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This is the author's manuscript

Original Citation:

Availability:

This version is available <http://hdl.handle.net/2318/59550> since

Published version:

DOI:10.1016/j.eja.2008.09.006

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(Article begins on next page)



UNIVERSITÀ DEGLI STUDI DI TORINO

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1 Regular paper

2

3 **Soil organic matter dynamics and losses in manured maize-based**
4 **forage systems**

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14 No. of text pages: 29

15 No. of tables: 7

16 No. of figures: 1

17

18 **Abstract**

19 Soil organic matter (SOM) produces positive effects on multiple soil properties. Increasing its level
20 also provides an opportunity to reduce atmospheric concentration of carbon dioxide (CO₂).
21 Recycling animal manure and returning crop residue are among the main practices to enhance
22 organic C stock in arable croplands. This study analysed data of soil organic carbon (SOC) stocks
23 from a medium-term field trial (established in 1992) through a Hénin-Dupuis-based equation to
24 determine the proportion of different organic materials retained in the soil as SOM.

25 The treatments included in the experiment simulated different typical management techniques and
26 implied the application to the soil of various organic materials, i.e. cattle slurry, cattle farmyard
27 manure, maize straw, root, maize and ley stubble. Soil Organic Carbon (SOC) and total nitrogen
28 (Kjeldhal N) were measured in the 0-30 cm layer during spring, 1999 and spring, 2003. The
29 relationship between SOC and N stocks measured in 1999 and 2003 and the annual additions of C
30 and N was described by the Hénin-Dupuis-based equation, assuming the presence of two C and N
31 pools (stable and fresh).

32 Our results showed that the application of farmyard manure, slurry and maize straw induced higher
33 C and N content compared to the application of urea without return of crop residue. The different
34 levels of urea application did not produce any significant difference in C and N soil content.

35 We found that approximately 2% of SOC is lost to the atmosphere annually. Furthermore, the
36 amount of C and N retained in the soil each year varied by organic materials: 46% C and 44% N
37 with farmyard manure, 26% C and 11% N with slurry, 28% C and 10% N with root and 6% C with
38 maize straw and ley stubble.

39 These results were used to inform an estimate of C lost or removed to/from atmosphere following
40 manure application and crop residue return for the compilation of greenhouse gas inventories. We
41 found that the most C conservative management is the production and spreading of farmyard
42 manure and that increasing amounts of mineral N fertiliser did not affect the C sequestration extent.

43

44 *Keywords:* Soil organic carbon; Nitrogen; Crop residue; Manure; Mineralization; Greenhouse gases

45 inventory; Fodder crops rotations.

46

47 **1. Introduction**

48 The importance of organic matter for sustainable soil functions has been acknowledged worldwide
49 for several decades (Smith et al., 2001; Lal et al., 2004). The positive effects of soil organic matter
50 (SOM) cover a wide range of well-documented physical, hydrological, chemical, biochemical and
51 productive properties (Thompson et al., 1989; Juma, 1993; Reeves, 1997; Shepherd et al., 2002;
52 Rawls et al., 2003; Cookson et al., 2005; Raiesi, 2006). Recent global warming concerns have
53 recommended maintaining and restoring soil carbon (C) as a measure to mitigate rising atmospheric
54 carbon dioxide (CO₂) concentration (Follett, 2001).

55 Soils are, in fact, the major reservoir of terrestrial C (McVay and Rice, 2002). However, unlike C
56 dissolved in the oceans, soil C content is likely to be modified by human activity. Besides growing
57 cover crops and no-tillage (Lal, 2004), returning crop residue is one of the main practices to
58 produce a net carbon sequestration in arable cropland. The use of manure as a tool to sequester C
59 is rather controversial. Some authors suggest not to consider it because its fate is not different from
60 that of the straw left in the field (INRA, 2002) or because for its production it is necessary to
61 subtract crop residue to a larger surface than that interested by its application (Schlesinger, 1999).
62 Nevertheless, other authors consider positively the manure effect on C sequestration also because it
63 can govern the redistribution of SOM between regions or fields (Smith and Powlson, 2000). The
64 fate of manure is then more relevant if its alternative use for energy production processes is
65 considered.

66 The studies on the fate of C additions to the soil can be used for the compilation of inventories of
67 anthropogenic greenhouse gases emissions on the basis of the methodologies set by the
68 International Panel on Climate Change (IPCC), under the United Nation Framework Convention on
69 Climate Change (UNFCCC) (IPCC, 2006). For estimating changes in soil C stock (useful to
70 quantify soil net CO₂ emission or removal) derived from the introduction of different management
71 practices, the IPCC suggests creating a monitoring network of benchmark sites at the territorial
72 level, of which our field trial described by Grignani et al. (2007) represents a good example in Italy,

73 where there is a need of further information. For example, in the last Italian Inventory Report
74 (APAT, 2006) CO₂ emissions from cropland were identified as a key category, but since no
75 management changes could be documented, the resulting change in C stock was reported as zero.

76 There are several examples of long and medium-term experiments aimed at exploring the effects of
77 the application of manures and crop residue on soil organic carbon (SOC) stocks (Jenkinson, 1990;
78 Paustian et al., 1995; Manna et al., 2005; Morari et al., 2006; Sleutel et al., 2006; Chivenge et al.,
79 2007; Xu et al., 2007). They provide baseline information for regional assessment of soil C
80 dynamics, often in combination with simulation models.

81 A number of sophisticated multi-compartmental models are available, such as Century-DayCent
82 (Parton et al., 1988; Parton et al., 1994; Parton et al., 1998), RothC (Jenkinson and Rayner, 1977;
83 Jenkinson, 1990), DNDC (Li et al., 1997), CANDY (Franko et al., 1997) and NCSOIL (Molina et
84 al., 1997). Nevertheless, some authors have recently taken up simple interpretations of SOC
85 dynamics proposed by Hénin and Dupuis (1945), for example the Janssen model (Janssen, 1984),
86 SOMM (Chertov and Komarov, 1997), ICBM (Andren and Katterer, 1997), or AMG (Saffih-Hdadi
87 and Mary, 2008). They require less detailed input data, are based on few assumptions, generally
88 closely fit SOC variations over a 10-100 year period, and are suitable for field-data interpretation
89 (Andren et al., 2004; Kemanian et al., 2005; Bayer et al., 2006; Kemanian, 2006).

90 The Hénin-Dupuis equation, originally conceived for SOC data, was mainly used in France (Boiffin
91 et al., 1986; Guérif, 1986; Plenet et al., 1993; Mary and Guérif, 1994; Andriulo et al., 1999; Nesme
92 et al., 2005) but has been also adopted at international level (Huggins et al., 1998a; Huggins et al.,
93 1998b; Bayer et al., 2006; Kemanian, 2006) and applied to soil nitrogen (N) (Woodruff, 1949;
94 Greenland, 1971; Saadi and Maslouhi, 2003; Nesme et al., 2005; Manna et al., 2007). It allows to
95 express the evolution of soil C and N content in a more comprehensible and exploitable way than
96 the simple presentation of the SOC and N variation (INRA, 2002).

97 The first objective of this study was to evaluate the SOC and N stock changes in the experiment
98 reported by Grignani et al. (2007), following the repeated addition to the soil of different organic

99 materials, expressing data in terms of Yearly Mineralization Rate (YMR) of the C and N in the
100 stable SOM and in the different organic additions.

101 As a second objective of this work, we used the obtained YMR to estimate the amount of CO₂ lost
102 from the system or removed by it, following the application to the soil of the different organic
103 materials.

104

105 **2. Materials and methods**

106 *2.1 Field trial*

107 The study was based on a medium-term field trial started in 1992, still ongoing, and described in
108 detail by Grignani et al. (2007). The experiment is located in the western part of the Po plain
109 (Piemonte Region, NW Italy), 44°52'58" N, 232 m a.s.l., characterized by a temperate sub-
110 continental climate (mean annual precipitation of 740 mm, maximum annual temperature of 28.5°C
111 and minimum of -3.8°C, during the period 1976-2004). The soil, alluvial, is classified as a Typic
112 Udifluent (USDA, 1977), with a loam texture in the 0-40 cm Ap horizon (7.5% clay, 48.2% sand),
113 sub-alkaline pH (8.1), low cation exchange capacity (9.1 meq 100 g⁻¹) and exchangeable K (0.20
114 meq 100 g⁻¹) and high Olsen P (21.4 mg kg⁻¹).

115 The treatments included in this experiment (set up as a randomised block design with three
116 replicates) are a combination of different cropping systems and various fertilization managements to
117 simulate the many management techniques present in the area at trial commencement (Table 1).

118 The cropping systems consisted of: maize (*Zea mays* L.) for silage (Ms), maize for grain (Mg),
119 double annual rotation of Italian ryegrass (*Lolium multiflorum* Lam.) and maize for silage (Mr),
120 rotation of 3 years of ley of tall fescue (*Festuca arundinacea* Schreb.) and 3 years of maize for
121 silage (Ml), rotation of 3 years of lucerne (*Medicago sativa* L.) and 3 years of maize for silage
122 (Mu). The fertilization management included the application of bovine farmyard manure or slurry at
123 two different levels (F_{High}, F_{Low}, S_{High}, S_{Low}), of urea at four levels (U₁₀₀, U₂₀₀, U₃₀₀, U₄₀₀) and a
124 control (0N). All the cropping systems were combined with the nine fertilization managements,

125 excepting maize-lucerne that was managed only as S_{Low} . The total number of treatments was
126 therefore 37. This set-up implied the application to the soil of different organic materials, i.e. cattle
127 slurry or farmyard manure, plant root, maize straw or stalk base, and ley stubble.

