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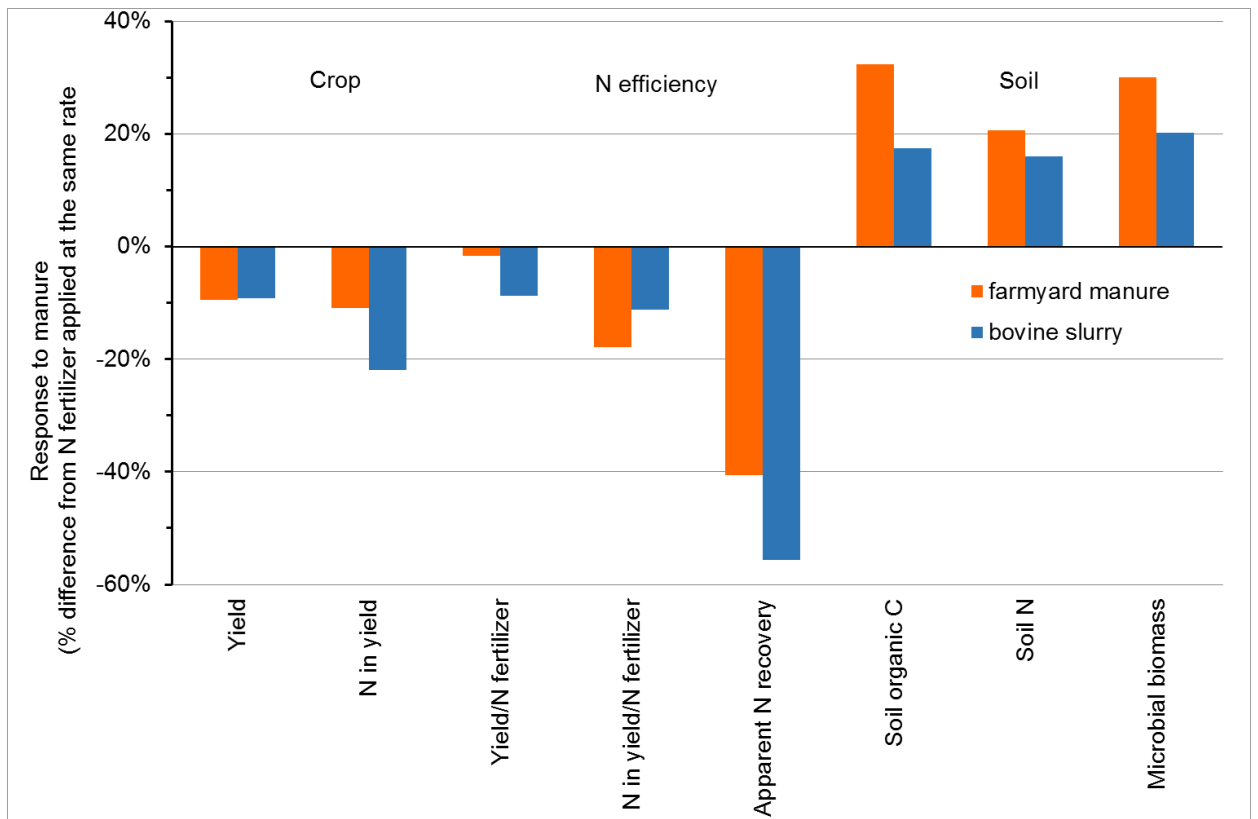
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1 Graphical abstract



2

1 **Research highlights**

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

1 **Agronomic effects of bovine manure: a review**

2 **of long-term European field experiments**

3

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24 **Abstract**

25 To evaluate the agronomic value of animal manure, we quantified the effects of pedo-
26 climatic, crop and management factors on crop productivity, N use efficiency, and soil
27 organic matter, described with simple indicators that compare manures with mineral
28 fertilizers. We selected 80 European long-term field experiments that used bovine
29 farmyard manure or bovine liquid slurry, alone (FYM and SLU) or combined with
30 mineral fertilizers (FYMm and SLUm), and compared them to mineral fertilizer only
31 reference treatments. We collected 5570 measurements from 107 papers. FYM produced
32 slightly lower crop yields (-9.5%) when used alone and higher (+11.3%) yields when used
33 in combination with N fertilizer (FYMm), compared to those obtained using mineral
34 fertilizers only. Conditions promoting manure-N mineralization (lighter soil texture,
35 warmer temperature, longer growing season, and shallower incorporation depth)
36 significantly increased the effect of FYM/FYMm on crop yield and yield N. The
37 production efficiency of FYM (yield:N applied ratio) was slightly lower than that of
38 mineral fertilizers (-1.6%). The apparent N recoveries of FYM and FYMm were 59.3%
39 and 78.7%, respectively, of mineral fertilizers. Manured soils had significantly higher C
40 (+32.9% on average for FYM and FYMm) and N (+21.5%) concentrations. Compared to
41 mineral fertilizers, yield was reduced by 9.1% with SLU, but not with SLUm. Influencing
42 factors were similar to those of FYM/FYMm. Efficiency indicators indicated SLU (but
43 not SLUm) was less effective than mineral fertilizers. Slurry significantly increased SOC
44 (on average for SLU and SLUm by +17.4%) and soil N (+15.7%) concentrations. In
45 conclusion, compared to mineral N fertilizers, bovine farmyard manure and slurry were

46 slightly less effective on the crop, but determined marked increases to SOC and soil N,
47 and thus, to long-term soil fertility maintenance.

48 **Keywords**

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

50 **1. Introduction**

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

59 Since the early 1990s, European legislation has regulated animal production, and
60 indirectly the use of animal manure, with a three-pronged objective: protecting human
61 health, preserving environmental quality, and better equilibrating milk and dairy markets
62 (Oenema, 2004). This legislation requires that management criteria, such as the best rate
63 and timing of manure application, are adapted to specific local conditions (soil, climate,
64 crop, manure type, farm organization). Consequently, official ranges of efficiency
65 indicators have been developed in various countries to guide the application of manures
66 and mineral N and P fertilizers. These official values for various European countries are
67 reported by Webb et al. (2013), who list the N fertilizer value of farmyard manure and
68 slurry relative to mineral fertilizers. For bovine farmyard manure, legal N fertilizer value
69 ranges between 10 and 65%, depending on the country. Higher values are used in Italy,
70 the Netherlands, and Denmark, while the UK uses a much lower coefficient. For slurry,
71 N fertilizer values varied within a narrower range (40-70%), with lower values again used

72 in the UK. Values for slurry are always above those of farmyard manure, with the
73 exception of Italy, where the two types of manures are valued the same. Some countries
74 differentiate soil- or season- or crop- or management-specific N fertilizer values. Ideally,
75 official N fertilizer values represent a compendium of scientific knowledge on the crop
76 response to amendments under local conditions.

