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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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12 October 2024

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Regular paper

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

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No. of text pages: 29

No. of tables: 7

No. of figures: 1

Abstract

Soil organic matter (SOM) produces positive effects on multiple soil properties. Increasing its level also provides an opportunity to reduce atmospheric concentration of carbon dioxide (CO_2). Recycling animal manure and returning crop residue are among the main practices to enhance organic C stock in arable croplands. This study analysed data of soil organic carbon (SOC) stocks from a medium-term field trial (established in 1992) through a Hénin-Dupuis-based equation to determine the proportion of different organic materials retained in the soil as SOM.

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

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

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

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

Keywords: Soil organic carbon; Nitrogen; Crop residue; Manure; Mineralization; Greenhouse gases inventory; Fodder crops rotations.

1. Introduction

The importance of organic matter for sustainable soil functions has been acknowledged worldwide for several decades (Smith et al., 2001; Lal et al., 2004). The positive effects of soil organic matter (SOM) cover a wide range of well-documented physical, hydrological, chemical, biochemical and productive properties (Thompson et al., 1989; Juma, 1993; Reeves, 1997; Shepherd et al., 2002; Rawls et al., 2003; Cookson et al., 2005; Raiesi, 2006). Recent global warming concerns have recommended maintaining and restoring soil carbon (C) as a measure to mitigate rising atmospheric carbon dioxide (CO_2) concentration (Follett, 2001).

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

The studies on the fate of C additions to the soil can be used for the compilation of inventories of anthropogenic greenhouse gases emissions on the basis of the methodologies set by the International Panel on Climate Change (IPCC), under the United Nation Framework Convention on Climate Change (UNFCCC) (IPCC, 2006). For estimating changes in soil C stock (useful to quantify soil net CO_2 emission or removal) derived from the introduction of different management practices, the IPCC suggests creating a monitoring network of benchmark sites at the territorial 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) CO_2 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 CO_2 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 Udifluvent (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 (U_{100}, U_{200}, U_{300}, U_{400}) 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 m^2 sampling
170 area for maize and in a 10 m^2 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 $$C_t = C_0 * e^{-k_C * t} + I * e^{-k_I * t} \quad (1)$$
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 $$C_t = C_0 * e^{-k_C * t} + I * e^{-k_I * 1} * e^{-k_C * (t-1)} \quad (2)$$

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:

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

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 rends 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 $YMR = 1\text{-}e^{-k*1}$

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.

256
$$
\begin{aligned}
&N_{2003} = a + b + c + d + e + f \\
&\text{where:} \\
&a = (N_{1999} - (RN_{m1998} * e^{-kN_R*0.5})) * e^{-k_N*4} \\
&b = \sum_{t=0}^{3} (RN_{m(1998+t)} * e^{-kN_R*1} * e^{-k_N*(3.5-t)}) + RN_{m2002} * e^{-kN_R*0.5} \\
&c = \sum_{t=0}^{3} (RN_{l(1999+t)} * e^{-kN_R*1} * e^{-k_N*(4-t)}) \\
&d = \sum_{t=0}^{3} (STN_{(1999+t)} * e^{-kN_{ST}*1} * e^{-k_N*(4-t)}) \\
&e = \sum_{t=0}^{3} (SLN_{(1999+t)} * e^{-kN_{SL}*1} * e^{-k_N*(4-t)}) \\
&f = \sum_{t=0}^{3} (FN_{(1999+t)} * e^{-kN_F*1} * e^{-k_N*(4-t)})
\end{aligned}
\qquad (4)
$$

257 As for C, we checked the goodness of fit through the R^2, 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 CO_2 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_I 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 form 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 CO_2 inventories*
329 In Table 6 we showed the F_I 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 CO_2 by the soil or stocked in the soil are
334 presented. This represents a very simple application useful to estimate CO_2 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 kg ha^{-1} 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 CO_2-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; Izaurralde 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 CO_2 emission, shown in Table 6, indicate that almost all the cases analysed are
416 SOC-conservative and lead instead to CO_2 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 F_I 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 m^3 $year^{-1}$ 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

5. Conclusions

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

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

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

Acknowledgment

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

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

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459

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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] (Ml)	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	-	-	-	-	-	-	-

[a]The treatment receiving slurry and farmyard manure received also 100 kg N ha^{-1} as urea at top-dressing.

