently textured soils. J. Agric. Sci. 135 (2), 151-159.

Thomsen, I.K., Schjønning, P., Christensen, B.T., 2003. Mineralisation of ^{15}N-labelled sheep manure in soils of different texture and water contents. Biology and Fertility of Soils 37, 295–301.

Tipping, E., Rowe, E.C., Evans, C.D., Mills, R.T.E., Emmett, B.A., Chaplow, J.S., Hall, J.R., 2012. N14C: A plant–soil nitrogen and carbon cycling model to simulate terrestrial ecosystem responses to atmospheric nitrogen deposition. Ecological Modelling 247, 11–26.

Tomasoni, C., Borrelli, L., Ceotto, E., 2011. Effect of integrated forage rotation and manure management on yield, nutrient balance and soil organic matter. Italian Journal of Agronomy 6, 55–60.

Tomasoni, C., Tosca, A., Valagussa, M., Borrelli, L., Ceotto, E., 2009. Effect of integrated forage rotation and manure management systems on soil Nitrogen content, in: Proceedings of the 16th Nitrogen Workshop - Connecting Different Scales of Nitrogen Use in Agriculture. Presented at the 16th Nitrogen Workshop - Connecting Different scales of Nitrogen use in Agriculture, Facoltà di Agraria, Università degli Studi di Torino, Turin (Italy).

Triberti, L., Nastri, A., Giordani, G., Comellini, F., Baldoni, G., Toderi, G., 2008. Can mineral and organic fertilization help sequestrate carbon dioxide in cropland? Eur. J. Agron. 29, 13–20.

Uhlen, G., 1991. Long-Term Effects of Fertilizers, Manure, Straw and Crop-Rotation on Total-N and Total-C in Soil. Acta Agriculturae Scandinavica 41, 119–127.

Vallejo, A., Skiba, U.M., García-Torres, L., Arce, A., López-Ferdandez, S., Sánchez-Martín, L., 2006. Nitrogen oxides emission from soils bearing a potato crop as influenced by fertilization with treated pig slurries and composts. Soil Biology & Biochemistry 38, 2782–2793.

van Eekeren, N., de Boer, H., Bloem, J., Schouten, T., Rutgers, M., de Goede, R., Brussaard, L., 2009. Soil biological quality of grassland fertilized with adjusted cattle manure slurries in comparison with organic and inorganic fertilizers. Biology and Fertility of Soils 45, 595–608.

van Kessel, J.S., Reeves, J.B., Meisinger, J.J., 2000. Nitrogen and Carbon Mineralization of Potential Manure Components. Journal of Environmental Quality 29, 1669–1677.

Velthof, G., Barot, S., Bloem, J., Butterbach-Bahl, K., de Vries, W., Kros, J., Lavelle, P., Olesen, J.E., Oenema, O., 2011. Nitrogen as a threat to European soil quality. In: Sutton, M.A., Howard, C.M., Erisman, J.W., Billen, G., Bleeker, A., Grennfelt, P., van Grinsven, H., Grizzetti, B. (Eds.), The European Nitrogen Assessment, Cambridge University Press, UK, pp. 495–512.

Vogeler, I., Rogasik, J., Funder, U., Panten, K., Schnug, E., 2009. Effect of tillage systems and P-fertilization on soil physical and chemical properties, crop yield and nutrient uptake. Soil and Tillage Research 103, 137–143.

Webb, J., Sørensen, P., Velthof, G., Amon, B., Pinto, M., Rodhe, L., Salomon, E., Hutchings, N., Burczyk, P., Reid, J., 2013. An assessment of the variation of manure nitrogen efficiency throughout Europe and an appraisal of means to increase manure-N efficiency, in: Advances in Agronomy. Elsevier, pp. 371–442.

Wei, W., Yan, Y., Cao, J., Christie, P., Zhang, F., Fan, M., 2016. Effects of combined application of organic amendments and fertilizers on crop yield and soil organic matter: An integrated analysis of long-term experiments. Agric., Ecosyst. and Environ. 225, 86-92.

Whalen, J., Chang, C., Olson, B., 2001. Nitrogen and phosphorus mineralization potentials of soils receiving repeated annual cattle manure applications. Biology and Fertility of Soils 34, 334–341. doi:10.1007/s003740100416

Widmer, F., Rasche, F., Hartmann, M., Fließbach, A., 2006. Community structures and substrate utilization of bacteria in soils from organic and conventional farming systems of the DOK long-term field experiment. Applied Soil Ecology 33, 294–307.

Witter, E., Martensson, A.M., Garcia, F.V., 1993. Size of the soil microbial biomass in a long-term field experiment as affected by different N-fertilizers and organic manures. Soil Biol. Biochem. 25, 659–669.

Zavattaro, L., Monaco, S., Sacco, D., Grignani, C., 2012. Options to reduce N loss from maize in intensive cropping systems in Northern Italy. Agriculture, Ecosystems & Environment 147, 24–35.

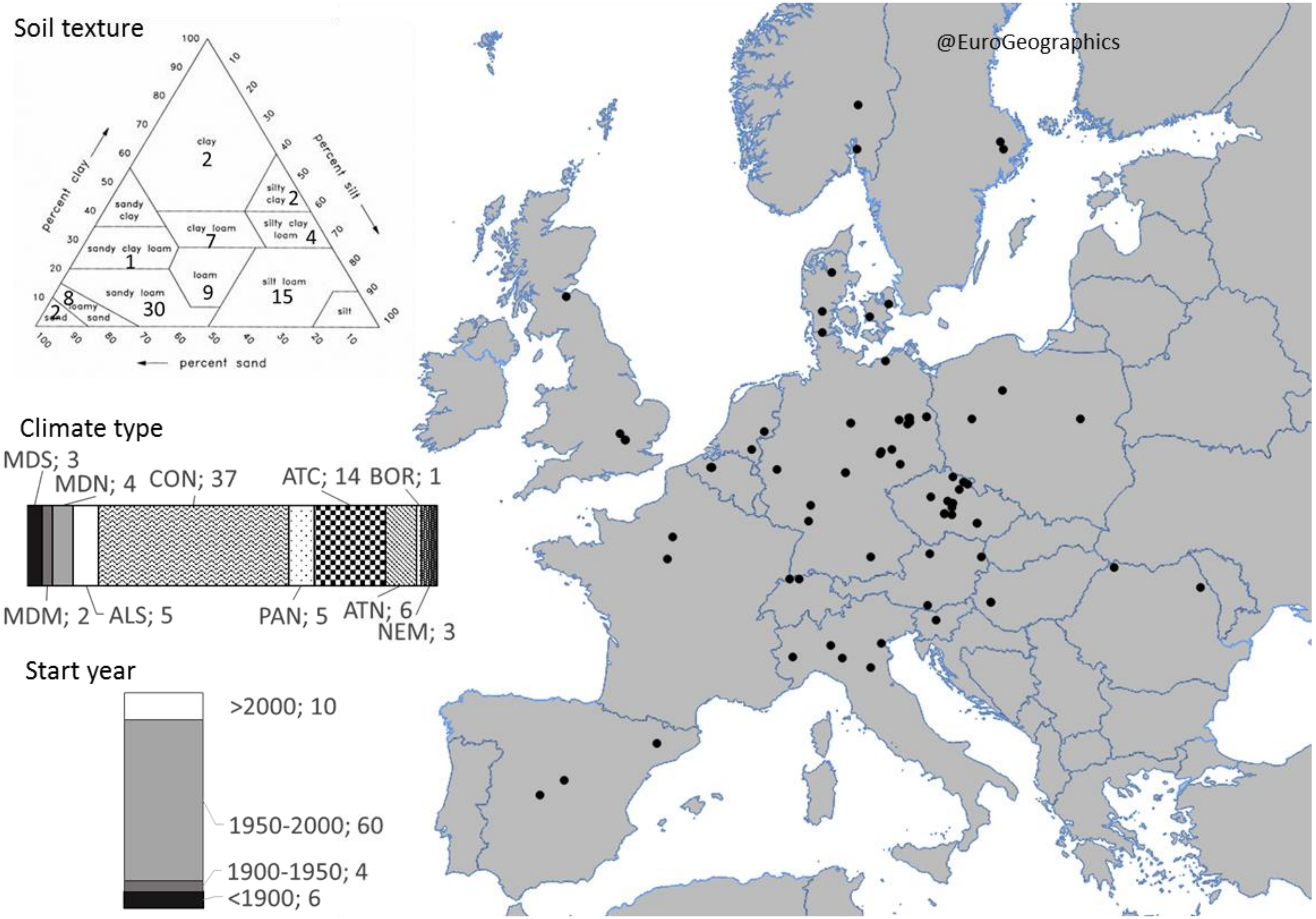
Zavattaro, L., Assandri, D., Grignani, C., 2016. Achieving legislation requirements with different nitrogen fertilization strategies: results from a long term experiment. Eur. J. Agron. 77, 199-208. doi:10.1016/j.eja.2016.02.004

Zhang, X., Davidson, E.A., Mauzerall, D.L., Searchinger, T.D., Dumas, P., Shen, Y., 2015. Managing nitrogen for sustainable development. Nature 528, 51–59. doi:10.1038/nature15743.

Zimmer, J., Roschke, M., Schulze, D., 2005. Influence of different treatments of organic and mineral fertilization on yield, soil organic matter and N-balance of a diluvial sandy soil – results after 45 years long-term field experiment P60 (Groß Kreutz, 1959 – 2003). Archives of Agronomy and Soil Science 51, 135–149.

Zorn, W., Heß, H., Schröder, H., Michel H., Gullich P., Horn A, Ilgen S., 2009. Landwirtschaftsamt Bad Salzungen Feldversuche in Bad Salzungen 1934 - 2009. Thüringer Landesanstalt für Landwirtschaft, Jena, Germany.

Figure 1. Map of LTEs used in this study. The number of LTEs for each soil texture, start year and climate type following Metzger et al. (2005) are also reported. Climate acronyms are as follows: Atlantic Central (ATC), Atlantic North (ATN), Atlantic South (ALS), Boreal (BOR), Continental (CON), Mediterranean Mountains (MDM), Mediterranean North (MDN), Mediterranean South (MDS), Nemoral (NEM), Pannonian (PAN). Supplementary data on LTE characteristics and available indicators are reported in Table S1. The list of consulted literature for each LTE is reported in Table S2.


Soil texture
percent clay
percent silt
percent sand
clay 2
sandy clay
silty clay 2
clay loam 7
silty clay loam 4
sandy clay loam 1
loam 9
silt loam 15
sandy loam 30
loamy sand 8
sand 2
silt
Climate type
MDS; 3
MDN; 4
CON; 37
ATC; 14
BOR; 1
MDM; 2
ALS; 5
PAN; 5
ATN; 6
NEM; 3
Start year
>2000; 10
1950-2000; 60
1900-1950; 4
<1900; 6
@EuroGeographics

Tables

Table 1. List of abbreviations and definitions used in this paper.