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

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

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

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

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

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

137 **2. Materials and methods**

138 **2.1. Database**

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

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

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

155 The 80 LTEs considered in this review ensure wide coverage of European climates, soils,
156 and duration (range: three to more than 150 years), with half of the experiments started
157 before 1979. Germany provided the largest number (22) of experiments, Eastern Europe
158 contributed 23 experiments, while Southern Europe was represented by nine LTEs. Light

159 texture soils characterized 53% of the LTEs considered; 38% were of medium texture and
160 only 10% were fine. The eastern European climate was most represented (59% of LTEs),
161 followed by the western (25%), southern (11%), and northern (5%) climates. Section 2.4
162 and Table 1 report the soil and climate definitions.

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

167 **2.2. Treatments**

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

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

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

183 **2.3. Data analyses**

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

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

199 Indicators NY/F and ANR describe fertilizer efficiency differently. ANR represents the
200 fraction of added N that is taken up by the crop, and the 0N treatment serves to estimate
201 the sum of soil N supply and N deposition. NY/F is a widely used indicator for N use
202 efficiency (Zhang et al., 2015). It is, admittedly, a rough expression for N use efficiency

203 because NY/F is larger than ANR as long as the unfertilized soil in the 0N treatment
204 continues to supply N to the crop. In our database, however, there were only few data (16
205 LTEs) permitting the calculation of ANR, which requires observations on an unfertilized
206 control (0N).

207 The soil indicators common to most LTEs were: soil organic carbon concentration (SOC),
208 soil total N concentration (SoilN), microbial biomass (often expressed as microbial
209 biomass C, sometimes as microbial biomass N, or as just biomass; MB), and all referred
210 to the tilled layer. Other indicators were reported less often: microbiological indicators,
211 pH, and soil physical indicators (Table S3). Because of their more frequent occurrence in
212 the database, we preferred SOC and SoilN concentrations (g/kg) over SOC and SoilN
213 stocks (g/m² or kg/ha). Where we found data expressed as SOC and SoilN stocks, these
214 were converted back to concentrations using reported soil bulk density and sampling
215 depth.

216 Both crop and soil indicators were standardized against values found in the reference
217 treatment (mineral fertilizer only), and expressed as a Response Ratio (RR): the value in
218 the manured treatment divided by that in the reference treatment. Therefore, an RR value
219 of 1 implies that the manure performed equally well as the reference. For cases where RR
220 indeed reaches a value of 1 or more, performance of the manure can be said to be at least
221 equal to that of mineral fertilizer. There is one obvious caveat here if we wish to apply
222 this approach to N use efficiency indicators: ideally, manures or manure-fertilizer
223 combinations are compared versus their mineral-fertilizer-only reference at the same total
224 N rate. However, N rates in LTEs are usually unequal between manured and reference
225 treatment and thus such direct comparison was not possible. This is why we introduced

226 the variable FR, to indicate by how much the total-N rate in manure (F_{man}) differed from
227 the mineral fertilizer N rate used as reference (F_{min}): $FR = F_{\text{man}}/F_{\text{min}}$. We used it to define
228 the subset of data where FR was between 0.8 and 1.2, and will refer to that subset as the
229 “central FR class data”.

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

234 **2.4. Statistical analysis**

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

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

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

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

268 We used a Type III Wald Chi-square statistic to test the effect of each factor. To separate
269 individual factor means that were different at a $p < 0.05$, we used a pairwise Bonferroni

270 test. Plots of residuals versus fitted values revealed that the variance was generally
271 homogeneous. The linear model was fitted using the GENLIN procedure of SPSS 22.0.

272 **3. Results**

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

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

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

296 **3.1. Farmyard manure (FYM and FYMm)**

297 **3.1.1. Crop**

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

301 The MLR model (Table 3a) showed that all factors except duration (so: climate, crop
302 type, soil type, tillage depth, N fertilizer ratio, and supplement with mineral fertilizer)
303 significantly affected RR_Y ($P < 0.05$). RR_Y was higher in Southern and Eastern Europe
304 than in Western Europe, and greater in long duration crops than in winter and combined
305 crops. Furthermore, RR_Y was greater on light-textured soils than on medium-textured
306 soils, and greater with shallow (11-20 cm) than with deeper tillage (21-30 cm). Manured
307 treatment yields exceeded the reference yields if N applied in FYM/FYMm exceeded the
308 reference N rate by 20% or more ($FR > 1.2$), likely a direct effect of a higher N rate.
309 Finally, supplementing FYM with mineral N (FYMm) increased RR_Y significantly (Table
310 3a).

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

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

317 The N offtake/fertilizer ratio ($RR_{NY/F}$) and the apparent N recovery ratio (RR_{ANR}) were
318 both significantly lower than 1, for FYM as well as FYMm (Table 2). With values of
319 0.716 (FYM) and 0.722 (FYMm) in the central class, we consider the RR_{ANR} values
320 relatively high. Factors affecting $RR_{NY/F}$ were soil texture (light > medium), climate type
321 (Southern > Eastern), and crop type (winter > spring short). No significant effects by the
322 respective factors were identified for RR_{ANR} , where only few data were available.

323 **3.1.2. Soil**

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

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

336 “0.8-1.2” > class “<0.8”), and of mineral N supplements (no supplement > with
337 supplement).

338 The few measurements available for soil physical properties (data not presented in figures
339 or tables) indicated no significant differences between manured and reference treatments.

340 We found only non-significant changes in aggregate stability ($n=4$ measurements) and in
341 soil bulk density ($n=4$), both for FYM. While we registered a significant increase in
342 FYMm of actinomycetes (+16.7%, $n=5$, $p = 0.020$) and earthworms (+155.5%, $n=4$, $p =$
343 0.024), we found a non-significant increase in fungi ($n=6$).

344 **3.2. Slurry**

345 **3.2.1. Crop**

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

351 Despite the fairly narrow range in RR_Y , the MLR (Table 3b) again identified influencing
352 factors, and they are similar to those found for FYM/FYMm. Patterns shared with
353 FYM/FYMm are that RR_Y was larger in Southern than in other climates, larger in spring
354 crops than in winter crops, larger in light-textured than other soils. Deep incorporation
355 (>30 cm) resulted in significantly lower RR_Y , an effect not documented for FYM/FYMm
356 for lack of data. While the effect of experiment duration was not significant for
357 FYM/FYMm, it seems erratic in the SLU/SLUm dataset, although the set is admittedly
358 unbalanced with only few data for the short duration. In any case, the RR_Y value for long

359 duration (> 20 years) based on 60 records is very close to 1. Final observations are that
360 high FR (>1.2) had significant positive effect on yield and that, as with farmyard manure,
361 fertilizer supplements in SLUm resulted in increased RR_Y (Table 3b).
362 $RR_{Y/F}$ was affected by climate, texture, and by mineral N supplements (Table 3b). As
363 with yield, a southern climate, light soil texture and shallow incorporation (11-20cm)
364 rendered SLU/SLUm an efficient N source as reflected by high $RR_{Y/F}$. In contrast, deep
365 incorporation of the slurry, and a high FR value (>1.2) had negative impacts on Y/F, the
366 latter possibly due to excess N. At a value of 0.444, mean RR_{ANR} was significantly below
367 1 for SLU, but not for SLUm (0.565; Table 2).