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

[c]The 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 ± St.dev.: 21.9 ± 4.9 Mg ha^{-1} y^{-1} (maize), 6.1 ± 2.5 Mg ha^{-1} y^{-1} (Italian ryegrass), 13.1 ± 2.6 Mg ha^{-1} y^{-1} (*Festuca arundinacea*) and 15.5 ± 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, *Festuca arundinacea* 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 *Festuca arundinacea*), 14.0 g kg^{-1} (lucerne)
Maize straw	Amount of stalks, cobs and bracts produced	Measured every year for Mg treatments	Average ± St.dev: 9.1 ± 2.5 Mg ha^{-1} y^{-1} (stalks), 2.3 ± 0.8 Mg ha^{-1} y^{-1} (cobs and bracts)
	C content of stalk, cobs and bracts	Measured in 2003 for Mg treatments	Average ± St.dev: 0.45 ± 0.04 kg kg^{-1} (stalks), 0.47 ± 0.04 kg kg^{-1} (cobs and bracts)
	N content of stalk, cobs and bracts	Measured every year for Mg treatments	Average ± St.dev: 6.7 ± 0.7 g kg^{-1} (stalks), 4.8 ± 1.0 g kg^{-1} (cobs and bracts)
Maize stalk base	Stalk biomass	Measured every year for Mg treatments	Average ± St.dev: 9.1 ± 2.5 Mg ha^{-1} y^{-1}
	Stalk:above ground biomass ratio	Measured in 1993-1996 for silage maize	Average ± St.dev: 0.50 ± 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 ± St.dev: 6.7 ± 0.7 g kg^{-1}
Ley stubble	Above-ground biomass	Measured every year for Ml treatments	Average ± St.dev.: 13.1 ± 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 Ml treatments	Average ± St.dev: 19.3 ± 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 ± St.dev.: 23.3 ± 7.2 kg Mg^{-1} for slurry, and 78.6 ± 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 ± St.dev.: 2.5 ± 0.3 kg Mg^{-1} for slurry, and 6.4 ± 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.

	Soil Organic Carbon			Total Nitrogen		
System/Fertilizer	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
Source of variation	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.

	Carbon		Nitrogen	
Soil carbon item	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
Straw and stubble	2.825	0.941	7.040	0.999

703

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 pruduction
	0.6 % of straw production

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710 Table 6. F_I 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).

	SOC_{REF}		
Cases	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}

712

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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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