Treatments		
FYM	farmyard manure as the only N fertilizer	(subscript: man)
FYMm	farmyard manure added with mineral N	
SLU	bovine slurry as the only N fertilizer	
SLUm	bovine slurry added with mineral N	
mineral	mineral fertilizers only	(subscript: min)
Unfertilized control, 0N	no additions of N as fertilizer	(subscript: 0N)
Indicators		**Equation (when applicable)**
F	total N applied as fertilizer (mineral + manure)	
Y	yield	
NY	N in yield	
Y/F	kg of yield produced by each kg of N applied	Y / F
NY/F	kg of N in yield per kg of total N applied	NY / F
ANR	apparent N recovery	$(NY - NY_{0N}) / F$
SOC	soil organic C concentration	
SoilN	soil organic N or Total N concentration	
MB	microbial biomass weight, or C, or N	

pH	soil pH	
AGGRS	aggregate stability	
BULKD	soil bulk density	
ACT	actynomycetes	
BAC	bacteria	
EARTW	earthworms (number or biomass)	
FUNGI	fungi	
PLFA	Phospholipid-derived fatty acids markers of bacteria	
Response ratios		**Equation**
FR	N Fertilizer Ratio	F_{man}/F_{min}
RR_{Y}	Response Ratio of Y	Y_{man} / Y_{min}
RR_{NY}	Response Ratio of NY	NY_{man} / NY_{min}
$RR_{Y/F}$	Response Ratio of Y/F	$(Y_{man}/F_{man}) / (Y_{min}/F_{min})$
$RR_{NY/F}$	Response Ratio of NY/F	$(NY_{man}/F_{man}) / (NY_{min}/F_{min})$
RR_{ANR}	Response Ratio of ANR	$((NY_{man}-NY_{0N})/F_{man}) / ((NY_{min}-NY_{0N})/F_{min})$
RR_{SOC}	Response Ratio of SOC	SOC_{man}/SOC_{min}
RR_{SoilN}	Response Ratio of SoilN	$SoilN_{man}/SoilN_{min}$
RR_{MB}	Response Ratio of MB	MB_{man}/MB_{min}
Model		
MLR	Multiple Linear Regression model	

MLR Factors		
Climate	Northern	Boreal (BOR), Nemoral (NEM)
	Eastern	Atlantic South (ALS), Continental (CON), Pannonian (PAN)
	Western	Atlantic North (ATN), Atlantic Central (ATC)
	Southern	Mediterranean Mountains (MDM), Mediterranean North (MDN), Mediterranean South (MDS)
Crops	Long duration	grass/mixed ley, lucerne, double cropping systems
	Spring	spring wheat, spring barley, minor spring small grain cereals, maize, potato, sunflower, sugarbeet, fodder beet, spring grain legumes
	Spring short	vegetables
	Winter	winter wheat, winter barley, minor winter small grain cereals, rapeseed, winter grain legumes
	Combined	data were referred to a rotation as a whole, without reference to a specific crop
Soil texture	Light	coarse sandy, loamy sand, sand, sandy clay loam, sandy loam, silty sand USDA classes
	Medium	clay loam, loam, silty loam USDA classes
	Heavy	clay, silty clay, silty clay loam USDA classes
Tillage depth	0	no tillage
	0-10 cm	tillage depth, intended as the incorporation depth
	11-20 cm	
	21-30 cm	
	>30 cm	
Duration	1- 5 yrs	years of practice after the experiment start

6-10 yrs
11-20 yrs
> 20 yrs

Table 2. Response Ratios (RR) of all indicators: number of cases (n), mean, probability that the mean is different from 1 (P(F)), standard deviation, and quartiles (Q1, Q2, Q3), for the whole dataset; number of cases, mean of RRs within the central class of FR, and probability that it is different from 1. Abbreviations are explained in Tab. 1

	N fertilizer ratio	**Crop indicators**					**Soil indicators**		
	FR	**RR_Y**	**RR_{NY}**	**$RR_{Y/F}$**	**$RR_{NY/F}$**	**RR_{ANR}**	**RR_{SOC}**	**RR_{SoilN}**	**RR_{MB}**
FYM									
n	263	133	23	130	23	18	60	26	25
Mean RR	1.098	0.905	0.891	0.984	0.821	0.593	1.324	1.206	1.301
P(F) mean ≠1	0.323	0.000	0.007	0.001	0.001	0.003	0.000	0.000	0.000
Std. Deviation	0.353	0.197	0.203	0.557	0.220	0.570	0.352	0.189	0.402
Q1	0.960	0.751	0.715	0.628	0.684	0.274	1.122	1.114	1.065
Q2	1.100	0.940	0.862	0.818	0.849	0.431	1.181	1.216	1.233
Q3	1.300	1.019	1.079	1.132	0.978	0.889	1.403	1.288	1.366
n of FR central class	124	51	16	51	16	11	23	19	5
Mean RR in FR central class	1.036	0.934	0.951	0.937	0.868	0.716	1.261	1.221	1.330
P(F) mean ≠1 in FR central class	0.000	0.006	0.223	0.009	0.007	0.148	0.000	0.000	0.014

	N fertilizer ratio	Crop indicators					Soil indicators		
	FR	**RR_{Y}**	**RR_{NY}**	**$RR_{Y/F}$**	**$RR_{NY/F}$**	**RR_{ANR}**	**RR_{SOC}**	**RR_{SoilN}**	**RR_{MB}**
FYMm									
n	201	82	32	82	32	16	54	17	15
Mean RR	1.681	1.113	1.266	0.830	0.729	0.787	1.334	1.224	1.211
P(F) mean ≠1	0.000	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.004
Std. Deviation	0.692	0.351	0.362	0.332	0.177	0.139	0.376	0.141	0.220
Q1	1.189	0.961	0.986	0.652	0.596	0.674	1.069	1.061	1.085
Q2	1.458	1.049	1.120	0.736	0.762	0.787	1.179	1.220	1.253
Q3	2.226	1.140	1.617	0.969	0.857	0.876	1.458	1.370	1.394
n of FR central class	51	24	9	23	9	9	10	3	3
Mean RR in FR central class	1.133	1.061	0.901	1.012	0.765	0.722	1.158	1.176	0.864
P(F) mean ≠1 in FR central class	0.000	0.629	0.011	0.586	0.000	0.000	0.003	0.013	0.068
SLU									
n	144	73	17	68	17	12	23	9	19
Mean RR	1.072	0.909	0.781	0.912	0.887	0.444	1.175	1.160	1.203
P(F) mean ≠1	0.325	0.000	0.000	0.001	0.024	0.029	0.000	0.000	0.000
Std. Deviation	0.475	0.187	0.156	0.366	0.311	0.769	0.108	0.067	0.102
Q1	0.742	0.791	0.699	0.631	0.739	0.265	1.072	1.101	1.125
Q2	1.000	0.945	0.833	0.897	0.820	0.716	1.182	1.159	1.222
Q3	1.207	0.995	0.882	1.023	0.902	0.808	1.241	1.214	1.259
n of FR central class	72	37	13	34	13	8	12	8	0
Mean RR in FR central class	1.017	0.883	0.836	0.928	0.796	0.565	1.143	1.153	-

	N fertilizer ratio	**Crop indicators**					**Soil indicators**		
	FR	**RR_{Y}**	**RR_{NY}**	**$RR_{Y/F}$**	**$RR_{NY/F}$**	**RR_{ANR}**	**RR_{SOC}**	**RR_{SoilN}**	**RR_{MB}**
P(F) mean ≠1 in FR central class	0.279	0.000	0.000	0.003	0.000	0.059	0.000	0.000	0.000
<u>SLUm</u>									
n	60	22	10	20	10	10	10	11	3
Mean RR	1.098	0.950	1.004	0.961	0.977	0.995	1.173	1.155	1.203
P(F) mean ≠1	0.000	0.059	0.916	0.240	0.394	0.775	0.000	0.000	0.003
Std. Deviation	0.160	0.128	0.067	0.288	0.094	0.125	0.091	0.077	0.023
Q1	1.034	0.839	0.957	0.821	0.919	0.881	1.083	1.078	1.180
Q2	1.043	0.994	1.010	0.974	0.968	0.976	1.167	1.146	1.205
Q3	1.130	1.051	1.041	1.038	1.046	1.102	1.239	1.176	-
n of FR central class	47	16	9	15	9	9	7	10	3
Mean RR in FR central class	1.030	0.965	1.003	0.993	0.995	1.011	1.200	1.165	1.203
P(F) mean ≠1 in FR central class	0.001	0.229	0.989	0.564	0.767	0.901	0.001	0.000	0.003

Table 3. Results of the Multiple Linear Regression model applied to selected sets of factors affecting different indicators. For each level of factors, number of cases (n), estimated marginal mean and pairwise Bonferroni post-hoc test of significant differences are reported, where p is the significance level of each factor (++ if p<0.01, + if 0.01<p<0.05). Factors are described in the text.

(a) Results for FYM/FYMm. (b) Results for SLU/SLUm. Abbreviations are explained in Table 1.

(a) Results for FYM/FYMm

Factor	**Level**	**Crop indicators**															**Soil indicators**								
		RR_{Y}			**RR_{NY}**			**$RR_{Y/F}$**			**$RR_{NY/F}$**			**RR_{ANR}**			**RR_{SOC}**			**RR_{SoilN}**			**RR_{MB}**		
		n	**mean**		**n**	**mean**		**n**	**mean**		**n**	**mean**		**n**	**mean**		**n**	**mean**		**n**	**mean**		**n**	**mean**	
Climate	***p***	*215*	*0.001*	*++*	*55*	*0.373*	*ns*	*212*	*0.149*	*ns*	*55*	*0.001*	*++*	*33*	*#*		*102*	*0.006*	*++*	*34*	*0.380*	*ns*	*38*	*0.002*	*++*
	Northern	#N/D			#N/D			#N/D			#N/D			#N/D			1	1.866	ab	#N/D			#N/D		
	Eastern	179	1.041	a	38	1.024		175	0.970		38	0.775	b	18	0.236	b	76	1.613	a	14	1.088		20	0.702	b
	Western	14	0.798	b	1	1.241		14	0.904		1	1.166	ab	#N/D			8	1.289	b	1	1.379		14	1.237	a
	Southern	22	1.168	a	16	1.118		23	1.096		16	1.146	a	15	2.744	a	17	1.915	a	19	1.241		4	1.208	a
Crop	***p***	*215*	*0.000*	*++*	*55*	*0.000*	*++*	*212*	*0.005*	*++*	*55*	*0.000*	*++*	*33*	*0.904*	*ns*	*102*	*0.378*	*ns*	*34*	*0.746*	*ns*	*38*	*0.048*	*+*
	Long duration	9	1.158	a	5	1.034	ab	9	1.000	ab	5	1.071	ab	4	0.683		1	1.701	ab	#N/D			1	0.911	
	Spring	104	0.966	ab	14	0.987	ab	104	0.843	ab	14	0.988	ab	9	0.671		14	1.330	b	11	1.220		7	1.334	
	Spring short	1	1.144	abc	12	0.743	b	1	1.787	a	12	0.829	b	12	1.046		#N/D			#N/D			#N/D		
	Winter	86	0.881	c	18	1.149	a	86	0.774	b	18	1.152	a	2	0.935		3	2.587	a	#N/D			1	0.717	
	Combined	15	0.845	bc	6	0.860	ab	12	0.804	ab	6	1.050	ab	6	0.753		84	1.269	b	23	1.241		29	1.223	
Soil texture	***p***	*215*	*0.000*	*++*	*55*	*0.178*	*ns*	*212*	*0.987*	*ns*	*55*	*0.000*	*++*	*33*	*#*		*102*	*0.032*	*+*	*34*	*#*		*38*	*. #*	
	Light	93	1.051	a	25	1.013		92	0.979		25	1.335	a	17	1.619	a	54	1.752		13	1.235		21	1.297	a
	Medium	116	0.866	b	30	0.880		114	0.979		30	0.767	b	16	0.400	b	45	1.603		21	1.226		17	0.796	b
	Heavy	6	1.067	ab	#N/D			6	1.003		#N/D			#N/D			3	1.603		#N/D			#N/D		
Tillage depth	***p***	*215*	*0.005*	*++*	*55*	*0.303*	*ns*	*212*	*0.062*	*ns*	*55*	*0.050*	*+*	*33*	*#*		*102*	*0.672*	*ns*	*34*	*0.018*	*+*	*38*	*0.046*	*+*
	surface	#N/D			1	1.050		#N/D			1	1.547		1	0.541	b	1	1.641		#N/D			#N/D		