368 **3.2.2. Soil**

369 Similar to FYM, slurry increased all three soil indicators significantly relative to the use
370 of mineral fertilizer (Table 2). The high mean RR values for each of these indicators in
371 SLU treatments are matched by exactly the same means for SLUm. Based on an average
372 of SLU and SLUm (Table 2), SOC and SoilN increased by 17.4% and 15.7%,
373 respectively, relative to the mineral fertilizer reference. Very similar values were obtained
374 for the central class of FR. RR_{SOC} and RR_{SoilN} were significantly affected by climate type
375 (Table 3b), but in both cases the contrast relies on a single data pair ($n=1$) and should
376 therefore be ignored. Significant factors for RR_{SoilN} included crop type (combined crops
377 $>$ spring crops) and FR (but cases are again too few here). Model outcomes (Table 3b)
378 also show that both SOC and SoilN increments from SLU/SLUm were independent of
379 the share of mineral N (which is larger in SLUm). This means that slurry can help build
380 SOC and SoilN pools irrespective of its large fraction of mineral N.

381 Microbial biomass increased significantly (+20.3%) in both SLU and SLUm (Table 2)
382 relative to the reference. These increases were of about the same size as those for SOC.
383 No significant factors were detected for RR_{MB} .
384 The few measurements available for soil physical properties (data not presented in figures
385 or tables) did not show important effects in the SLU treatment relative to the reference.
386 We found only a non-significant increase in aggregate stability ($n=2$) and a reduction in
387 soil bulk density ($n=3$). Biological indicators (data not shown) revealed a significant
388 increase of actinomycetes (+16.6%, $n=5$, $p = 0.001$) for SLU. Non-significant effects
389 ($n=5$) were also found for earthworms (number or biomass) in SLU.

390 **4. Discussion**

391 **4.1. Farmyard manure**

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

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

412 (Cusick et al., 2006; Schröder et al., 2013). Another possible explanation is that duration
413 of FYM application could influence crop productivity to an extent that is too variable
414 with experimental conditions to emerge as statistically significant. When all N was
415 supplied using FYM, crop productivity was decreased, while when some supplied N came
416 from mineral fertilizers, as in the FYMm treatment, it was instead increased to a larger
417 extent than when all N was given as mineral, as evidenced by $RR_Y = 1.113$ (Table 2). Our
418 results for FYM/FYMm are in line with Edmeades (2003), who analyzed various
419 experiments in which FYM or FYMm was used and who reported an average RR_Y of
420 0.95. The increased yield response to manure + mineral fertilizer compared to mineral
421 fertilizer only is frequently observed in field experiments (e.g. Kong et al., 2007; Pan et
422 al., 2009; Shah et al., 2009; Liang et al., 2013; Pincus et al., 2016) and the reason could
423 be due to other positive effects of manure other than N supply, such as other nutrients,
424 soil organic matter increase, improvement of soil physical and chemical properties,
425 stimulation of soil microorganism activities, and minor losses (Singh et al., 2001; Sanz-
426 Cobena et al., 2017). In fact, Abbasi and Khaliq (2016) in an incubation study observed
427 that mineral N release from fertilizer was slowed down in the presence of organic sources
428 because soil microbes immobilized mineral N to decompose the organic compounds, and
429 this resulted in a longer persistence and retention of N in the soil mineral pool.

430 The production efficiency of FYM was similar to that of mineral fertilizers, as testified
431 by a $RR_{Y/F}$ which was not significantly different from 1 (Table 2). We hypothesized that
432 the markedly higher standard deviation of $RR_{Y/F}$ *versus* RR_Y was due to Y/F decrease as
433 the fertilizer rate increased, compared to crop yield that did not respond strongly to
434 fertilizer rates at the tested levels. The MLR confirmed this hypothesis by identifying N

435 fertilizer ratio (FR) as one of the most influential factors to explain $RR_{Y/F}$ variability
436 (Table 3a). Whether mineral fertilizer was added or not did not significantly affect the
437 $RR_{Y/F}$ (Table 3a), but the reason for this remains unclear.

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

446 The crop uptake efficiency of manure N was significantly lower than that of mineral N in
447 the reference treatment, as indicated by $RR_{NY/F}$ and RR_{ANR} (Table 2). The difference
448 between NY/F and ANR lies in the fact that NY/F does not take into account the
449 unfertilized control, while ANR does. The crop N offtake in the unfertilized control
450 (Figure S1b) was high due to high N availability derived from soil mineralization and to
451 a lesser extent from atmospheric deposition (Tipping et al., 2012). High soil N
452 mineralization is consistent with factors that increase NY/F and ANR of FYM: southern
453 climate and light soil texture (Table 3a). In addition, the same conditions are associated
454 with higher microbial biomass in FYM/FYMm than in the reference treatment (Table 3a).
455 As for yield, we expected that experiment duration would affect ANR, which normally
456 increases over time because of residual effects. However, in this case also we found a
457 lack of significance for duration on ANR (Table 3a), probably for the same reason as that

458 outlined for yield – stabilization of manure effects after the first 10 years (Schröder et al.,
459 2013). Following repeated FYM applications to soil, indeed, recalcitrant compounds not
460 mineralized in the short term are gradually and slowly decomposed in the long term
461 (Muñoz et al., 2003). This gives rise to an increase of N mineralization and thus of crop
462 N availability over time (Indraratne et al., 2009). Gutser et al. (2005) reported mineral
463 fertilizer equivalents (same as RR_{ANR}) of 10-20% for solid manure in the first year of
464 application, and of 40-50% for the longer term, which is roughly consistent with our value
465 of 59.3% for FYM, that includes short and long term effects. Webb et al. (2013) indicated
466 that the sum of N availability in the short term (application year) and long term (residual
467 effects between one and 10 years) averages 50-80% for all manure types (solid and
468 liquid). All these findings are in contrast with officially recommended N fertilizer
469 replacement values of 30% to 60% (first-year and residual effects combined) (Webb et
470 al., 2013; Schröder et al., 2013).

471 A SOC increase in the manured treatment, as opposed to the reference treatment (Table
472 2), was expected because C was applied in the manured treatments, but not in the
473 reference treatment with mineral fertilizers. Even if part of manure C is decomposed by
474 soil microorganisms, part of it remains in the soil and thus contributes to long-term C
475 storage. For SoilN we have a different situation, because similar amounts of this element
476 are supplied in both manured and reference treatments. The increase of SoilN in manured
477 treatments compared to reference (Table 2) is thus due to the fact that part of supplied N
478 is recalcitrant to decomposition. Indeed, the fraction of applied manure N not utilized by
479 the crop was greater in FYM and in FYMm than in the reference treatment, as shown by
480 $RR_{NY} < 1$ (at equal N supplied; Table 2). Evidence from the literature confirms that

481 manure C and N can partially remain in the soil after the year of application. Edmeades
482 (2003) analyzed experiments in which FYM was used; for nine experiments, the RR_{SOC}
483 averaged 1.48 and RR_{SoilN} for seven experiments averaged 1.51. Manure incubation
484 studies, too, indicate that a fraction of applied manure C is not easily mineralized. For
485 example, Thomsen and Olesen (2000) indicated that (on average for six farmyard
486 manures) only 14% of manure C was in pools having relatively high relative
487 mineralization rates of 0.0693 to 0.00693 d^{-1} (these values indicate that manure C was
488 totally or almost totally mineralized in one year), while the rest had slower turnover rates.
489 This is probably due to the presence in the manure of lignified compounds originating
490 both from the bedding material (generally winter cereal straw) and from recalcitrant
491 compounds in the feed (van Kessel et al., 2000), which are still undecomposed after the
492 passage of the forage in the digestive tract and the storage of feces and urine to produce
493 FYM.