128 Slurry and farmyard manure were supplied as constant amounts throughout the experiment. The two
129 different levels “low” and “high”, corresponded respectively to 50 and 100 Mg ha⁻¹ for slurry, and
130 20 and 40 Mg ha⁻¹ for farmyard manure. Therefore the amount of C and N supplied in the same
131 treatment slightly changed in different years. In addition to manures, the treatments receiving slurry
132 and farmyard manure (both supplied at seeding and incorporated into the soil within one day) were
133 top-dressed at maize jointing stage with 100 kg N ha⁻¹ as urea. The treatments receiving only urea
134 were fertilized as well with 100 kg N ha⁻¹ at maize jointing stage and the rest at seeding. Manures
135 and urea were incorporated into the soil just before seeding by ploughing at 30 cm depth; top-
136 dressed urea was incorporated by ridging.

137 The slurry used in the experiment had on average 5.6% of dry matter (DM), 36.8% DM of organic
138 C and 4.1% DM of Kjeldhal N (C to N ratio of 9.0) while the farmyard manure had 25.9% of DM,
139 29.0% DM of organic C and 2.4% DM of Kjeldhal N (C to N ratio of 12.1).

140 Maize was sown in mid-April to mid-May in Ms, Mg, Ml and Mu systems and at the end of May in
141 Mr, after Italian ryegrass harvest. Silage maize was harvested at the beginning of September and
142 maize for grain at the end of September or beginning of October. Maize straw in Mg treatments was
143 chopped after harvest and incorporated into the soil by ploughing in the following spring. Italian
144 ryegrass in Mr treatments was sown immediately after maize harvest. Grass sods in Ml and Mu
145 treatments were chopped and incorporated into the soil in the following spring. During the period of
146 time considered in this work, the systems Ml and Mu had 3 years of ley (1999-2001), and one year
147 of silage maize (2002). The ley of lucerne in MuS_{Low} received slurry once at sowing (spring 1999);
148 fertilization was nil for the subsequent three years. The silage maize followed the same fertilization
149 management course as that used for MsS_{Low} . A more detailed description of crop management is
150 provided by Grignani et al. (2007).

151 *2.2 SOC and N content*

152 Soil organic C and N content were determined in all plots in the spring 1999 and 2003 before
153 fertilizer application and tillage. We sampled three soil cores per plot, at 0-30 cm depth, using a
154 steel auger and then pooled them to obtain one sample per plot. Soil samples were then analysed for
155 organic C through chromic acid digestion (Walkley and Black, 1934) and for total N using the
156 Kjeldhal method (Bremner, 1996). Values obtained from the analyses, expressed as g of C or N kg⁻¹
157 of dry soil, were converted into Mg of C or N ha⁻¹ (30 cm deep), taking into account the soil bulk
158 density of the different treatments (average of 1.38 Mg m⁻³). Data were analysed through a
159 Repeated-Measures ANOVA, including in the model: cropping system, fertilization management
160 and block as main effects, year as repeated measure, and system*fertilization, system*year and
161 fertilizer*year as interactions. The Bonferroni post-hoc test was applied to separate significantly
162 different means. The treatment MuS_{Low} was not included in the statistical analysis in order not to
163 unbalance the dataset.

164

165 *2.3 C and N additions*

166 C and N additions were partly measured directly and partly calculated on values measured in other
167 ongoing field trials at similar sites or chosen after an accurate analysis of the literature, as
168 summarized in Table 2.

169 Each year, we determined the total above-ground biomass produced at harvest in a 18 m² sampling
170 area for maize and in a 10 m² sampling area for Italian ryegrass and ley (4 to 5 cuts per year),
171 separating the different fractions (grain and straw) for Mg treatments. Crop C and N content was
172 determined using a CHN elemental analyser (NA1500 Nitrogen Analyser, Carlo Erba Instruments).
173 The nutrient content in the manures was determined each year by the Kjeldhal method for N and by
174 the Springer-Klee method for C (Springer and Klee, 1954).

175 The below ground to above ground biomass ratio measured for maize (0.22 kg kg⁻¹) and for Italian
176 ryegrass and ley (0.43 kg kg⁻¹) were consistent with those reviewed by Bolinder et al. (1999) and

177 Amos and Walters (2006) and measured by Buyanovsky and Wagner (1997) for maize, and with
178 those measured by Schneider et al. (2006) for ley and by Pietola and Alakukku (2005) for ryegrass.
179 Moreover, we chose a root C content to root biomass ratio of 0.40 kg kg⁻¹ regardless of the type of
180 crop, according with Whipps (1990) and Boiffin et al. (1986). Similar values were also proposed by
181 Bolinder et al. (1999) for maize and by Magid et al. (2004) for Italian ryegrass. The root N content
182 used for lucerne was 14.0 g kg⁻¹ (Teixeira et al., 2007).

183 The C content of maize stalks measured in this trial in 2003 is in agreement with that found by
184 Rasse et al. (2006) and Clay et al. (2006). We considered the stalk base left in the field after maize
185 harvest as a C and N input. As proposed by Rasse et al. (2006), we assumed 12% of the total stalk
186 remained on the soil, given that stalks were cut at 20 cm above ground.

187 N additions through dry and wet atmospheric depositions were measured during the 4-year period
188 and were on average 27 kg N ha⁻¹ while the N dissolved in irrigation water was about 1 kg N ha⁻¹.
189 However, these two entries, while common to all treatments, were not considered among the N
190 input items.

191

192 *2.4 Coefficients of SOM evolution and organic materials decomposition*

193 The relationship between the SOC stocks measured in 1999 and 2003 and the annual additions of C
194 was based on the first order kinetics proposed by Hénin and Dupuis (1945):

$$195 \quad C_t = C_0 * e^{-k_C * t} + I * e^{-k_I * t} \quad (1)$$

196 where C_t is the SOC stock at time t , C_0 is the initial SOC stock, I is the annual C addition of fresh
197 organic matter, k_C is the decay constant of SOC, k_I is the decay constant of the generic fresh organic
198 addition I . The term of Equation (1) given by $C_0 * e^{-k_C * t}$ represents the fraction of C_0 still in the soil
199 at time t while the term $I * e^{-k_I * t}$ is the amount of I still in the soil at time t .

200 Our interpretation of the equation assumed the following: i) two main types of C pools were present
201 in the soil (i.e. stable organic C or the pool that has remained in the soil for at least one year, called

202 C_0 in the equation; fresh organic C, that is the newly added organic C for one year after its
203 incorporation into the soil, called I in the equation. It was possible to distinguish as many different I
204 pools as different organic materials added); ii) outflows from pool(s) I to pool C_0 and from C_0 to the
205 atmosphere followed first-order kinetics; iii) each organic addition I followed its own unique decay
206 dynamics, described by its own k_I , for one year from its incorporation into the soil; thereafter, the
207 remaining fraction was pooled with C_0 ; iv) the k_C and the individual k_I 's were constant throughout
208 the time period considered and independent of temperature and humidity conditions in the different
209 years.

210 On the basis of these assumptions, Equation (1) was modified as follows:

$$211 \quad C_t = C_0 * e^{-k_C * t} + I * e^{-k_I * 1} * e^{-k_C * (t-1)} \quad (2)$$

212 We considered the following organic addition I , or fresh organic C pools:

- 213 - slurry C (SLC),
- 214 - farmyard manure C (FC),
- 215 - maize (RC_m), ley or ryegrass root C (RC_l), and
- 216 - maize straw, stalk base and ley stubble C (STC).

217 We assigned a different decay rate (k_{SL} , k_F , k_R , k_{ST}) to each. Given that root exudates are rapidly
218 decomposable molecules, they were not included in the equation.

219 Since the soil sampling for SOC determination was performed in the springs of 1999 and 2003, we
220 regarded these moments as time 0 and time t . We assumed that the first-order decomposition
221 kinetics of fresh organic matter started at the moment of soil incorporation - spring for all the
222 different I pools considered except maize root, which began its decomposition at harvest (i.e.
223 autumn). For this reason, we did not consider the whole C measured in spring 1999 as C_0 , but
224 instead reduced it by the fraction of C in the maize root that were not yet pooled with the SOC and
225 were still decomposing. We further assumed that maize stalks and stem base, as with ley stubble,
226 were not significantly transformed in the off-soil period following harvest, but rather starting

227 decomposing after soil incorporation in the spring. Finally, we assumed a complete annual turnover
 228 of ley root (Watson et al., 2000). Equation (2) was therefore modified as follows:

$$\begin{aligned}
 C_{2003} &= a + b + c + d + e + f \\
 \text{where:} \\
 a &= (C_{1999} - (RC_{m1998} * e^{-k_R * 0.5})) * e^{-k_C * 4} \\
 b &= \sum_{t=0}^3 (RC_{m(1998+t)} * e^{-k_R * 1} * e^{-k_C * (3.5-t)}) + RC_{m2002} * e^{-k_R * 0.5} \\
 229 \quad c &= \sum_{t=0}^3 (RC_{l(1999+t)} * e^{-k_R * 1} * e^{-k_C * (4-t)}) \tag{3} \\
 d &= \sum_{t=0}^3 (STC_{(1999+t)} * e^{-k_{ST} * 1} * e^{-k_C * (4-t)}) \\
 e &= \sum_{t=0}^3 (SLC_{(1999+t)} * e^{-k_{SL} * 1} * e^{-k_C * (4-t)}) \\
 f &= \sum_{t=0}^3 (FC_{(1999+t)} * e^{-k_F * 1} * e^{-k_C * (4-t)})
 \end{aligned}$$

230 In Equation (3), SOC measured in 2003 (C_{2003}) is equal to the sum of the variable a , i.e. the fraction
 231 of SOC measured in 1999 (C_{1999} minus the fraction of maize root supplied in autumn 1998 and still
 232 in the soil at the moment of the initial soil sampling) that remains in the soil in 2003, and variables
 233 b - f , representing the amount of C left in the soil by the other C additions. In detail, b is that fraction
 234 of C applied with maize root in the autumns 1998-2002 still in the soil in the spring 2003; the
 235 addenda c - f are the quantity of C applied in the springs 1999-2002 with ley and ryegrass root (c),
 236 maize straw, stalk base and ley stubble (d), slurry (e) and farmyard manure (f) still present in the
 237 soil in the spring 2003.