Factor	**Level**	**Crop indicators**															**Soil indicators**								
		RR_Y			**RR_{NY}**			**$RR_{Y/F}$**			**$RR_{NY/F}$**			**RR_{ANR}**			**RR_{SOC}**			**RR_{SoilN}**			**RR_{MB}**		
		n	**mean**		**n**	**mean**		**n**	**mean**		**n**	**mean**		**n**	**mean**		**n**	**mean**		**n**	**mean**		**n**	**mean**	
	1-10 cm	#N/D			1	0.884		#N/D			1	0.861		#N/D			#N/D			#N/D			#N/D		
	11-20 cm	61	1.044	a	12	0.967		57	0.944		12	0.913		2	1.780	a	55	1.670		8	1.142	b	24	1.085	a
	21-30 cm	154	0.939	b	41	0.884		155	1.032		41	0.861		30	0.541	b	46	1.641		26	1.326	a	14	0.951	b
	>30 cm	#N/D			#N/D			#N/D			#N/D			#N/D			#N/D			#N/D			#N/D		
Duration	***p***	*215*	*0.530*	*ns*	*55*	*0.111*	*ns*	*212*	*0.015*	*+*	*55*	*0.016*	*+*	*33*	*#*		*102*	*0.000*	*++*	*34*	*#*		*38*	*0.261*	*ns*
	1-5 yrs	2	1.012		1	0.924		2	0.725		1	0.968	b	#N/D			1	1.509	b	1	1.230		5	1.085	
	6-10 yrs	4	0.875		2	0.825		3	0.907		2	0.864	ab	2	0.805		15	2.180	a	#N/D			3	0.941	
	11-20 yrs	84	1.042		24	1.126		86	1.138		24	1.295	a	15	0.805		23	1.497	b	20	1.230		4	1.021	
	>20 yrs	125	1.042		28	0.924		121	1.267		28	0.968	b	16	0.805		63	1.509	b	13	1.230		26	1.021	
N fertilizer ratio (FR)	***p***	*215*	*0.000*	*++*	*55*	*0.145*	*ns*	*212*	*0.000*	*++*	*55*	*0.160*	*++*	*33*	*0.005*	*++*	*102*	*0.011*	*+*	*34*	*0.251*	*ns*	*38*	*0.000*	*++*
	<0.8	32	0.925	b	3	0.916		32	1.681	a	3	1.249	a	3	0.605	b	12	1.585	ab	#N/D			13	0.805	c
	0.8-1.2	75	0.976	b	25	0.906		74	0.895	b	25	0.976	ab	19	1.063	a	31	1.593	b	22	1.186		8	1.060	b
	>1.2	108	1.076	a	27	1.013		106	0.639	c	27	0.849	b	11	0.811	b	59	1.783	a	12	1.276		17	1.229	a
Addition of mineral N	***p***	*215*	*0.000*	*++*	*55*	*0.000*	*++*	*212*	*0.042*	*+*	*55*	*0.384*	*ns*	*33*	*0.066*	*ns*	*102*	*0.385*	*ns*	*34*	*0.236*	*ns*	*38*	*0.000*	*++*
	FYM	133	0.883	b	23	0.857	b	130	0.949	b	23	0.971		17	0.731		54	1.676		21	1.278		23	1.175	a
	FYMm	82	1.110	a	32	1.039	a	82	1.026	a	32	1.054		16	0.886		48	1.626		13	1.184		15	0.878	b
Model fit	**R^2**		0.382			0.744			0.260			0.641			0.813			0.516			0.443			0.671	

(b) Results for SLU/SLUm

Factor	**Level**	**Crop indicators**															**Soil indicators**								
		RR$_{Y}$			**RR$_{NY}$**			**RR$_{Y/F}$**			**RR$_{NY/F}$**			**RR$_{ANR}$**			**RR$_{SOC}$**			**RR$_{SoilN}$**			**RR$_{MB}$**		
		n	**mean**		**n**	**mean**		**n**	**mean**		**n**	**mean**		**n**	**mean**		**n**	**mean**		**n**	**mean**		**n**	**mean**	
Climate	***p***	*95*	*0.000*	*++*	*27*	*#*		*88*	*0.001*	*++*	*27*	*#*		*20*	*#*		*33*	*0.012*	*+*	*20*	*#*		*22*	*#*	
	Northern	#N/D			#N/D			#N/D			#N/D			#N/D			1	0.995	b	#N/D			#N/D		
	Eastern	55	0.793	b	#N/D			47	0.665	b	#N/D			#N/D			9	1.291	a	#N/D			#N/D		
	Western	7	0.703	b	8	0.705	b	7	0.691	b	8	0.908		3	1.154		6	1.216	ab	1	1.271	a	19	1.210	
	Southern	33	1.118	a	19	0.956	a	34	1.143	a	19	0.741		17	0.672		17	1.232	ab	19	1.085	b	3	1.196	
Crop	***p***	*95*	*0.000*	*++*	*27*	*0.808*	*ns*	*88*	*0.349*	*ns*	*27*	*0.709*	*ns*	*20*	*0.670*	*ns*	*33*	*0.407*	*ns*	*20*	*0.004*	*++*	*22*	*#*	
	Long duration	6	0.814	ab	7	0.897		6	0.674		7	0.758		4	0.969		3	1.363		#N/D			#N/D		
	Spring	41	0.821	a	12	0.863		39	0.737		12	0.726		9	0.827		9	1.081		11	1.137	b	3	1.203	
	Spring short	1	1.208	a	#N/D			1	1.375		#N/D			#N/D			#N/D			#N/D			#N/D		
	Winter	37	0.722	b	6	0.701		37	0.703		6	0.980		5	0.754		#N/D			#N/D			#N/D		
	Combined	10	0.780	ab	2	0.837		5	0.713		2	0.837		2	0.995		21	1.108		9	1.213	a	19	1.203	
Soil texture	***p***	*95*	*0.000*	*++*	*27*	*#*		*88*	*0.000*	*++*	*27*	*#*		*20*	*#*		*33*	*0.599*	*ns*	*20*	*#*		*22*	*#*	
	Light	46	0.974	a	5	0.853	b	45	1.074	a	5	0.863		3	0.881		11	1.211		#N/D			12	1.175	
	Medium	49	0.749	b	22	0.790	a	43	0.607	b	22	0.779		17	0.881		22	1.145		20	1.174		10	1.231	
	Heavy	#N/D			#N/D			#N/D			#N/D			#N/D			#N/D			#N/D			#N/D		
Tillage depth	***p***	*95*	*0.000*	*++*	*27*	*#*		*88*	*0.027*	*+*	*27*	*#*		*20*	*#*		*33*	*0.959*	*ns*	*20*	*#*		*22*	*#*	
	surface	#N/D			#N/D			#N/D			#N/D			#N/D			3	1.180		#N/D			#N/D		
	1-10 cm	3	0.958	a	6	0.876		3	0.813	ab	6	0.639		2	0.881		#N/D			#N/D			#N/D		
	11-20 cm	42	0.954	a	4	0.795		34	1.064	a	4	0.929		3	0.881		8	1.174		1	1.174		19	1.203	
	21-30 cm	44	0.943	a	17	0.795		45	0.890	ab	17	0.929		15	0.881		22	1.180		19	1.174		3	1.203	
	>30 cm	6	0.618	b	#N/D			6	0.551	b	#N/D			#N/D			#N/D			#N/D			#N/D		
Duration	***p***	*95*	*0.003*	*++*	*27*	*0.361*	*ns*	*88*	*0.050*	*+*	*27*	*0.578*	*ns*	*20*	*#*		*33*	*0.368*	*ns*	*20*	*#*		*22*	*0.370*	*ns*
	1-5 yrs	4	0.875	a	5	0.845		4	0.814		5	0.841		2	0.881		3	1.125		1	1.174		5	1.244	
	6-10 yrs	7	0.711	b	1	0.753		6	0.613		1	0.761		#N/D			1	1.270		#N/D			2	1.183	
	11-20 yrs	24	0.866	a	20	0.845		26	0.884		20	0.841		18	0.881		20	1.196		19	1.174		15	1.183	
	>20 yrs	60	0.987	a	1	0.845		52	0.961		1	0.841		#N/D			9	1.125		#N/D			#N/D		

Factor	Level	Crop indicators															Soil indicators							
		RR_Y			RR_{NY}			$RR_{Y/F}$			$RR_{NY/F}$			RR_{ANR}			RR_{SOC}			RR_{SoilN}			RR_{MB}	
		n	**mean**		**n**	**mean**		**n**	**mean**		**n**	**mean**		**n**	**mean**		**n**	**mean**		**n**	**mean**		**n**	**mean**
N fertilizer ratio (FR)	***p***	*95*	*0.000*	*++*	*27*	*0.857*	*ns*	*88*	*0.000*	*++*	*27*	*0.171*	*ns*	*20*	*0.491*	*ns*	*33*	*0.155*	*ns*	*20*	*0.005*	*++*	*22*	*#*
	<0.8	18	0.797	b	4	0.829		16	1.014	a	4	0.736		3	0.792		2	1.157		#N/D			12	1.203
	0.8-1.2	53	0.809	b	22	0.805		49	0.857	a	22	1.018		16	1.087		19	1.220		18	1.261	a	3	1.203
	>1.2	24	0.966	a	1	0.829		23	0.605	b	1	0.736		1	0.792		12	1.157		2	1.094	b	7	1.203
Addition of mineral N	***p***	*95*	*0.001*	*++*	*27*	*0.016*	*++*	*88*	*0.000*	*++*	*27*	*0.047*	*+*	*20*	*0.015*	*+*	*33*	*0.284*	*ns*	*20*	*0.310*	*ns*	*22*	*#*
	SLU	73	0.798	b	17	0.760	b	68	0.684	b	17	0.749	b	10	0.707	b	23	1.161		9	1.161		19	1.203
	SLUm	22	0.914	a	10	0.886	a	20	0.952	a	10	0.897	a	10	1.097	a	10	1.195		11	1.188		3	1.203
Model fit	**R^2**		0.595			0.720			0.384			0.413			0.303			0.534			0.403			0.255

‘#’ = Unable to compute the level of significance of P due to numerical problems, even if the post-hoc test could be performed (as indicated by ‘++’, ‘+’ and letters).

Table S1. Main characteristics of each LTE with the indicators and number of measurements provided by each LTE to calculate indicators. Treatment codes are explained in the text. Indicator abbreviations are explained in Table 1 and in a footnote to this table. Climate abbreviations are those of Metzger et al. (2005) and are explained in Table 1.