494 **4.2. Slurry**

495 Crop productivity is slightly reduced (Table 2; RR_Y) when N is provided with cattle slurry
496 compared to when it is provided with mineral fertilizer. We hypothesize that the reduction
497 of crop yield with cattle slurry compared to mineral fertilizer is due to a more prompt
498 effect of the latter; our hypothesis is at least partly confirmed by the yield obtained when
499 slurry is supplied without extra mineral fertilization, similarly to what was observed in
500 FYM/FYMm. Spring crops performed better than other types of crops, probably because
501 of more favourable conditions for mineralization that led to a better synchrony of N
502 release and crop N uptake. The dry mass produced per unit of applied slurry-N equaled

503 the dry mass produced per unit of applied mineral N (Table 2; $RR_{Y/F}$). Similarly to what
504 was observed for FYM/FYMm, for SLU/SLUm the conditions enhancing crop yield
505 (RR_Y) and the production of dry mass per unit of applied N ($RR_{Y/F}$) are: southern climate,
506 light soil texture, and shallow incorporation depth – a set of conditions where N
507 mineralization is faster (Table 3b). We interpret these findings to mean that favorable
508 conditions cause faster mineral N release and higher crop N uptake that result in higher
509 crop yields (Table 3b).

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

518 Laboratory experiments confirm (Cavalli et al., 2014 and 2016b) and help to explain the
519 increase of SOC and SoilN after the application of slurry. Firstly, incubation experiments
520 show that part of the slurry ammonium-N is quickly immobilized by microbial biomass
521 that decomposes slurry organic matter, in particular compounds – like volatile fatty acids,
522 VFAs – with high C/N ratio (Sørensen, 1998). Part of this N remains immobilized for
523 several years (Sørensen, 2004) and explains the SOC and SoilN increase that we have
524 registered in the LTEs. Secondly, slurries contain organic compounds that are chemically
525 recalcitrant to microbial decomposition (van Kessel et al., 2000) and that remain in the

526 soil longer than the N applied with mineral fertilizers ($RR_{\text{SoilN}} > 1$) (Spiegel et al., 2010).
527 Thirdly, the rapid fixation of slurry ammonium in non-exchangeable form by clay
528 minerals may also contribute to soil N retention (Nieder et al., 2011), because normally
529 the release of fixed ammonium is slow (Cavalli et al., 2015). The fact that C and N
530 increased quite similarly in the LTEs might indicate that the first two mechanisms
531 (microbial immobilization and chemical recalcitrance) were more important than the third
532 one (ammonium fixation by clay minerals).

533

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

545

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

548 2013), and an average N fertilizer replacement value of the four treatments (referred to
549 the central class of FR) of 0.754, European livestock produces in the manure 4,317,033 t
550 of fertilizer-equivalent N annually, capable of supplying 170 kg of N ha⁻¹ to more than
551 25,000,000 ha. This illustration shows the importance of properly accounting for the
552 manure fertilizer value; if this is underestimated, it could result in calculation of an
553 excessive need for mineral N integration to crops, with consequent increases in farmer
554 costs, environmental pollution risks, and GHG emissions.

555 **4.3. Issues and recommendations**

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

566 Not all available experiments provided data that were easily usable. Several decades-long
567 experiments did not permit direct comparison of manured and mineral fertilizer
568 treatments. Moreover, supplied amounts of organic amendments in some experiments

569 were based on a fixed total fresh mass, whereas N and P contents may have varied by
570 year. This data should have been reported in publications.

571 LTEs are expensive to manage and provide information that becomes relevant only when
572 combined with that derived from other LTEs. Difficult as it is to start and maintain new
573 long-term trials, it remains important to preserve those that are ongoing at the very least.

574 In addition to compile meta-analyses and reviews, it is important to establish networks of
575 existing LTEs to coordinate research projects, study processes, and to provide a forum
576 for researchers to exchange and share measurement protocols. Some attempts have been
577 made in this direction (e.g., IC-FAR, ExpeER, AnaEE, ESFRI, ICOS), but others should
578 be promoted as proposed by Stützel et al. (2016).

579 **5. Conclusions**

580 The positive long-term effects of bovine farmyard manure and bovine slurry were strong,
581 both on crop and soil. Indeed, when we compared manures to mineral fertilizers, their
582 capacity to sustain crop yield and N uptake was very similar (yield reduction of 9%). A
583 clear pedo-climatic effect also emerged; light-textured soils and warm climates performed
584 better than medium-textured soils and cool climates provided the most favourable
585 conditions for crop performance and soil organic C increase. Among crop types, the best
586 results were obtained by long-duration crops with farmyard manure, and by spring crops
587 with slurry. Integration of farmyard manure and slurry with mineral N fertilizers resulted
588 in significantly higher crop yield and N offtake than without integration; differences with
589 pure mineral fertilization did not exceed 4%. Conversely, soil C and N increased at least
590 14% when manures were used in combination with mineral N fertilizers, similar to what
591 was obtained using manures only. These findings are important because the integration
592 of manure with mineral N is a practice frequently adopted by farmers. In conclusion, this
593 review has highlighted that the potential of farmyard manure and slurry to substitute
594 mineral fertilizers is high.

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602

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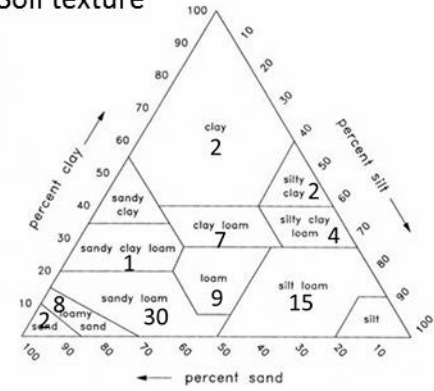
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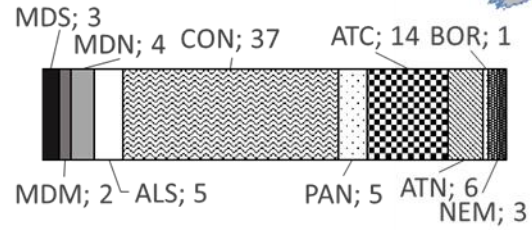
1 Figure 1. Map of LTEs used in this study. The number of LTEs for each soil texture, start year and climate type following Metzger et al.
2 (2005) are also reported. Climate acronyms are as follows: Atlantic Central (ATC), Atlantic North (ATN), Atlantic South (ALS), Boreal
3 (BOR), Continental (CON), Mediterranean Mountains (MDM), Mediterranean North (MDN), Mediterranean South (MDS), Nemoral (NEM),
4 Pannonian (PAN). Supplementary data on LTE characteristics and available indicators are reported in Table S1. The list of consulted literature
5 for each LTE is reported in Table S2.