238 Equation (3) was fitted to data with a non-linear regression, using the Levenberg-Marquardt
 239 algorithm, in order to obtain an estimation of the decay constants k_C , k_{SL} , k_F , k_R , k_{ST} . We used the
 240 mean value for each treatment, therefore totalling 37 cases. We chose the Levenberg-Marquardt
 241 method because of its high robustness that renders it the most useful method for solving non-linear
 242 least squares problems (Dimitrov and Kamenski, 1997). The fitting was performed through the
 243 SPSS 12.1.1 software (2003). The goodness of fit was checked through the coefficient of
 244 determination R^2 , the NRMSE (root mean square error normalized dividing by the average of

245 observed values), and by the analysis of the regression between fitted and measured values (we
 246 tested the hypothesis that the linear regression did not significantly deviate from the first quadrant
 247 bisector).

248 From the obtained decay constant, we calculated the YMR values that correspond to the fraction of
 249 SOC or of the organic C supplied via added organic materials lost by the soil in one year:

$$250 \quad YMR = 1 - e^{-k*1}$$

251 Data from measured soil N and N additions were fitted to an equation analogous to that used for C,
 252 (Equation 4). The equation included N added with slurry (defined as *SLN*), farmyard manure (*FN*),
 253 maize root (*RN_m*), ley and ryegrass root (*RN_l*), and maize straw, stalk base and ley stubble (*STN*). As
 254 with soil N (*k_N*), we associated a specific decay constant to each (*kN_{SL}*, *kN_F*, *kN_R*, *kN_{ST}*), addition
 255 considered.

$$N_{2003} = a + b + c + d + e + f$$

where:

$$\begin{aligned}
 a &= (N_{1999} - (RN_{m1998} * e^{-kN_R*0.5})) * e^{-k_N*4} \\
 b &= \sum_{t=0}^3 (RN_{m(1998+t)} * e^{-kN_R*1} * e^{-k_N*(3.5-t)}) + RN_{m2002} * e^{-kN_R*0.5} \\
 256 \quad c &= \sum_{t=0}^3 (RN_{l(1999+t)} * e^{-kN_R*1} * e^{-k_N*(4-t)}) \quad (4) \\
 d &= \sum_{t=0}^3 (STN_{(1999+t)} * e^{-kN_{ST}*1} * e^{-k_N*(4-t)}) \\
 e &= \sum_{t=0}^3 (SLN_{(1999+t)} * e^{-kN_{SL}*1} * e^{-k_N*(4-t)}) \\
 f &= \sum_{t=0}^3 (FN_{(1999+t)} * e^{-kN_F*1} * e^{-k_N*(4-t)})
 \end{aligned}$$

257 As for C, we checked the goodness of fit through the R², the NRMSE, and the analysis of the
 258 regression between fitted and measured values, and we calculated the YMR.

259 YMR represents the fraction of organic N transformed to mineral after one year that is the net result
 260 of the mineralisation and immobilisation processes. We subsequently expressed this amount also as
 261 a fraction of the amount of organic materials supplied.

262

263 2.5 CO₂ emissions inventory

264 The amount of C sequestered or emitted by croplands is taken into account in the IPCC greenhouse
265 gases inventories when changes in management impacting on SOC occur (IPCC, 2006).

266 The calculation of annual C change as proposed in the IPCC guidelines default method is based on
267 the following equation:

$$268 \Delta C_{Mineral} = \frac{SOC_t - SOC_0}{D}$$

269 where the annual change in C stock ($\Delta C_{Mineral}$) is equal to the difference in SOC stocks between two
270 different moments (t and 0) divided by the default time period (D) necessary for the transition to a
271 new SOC equilibrium following a management change. For the estimate of SOC_t and SOC_0 , the
272 equation:

$$273 SOC = SOC_{REF} * F_{LU} * F_{MG} * F_I$$

274 is used, where SOC_{REF} is a default value depending on the soil and climate situation, with correction
275 factors taking into account land use (F_{LU}), tillage (F_{MG}) and C inputs (F_I). For more accurate
276 estimates it is possible to use country-specific values and factors.

277 In order to provide site-specific values for the above-described IPCC method, we could estimate the
278 correction factor F_I for the different organic materials added to the soil in the maize-based forage
279 systems included in our dataset. More specifically, we calculated the SOC stock change following
280 the application of crop residue, bovine slurry, and farmyard manure. Since the extent of SOC
281 increase due to the addition of these materials is strongly dependent on the initial SOC stock, we
282 analysed different case studies, starting from three different C contents (or SOC_{REF} values). The
283 chosen SOC_{REF} values represent the tenth, fiftieth, and ninetieth percentiles, respectively of the
284 distribution of maize-cropped Entisols in the Piemonte Region plane (Bourlot et al., 2007).
285 Different C inputs were applied on these initial SOC stocks. C inputs were different combinations
286 of the following techniques: no supply or yearly supply of slurry or farmyard manure at two
287 different levels (one at 170 kg N ha⁻¹ set by the Nitrate Directive, and one at 240 kg N ha⁻¹,

288 derogating the directive) in the presence or absence of crop residue return. We extrapolated data on
289 a 20-year basis, applying Equation (3) and we calculated the F_1 values for the different management
290 options considered.

291 Furthermore, assuming that C is lost from the system completely as CO_2 , the YMR represents the
292 fraction of C supplied via each organic material lost as CO_2 . We expressed the amount of C- CO_2
293 lost or removed by the soil also as a fraction of the amount of organic material supplied.

294

295 **3. Results**

296 *3.1 Measured SOC and N content*

297 Data of SOC and N measured in 1999 and 2003 are shown in Table 3.

298 SOC was higher when maize straw was returned to the soil and, secondly, when ryegrass or ley
299 were present in the rotation ($Mg > Mr$, $Ml > Ms$), regardless of the year. The fertiliser management
300 also influenced the SOC: the high farmyard manure input produced the highest SOC content,
301 followed by the low farmyard manure and both levels of slurry application. The different levels of
302 urea use did not lead to significant differences in SOC, which was always as low as the control
303 treatment. Although ranking of the different fertilisation managements was the same in the two
304 years, the differences were more clearly defined in 2003.

305 Total N content in the soil showed very similar ranking : in 1999 it was the highest for Mg and Mr,
306 while in 2003 for Mg and Ml; soil N content of Ms was the lowest in both years. Soil N content was
307 higher following the application of manures compared to urea treatments (farmyard manure > slurry
308 > urea). No difference was observed between the urea treatments, which did not differ from the
309 control. Differences due to the fertilisation managements were independent of the year. These
310 findings agree with the results from other long-term field trials (Jenkinson, 1990; Nardi et al.,
311 2004).

312 The absence of the year effect between 1999 and 2003 means that our treatments already reached a
313 new SOM equilibrium. Therefore this is a suitable moment to obtain appropriate values for the
314 decay rate of the different organic additions.

315

316 *3.2 Coefficients of SOM evolution and organic materials decomposition*

317 We explained the relationship between SOC in 1999 and 2003 and C inputs from the different fresh
318 organic materials, through Equation (3). Resulting decay constants are summarized in Table 4, as
319 well as the yearly mineralization rate (YMR) representing the yearly mean disappearance rate of C
320 stocks. For fresh organic materials, the complement to one of YMR corresponds to their isohumic
321 coefficients. The analysis of the regression between the equation-fitted SOC stock and the measured
322 SOC in 2003 (Figure 1a) suggests that more than 85% of data variability is explained by the
323 equation and that the linear regression did not significantly deviate from the first quadrant bisector.

324 The decay constant and YMR for N are summarized in Table 4 while Figure 1b displays measured
325 N vs. fitted N in 2003. In Table 5 we presented data of the net amount of mineral N released in one
326 year from the different organic inputs.

327

328 *3.3 Factors for the CO₂ inventories*

329 In Table 6 we showed the F_1 values for the different investigated C inputs obtained as from the three
330 SOC_{REF} considered. The values ranged from 0.8 (when SOC_{REF} was high and nothing but crop root
331 was left in the soil) to 2.1 (when SOC_{REF} was low and a high amount of farmyard manure was
332 applied in combination with crop residue return).

333 In Table 7, the fractions of added organic materials lost as CO₂ by the soil or stocked in the soil are
334 presented. This represents a very simple application useful to estimate CO₂ losses or removals as a
335 result of a balance between the processes of SOC mineralization and humification following the
336 addition of different organic materials.