LTE	Country	Latitude and longitude	Start year	Latest year used	Texture	Climate	FYM	FYMm	SLU	SLUm	Y	NY	Y/F	NY/F	ANR	SOC	SOILN	MB	Other variables[a]
Fuchsenbigl	AT	48°12'N 16°44'E	1967	2004	sandy loam	PAN	4	0	0	0	0	0	0	0	0	2	2	0	
Linz	AT	48°18'N 14°17'E	1991	2012	silty loam	CON	50	41	0	0	38	0	38	0	0	4	4	7	BULKD, ACT, PLFA
Melle 1	BE	50°59'N 03°49'E	2005	2010	silty loam	ATC	0	36	36	0	4	0	4	0	0	2	2	14	BULKD, ACT, BAC, EARW, PLFA
Melle 2	BE	50°59'N 03°49'E	1983	2001	sandy loam	ATC	0	0	6	0	1	2	1	2	0	0	0	0	pH, BULKD
Melle 3	BE	50°59'N 03°46'E	2010	2013	sandy loam	ATC	0	0	17	19	5	7	5	7	0	2	2	2	pH, BULKD, ACT, BAC, EARW, FUNGI, PLFA,
Vlaco	BE	50°59'N 03°49'E	1997	2005	sandy loam	ATC	0	0	2	0	0	0	0	0	0	0	0	0	EARW, FUNGI
DOK	CH	47°30'N 07°33'E	1978	2005	silty clay	ATC	6	0	0	0	0	0	0	0	0	0	0	6	
Frick	CH	47°30'N 08°01'E	2002	2008	clay	CON	14	0	13	0	12	0	11	0	0	0	0	4	BULKD, PLFA
Caslav	CZ	49°54'N 15°23'E	1956	2008	loam	CON	1	1	0	0	0	0	0	0	0	2	0	0	
Hnevceves	CZ	50°18'N 15°42'E	1979	2008	clay loam	CON	1	1	0	0	0	0	0	0	0	2	0	0	
Humpolec	CZ	49°32'N 15°21'E	1979	2008	sandy loam	CON	1	1	0	0	0	0	0	0	0	2	0	0	
Ivanovice 1	CZ	49°15'N 16°33'E	1984	2008	loam	CON	1	1	0	0	0	0	0	0	0	2	0	0	
Ivanovice 2	CZ	49°15'N 16°33'E	1956	2008	loam	CON	1	0	0	0	0	0	0	0	0	1	0	0	
Jable	CZ	46°08'N 14°34'E	1993	2010	silty loam	ALS	7	21	0	0	12	0	12	0	0	4	0	0	BULKD
Kostelec	CZ	50°28'N 16°05'E	1979	2008	sandy loam	ALS	1	1	0	0	0	0	0	0	0	2	0	0	
Lukavec 1	CZ	49°33'N 14°59'E	1956	2008	sandy loam	CON	1	1	0	0	0	0	0	0	0	2	0	0	
Lukavec 2	CZ	49°33'N 14°59'E	1984	2008	sandy loam	CON	1	1	0	0	0	0	0	0	0	2	0	0	
Lukavec 3	CZ	49°33'N 14°59'E	1997	2005	sandy loam	CON	5	0	0	0	0	1	0	1	1	1	0	0	
Pernolec	CZ	49°46'N 15°21'E	1979	2008	sandy loam	CON	1	1	0	0	0	0	0	0	0	2	0	0	
Praha-Ruzyne	CZ	50°05'N 14°18'E	1955	2008	clay loam	CON	2	2	0	0	0	0	0	0	0	4	0	0	
Suchdol	CZ	49°57'N 15°09'E	1997	2005	loam	CON	5	0	0	0	0	1	0	1	1	1	0	0	
Trutnov	CZ	50°33'N 15°53'E	1966	2010	sandy loam	ALS	9	9	0	0	2	2	2	2	2	2	2	2	pH, AGGRS, BULKD, ACT, PLFA
Vysoké nad Jizerou	CZ	50°41'N 15°24'E	1979	2008	loamy sand	ALS	1	1	0	0	0	0	0	0	0	2	0	0	
Bad Lauchstädt 1	DE	51°24'N 11°53'E	1902	2010	silty loam	CON	21	8	0	0	14	0	14	0	0	1	0	0	BULKD
Bad Lauchstädt 2	DE	51°24'N 11°53'E	1983	2008	silty clay loam	CON	1	0	0	0	0	0	0	0	0	1	0	0	
Bad Salzungen 1	DE	50°49'N 10°14'E	1966	2008	sandy loam	ATN	4	0	4	0	2	0	2	0	0	4	0	0	BULKD
Bad Salzungen 2	DE	50°49'N 10°14'E	1997	2008	sandy loam	ATN	9	1	10	0	8	0	8	0	0	4	0	0	BULKD
Berlin-Dahlem 1	DE	52°27'N 13°17'E	1923	2007	sandy loam	CON	20	24	0	0	8	8	8	8	0	0	8	0	pH, AGGRS, BULKD

LTE	Country	Latitude and longitude	Start year	Latest year used	Texture	Climate	FYM	FYMm	SLU	SLUm	Y	NY	Y/F	NY/F	ANR	SOC	SOILN	MB	Other variables[a]
Berlin-Dahlem 2	DE	52°28'N 13°18'E	1984	2003	sandy loam	CON	6	0	0	0	0	0	0	0	0	0	0	6	
Braunschweig 1	DE	52°18'N 10°27'E	1985	2006	silty loam	CON	0	50	0	0	12	12	12	12	0	2	0	0	pH, BULKD
Braunschweig 2	DE	52°18'N 10°27'E	1952	2000	silty loam	CON	0	3	0	0	1	0	1	0	0	1	0	0	BULKD
Cologne	DE	50°56'N 06°57'E	1969	2000	silty loam	ATC	5	0	0	0	0	0	0	0	0	1	1	1	BAC, FUNGI
Darmstadt	DE	49°50'N 08°34'E	1980	2007	loamy sand	PAN	36	0	0	0	12	0	12	0	0	3	3	3	BULKD
Gross Kreutz	DE	52°24'N 12°47'E	1959	2003	loamy sand	CON	22	0	22	0	20	0	20	0	0	4	0	0	BULKD
Grossbeeren 1	DE	52°21'N 13°18'E	1972	2011	silty sand	CON	34	36	0	0	5	12	5	12	12	6	0	6	pH, AGGRS, BULKD, PLFA
Grossbeeren 2	DE	52°21'N 13°18'E	1972	2003	loamy sand	CON	4	4	0	0	4	0	4	0	0	0	0	0	BULKD
Halle	DE	51°28'N 11°58'E	1878	2002	sandy loam	CON	1	0	0	0	0	0	0	0	0	0	0	1	
Methau	DE	51°04'N 12°51'E	1966	2010	silty loam	CON	17	3	0	0	8	0	8	0	0	2	0	0	
Müncheberg 1	DE	52°30'N 14°08'E	1978	2005	sandy loam	CON	32	0	32	0	32	0	32	0	0	0	0	0	BULKD
Müncheberg 2	DE	52°30'N 14°08'E	1962	2000	silty loam	CON	1	0	0	0	0	0	0	0	0	1	0	0	
Puch	DE	48°11'N 11°25'E	1984	2004	silty loam	CON	12	11	23	22	36	0	24	0	0	8	0	0	BULKD
Rostock	DE	54°05'N 12°08'E	1954	1998	loam	CON	4	4	0	4	0	0	0	0	0	0	0	0	
Speyer	DE	49°19'N 08°26'E	1984	1995	loamy sand	PAN	1	2	0	0	0	0	0	0	0	3	0	0	
Spröda	DE	51°32'N 12°26'E	1966	2010	sandy loam	CON	9	3	0	0	4	0	4	0	0	2	0	0	
Thyrow	DE	52°16'N 13°12'E	1938	2005	loamy sand	CON	9	8	0	0	6	0	6	0	0	5	0	0	BULKD
Askov	DK	55°28'N 09°07'E	1894	2002	sandy loam	ATN	16	0	0	0	6	0	6	0	0	3	0	0	BULKD
Flakkebjerg	DK	55°19'N 11°23'E	1997	2004	sandy loam	CON	0	0	10	0	2	2	2	2	2	0	0	0	pH, AGGRS, BULKD
Foulum	DK	56°30''N 09°34'E	1997	2008	sandy loam	ATN	0	0	52	0	6	6	6	4	6	2	0	12	pH, AGGRS, BULKD
Jyndevad	DK	54°54'N 09°08'E	1997	2004	coarse sandy	ATN	5	0	8	0	3	3	3	1	3	0	0	0	AGGRS, BULKD
Taastrup	DK	55°40'N 12°18'E	2007	2009	sandy loam	CON	0	0	6	0	0	0	0	0	0	0	0	0	
El Encín	ES	40°32'N 03°17'W	2010	2011	clay loam	MDS	2	0	0	12	2	2	2	2	2	0	0	0	pH, AGGRS, BULKD
Gimenells	ES	41°65'N 00°39'E	2002	2011	loam	MDS	0	0	4	0	1	1	1	1	0	0	0	0	pH, BULKD
La Higuerela	ES	40°01'N 04°26'W	1990	1999	sandy clay loam	MDS	1	0	0	0	0	0	0	0	0	0	0	1	
Oliola	ES	41°52'N 01°09'E	2002	2010	silty loam	MDM	0	0	6	0	2	0	2	0	0	0	0	0	BULKD, EARW
Grignon	FR	48°51'N 01°55'E	1875	1989	loam	ATC	6	0	0	0	0	0	0	0	0	0	0	6	
Rennes	FR	48°07'N 01°40'E	1993	2005	silty loam	ATC	0	0	0	8	4	0	0	0	0	2	0	0	
Keszthely 1	HU	46°44'N 17°13'E	1983	2010	sandy loam	PAN	13	13	0	0	8	2	8	2	2	2	0	0	pH, AGGRS, BULKD
Keszthely 2	HU	46°44'N 17°13'E	1960	2002	sandy loam	PAN	2	1	0	0	0	0	0	0	0	0	0	2	PLFA
Bologna	IT	44°33'N 11°26'E	1966	2007	silty loam	MDN	5	0	5	0	4	0	4	0	0	2	0	0	
Fidenza	IT	44°52'N 10°04'E	1985	1997	clay	MDN	2	0	0	0	0	0	0	0	0	0	0	0	pH, BULKD
Legnaro	IT	45°21'N 11°58'E	1962	2001	sandy loam	MDN	0	0	12	0	6	0	6	0	0	0	0	0	BULKD
Lodi	IT	45°18'N 09°30'E	1995	2009	sandy loam	MDN	24	5	17	5	32	0	7	0	0	6	4	0	BULKD, BAC