6

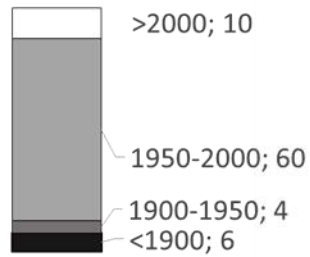
Soil texture



Climate type



Start year



1 Tables

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

3

Treatments		
FYM	farmyard manure as the only N fertilizer	
FYMm	farmyard manure added with mineral N	(subscript: man)
SLU	bovine slurry as the only N fertilizer	
SLUm	bovine slurry added with mineral N	
mineral	mineral fertilizers only	(subscript: min)
Unfertilized control, ON	no additions of N as fertilizer	(subscript: ON)
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	$F_{\text{man}}/F_{\text{min}}$
RR _Y	Response Ratio of Y	$Y_{\text{man}}/Y_{\text{min}}$
RR _{NY}	Response Ratio of NY	$NY_{\text{man}}/NY_{\text{min}}$
RR _{Y/F}	Response Ratio of Y/F	$(Y_{\text{man}}/F_{\text{man}}) / (Y_{\text{min}}/F_{\text{min}})$
RR _{NY/F}	Response Ratio of NY/F	$(NY_{\text{man}}/F_{\text{man}}) / (NY_{\text{min}}/F_{\text{min}})$
RR _{ANR}	Response Ratio of ANR	$((NY_{\text{man}}-NY_{0N})/F_{\text{man}}) / ((NY_{\text{min}}-NY_{0N})/F_{\text{min}})$
RR _{SOC}	Response Ratio of SOC	$SOC_{\text{man}}/SOC_{\text{min}}$
RR _{SoilN}	Response Ratio of SoilN	$SoilN_{\text{man}}/SoilN_{\text{min}}$
RR _{MB}	Response Ratio of MB	$MB_{\text{man}}/MB_{\text{min}}$
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	
	11-20 cm	
	21-30 cm	tillage depth, intended as the incorporation depth
	>30 cm	
Duration	1- 5 yrs	years of practice after the experiment start

6-10 yrs

11-20 yrs

> 20 yrs

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

9

	N fertilizer ratio		Crop indicators				Soil indicators			
	FR	FR	RR _Y	RR _{NY}	RR _{Y/F}	RR _{NY/F}	RR _{ANR}	RR _{SOC}	RR _{SoilN}	RR _{MB}
<u>FYM</u>										
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	FR	RR _Y	RR _{NY}	RR _{Y/F}	RR _{NY/F}	RR _{ANR}	RR _{SOC}	RR _{soilN}	RR _{MB}
<u>FYMm</u>										
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	
<u>SLU</u>										
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	

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

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

15 (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	<i>p</i>	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	<i>p</i>	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		#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	<i>p</i>	215	0.000	++	55	0.178	ns	212	0.987	ns	55	0.000	++	33	#	102	0.032	+	34	#		38	.#	
Soil texture	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		#N/D		3	1.603		#N/D		#N/D		#N/D			
Tillage depth	<i>p</i>	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		#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		#N/D	
Duration	<i>p</i>	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)	<i>p</i>	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	<i>p</i>	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		

17 (b) Results for SLU/SLUm

Factor	Level	Crop indicators										Soil indicators												
		RR _V		RR _{NY}		RR _{V/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	<i>p</i>	95	0.000	++	27	#	88	0.001	++	27	#	20	#	33	0.012	+	20	#	22	#				
	Northern	#N/D			#N/D		#N/D			#N/D		1	0.995	b	#N/D		#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	<i>p</i>	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		#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		#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	<i>p</i>	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		#N/D				
Tillage depth	<i>p</i>	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		#N/D					
Duration	<i>p</i>	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)	<i>p</i>	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	<i>p</i>	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							

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19 ‘#’ = 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, EARW, FUNGI
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	
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-Ruzyně	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 Salzigungen 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 Salzigungen 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, FUNG
Gross Kreuzt	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 Higuera	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 Iasi	PL	53°15'N 17°47'E	1979	1991	sandy loam	CON	1	1	0	0	0	0	0	0	0	2	0	0	
RO	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, actinomycetes; 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; Korsæth 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 Salzung 1	Zorn et al., 2009	DE
Bad Salzung 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	Vogeleson 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; Rühlmann, 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
Jynde vad	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 Higuera	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	Neuens 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	ON
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:

$\exp(\text{intercept}) \times \exp(\text{regression coefficient of the factor level}) \times \exp(\text{sum of mean regression coefficients of the other factors})$

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.

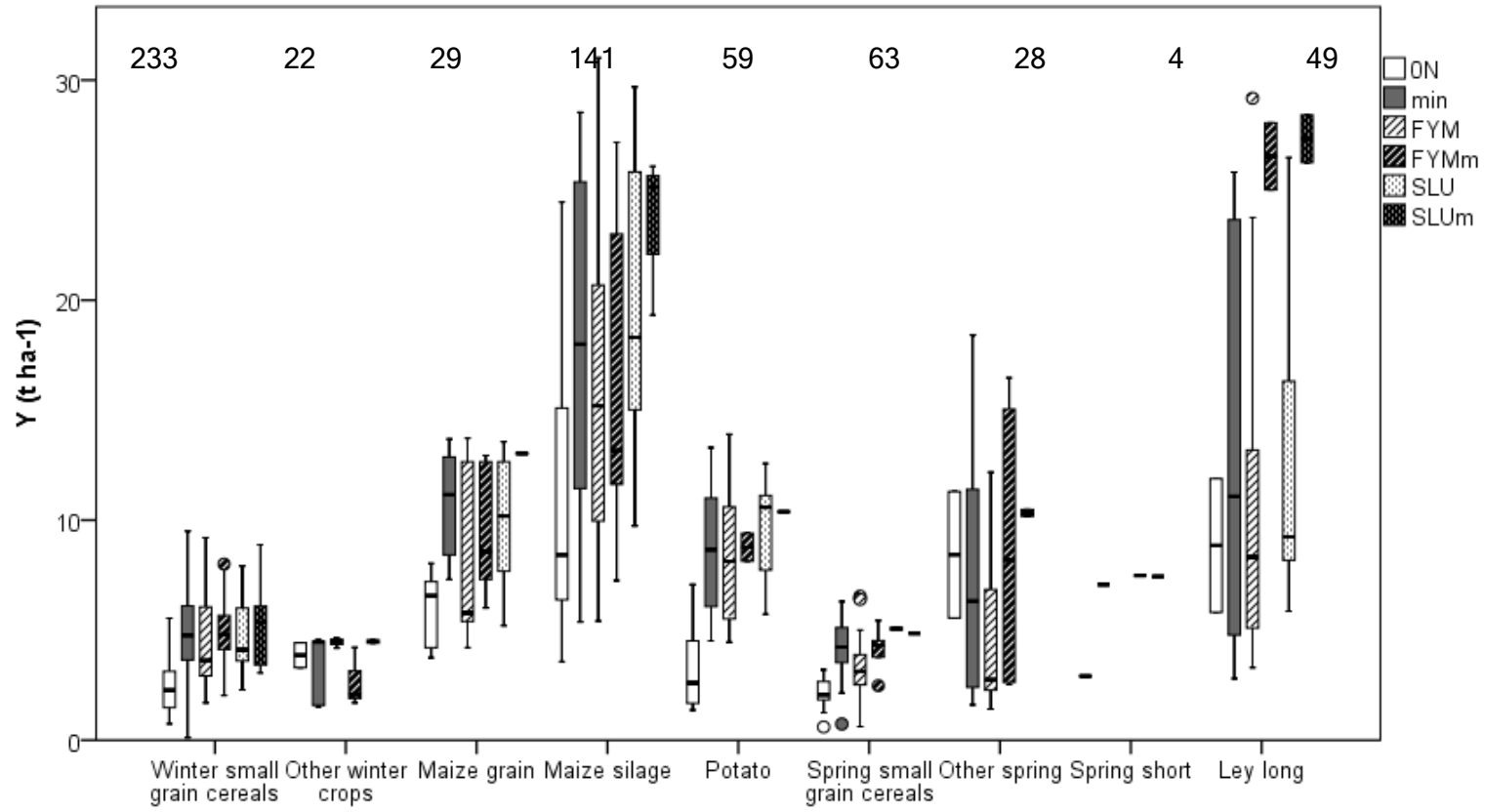
All three indicators used to evaluate nitrogen use efficiency (Y/F, NY/F and ANR) revealed high variability across the studied LTEs, but varied less among crop types than did yield. The indicator Y/F (Figure S1c) displayed high variability within crop types. The ratio “N in yield to N applied with fertilizer” (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) *versus* that after continuous maize (125 kg N/ha).