337

338 4. Discussion

339 The estimated value of the decay constant k_C was 0.020 year^{-1} which corresponds to 0.020 year^{-1}
340 YMR, meaning that 2.0% of SOC is lost (or mineralized) by the soil system every year. With this
341 decay constant, the half-life of the SOC stock of this soil is calculated to be approximately 34 years.
342 This rate is consistent with values reported in the literature from field trials considering the loam
343 texture of the soil and the climate conditions of our experimental site (Larson et al., 1972; Barber,
344 1979; Allmaras et al., 2004). For example, on a soil with a similar texture, Pedra et al. (2007)
345 showed that 2.0% of SOC per year was lost through mineralization. On the contrary, according to
346 the estimate method proposed by Boiffin et al. (1986) and also adopted by Bocchi et al. (2001),
347 based on clay and lime content, our soil SOC mineralization rate would be higher than what we
348 found (about 2.9%).

349 The decay rate found of crop residue (maize straw, stalk base, and ley stubble) and its related
350 isohumic coefficient indicate that one year after soil incorporation, only 6% of the C present in the
351 straw remained in the soil. It is acknowledged that crop residue is rapidly decomposed in the soil
352 (Jenkinson, 1990), and that C accumulation following the application of large amounts of straw is
353 quite limited (Grignani et al., 2007). Nevertheless, the fraction of crop residue C remaining in the
354 soil after one year is slightly lower than reported by other authors. Both Barber (1979) and Allmaras
355 et al. (2004), in two field studies analysing soil organic matter dynamics over a medium term
356 period, found that 11% of C supplied with maize straw became soil organic matter after one year. In
357 a 15-year field study by Bolinder et al. (1999), the estimated fraction of above-ground maize
358 biomass C retained in the soil after one year ranged from 7.7% to 20.0%. In our experiment,
359 because maize straw spent about six months off soil before incorporation, decomposition had likely
360 already begun. However, because the number of cases used in the equation could not support the
361 introduction of a new parameter, it was not possible to insert a specific decay constant for off-soil
362 straw decomposition. Furthermore, attributing the k_{ST} decay constant also to the off-soil
363 decomposition period would be incorrect since the two processes occurred in dissimilar

364 environmental conditions and involved different microbial populations (Potthoff et al., 2001;
365 Potthoff et al., 2005). Therefore, our maize straw decay constant refers solely to the specific
366 conditions that occurred in our experiment, i.e. spring incorporation after a winter off-soil period, a
367 frequent practice in our area.

368 Our setup generally provided the return of crop residue in combination with good N fertilization (on
369 average $230 \text{ kg ha}^{-1} \text{ y}^{-1}$, of which 175 was from inorganic fertilizer). This fact probably implied an
370 acceleration of residue decomposition (Recous et al., 1995), and resulted in the decay constant
371 found applicable in a non-limiting mineral N supply situation as is often found in normal farm
372 practices.

373 Root decomposed along slower dynamics than above-ground crop residue, leading to recovery of
374 approximately 28% C after one year. Several studies showed that crop root is decomposed in the
375 soil at a lower rate than crop shoots (Bolinder et al., 1999 and references therein). This phenomenon
376 indicates that their larger enhancement of the SOM content is due to their chemical composition and
377 decomposition conditions (Balesdent and Balabane, 1996; Bolinder et al., 1999; Abiven et al.,
378 2005). Our setup confirmed the need to separate the decay dynamics of above and below ground
379 crop biomass. The root decay rate found in this study generally agrees with values from other
380 experiments, even if slightly high when compared with crop residue (root isohumic coefficient of
381 14.4 to 30.0% after one year for Bolinder et al. (1999)). We hypothesized to underestimate root C
382 supply and therefore, to overestimate root humification by not considering the extra-root C
383 produced during the growing season by exudates and root turnover (Barber, 1979; Plenet et al.,
384 1993).

385 Carbon applied via slurry and farmyard manure was lost by 74% and 54%, respectively in one year.
386 These results confirm those found by the different approaches on the same trial of Grignani et al.
387 (2007), who used a wider database, and Monaco et al. (2008), who analysed some soil properties on
388 a selection of treatments, both over a period of eleven years. The isohumic coefficients found for

389 manure are in line with those traditionally found in the literature (Rémy and Marin-Laflèche, 1976;
390 Decoopman et al., 2004).

391 The principal difference between C recovery in crop residue and manures can be explained by the
392 fact that animal manures have passed through the digestive tract where they were made rich in
393 refractory C compounds (Paustian et al., 1995). Furthermore, farmyard manure is composed of
394 excreta mixed with straw or other bedding materials, generally prone to a CO₂-losing process of
395 composting, thus implying the presence of more recalcitrant C compounds than in excreta simply
396 mixed with water (i.e. slurry). Data from a long-term trial in the South eastern Po valley confirm the
397 higher content of stabilised organic compounds in the manure than in liquid slurry (Triberti et al.,
398 2008).

399 Some authors assert that increasing amounts of mineral N fertiliser result in a positive net carbon
400 sequestration because of the higher production of root and residue (Paustian et al., 1997; Bruce et
401 al., 1999; Izaurrealde et al., 2000). Others suggest that the application of mineral N fertiliser
402 promotes the acceleration of SOM mineralisation (Kuzyakov et al., 2000). Our results showed that
403 increasing amount of urea did not produce any significant difference in SOC content, indicating that
404 the amount of mineral N supplied is not determinant for C sequestration.

405 The YMR's (Table 4) are higher for N than for C and this difference is low for farmyard manure
406 and straw, the fresh organic matter compounds more recalcitrant to mineralization. The relationship
407 between C and N YMR is not simply controlled by the C to N ratio of the different added organic
408 materials since the presence of urea N interacted with the mineralisation of the different organic
409 inputs; however, the applied equation could not separate this effect. For freshly added organic
410 materials, the YMR can easily be used to estimate the amount of N made available for crops during
411 the growing season (Table 5). This information can be an effective tool for the realization of N
412 balance, increasingly adopted at the international level as a policy tool to estimate long-term
413 sustainability of a system (see Nitrate directive) and useful at the farm level to properly plan
414 fertilization (Rees et al., 2001; Bassanino et al., 2007).

415 The results about CO₂ emission, shown in Table 6, indicate that almost all the cases analysed are
416 SOC-conservative and lead instead to CO₂ removal when the initial SOC content is low or medium.
417 The sole exception is represented by the absence of further organic input besides crop root, that is a
418 C-depleting management with an initial medium SOC content. When the initial SOC stock is
419 already high, the potential for sequestration is rather low and limited to the addition of large
420 amounts of C via manure and crop residue. The F₁ correction factors are not only a useful tool for a
421 more complete and precise quantification of C sequestered or lost for the greenhouse gas
422 inventories. They furnish site-specific numerical values for the evaluation of different soil organic
423 carbon accumulation scenarios, as outlined at regional level by Bocchi et al. (2001) in Lombardia
424 (Italy) and as developed in detail at national level by the INRA (2002) for France.

425 On the basis of these results, we compared two management options, both possible for a livestock
426 farm: i) use maize straw for litter and produce farmyard manure, and ii) leave straw in the field and
427 spread liquid slurry. A dairy cow on average produces about 60-65 m³ year⁻¹ of liquid slurry
428 (excreta and water), when bred on slatted floor, or about 20 Mg year⁻¹ of farmyard manure, when
429 kept on permanent litter, and about 0.15 Mg of straw is necessary for the production of 1 Mg of
430 farmyard manure (RAC, 2001; RegionePiemonte, 2002). In order to spread 30 Mg ha⁻¹ of farmyard
431 manure (corresponding to about 170 kg N ha⁻¹), 4.5 Mg of maize straw are removed from the field
432 (namely from a surface approximately equal to 0.4 ha). On the basis of our results, we can calculate
433 that producing and spreading for 20 years farmyard manure on a 1 ha field, we would increase the C
434 content by about 20 Mg ha⁻¹ in the first 30 cm deep layer. On the contrary, leaving all the straw in
435 the field and spreading the corresponding amount of liquid slurry would produce a C increase of
436 about 16 Mg ha⁻¹. This confirms that producing and spreading farmyard manure is more C
437 conservative than applying liquid slurry, since the process of composting promotes the soil organic
438 matter stability (Fliessbach et al., 2007).

439
440

441 **5. Conclusions**

442 Data of SOC and total N from a medium-term field trial allowed us to estimate the proportion of
443 different added organic materials retained in the soil as SOM and their potentiality to enrich soil
444 pools of C and N.

445 SOC was generally enhanced by the application of farmyard manure as compared to the return of
446 crop residue and the application of slurry.

447 The obtained results are a potentially useful tool at the territorial level for the compilation of
448 greenhouse gas inventories and N balance following certain agricultural practices, such as crop
449 residue return or manuring.

450

451 **Acknowledgment**

452 This work was partially financed by the EU (CAMAR project no.8001-CT91-0103), National
453 Council of Research CNR (RAISA Project), Italian Ministry of Agriculture and Forestry (PANDA
454 project) and Regione Piemonte-Assessorato all'Ambiente, Agricoltura e Qualità.

455 The authors are grateful to Mario Gilardi, Gabriele Gariglio, Mauro Gilli, and to all the people
456 involved in field trial management, and to Joan C. Leonard for her precious help in the text revision.

457

458 **References**

459

460 Abiven, S., Recous, S., Reyes, V., Oliver, R., 2005. Mineralisation of C and N from root, stem and
461 leaf residues in soil and role of their biochemical quality. *Biology and Fertility of Soils* 42, 119-128.

462 Allmaras, R.R., Linden, D.R., Clapp, C.E., 2004. Corn-residue transformations into root and soil
463 carbon as related to nitrogen, tillage, and stover management. *Soil Science Society of America*
464 *Journal* 68, 1366-1375.

465 Amos, B., Walters, D.T., 2006. Maize root biomass and net rhizodeposited carbon: An analysis of
466 the literature. *Soil Science Society of America Journal* 70, 1489-1503.