LTE	Country	Latitude and longitude	Start year	Latest year used	Texture	Climate	FYM	FYMm	SLU	SLUm	Y	NY	Y/F	NY/F	ANR	SOC	SOILN	MB	Other variables[a]
Tetto Frati	IT	44°53'N 07°41'E	1992	2011	loam	MDM	80	86	80	86	52	44	52	44	32	32	38	6	pH, AGGRS, BULKD, ACT, PLFA
De Merke	NL	52°03'N 06°18'E	2002	2005	loam	ATC	2	0	6	0	0	4	0	4	0	0	0	0	
Grassland	NL	51°31'N 05°42'E	2000	2004	sand	ATC	1	0	3	0	0	0	0	0	0	4	0	0	
Apelsvoll	NO	60°42'N 10°51'E	1989	2004	sandy loam	BOR	0	0	2	0	0	0	0	0	0	1	0	0	
Ås	NO	59°39'N 10°47'E	1953	1984	clay loam	NEM	0	8	0	0	0	0	0	0	0	4	4	0	ACT
Brody	PL	52°26'N 16°18'E	1999	2002	loamy sand	CON	6	6	0	0	0	0	0	0	0	12	0	0	
Grabow	PL	52°25'N 21°30'E	1979	2012	sandy loam	CON	12	0	0	0	0	0	0	0	0	4	4	0	pH
Wierzchucinek	PL	53°15'N 17°47'E	1979	1991	sandy loam	CON	1	1	0	0	0	0	0	0	0	2	0	0	
Iasi	RO	47°12'N 27°16'E	1968	2011	clay loam	CON	0	2	0	0	0	0	0	0	0	2	0	0	
Livada	RO	47°51'N 23°08'E	1961	2002	silty loam	CON	1	1	0	0	0	0	0	0	0	2	0	0	
Ultuna	SE	59°49'N 17°39'E	1956	2009	clay loam	NEM	17	0	0	0	1	0	1	0	0	2	0	6	BAC, FUNGI, PLFA
Uppsala	SE	59°38'N 17°49'E	2003	2005	silty clay	NEM	0	0	2	0	0	0	0	0	0	0	0	0	
Rakican	SI	46°38'N 14°11'E	1993	2010	loamy sand	ALS	8	24	0	0	12	0	12	0	0	4	4	0	BULKD, ACT
Barnfield	UK	51°48'N 00°22'W	1849	1973	silty clay loam	ATC	8	0	0	0	4	0	4	0	0	0	0	0	
Broadbalk	UK	51°48'N 00°22'W	1843	2006	silty clay loam	ATC	6	2	0	0	1	0	1	0	0	5	0	0	BULKD
Edinburgh	UK	55°52'N 03°12'W	1995	2004	clay loam	ATN	0	0	7	0	0	0	0	0	0	0	0	0	
Hoosefield	UK	51°48'N 00°22'W	1849	1967	silty clay loam	ATC	2	0	0	0	1	0	1	0	0	0	0	0	
Woburn	UK	51°59'N 00°37'W	1938	2006	sandy loam	ATC	5	1	0	0	0	0	0	0	0	2	0	1	PLFA
Total	**80**						**587**	**425**	**394**	**150**	**389**	**109**	**63**	**105**	**63**	**181**	**78**	**87**	

[a] pH, soil pH; AGGRS, soil aggregate stability; BULKD, soil bulk density; ACT, actynomycetes; BAC, bacteria; EARTW, earthworms (number or biomass); FUNGI, fungi; PLFA, phospholipid-derived fatty acids markers of bacteria.

Table S2. Literature sources consulted for each Long Term Experiment (LTE).

LTE	**References**	**Country**
Apelsvoll	Riley et al., 2008; Korsaeth and Eltun, 2000	NO
Ås	Uhlen, 1991	NO
Askov	Edmeades, 2003; Schjønning et al., 1994; Schjønning et al., 2005; Schjønning et al., 2002	DK
Bad Lauchstädt 1	Langer and Klimanek, 2006; Ludwig et al., 2010; Merbach and Schulz, 2013	DE
Bad Lauchstädt 2	Jäger et al., 2011	DE
Bad Salzungen 1	Zorn et al., 2009	DE
Bad Salzungen 2	Zorn et al., 2009; Zimmer et al., 2005	DE
Barnfield	Johnston et al., 2009	UK
Berlin-Dahlem 1	Barkusky et al., 2009; Ellmer et al., 2000; Sümer, 2012	DE
Berlin-Dahlem 2	Kautz et al., 2004	DE
Bologna	Triberti et al., 2008	IT
Braunschweig 1	Vogele et al., 2009	DE
Braunschweig 2	Rogasik et al., 2001	DE
Broadbalk	Blair et al., 2006; Clark et al., 2012; Ogilvie et al., 2008	UK
Brody	Blecharczyk et al., 2005	PL
Caslav	Šimon et al., 2011	CZ
Cologne	Marschner et al., 2003	DE
Darmstadt	Heitkamp et al., 2009; Heitkamp et al., 2011	DE
De Merke	Schröder et al., 2007	NL
DOK	Widmer et al., 2006; Birkhofer et al., 2008; Esperschütz et al., 2007; Leifeld et al., 2009	CH
Edinburgh	Jones et al., 2006; Jones et al., 2005	UK
El Encín	Abalos et al., 2013; Sánchez-Martín et al., 2010; Sanz-Cobena et al., 2012	ES
Fidenza	Sanz-Cobena et al., 2014	IT
Flakkebjerg	Olesen et al., 2000; Chirinda et al., 2010b	DK
Foulum	Chirinda et al., 2010a; Olesen et al., 2009	DK
Frick	Berner et al., 2008; Krauss et al., 2010	CH
Fuchsenbigl	Tatzber et al., 2009; Spiegel et al., 2010	AT
Gimenells	Biau et al., 2013	ES
Grabow	Kondratowicz-Maciejewska, 2007	PL
Grassland	van Eekeren et al., 2009	NL
Grignon	Houot and Chaussod, 1995	FR
Gross Kreutz	Zimmer et al., 2005	DE

LTE	References	Country
Grossbeeren 1	Rühlmann, 2003; Rühlmann and Ruppel, 2005; Rühlmann, 2006; Ruehlmann, 2013	DE
Grossbeeren 2	Barkusky et al., 2009	DE
Halle	Langer and Klimanek, 2006	DE
Hnevceves	Šimon et al., 2011	CZ
Hoosefield	Johnston et al., 2009	UK
Humpolec	Šimon et al., 2011	CZ
Iasi	Ailincăi and Ailincăi, 2012	RO
Ivanovice 1	Šimon et al., 2011	CZ
Ivanovice 2	Šimon et al., 2011	CZ
Jable	Cvetkov and Tajnšek, 2009; Tajnšek et al., 2013	CZ
Jyndevad	Olesen et al., 2009	DK
Keszthely 1	Kismányoky and Tóth, 2010; Kismányoky and, Tóth, 2013	HU
Keszthely 2	Hoffmann et al., 2002	HU
Kostelec	Šimon et al., 2011	CZ
La Higuerela	García-Gil et al., 2000	ES
Legnaro	Giardini et al., 1999; Giardini et al., 1995	IT
Linz	Ros et al., 2006a; Ros et al., 2006b	AT
Livada	Rogasik et al., 2004	RO
Lodi	Borrelli and Tomasoni, 2010; Ceotto et al., 2010; Tomasoni et al., 2011; Tomasoni et al., 2009	IT
Lukavec 1	Šimon et al., 2011	CZ
Lukavec 2	Šimon et al., 2011	CZ
Lukavec 3	Nedvěd et al., 2008	CZ
Melle 1	Leroy, 2008; Leroy et al., 2008	BE
Melle 2	Nevens and Reheul, 2005	BE
Melle 3	D'Hose et al., 2012	BE
Methau	Jäger et al., 2011; Albert and Grunert, 2013	DE
Müncheberg 1	Rogasik et al., 2001	DE
Müncheberg 2	Rogasik et al., 2004	DE
Oliola	Yagüe et al., 2012	ES
Pernolec	Šimon et al., 2011	CZ
Praha-Ruzyne	Šimon et al., 2011	CZ
Puch	Hege and Offenberger, 2006	DE
Rakican	Cvetkov et al., 2010; Cvetkov and Tajnšek, 2009; Tajnšek et al., 2013	SI
Rennes	Dambreville et al., 2008	FR

LTE	References	Country
Rostock	Leidel et al., 2000; Leinweber and Reuter, 1992	DE
Speyer	Bischoff and Emmerling, 2001	DE
Spröda	Albert and Grunert, 2013	DE
Suchdol	Nedvěd et al., 2008	CZ
Taastrup	Carter et al., 2012	DK
Tetto Frati	Zavattaro et al., 2012; Borda et al., 2011; Monaco et al., 2008	IT
Thyrow	Barkusky et al., 2009	DE
Trutnov	Šimon et al., 2013	CZ
Ultuna	Elfstrand et al., 2007; Witter et al., 1993; Borjesson et al., 2012; Ellmer and Baumecker, 2005	SE
Uppsala	Rodhe et al., 2006	SE
Vlaco	Leroy et al., 2009	BE
Vysoké nad Jizerou	Šimon et al., 2011	CZ
Wierzchucinek	Janowiak, 1995	PL
Woburn	Abaye et al., 2005; Maxfield et al., 2011; Murphy et al., 2007	UK

Table S3. Total number of measurements available for all indicators by treatment. Abbreviations are explained in Table 1

Indicator	FYM	FYMm	SLU	SLUm	min	0N
Indicators reported in figures or tables						
Y	153	102	99	35	209	95
NY	28	34	32	15	62	34
Y/F	143	95	87	26	198	-
NY/F	28	34	28	15	62	2
ANR	19	16	18	10	36	-
SOC	84	59	27	11	89	51
SoilN	35	21	10	12	38	8
MB	45	16	21	5	56	40
Indicators not reported in figures or tables						
pH	6	1	3	1	10	4
AGGRS	4	1	4	1	5	2
BULKD	6	0	3	2	7	3
ACT	0	5	5	0	5	5
BAC	3	1	1	0	4	4
EARTW	0	4	5	1	6	4
FUNGI	3	6	6	0	9	9
PLFA	6	6	5	0	9	9

Table S4. Regression coefficients and significance as estimated by the Multiple Linear Regression model applied to selected sets of factors affecting different indicators. Abbreviations are explained in Table 1. Response ratio indicators were transformed using natural logarithm before analysis.

Estimated marginal means reported in Table 3 can be calculated as:

exp (intercept) × exp (regression coefficient of the factor level) × exp (sum of mean regression coefficients of the other factors)