727 Figure 1 a,b
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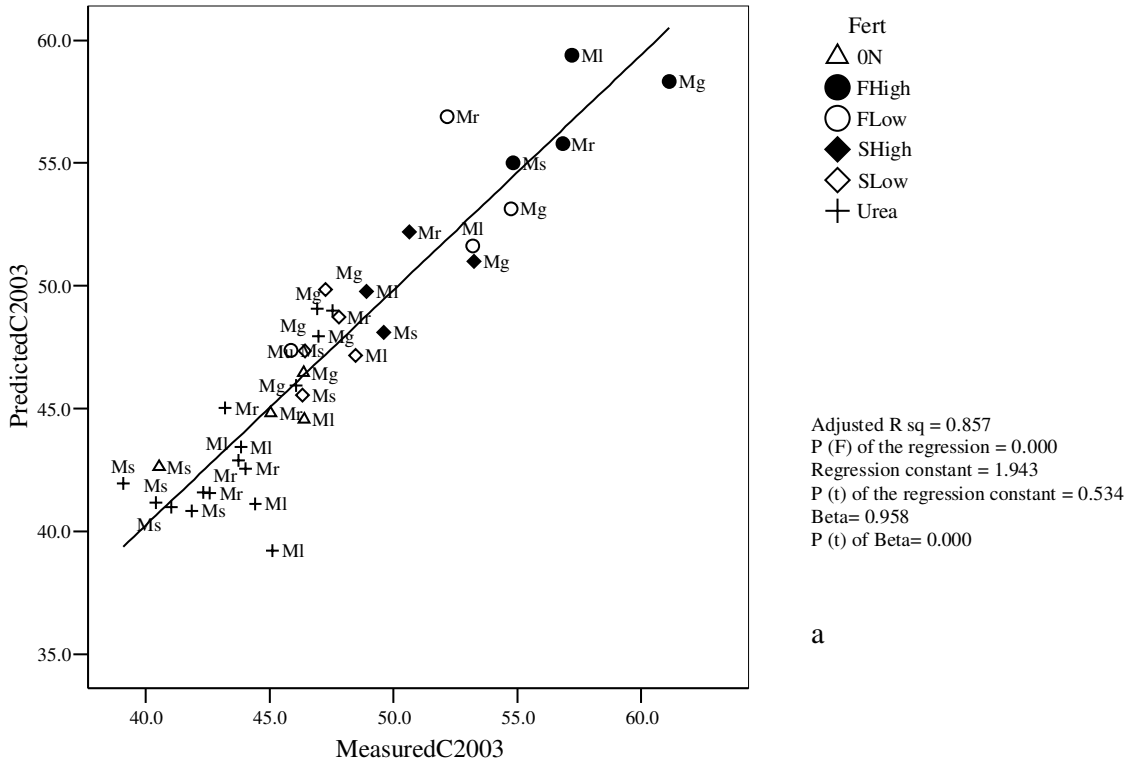

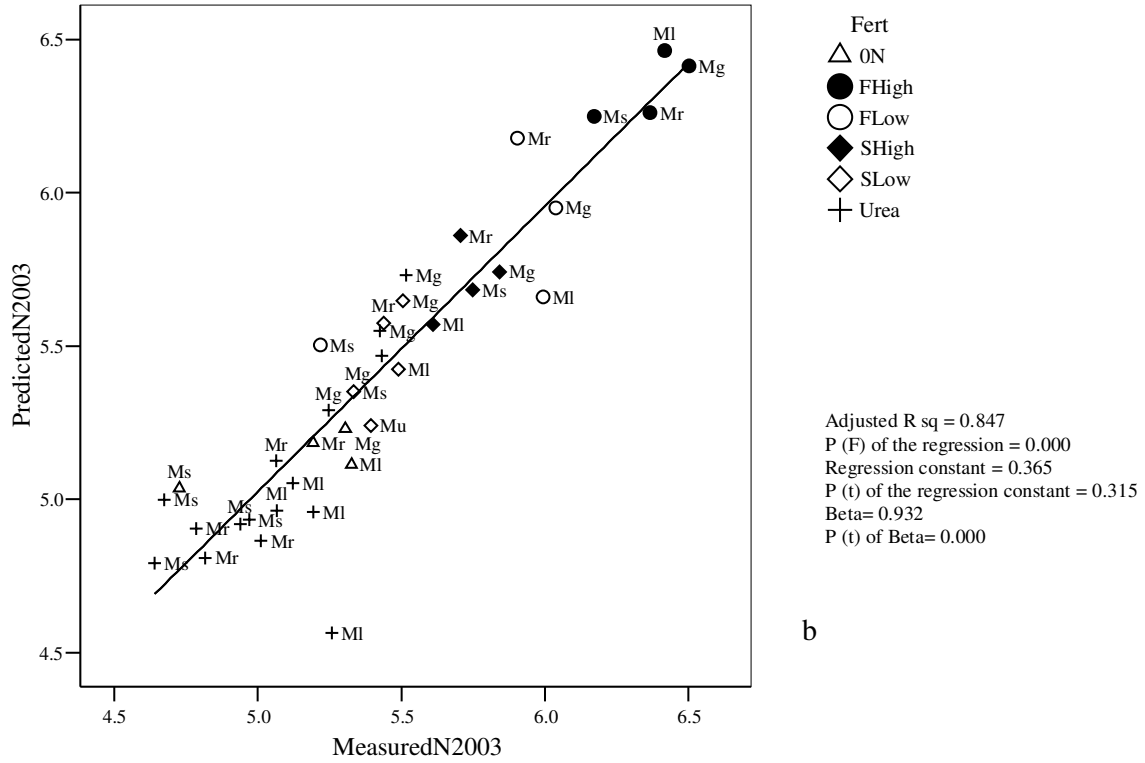

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