467 Andren, O., Katterer, T., 1997. ICBM: The introductory carbon balance model for exploration of
468 soil carbon balances. *Ecological Applications* 7, 1226-1236.

469 Andren, O., Katterer, T., Karlsson, T., 2004. ICBM regional model for estimations of dynamics of
470 agricultural soil carbon pools. *Nutrient Cycling in Agroecosystems* 70, 231-239.

471 Andriulo, A., Mary, B., Guerif, J., 1999. Modelling soil carbon dynamics with various cropping
472 sequences on the rolling pampas. *Agronomie* 19, 365-377.

473 APAT, 2006. Italian greenhouse gas inventory 1990-2004. National inventory report 2006. Rome.

474 Balesdent, J., Balabane, M., 1996. Major contribution of roots to soil carbon storage inferred from
475 maize cultivated soils. *Soil Biology & Biochemistry* 28, 1261-1263.

476 Barber, S.A., 1979. Corn residue management and soil organic matter. *Agronomy Journal* 71, 624-
477 627.

478 Bassanino, M., Grignani, C., Sacco, D., Allisiardi, E., 2007. Nitrogen balances at the crop and farm-
479 gate scale in livestock farms in Italy. *Agriculture Ecosystems & Environment* 122, 282-294.

480 Bayer, C., Lovato, T., Dieckow, J., Zanatta, J.A., Mielniczuk, J., 2006. A method for estimating
481 coefficients of soil organic matter dynamics based on long-term experiments. *Soil & Tillage*
482 *Research* 91, 217-226.

483 Bocchi, S., De Ferrari, G., Bechini, L., 2001. Application of the Hénin-Dupuis model to
484 georeferenced soil analyses. 2nd International Symposium "Modelling Cropping Systems" -
485 European Society of Agronomy. pp. 107-108.

486 Boiffin, J., Keli Zagbahi, J., Sebillotte, M., 1986. Systèmes de culture et statut organique des sols
487 dans le Noyonnais : application du modèle de Hénin-Dupuis. *Agronomie* 6, 437-446.

488 Bolinder, M.A., Angers, D.A., Giroux, M., Laverdiere, M.R., 1999. Estimating C inputs retained as
489 soil organic matter from corn (*Zea Mays* L.). *Plant and Soil* 215, 85-91.

490 Bourlot, G., Barberis, E., Del Vecchio, A., Sacco, D., 2007. Il suolo agrario piemontese. Analisi,
491 organizzazione dei dati e applicazioni. Supplemento al n.56 dei "Quaderni della Regione Piemonte-
492 Agricoltura", Torino.

493 Bremner, J.M., 1996. Nitrogen-total. In: Bartels, J.M. (Ed.) *Methods of soil analysis. Part 3.*
494 *Chemical Methods.* SSSA-ASA, Madison, pp. 1085-1121.

495 Bruce, J.P., Frome, M., Haites, E., Janzen, H., Lal, R., Paustian, K., 1999. Carbon sequestration in
496 soils. *Journal of Soil and Water Conservation* 54, 382-389.

497 Buyanovsky, G.A., Wagner, G.H., 1997. Crop residue input to soil organic matter in the Sanborn
498 field. In: Paul, E.A. (Ed.) *Soil organic matter in temperate ecosystems: Long-term experiments in*
499 *North America.* CRC Press, Boca Raton.

500 Chertov, O.G., Komarov, A.S., 1997. SOMM: A model of soil organic matter dynamics. *Ecological*
501 *Modelling* 94, 177-189.

502 Chivenge, P.P., Murwira, H.K., Giller, K.E., Mapfumo, P., Six, J., 2007. Long-term impact of
503 reduced tillage and residue management on soil carbon stabilization: Implications for conservation
504 agriculture on contrasting soils. *Soil & Tillage Research* 94, 328-337.

505 Clay, D.E., Carlson, C.G., Clay, S.A., Reese, C., Liu, Z., Chang, J., Ellsbury, M.M., 2006.
506 Theoretical derivation of stable and nonisotopic approaches for assessing soil organic carbon
507 turnover. *Agronomy Journal* 98, 443-450.

508 Cookson, W.R., Abaye, D.A., Marschner, P., Murphy, D.V., Stockdale, E.A., Goulding, K.W.,
509 2005. The contribution of soil organic matter fractions to carbon and nitrogen mineralization and
510 microbial community size and structure. *Soil Biology & Biochemistry* 37, 1726-1737.

511 Decoopman, B., Menasseri, S., Collet, J.M., Porteneuve, C., L'Aminot, A.M., 2004. Effectiveness
512 of organic amendments to loamy soil - presentation of the study (Part 1). *Infos-Ctifl*.

513 Dimitrov, S.D., Kamenski, D.I., 1997. Overall stability constants: Estimation by non-linear least
514 squares methods. *Computers & Chemistry* 21, 167-173.

515 Fliessbach, A., Oberholzer, H.R., Gunst, L., Mader, P., 2007. Soil organic matter and biological soil
516 quality indicators after 21 years of organic and conventional farming. *Agriculture Ecosystems &*
517 *Environment* 118, 273-284.

518 Follett, R.F., 2001. Soil management concepts and carbon sequestration in cropland soils. *Soil &*
519 *Tillage Research* 61, 77-92.

520 Franko, U., Crocker, G.J., Grace, P.R., Klir, J., Korschens, M., Poulton, P.R., Richter, D.D., 1997.
521 Simulating trends in soil organic carbon in long-term experiments using the CANDY model.
522 *Geoderma* 81, 109-120.

523 Greenland, D.J., 1971. Changes in the nitrogen status and physical condition of soils under pasture,
524 with special reference to the maintenance of the fertility of Australian soils used for growing wheat.
525 *Soil Fertility* 34, 237-251.

526 Grignani, C., Zavattaro, L., Sacco, D., Monaco, S., 2007. Production, nitrogen and carbon balance
527 of maize-based forage systems. *European Journal of Agronomy* 26, 442-453.

528 Guérif, J., 1986. Modification de la répartition et de l'évolution des matières organiques par la
529 implication du travail du sol: conséquences sur quelques propriétés physiques. In: *Les rotations*
530 *céréalières intensives. Dix années d'études concertées, Inra-ONIC-ITCF, 1973-1983. Paris, pp. 63-*
531 *68.*

532 Hénin, S., Dupuis, M., 1945. Essai de bilan de la matière organique du sol. *Annales agronomiques*
533 15, 17-19.

534 Huggins, D.R., Buyanovsky, G.A., Wagner, G.H., Brown, J.R., Darmody, R.G., Peck, T.R.,
535 Lesoing, G.W., Vanotti, M.B., Bundy, L.G., 1998a. Soil organic C in the tallgrass prairie-derived
536 region of the corn belt: effects of long-term crop management. *Soil & Tillage Research* 47, 219-
537 234.

538 Huggins, D.R., Clapp, C.E., Allmaras, R.R., Lamb, J.A., Layese, M.F., 1998b. Carbon dynamics in
539 corn-soybean sequences as estimated from natural carbon-13 abundance. *Soil Science Society of*
540 *America Journal* 62, 195-203.

541 INRA, 2002. Stocker du carbone dans les sols agricoles? - Rapport d'expertise réalisé par IINRA à
542 la demande du Ministère de l'Ecologie et du Développement Durable.

543 IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. IGES, Hayama.

544 Izaurrealde, R.C., McGill, W.B., Rosenberg, N.J., 2000. Carbon cost of applying nitrogen fertilizer.
545 *Science* 288, 811-812.

546 Janssen, B.H., 1984. A simple method for calculating decomposition and accumulation of 'young'
547 soil organic matter. *Plant and Soil* 76, 297-304.

548 Jenkinson, D.S., 1990. The Turnover of Organic-Carbon and Nitrogen in Soil. *Philosophical*
549 *Transactions of the Royal Society of London Series B-Biological Sciences* 329, 361-368.

550 Jenkinson, D.S., Rayner, J.H., 1977. The turnover of soil organic matter in some of the Rothamsted
551 classical experiments. *Soil Science* 123, 298-305.

552 Juma, N.G., 1993. Interrelationships between Soil-Structure Texture, Soil Biota Soil Organic-
553 Matter and Crop Production. *Geoderma* 57, 3-30.

554 Kemanian, A.R., 2006. Simple model to evaluate the carbon balance of soil profiles. 2006 Soil and
555 Water Assessment Tool Model Developers Workshop. Potsdam.

556 Kemanian, A.R., Manoranjan, V.S., Huggins, D.R., Stöckle, C.O., 2005. Assessing the usefulness
557 of simple mathematical models to describe soil carbon dynamics. Third USDA symposium on
558 greenhouse gases & carbon sequestration in agriculture and forestry. Baltimore.

559 Kuzyakov, Y., Friedel, J.K., Stahr, K., 2000. Review of mechanisms and quantification of priming
560 effects. *Soil Biology & Biochemistry* 32, 1485-1498.

561 Lal, R., 2004. Agricultural activities and the global carbon cycle. *Nutrient Cycling in*
562 *Agroecosystems* 70, 103-116.

563 Lal, R., Griffin, M., Apt, J., Lave, L., Morgan, M.G., 2004. Ecology - Managing soil carbon.
564 *Science* 304, 393-393.

565 Larson, W.E., Clapp, C.E., Pierre, W.H., Morachan, J.B., 1972. Effects of increasing amounts of
566 organic residues on continuous corn. 2. Organic carbon, nitrogen, phosphorus, and sulfur.
567 *Agronomy Journal* 64, 204-208.