(a) Results for FYM/FYMm

Factor	Level	Crop indicators										Soil indicators					
		RR_{Y}		RR_{NY}		$RR_{Y/F}$		$RR_{NY/F}$		RR_{ANR}		RR_{SOC}		RR_{SoilN}		RR_{MB}	
		B	***Sig.***	B	***Sig.***	B	***Sig.***	*B*	***Sig.***	B	***Sig.***	B	***Sig.***	B	***Sig.***	B	***Sig.***
Intercept		-0.281	*0.011*	0.084	*0.684*	-0.453	*0.001*	-0.334	*0.126*	0.167	*0.657*	0.639	*0.000*	0.399	*0.002*	-0.395	*0.198*
Climate	**Northern**	#N/D		#N/D		#N/D		#N/D		#N/D		0.370	*0.041*	#N/D		#N/D	
	Eastern	0.266	*0.030*	0.147	*0.493*	0.070	*0.519*	-0.408	*0.070*	-2.453	*0.000*	0.224	*0.070*	-0.237	*0.168*	-0.567	*0.000*
	Western	0.000		0.000		0.000		0.000		#N/D		0.000		0.000		0.000	
	Southern	0.381	*0.000*	0.048	*0.809*	0.193	*0.125*	-0.018	*0.933*	0.000		0.396	*0.001*	-0.105	*0.442*	-0.024	*0.827*
Crop	**Long duration**	0.274	*0.000*	-0.105	*0.383*	0.256	*0.008*	-0.073	*0.568*	-0.314	*0.464*	-0.419	*0.027*	#N/D		0.239	*0.376*
	Spring	0.093	*0.020*	-0.152	*0.078*	0.085	*0.019*	-0.154	*0.091*	-0.332	*0.430*	-0.665	*0.000*	-0.017	*0.746*	0.621	*0.015*
	Spring short	0.261	*0.344*	-0.436	*0.000*	0.837	*0.013*	-0.329	*0.000*	0.112	*0.576*	#N/D		#N/D		#N/D	
	Winter	0.000		0.000		0.000		0.000		0.000		0.000		#N/D		0.000	
	Combined	-0.042	*0.466*	-0.290	*0.007*	0.038	*0.623*	-0.092	*0.415*	-0.216	*0.510*	-0.712	*0.000*	0.000		0.533	*0.032*
Soil texture	**Light**	0.193	*0.000*	0.141	*0.178*	0.000	*0.996*	0.554	*0.000*	1.399	*0.000*	0.089	*0.032*	0.008	*0.955*	0.488	*0.000*
	Medium	0.000		0.000		0.000		0.000		0.000		0.000		0.000		0.000	
	Heavy	0.208	*0.107*	#N/D		0.024	*0.880*	#N/D		#N/D		0.000		#N/D		#N/D	
Tillage depth	**surface**	#N/D		0.172	*0.477*	#N/D		0.585	*0.022*	0.000		0.000		#N/D		#N/D	
	1-10 cm	#N/D		0.000		#N/D		0.000		#N/D		#N/D		#N/D		#N/D	
	11-20 cm	0.106	*0.005*	0.089	*0.169*	-0.088	*0.062*	0.058	*0.395*	1.191	*0.001*	0.018	*0.672*	-0.149	*0.018*	0.132	*0.046*
	21-30 cm	0.000		0.000		0.000		0.000		0.000		0.000		0.000		0.000	
	>30 cm	#N/D		#N/D		#N/D		#N/D		#N/D		#N/D		#N/D		#N/D	
Duration	**1-5 yrs**	-0.030	*0.891*	0.000		-0.558	*0.035*	0.000		#N/D		0.000		0.000		0.061	*0.614*
	6-10 yrs	-0.175	*0.144*	-0.114	*0.571*	-0.334	*0.044*	-0.114	*0.590*	0.000		0.368	*0.000*	#N/D		-0.082	*0.538*
	11-20 yrs	-0.001	*0.984*	0.197	*0.041*	-0.108	*0.039*	0.291	*0.004*	0.000		-0.008	*0.906*	0.000		0.000	
	>20 yrs	0.000		0.000		0.000		0.000		0.000		0.000		0.000		0.000	
N fertilizer ratio (FR)	**<0.8**	-0.151	*0.000*	-0.101	*0.374*	0.967	*0.000*	0.386	*0.001*	-0.294	*0.136*	-0.118	*0.054*			-0.422	*0.000*
	0.8-1.2	-0.098	*0.004*	-0.112	*0.053*	0.338	*0.000*	0.139	*0.023*	0.270	*0.016*	-0.113	*0.004*	-0.073	*0.251*	-0.148	*0.016*
	>1.2	0.000		0.000		0.000		0.000		0.000		0.000		0.000		0.000	
Addition of mineral N	**FYM**	-0.228	*0.000*	-0.192	*0.000*	-0.078	*0.042*	-0.081	*0.160*	-0.192	*0.066*	0.031	*0.385*	0.076	*0.236*	0.291	*0.000*
	FYMm	0.000		0.000		0.000		0.000		0.000		0.000		0.000		0.000	

(b) Results for SLU/SLUm

Factor	**Level**	**Crop indicators**										**Soil indicators**					
		RR_{Y}		**RR_{NY}**		**$RR_{Y/F}$**		**$RR_{NY/F}$**		**RR_{ANR}**		**RR_{SOC}**		**RR_{SoilN}**		**RR_{MB}**	
		B	***Sig.***	B	***Sig.***	B	***Sig.***	B	***Sig.***	B	***Sig.***	B	***Sig.***	B	***Sig.***	B	***Sig.***
Intercept		-0.640	*0.000*	-0.463	*0.009*	-1.124	*0.000*	0.162	*0.523*	0.103	*0.691*	0.060	*0.814*	0.213	*0.000*	0.197	*0.000*
Climate	**Northern**	#N/D		#N/D		#N/D		#N/D		#N/D		-0.201	*0.086*	#N/D		#N/D	
	Eastern	0.121	*0.151*	#N/D		-0.039	*0.810*	#N/D		#N/D		0.060	*0.690*	#N/D		#N/D	
	Western	0.000		0.000		0.000		0.000		0.000		0.000		0.000		0.000	
	Southern	0.464	*0.000*	0.305	*0.049*	0.503	*0.008*	-0.203	*0.357*	-0.541	*0.347*	0.013	*0.945*	-0.158	*0.020*	-0.012	*0.840*
Crop	**Long duration**	0.121	*0.097*	0.247	*0.058*	-0.042	*0.779*	-0.256	*0.167*	0.250	*0.398*	0.208	*0.218*	#N/D		#N/D	
	Spring	0.129	*0.000*	0.207	*0.076*	0.048	*0.538*	-0.300	*0.072*	0.091	*0.738*	-0.024	*0.407*	-0.065	*0.004*	0.000	
	Spring short	0.515	*0.004*	#N/D		0.672	*0.053*	#N/D		#N/D		#N/D		#N/D		#N/D	
	Winter	0.000		0.000		0.000		0.000		0.000		#N/D		#N/D		#N/D	
	Combined	0.077	*0.146*	0.178	*0.128*	0.015	*0.917*	-0.158	*0.344*	0.277	*0.486*	0.000		0.000		0.000	
Soil texture	**Light**	0.263	*0.000*	0.076	*0.618*	0.571	*0.000*	0.103	*0.638*	0.000		0.056	*0.599*	#N/D		-0.046	*0.362*
	Medium	0.000		0.000		0.000		0.000		0.000		0.000		0.000		0.000	
	Heavy	#N/D		#N/D		#N/D		#N/D		#N/D		#N/D		#N/D		#N/D	
Tillage depth	**surface**	#N/D		#N/D		#N/D		#N/D		#N/D		0.000		#N/D		#N/D	
	1-10 cm	0.439	*0.001*	0.097	*0.405*	0.389	*0.125*	-0.374	*0.025*	0.000		#N/D		#N/D		#N/D	
	11-20 cm	0.434	*0.000*	0.000		0.659	*0.003*	0.000		0.000		-0.005	*0.959*	0.000		0.000	
	21-30 cm	0.423	*0.000*	0.000		0.480	*0.014*	0.000		0.000		0.000		0.000		0.000	
	>30 cm	0.000		#N/D		0.000		#N/D		#N/D		#N/D		#N/D		#N/D	
Duration	**1-5 yrs**	-0.121	*0.286*	0.000		-0.166	*0.450*	0.000		0.000		0.000		0.000		0.050	*0.370*
	6-10 yrs	-0.328	*0.000*	-0.115	*0.361*	-0.449	*0.010*	-0.100	*0.578*	#N/D		0.121	*0.489*	#N/D		0.000	
	11-20 yrs	-0.131	*0.033*	0.000		-0.083	*0.479*	0.000		0.000		0.061	*0.368*	0.000		0.000	
	>20 yrs	0.000		0.000		0.000		0.000		#N/D		0.000		#N/D		#N/D	
N fertilizer ratio (FR)	**<0.8**	-0.193	*0.000*	0.000		0.517	*0.000*	0.000		0.000		0.000		#N/D		0.000	
	0.8-1.2	-0.178	*0.000*	-0.030	*0.857*	0.348	*0.000*	0.324	*0.171*	0.316	*0.491*	0.053	*0.155*	0.142	*0.005*	0.000	
	>1.2	0.000		0.000		0.000		0.000		0.000		0.000		0.000		0.000	
Addition of mineral N	**SLU**	-0.136	*0.001*	-0.153	*0.016*	-0.330	*0.000*	-0.180	*0.047*	-0.440	*0.015*	-0.029	*0.284*	-0.022	*0.310*	0.000	
	SLUm	0.000		0.000		0.000		0.000		0.000		0.000		0.000		0.000	

S1. Description of the data set

Figure S1 reports the statistical distribution of crop and soil indicators across all experiments. Maize, wheat, and barley represented those crops with the most available and complete data on yield (Figure S1a) and N in yield (Figure S1b). Among them, maize silage showed the highest measures of average yield, N in yield (251 kg N/ha in fertilized treatments), and variability. The maize yields for SLUm treatments were reported in three LTEs only. Maize grain had the second largest NY among arable crops (184 kg N/ha). All reports of wheat and barley yields came from LTEs located in northern and central Europe with three exceptions: wheat from Bologna (IT) and Legnaro (IT) and barley from El Encín (ES). Wheat and barley NY in fertilized treatments averaged 79 kg N/ha (Figure S1b). Unfortunately, only 3 of 59 LTEs of potato—studied mostly in central and northern Europe in response to FYM application—reported NY data.

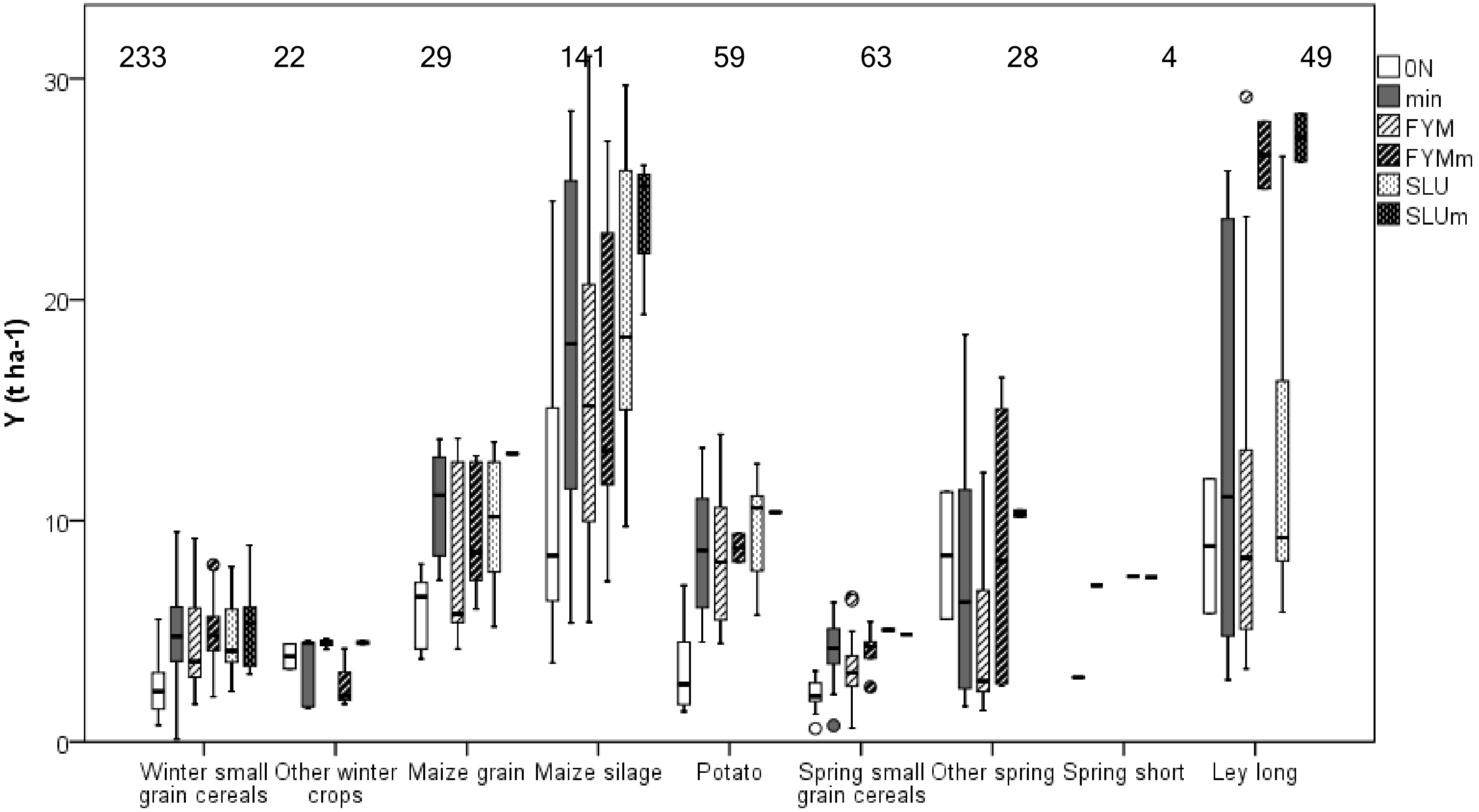
All three indicators used to evaluate nitrogen use efficiency (Y/F, NY/F and ANR) revealed high variability across the studied LTEs, but varied less among crop types than did yield. The indicator Y/F (Figure S1c) displayed high variability within crop types. The ratio "N in yield to N applied with fertilizer" (NY/F, Figure S1d) across all fertilized treatments averaged 1.02 kg N/kg N. Only a small number of LTEs included measures for apparent N recovery (ANR, Figure S1e), the third efficiency indicator. ANR was slightly negative in some winter cereal and maize LTEs. Overall, the mean for all crop types (n=99) was 0.39 kg N/kg N.