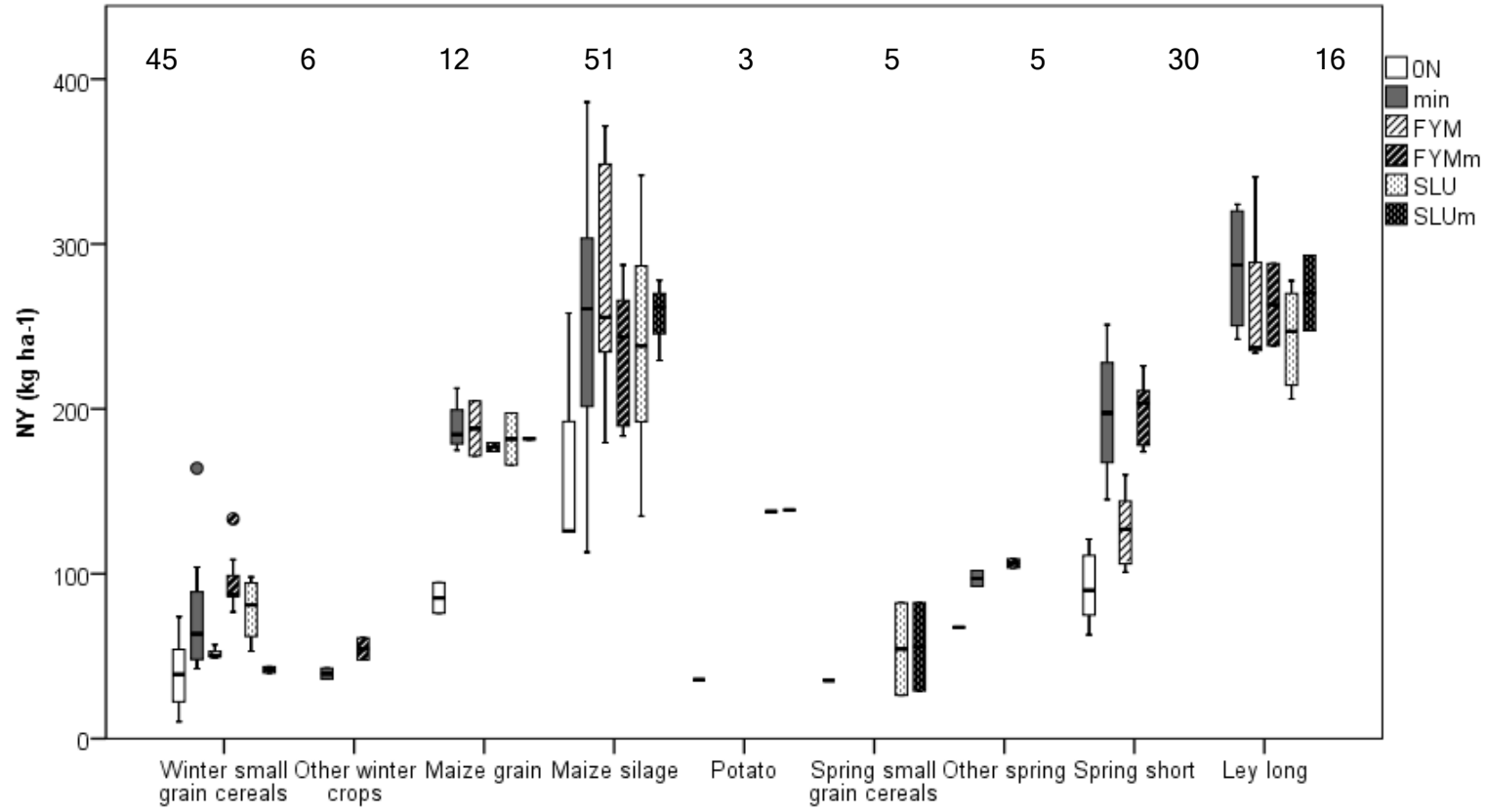
As reported in Figures S1f and S1g, the means for soil organic C (SOC) and N (SoilN) in the tilled layer (in most cases, 20 to 30 cm deep), were 13.7 g C/kg (n=269) and 1.32 g N/kg (n=112) in fertilized treatments. Most of these results came from light- or medium-textured soils. We found no marked differences 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.