568 Li, C.S., Frolking, S., Crocker, G.J., Grace, P.R., Klir, J., Korchens, M., Poulton, P.R., 1997.
569 Simulating trends in soil organic carbon in long-term experiments using the DNDC model.
570 *Geoderma* 81, 45-60.

571 Magid, J., Luxhoi, J., Lyshede, O.B., 2004. Decomposition of plant residues at low temperatures
572 separates turnover of nitrogen and energy rich tissue components in time. *Plant and Soil* 258, 351-
573 365.

574 Manna, M.C., Swarup, A., Wanjari, R.H., Mishra, B., Shahi, D.K., 2007. Long-term fertilization,
575 manure and liming effects on soil organic matter and crop yields. *Soil & Tillage Research* 94, 397-
576 409.

577 Manna, M.C., Swarup, A., Wanjari, R.H., Ravankar, H.N., Mishra, B., Saha, M.N., Singh, Y.V.,
578 Sahi, D.K., Sarap, P.A., 2005. Long-term effect of fertilizer and manure application on soil organic
579 carbon storage, soil quality and yield sustainability under sub-humid and semi-arid tropical India.
580 *Field Crops Research* 93, 264-280.

581 Mary, B., Guérif, J., 1994. Intérêts et limites des modèles de prévision de l'évolution des matières
582 organiques et de l'azote dans le sol. *Cahiers Agricultures* 3, 247-257.

583 McVay, K.A., Rice, C.W., 2002. Soil organic carbon and the global carbon cycle. Kansas State
584 University, Manhattan.

585 Molina, J.A.E., Crocker, G.J., Grace, P.R., Klir, J., Korschens, M., Poulton, P.R., Richter, D.D.,
586 1997. Simulating trends in soil organic carbon in long-term experiments using the NCSOIL, and
587 NCSWAP models. *Geoderma* 81, 91-107.

588 Monaco, S., Hatch, D.J., Sacco, D., Bertora, C., Grignani, C., 2008. Changes in chemical and
589 biochemical soil properties induced by 11-yr repeated additions of different organic materials in
590 maize-based forage systems. *Soil Biology & Biochemistry* 40, 608-615.

591 Morari, F., Lugato, E., Berti, A., Giardini, L., 2006. Long-term effects of recommended
592 management practices on soil carbon changes and sequestration in north-eastern Italy. *Soil Use and*
593 *Management* 22, 71-81.

594 Nardi, S., Morari, F., Berti, A., Tosoni, M., Giardini, L., 2004. Soil organic matter properties after
595 40 years of different use of organic and mineral fertilisers. *European Journal of Agronomy* 21, 357-
596 367.

597 Nesme, T., Bellon, S., Lescouret, F., Senoussi, R., Habib, R., 2005. Are agronomic models useful
598 for studying farmers' fertilisation practices? *Agricultural Systems* 83, 297-314.

599 Parton, W.J., Hartman, M., Ojima, D., Schimel, D., 1998. DAYCENT and its land surface
600 submodel: description and testing. *Global and Planetary Change* 19, 35-48.

601 Parton, W.J., Ojima, D.S., Cole, C.V., Schimel, D.S., 1994. A general model for soil organic matter
602 dynamics: sensitivity to litter chemistry, texture and management. In: *Quantitative modelling of*
603 *soil forming processes*. SSSA Special Publications, Madison, pp. 147-167.

604 Parton, W.J., Stewart, J.W.B., Cole, C.V., 1988. Dynamics of C, N, P, and S in grassland soils: a
605 model. *Biogeochemistry* 5, 109-131.

606 Paustian, K., Elliott, E.T., Collins, H.P., Cole, C.V., Paul, E.A., 1995. Use of a network of long-
607 term experiments for analysis of soil carbon dynamics and global change: The North American
608 model. *Australian Journal of Experimental Agriculture* 35, 929-939.

609 Paustian, K., Levine, E., Post, W.M., Ryzhova, I.M., 1997. The use of models to integrate
610 information and understanding of soil C at the regional scale. *Geoderma* 79, 227-260.

611 Pedra, F., Polo, A., Ribeiro, A., Domingues, H., 2007. Effects of municipal solid waste compost
612 and sewage sludge on mineralization of soil organic matter. *Soil Biology & Biochemistry* 39, 1375-
613 1382.

614 Pietola, L., Alakukku, L., 2005. Root growth dynamics and biomass input by Nordic annual field
615 crops. *Agriculture Ecosystems & Environment* 108, 135-144.

616 Plenet, D., Lubet, E., Juste, C., 1993. Change in the Organic-Carbon Content of Soil in a Long-
617 Term Continuous Non Irrigated Maize Crop. *Agronomie* 13, 685-698.

618 Potthoff, M., Dyckmans, J., Flessa, H., Muhs, A., Beese, F., Joergensen, R.G., 2005. Dynamics of
619 maize (*Zea mays* L.) leaf straw mineralization as affected by the presence of soil and the
620 availability of nitrogen. *Soil Biology & Biochemistry* 37, 1259-1266.

621 Potthoff, M., Joergensen, R.G., Wolters, V., 2001. Short-term effects of earthworm activity and
622 straw amendment on the microbial C and N turnover in a remoistened arable soil after summer
623 drought. *Soil Biology & Biochemistry* 33, 583-591.

624 RAC, 2001. Données de base pour la fumure des grandes cultures et des herbages. *Revue suisse*
625 *d'agriculture* 33, 1-80.

626 Raiesi, F., 2006. Carbon and N mineralization as affected by soil cultivation and crop residue in a
627 calcareous wetland ecosystem in Central Iran. *Agriculture Ecosystems & Environment* 112, 13-20.

628 Rasse, D.P., Mulder, J., Moni, C., Chenu, C., 2006. Carbon turnover kinetics with depth in a french
629 loamy soil. *Soil Science Society of America Journal* 70, 2097-2105.

630 Rawls, W.J., Pachepsky, Y.A., Ritchie, J.C., Sobecki, T.M., Bloodworth, H., 2003. Effect of soil
631 organic carbon on soil water retention. *Geoderma* 116, 61-76.

632 Recous, S., Robin, D., Darwis, D., Mary, B., 1995. Soil inorganic N availability: Effect on maize
633 residue decomposition. *Soil Biology & Biochemistry* 27, 1529-1538.

634 Rees, R.M., Ball, B.C., Campbell, C.D., Watson, C.A., 2001. Sustaining soil organic matter. In:
635 Rees, R.M., Ball, B.C., Campbell, C.D., Watson, C.A. (Eds.), *Sustainable management of soil*
636 *organic matter*. CAB International, Wallingford, pp. 413-425.

637 Reeves, D.W., 1997. The role of soil organic matter in maintaining soil quality in continuous
638 cropping systems. *Soil & Tillage Research* 43, 131-167.

639 Regione Piemonte, 2002. Regolamento regionale recante: Designazione delle zone vulnerabili da
640 nitrati di origine agricola e relativo programma di azione. D.P.G.R. 18/10/2002 no. 9/R.

641 Rémy, J.C., Marin-Lafèche, A., 1976. L'entretien organique des terres. Coût d'une politique de
642 l'humus. *Entreprises Agricoles*. Novembre, 63-67.

643 Saadi, Z., Maslouhi, A., 2003. Modeling nitrogen dynamics in unsaturated soils for evaluating
644 nitrate contamination of the Mnasra groundwater. *Advances in Environmental Research* 7, 803-823.

645 Saffih-Hdadi, K., Mary, B., 2008. Modeling consequences of straw residues export on soil organic
646 carbon. *Soil Biology & Biochemistry* 40, 594-607.

647 Schlesinger, W.H., 1999. Carbon and agriculture - Carbon sequestration in soils. *Science* 284, 2095-
648 2095.

649 Schneider, M.K., Luscher, A., Frossard, E., Nosberger, J., 2006. An overlooked carbon source for
650 grassland soils: loss of structural carbon from stubble in response to elevated pCO₂ and nitrogen
651 supply. *New Phytologist* 172, 117-126.

652 Shepherd, M.A., Harrison, R., Webb, J., 2002. Managing soil organic matter - implications for soil
653 structure on organic farms. *Soil Use and Management* 18, 284-292.

654 Sleutel, S., De Neve, S., Nemeth, T., Toth, T., Hofman, G., 2006. Effect of manure and fertilizer
655 application on the distribution of organic carbon in different soil fractions in long-term field
656 experiments. *European Journal of Agronomy* 25, 280-288.

657 Smith, P., Goulding, K.W., Smith, K.A., Powlson, D.S., Smith, J.U., Falloon, P., Coleman, K.,
658 2001. Enhancing the carbon sink in European agricultural soils: including trace gas fluxes in
659 estimates of carbon mitigation potential. *Nutrient Cycling in Agroecosystems* 60, 237-252.

660 Smith, P., Powlson, D.S., 2000. Considering manure and carbon sequestration. *Science* 287, 428-
661 429.

662 Springer, U., Klee, J., 1954. Prufung der Leistungsfahigkeit von einigen wichtigen verfahren zur
663 Bestimmung des Kohlenstoffe mittels Chromschwefelsaure sowie Vorschlag einer neuen
664 Schnellmethode. Z. Pflanzenernahr. Dung. Bodenk. 64, 1-26.

665 Teixeira, E.I., Moot, D.J., Mickelbart, M.V., 2007. Seasonal patterns of root C and N reserves of
666 lucerne crops (*Medicago sativa* L.) grown in a temperate climate were affected by defoliation
667 regime. *European Journal of Agronomy* 26, 10-20.

668 Thompson, M.L., Zhang, H., Kazemi, M., Sandor, J.A., 1989. Contribution of organic matter to
669 cation exchange capacity and specific surface area of fractionated soil materials. *Soil Science* 148,
670 250-257.