Nitrogen in yield in the unfertilized controls (Figure S1b) is a proxy for N made available through natural processes (atmospheric deposition and N mineralization). Nitrogen in yield in the unfertilized controls of 11 experiments averaged 81 kg N/ha. In those of winter crops (n=7 crops), NY averaged 39 kg N/ha, while these values for summer crops (spring + spring short; n=15 crops) averaged 100 kg N/ha. Within summer crops, the unfertilized control of maize silage was particularly high, but the dataset included the Tetto Frati (IT) experiment, in which NY was skewed by the very high value of unfertilized control in maize after meadow (N fixation of 258 kg N/ha) *versu*s that after continuous maize (125 kg N/ha).

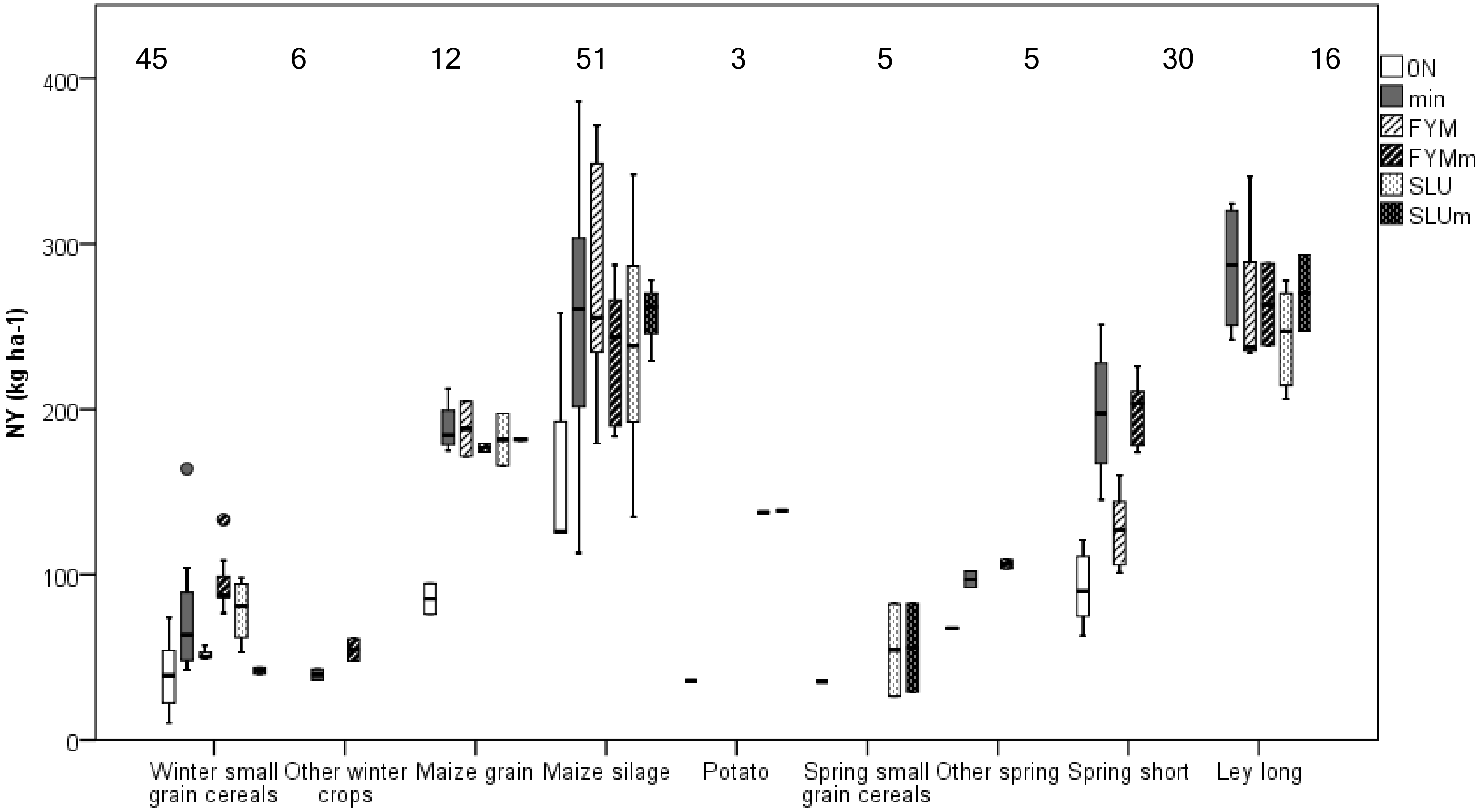
As reported in Figures S1f and S1g, the means for soil organic C (SOC) and N (SoilN) in the tilled layer (in most cases, 20 to 30 cm deep), were 13.7 g C/kg (n=269) and 1.32 g N/kg (n=112) in fertilized treatments. Most of these results came from light- or medium-textured soils. We found no marked differences in SOC or SoilN among soil types or fertilization treatments. In unfertilized controls, the statistical distributions of SOC (n=51) and SoilN (n=12) were similar to the fertilized treatments, but the mean value was 10% lower.

Figure S1. Boxplot of Y (yield), NY (N in yield), Y/F (yield/applied N), NY/F (N in yield/applied N), and ANR (apparent N recovery) indicators, each as a function of crop (a-e). Boxplot of SOC (soil organic carbon) and SoilN (soil nitrogen), each as a function of soil texture (f, g). In all plots, box size indicates 25th and 75th percentiles and the dark line in the middle of each box is the median value. The T-bars extend 1.5 times beyond box height, or if no case has a value in that range, then to the minimum or maximum value. Points denote outliers; asterisks or stars denote extreme values. Crop types and soil textures are defined in Table 1.

a)

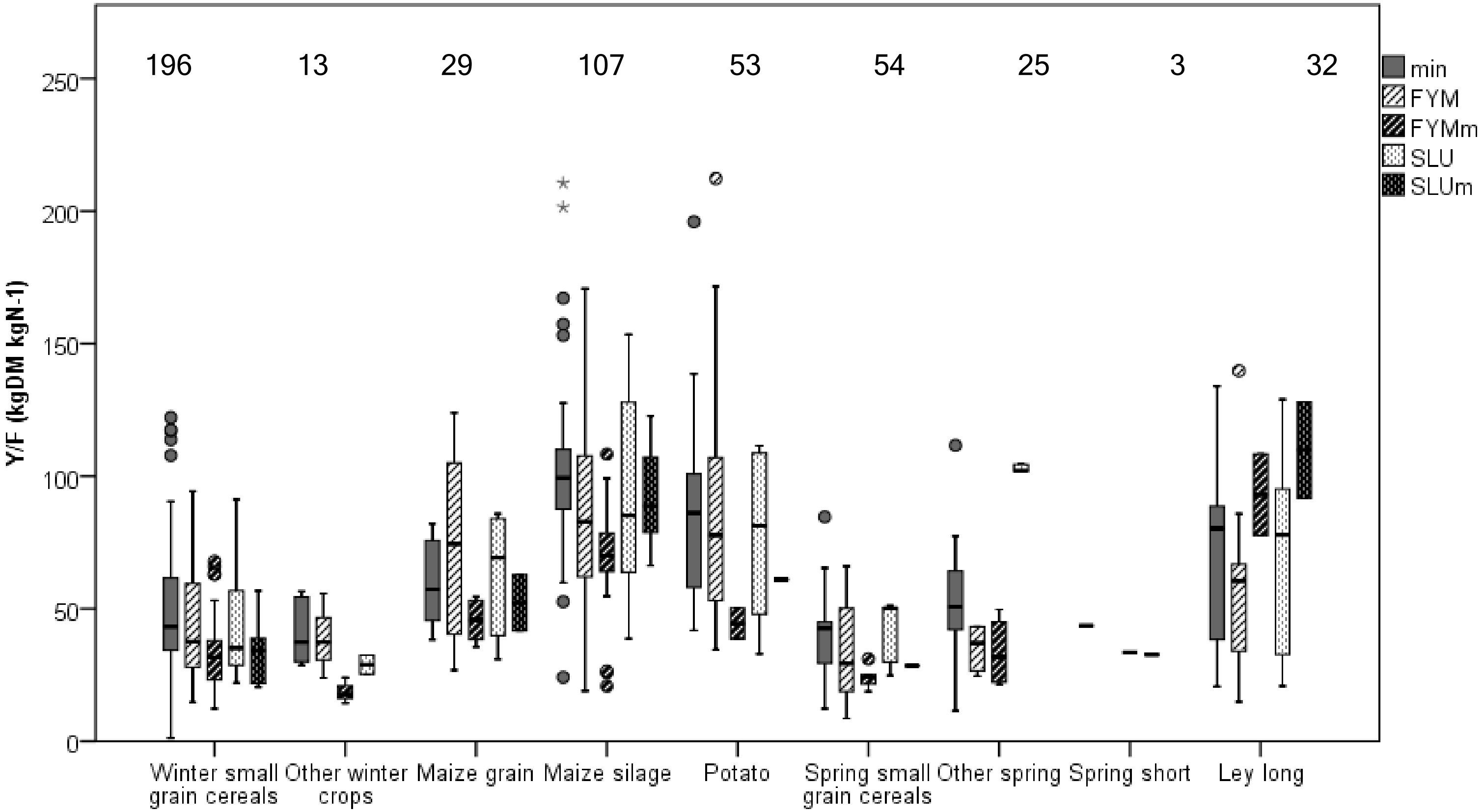

233
22
29
141
59
63
28
4
49
Y (t ha-1)
0
10
20
30
Winter small grain cereals
Other winter crops
Maize grain
Maize silage
Potato
Spring small grain cereals
Other spring
Spring short
Ley long
0N
min
FYM
FYMm
SLU
SLUm

b)