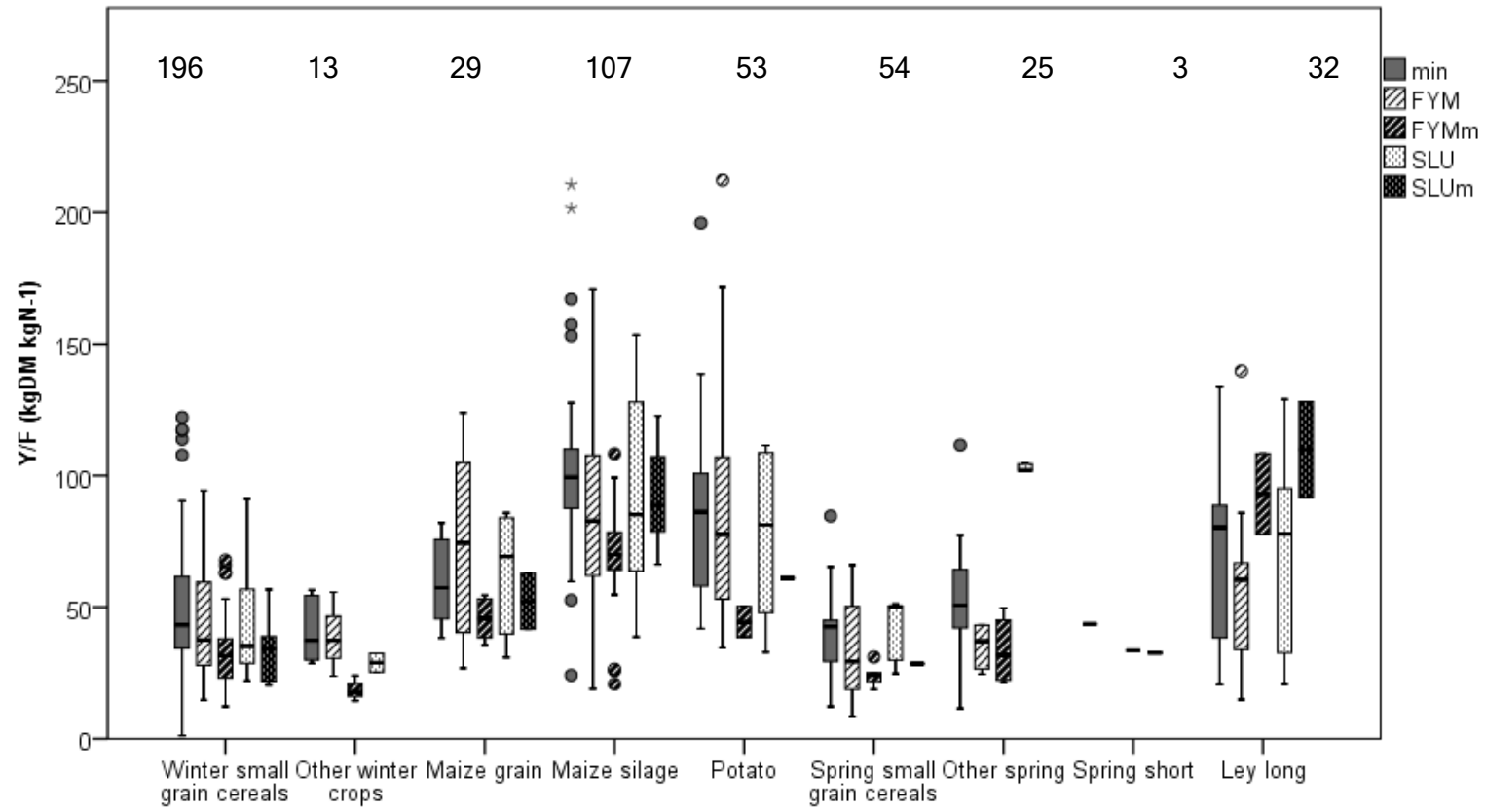
a)



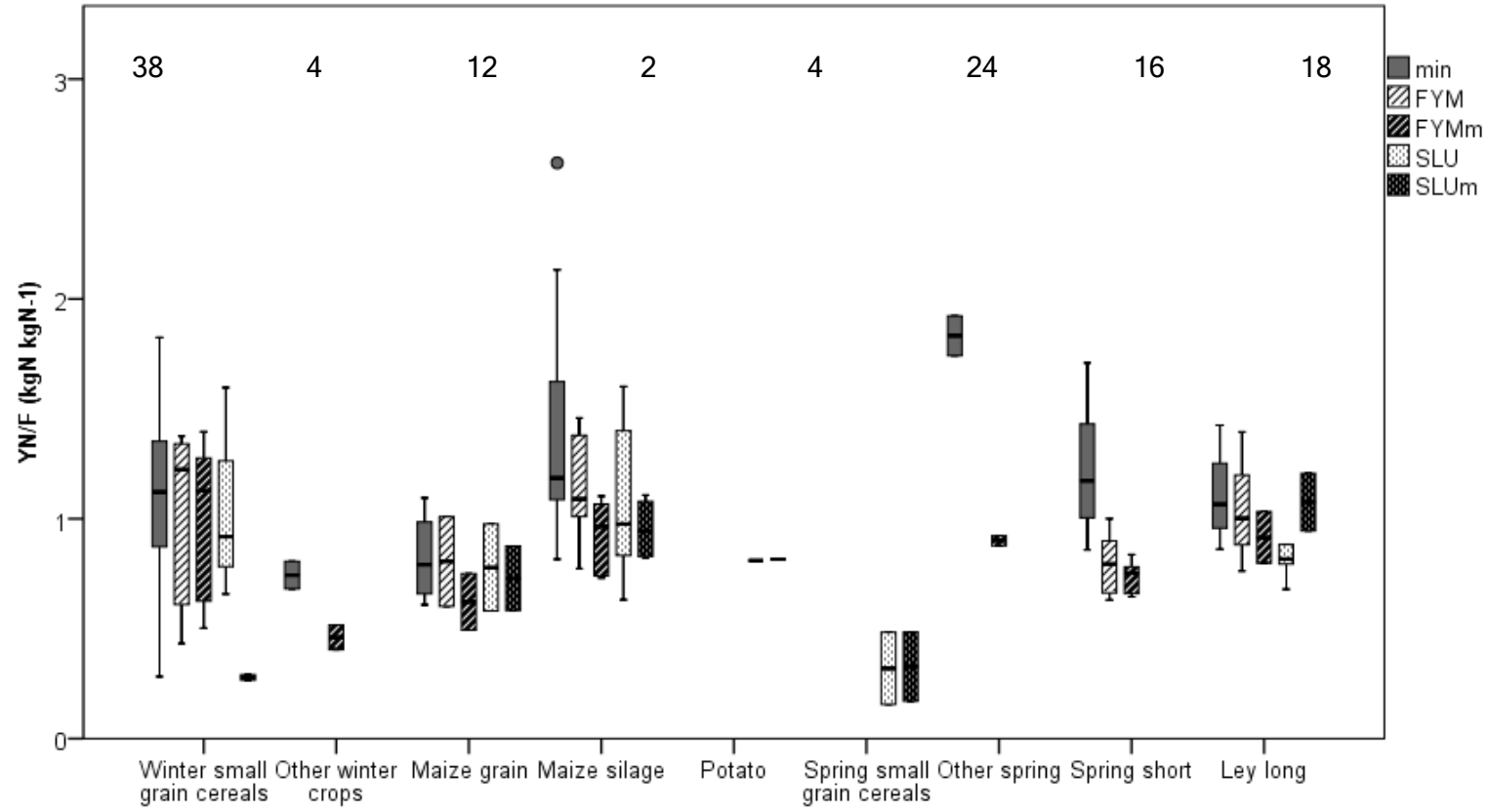
b)