671 Triberti, L., Nastri, A., Giordani, G., Comellini, F., Baldoni, G., Toderi, G., 2008. Can mineral and
672 organic fertilization help sequester carbon dioxide in cropland? *European Journal of Agronomy*
673 29, 13-20.

674 USDA, 1977. Keys to Soil Taxonomy. Soil Survey Staff, Soil Conservation Service U.S. Dept. Of
675 Agriculture, 7th edition. Pocahontas Press Inc., Blacksburg.

676 Walkley, A., Black, L.A., 1934. An examination of the Degtjareff method for determining soil
677 organic matter and a proposed modification of the chromic acid titration method. *Soil Science* 37,
678 29-38.

679 Watson, C.A., Ross, J.M., Bagnaresi, U., Minotta, G.F., Roffi, F., Atkinson, D., Black, K.E.,
680 Hooker, J.E., 2000. Environment-induced modifications to root longevity in *Lolium perenne* and
681 *Trifolium repens*. *Annals of Botany* 85, 397-401.

682 Whipps, J.M., 1990. Carbon economy. In: Lynch, J.M. (Ed.) *The rhizosphere*. J. Wiley, Chichester.

683 Woodruff, C.M., 1949. Estimating the nitrogen delivery of soil from the organic matter
684 determination as reflected by sanborn field. *Soil Science Society of America Journal* 14, 208-212.

685 Xu, Y.C., Chen, W., Shen, Q.R., 2007. Soil organic carbon and nitrogen pools impacted by long-
686 term tillage and fertilization practices. *Communications in Soil Science and Plant Analysis* 38, 347-
687 357.

688 Table 1. Amount of N (kg N ha⁻¹) received by the treatments included in the experiment.

Cropping system	Fertilization								
	No fertilization (0)	Low level bovine slurry ^a (S _{Low})	High level bovine slurry ^a (S _{High})	Low level bovine farmyard manure ^a (F _{Low})	High level bovine farmyard manure ^a (F _{High})	Urea at 100 N kg ha ⁻¹ (U ₁₀₀)	Urea at 200 N kg ha ⁻¹ (U ₂₀₀)	Urea at 300 N kg ha ⁻¹ (U ₃₀₀)	Urea at 400 N kg ha ⁻¹ (U ₄₀₀)
Maize for silage (Ms)	0	126	252	119	238	100	200	300	400
Maize for grain (Mg)	0	126	252	119	238	100	200	300	400
Double annual rotation of Italian ryegrass and maize for silage ^b (Mr)	0	116	232	116	231	100	200	300	400
Rotation of 3 years of ley of tall fescue and 3 years of maize for silage ^b (MI)	0	129	257	119	238	100	200	300	400
Rotation of 3 years of ley of lucerne and 3 years of maize for silage ^{b,c} (Mu)	-	129	-	-	-	-	-	-	-

^aThe treatment receiving slurry and farmyard manure received also 100 kg N ha⁻¹ as urea at top-dressing.

^bIn the period considered in this work, there were 3 years of ley (1999-2002) and 1 year of maize (2002-2003).

^cThe ley of *Medicago sativa* received bovine slurry once only at sowing (i.e. spring 1999), while maize for silage received it every year at seeding (i.e. spring 2002).

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692 Table 2. Origin of the values used for the estimate of C and N additions (values are expressed on a dry matter basis, except when explicitly
693 indicated).

Addition	Variables used for the estimate	Source	Values
Roots	Above-ground biomass	Measured every year for all treatments	Average \pm St.dev.: 21.9 \pm 4.9 Mg ha ⁻¹ y ⁻¹ (maize), 6.1 \pm 2.5 Mg ha ⁻¹ y ⁻¹ (Italian ryegrass), 13.1 \pm 2.6 Mg ha ⁻¹ y ⁻¹ (<i>Festuca arundinacea</i>) and 15.5 \pm 1.9 Mg ha ⁻¹ y ⁻¹ (lucerne)
	Below ground: above ground biomass ratio	From Grignani, unpublished data	0.22 kg kg ⁻¹ (maize), 0.43 kg kg ⁻¹ (Italian ryegrass, <i>Festuca arundinacea</i> and lucerne)
	C content of roots	From Boiffin et al., 1986; Whipps, 1990	0.40 kg kg ⁻¹ (all crops)
	N content of roots	From Grignani, unpublished data; Teixeira, 2007	15.2 g kg ⁻¹ (maize), 9.2 g kg ⁻¹ (Italian ryegrass and <i>Festuca arundinacea</i>), 14.0 g kg ⁻¹ (lucerne)
Maize straw	Amount of stalks, cobs and bracts produced	Measured every year for Mg treatments	Average \pm St.dev.: 9.1 \pm 2.5 Mg ha ⁻¹ y ⁻¹ (stalks), 2.3 \pm 0.8 Mg ha ⁻¹ y ⁻¹ (cobs and bracts)
	C content of stalk, cobs and bracts	Measured in 2003 for Mg treatments	Average \pm St.dev.: 0.45 \pm 0.04 kg kg ⁻¹ (stalks), 0.47 \pm 0.04 kg kg ⁻¹ (cobs and bracts)
	N content of stalk, cobs and bracts	Measured every year for Mg treatments	Average \pm St.dev.: 6.7 \pm 0.7 g kg ⁻¹ (stalks), 4.8 \pm 1.0 g kg ⁻¹ (cobs and bracts)
Maize stalk base	Stalk biomass	Measured every year for Mg treatments	Average \pm St.dev.: 9.1 \pm 2.5 Mg ha ⁻¹ y ⁻¹
	Stalk:above ground biomass ratio	Measured in 1993-1996 for silage maize	Average \pm St.dev.: 0.50 \pm 0.07 kg kg ⁻¹
	Stalk base left in the field: stalk biomass ratio	From Rasse, 2006	0.12 kg kg ⁻¹
	C content of stalk	Measured in 2003 for Mg treatments	0.45 kg kg ⁻¹
	N content of stalk	Measured every year for Mg treatments	Average \pm St.dev.: 6.7 \pm 0.7 g kg ⁻¹
Ley stubble	Above-ground biomass	Measured every year for M1 treatments	Average \pm St.dev.: 13.1 \pm 2.6 Mg ha ⁻¹ y ⁻¹
	Stubble:above-ground biomass ratio	From Schneider, 2006	0.37 kg kg ⁻¹
	C content of stubble	From Whipps, 1990	0.4 kg kg ⁻¹
	N content of stubble	Measured every year for M1 treatments	Average \pm St.dev.: 19.3 \pm 2.9 g kg ⁻¹
Manures	Amount of slurry and farmyard manure applied	Measured every year for all treatments	50 or 100 Mg ha ⁻¹ y ⁻¹ for slurry, and 20 or 40 Mg ha ⁻¹ y ⁻¹ for farmyard manure (fresh weight)
	C content of slurry and farmyard manure	Measured every year for all treatments	Average \pm St.dev.: 23.3 \pm 7.2 kg Mg ⁻¹ for slurry, and 78.6 \pm 17.4 kg Mg ⁻¹ for farmyard manure (on fresh weight)
	N content of slurry and farmyard manure	Measured every year for all treatments	Average \pm St.dev.: 2.5 \pm 0.3 kg Mg ⁻¹ for slurry, and 6.4 \pm 0.6 kg Mg ⁻¹ for farmyard manure (on fresh weight)

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695 Table 3. Soil Organic Carbon (Mg ha⁻¹) and Total Nitrogen (Mg ha⁻¹) of the 0-30 cm layer in
 696 1999 and 2003, shown per type of system and fertilizer. Different letters denote different means
 697 (P<0.05). Different letters in System*Year or Fertilizer*Year interaction denote different means
 698 between 1999 and 2003 within the single System or Fertilizer.

System/Fertilizer	Soil Organic Carbon			Total Nitrogen		
	1999	2003	Average	1999	2003	Average
Ms	44.6	44.4	44.5 c	5.51 b	5.21 c	5.36
Mr	46.8	47.2	47.0 b	5.65 a b	5.32 b c	5.48
Ml	45.8	47.9	46.9 b	5.53 b	5.50 a b	5.51
Mg	49.0	50.0	49.5 a	5.93 a	5.65 a	5.79
0N	45.6 c d	44.6 d e	45.1	5.54	5.14	5.34 c d
S _{Low}	47.1 b c d	47.5 c d	47.3	5.79	5.44	5.62 b c
S _{High}	48.3 a b c	50.6 b c	49.4	5.93	5.73	5.83 b
F _{Low}	50.4 a b	51.5 b	50.9	5.98	5.79	5.88 b
F _{High}	52.7 a	57.5 a	55.1	6.30	6.36	6.33 a
U ₁₀₀	43.6 c d	43.1 e	43.3	5.33	4.97	5.15 d
U ₂₀₀	43.6 c d	44.3 d e	44.0	5.37	5.11	5.24 d
U ₃₀₀	42.5 d	43.9 d e	43.2	5.19	5.12	5.15 d
U ₄₀₀	45.0 c d	43.4 e	44.2	5.45	5.10	5.27 c d
Average	46.5	47.4	47.0	5.65	5.42	5.53
<i>Source of variation</i>	P(F)	St.err.	n	P(F)	St.err.	n
System	0.00	0.67	27	0.00	0.07	27
Fertilizer	0.00	1.01	12	0.00	0.11	12
Block	0.00	0.58	36	0.00	0.06	36
Year	0.06	0.32	108	0.00	0.03	108
System*Fertilizer	0.64	2.01	3	0.27	0.22	3
System*Year	0.33	0.64	27	0.04	0.08	27
Fertilizer*Year	0.05	0.97	12	0.12	0.08	12

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700

701 Table 4. Decay constant (k) and yearly mineralization rate (YMR) of C and N in SOM, slurry,
702 farmyard manure, root, straw and stubble.