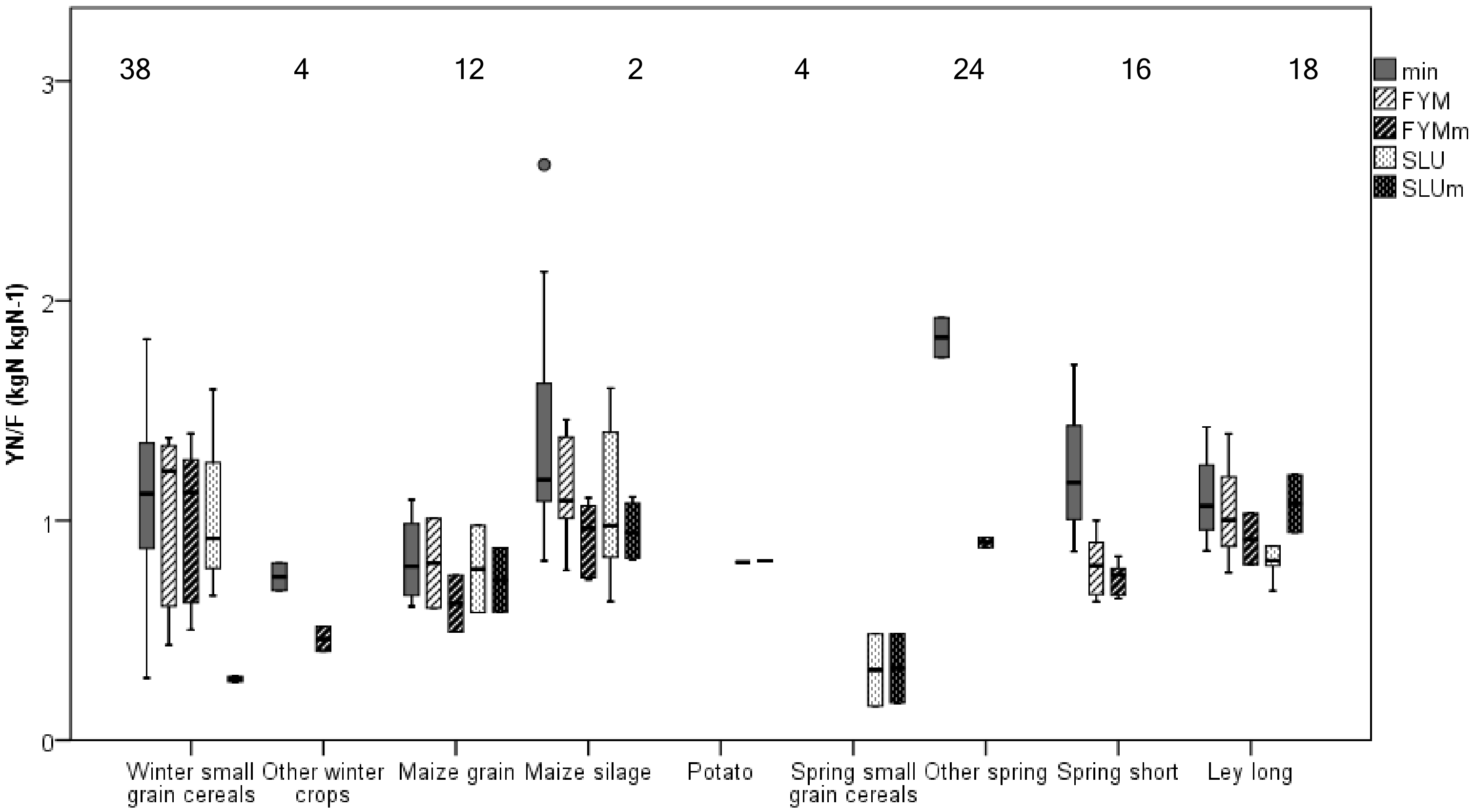


45
6
12
51
3
5
5
30
16
400
300
200
100
0
NY (kg ha-1)
Winter small grain cereals
Other winter crops
Maize grain
Maize silage
Potato
Spring small grain cereals
Other spring
Spring short
Ley long
0N
min
FYM
FYMm
SLU
SLUm

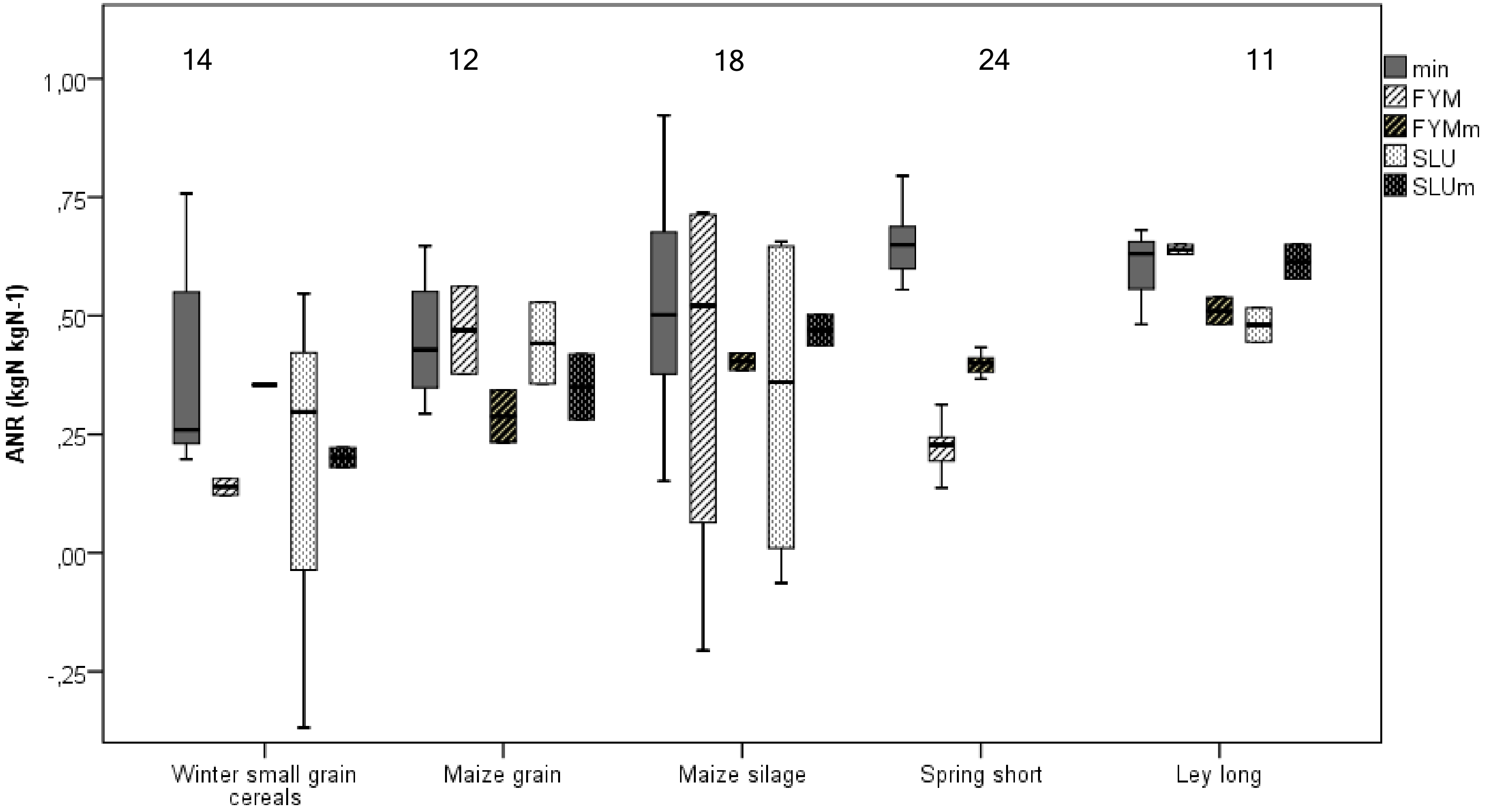
c)


196
13
29
107
53
54
25
3
32
min
FYM
FYMm
SLU
SLUm
Y/F (kgDM kgN-1)
0
50
100
150
200
250
Winter small grain cereals
Other winter crops
Maize grain
Maize silage
Potato
Spring small grain cereals
Other spring
Spring short
Ley long

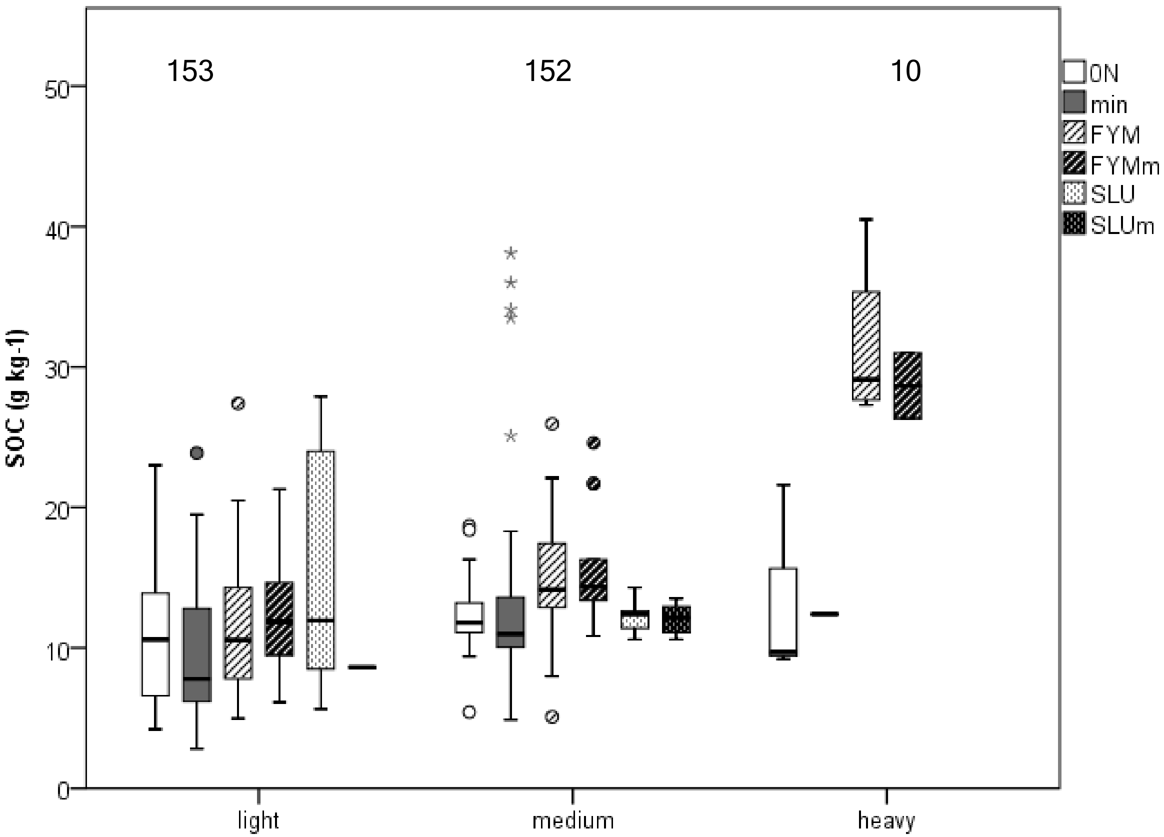
d)


38
4
12
2
4
24
16
18
min
FYM
FYMm
SLU
SLUm
YN/F (kgN kgN-1)
3
2
1
0
Winter small grain cereals
Other winter crops
Maize grain
Maize silage
Potato
Spring small grain cereals
Other spring
Spring short
Ley long

e)


14
12
18
24
11
1,00
,75
,50
,25
,00
-,25
ANR (kgN kgN-1)
Winter small grain cereals
Maize grain
Maize silage
Spring short
Ley long
min
FYM
FYMm
SLU
SLUm

f)


153
152
10
0N
min
FYM
FYMm
SLU
SLUm
SOC (g kg-1)
0
10
20
30
40
50
light
medium
heavy

g)