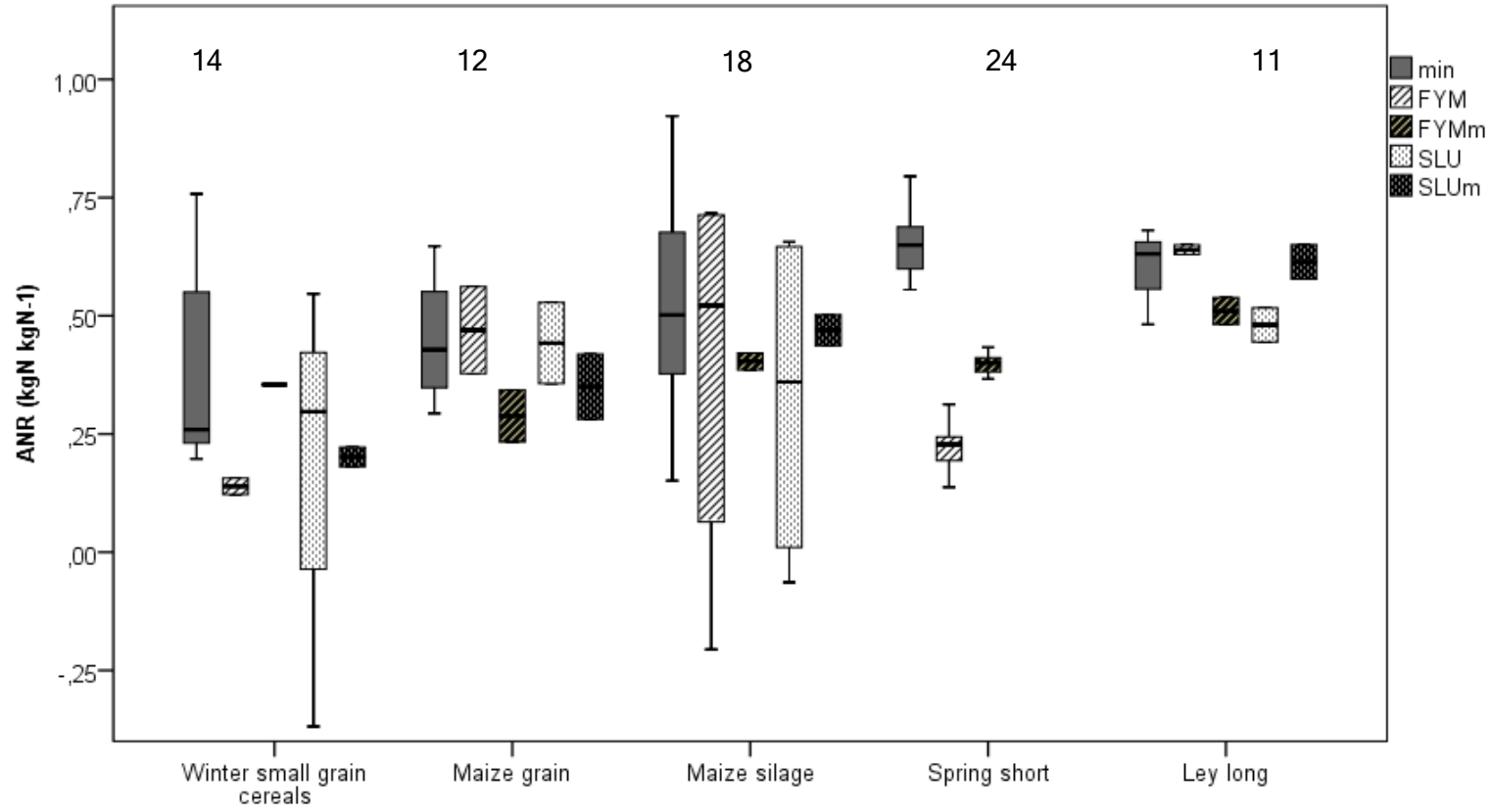
c)



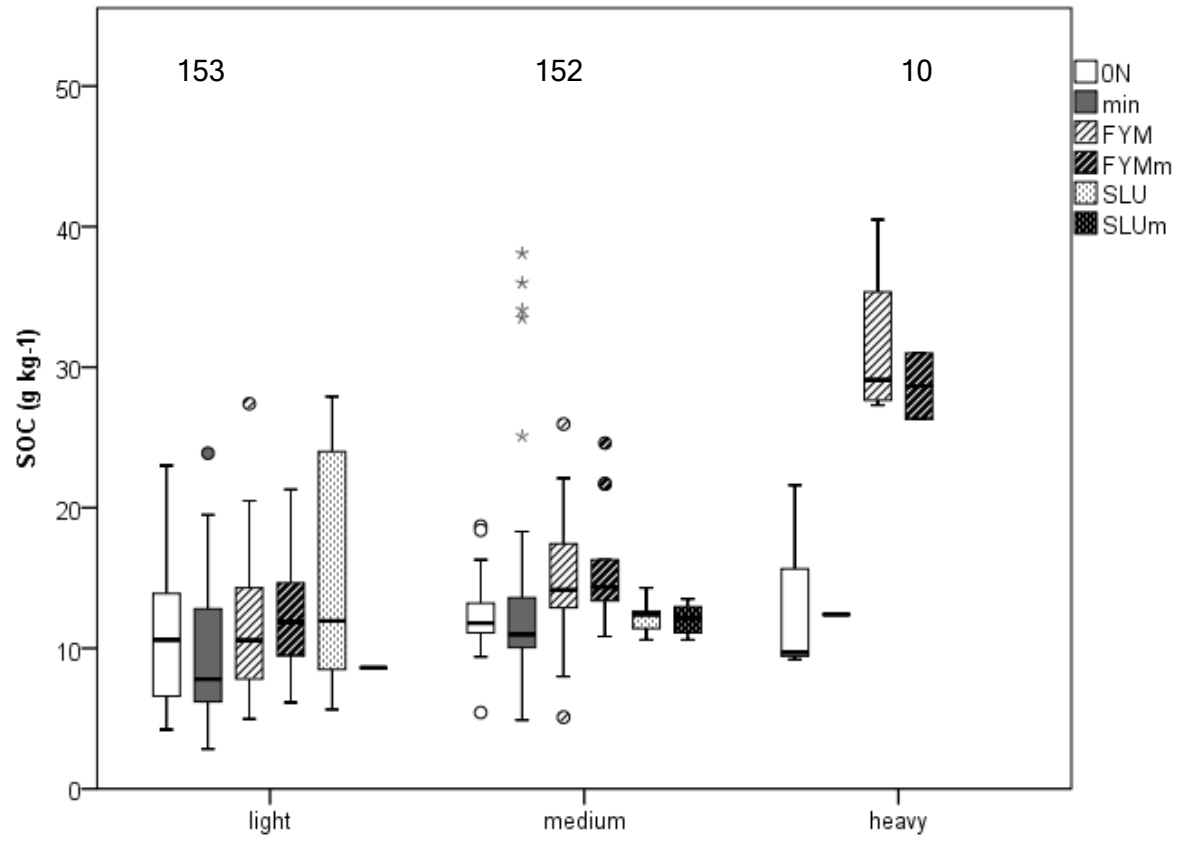
d)



e)



f)



g)