Soil carbon item	Carbon		Nitrogen	
	k (year ⁻¹)	YMR (year ⁻¹)	k (year ⁻¹)	YMR (year ⁻¹)
SOM	0.020	0.020	0.017	0.016
Slurry	1.361	0.744	2.203	0.890
Farmyard manure	0.784	0.543	0.827	0.562
Roots	1.289	0.725	2.265	0.896
703 Straw and stubble	2.825	0.941	7.040	0.999

704

705 Table 5. Mineral N released by different organic materials in one year after their application to
706 the soil.

Organic material	Released mineral N (year ⁻¹)
Slurry	0.2 % of slurry applied (fresh weight)
	4.3 % of slurry applied (dry weight)
Farmyard manure	0.4 % of farmyard manure applied (fresh weight)
	1.3 % of farmyard manure applied (dry weight)
Maize straw	0.3 % of above ground biomass production
	0.6 % of straw production

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710 Table 6. F_1 correction factors for the estimate of CO_2 emissions following the IPCC default
 711 method ("Low" is a 170 kg N ha^{-1} input, and "High" is a 240 kg N ha^{-1} input).

Cases	SOC_{REF}		
	Low ^a	Medium ^b	High ^c
Nothing but root	1.05	0.91	0.82
Crop residue	1.30	1.07	0.91
Low slurry without crop residue	1.27	1.05	0.90
High slurry without crop residue	1.36	1.11	0.93
Low farmyard manure without crop residue	1.62	1.28	1.03
High farmyard manure without crop residue	1.86	1.43	1.12
Low slurry with crop residue	1.52	1.21	0.99
High slurry with crop residue	1.61	1.27	1.03
Low farmyard manure with crop residue	1.87	1.44	1.13
High farmyard manure with crop residue	2.11	1.59	1.22

^a 11.5 g kg^{-1}

^b 18.1 g kg^{-1}

^c 30.1 g kg^{-1}

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713 Table 7. C lost to the atmosphere or stocked in the soil following the addition of different
 714 organic materials. Values are expressed as a percentage of the amount of added organic
 715 materials, per year.

716

Soil carbon item	C lost by the soil (%)	C stocked in the soil (%)	
SOC	2.0	-	of C in the soil
Slurry	1.7	0.6	of slurry applied (fresh weight)
	31.8	10.9	of slurry applied (dry weight)
Farmyard manure	5.6	1.9	of farmyard manure applied (fresh weight)
	20.1	6.9	of farmyard manure applied (dry weight)
Maize roots	6.4	2.4	of above ground biomass produced (on a dry matter basis)
	29.0	11.0	of below ground biomass produced (on a dry matter basis)
Italian ryegrass and ley roots	12.5	4.7	of above ground biomass produced (on a dry matter basis)
	29.0	11.0	of below ground biomass produced (on a dry matter basis)
Maize straw	20.4	1.3	of above ground biomass produced (on a dry matter basis)
	42.7	2.7	of straw produced (on a dry matter basis)
Maize stalk base	2.3	0.1	of above ground biomass produced (on a dry matter basis)
	4.9	0.3	of stalk produced (on a dry matter basis)
Ley stubble	13.9	0.9	of above ground biomass produced (on a dry matter basis)
	37.6	2.4	of stubble produced (on a dry matter basis)

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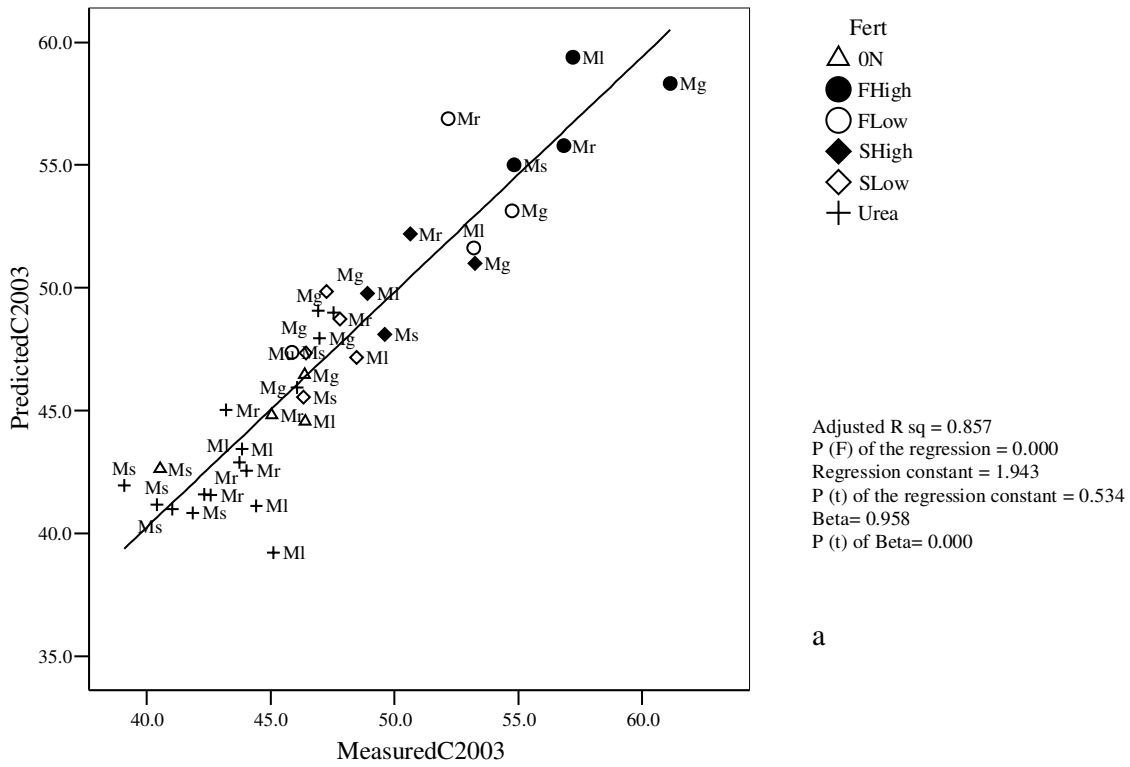
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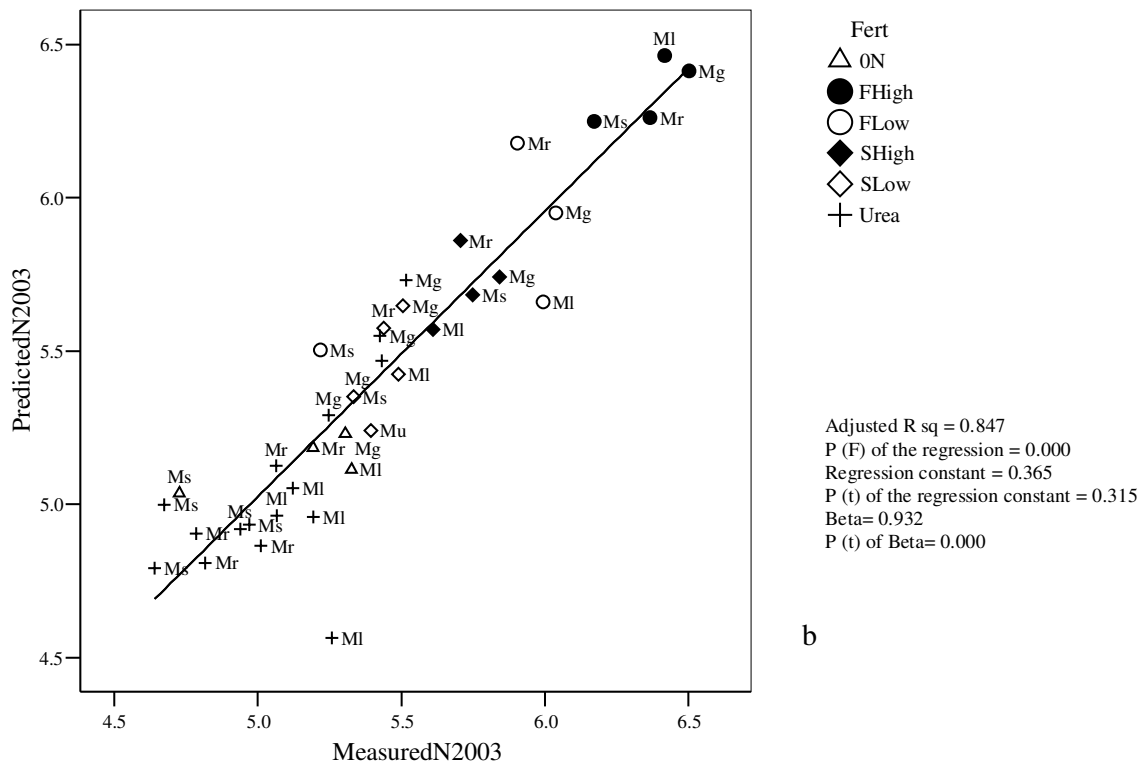
722 **List of figures**

723 Figure 1 a,b. Relationship between SOC measured in 2003 and equation-fitted SOC 2003, both
724 expressed as Mg C ha⁻¹ (a), and between total N measured in 2003 and equation-fitted total N
725 2003, both expressed as Mg N ha⁻¹ (b). The broken line represents the first quadrant bisector.

726



a



b