

1 **Title:** Potentials to mitigate greenhouse gas emissions from Swiss agriculture

2

3 **Author names and affiliations:**

4 Magdalena Necpalova¹, magdalena.necpalova@usys.ethz.ch

5 Juhwan Lee¹, juhwan.lee@usys.ethz.ch

6 Colin Skinner², skinner.colin@gmail.com

7 Lucie Büchi³, lucie.buchi@agroscope.admin.ch

8 Raphael Wittwer⁴, raphael.wittwer@agroscope.admin.ch

9 Andreas Gattinger⁵, andreas.gattinger@fibl.org

10 Marcel van der Heijden⁴, marcel.vanderheijden@agroscope.admin.ch

11 Paul Mäder², paul.maeder@fibl.org

12 Raphael Charles³, raphael.charles@agroscope.admin.ch

13 Alfred Berner², alfred.berner@fibl.org

14 Jochen Mayer⁴, jochen.mayer@agroscope.admin.ch

15 Johan Six¹, jsix@ethz.ch

16

17 ¹ Sustainable Agroecosystems Group, Department of Environmental Systems Science, Swiss
18 Federal Institute of Technology, Zurich, Switzerland

19 ² Department of Soil Sciences, Research Institute of Organic Agriculture (FiBL), Ackerstrasse
20 113, CH 5070 Frick, Switzerland

21 ³ Plant Production Systems, Agroscope, Nyon, Switzerland

22 ⁴ Plant-Soil-Interactions group, Agroscope, Reckenholzstrasse 191, CH-8046 Zurich,
23 Switzerland

24 ⁵ Chair in Organic Farming with focus on sustainable soil use, Justus-Liebig-University,
25 Giessen, Germany

26

27 **Corresponding author:** Magdalena Necpalova, magdalena.necpalova@usys.ethz.ch, phone
28 +41 44 6338607; address: Department for Environmental Systems Science (D-USYS), Swiss
29 Federal Institute of Technology (ETH), Tannenstrasse 1, 8092 Zürich, Switzerland

30

31 **Paper type:** Original research paper

32 **Abstract**

33 There is an urgent need to identify and evaluate management practices for their biophysical
34 potential to maintain productivity under climate change while mitigating greenhouse gas
35 (GHG) emissions from individual cropping systems under specific pedo-climatic conditions.
36 Here, we examined, through DayCent modeling, the long-term impact of soil management
37 practices and their interactions on soil GHG emissions and GHG intensity from Swiss
38 cropping systems. Based on experimental data from four long-term experimental sites in
39 Switzerland (Therwil, Frick, Changins, and Reckenholz), we robustly parameterized and
40 evaluated the model for simulating crop productivity, soil C dynamics and soil N₂O emissions
41 across a range of management practices and pedo-climatic conditions. Net soil GHG
42 emissions (NSGHGE) were derived from changes in soil C, N₂O emissions and CH₄
43 oxidation. Soils under conventional management acted as a net source of soil GHG emissions
44 (1361–1792 kg CO₂eq ha⁻¹ yr⁻¹) and NSGHGE were dominated by N₂O (50 – 63%). Reduced
45 tillage and no-tillage reduced long-term NSGHGE by up to 31 and 58%, respectively.
46 **Organic farming, represented by organic fertilization**, reduced NSGHGE by up to 31%
47 compared to systems based solely on mineral fertilization. Replacement of slurries with a
48 composted FYM led to an additional reduction in NSGHGE by 46%, **although our approach**
49 **considered only soil GHG emissions and thus did not take into account GHG emissions from**
50 **the composting process**. Cover cropping did not significantly influence NSGHGE, however
51 vetch tended to reduce NSGHGE (-19%). The highest mitigation potential was associated
52 with organic farming plus reduced tillage management, it reduced long-term NSGHGE by up
53 to 128%. Soil C sequestration accounted, on average, for 89% of GHG mitigation potentials.
54 Not all the management practices sustained crop yields. Nevertheless, composting of organic
55 manures, reduced tillage and no-tillage effectively reduced NSGHGE and GHG intensity
56 without a noticeable yield reduction. Our results suggest that implementation of the above soil

57 management practices in Swiss cropping systems have a considerable potential for climate
58 change mitigation, although time-limited.

59

60 **Highlights:**

- 61 ▪ DayCent was parameterized and evaluated using data from four LTEs in Switzerland
- 62 ▪ Organic farming with reduced tillage reduced net soil GHG emissions and also yield
- 63 ▪ Composting, RT and NT reduced net soil GHG emissions without a yield reduction
- 64 ▪ Soil C sequestration accounted, on average, for 89% of GHG mitigation potentials

65

66 **Key words:** soil management; cropping system; soil organic carbon; nitrous oxide; methane
67 oxidation; greenhouse gas mitigation; greenhouse gas intensity; greenhouse gas sink;
68 DayCent; biogeochemical modeling

69 **1. Introduction**

70 There is a global concern related to the increase in greenhouse gases (GHG) in the
71 atmosphere, primarily CO₂, N₂O, and CH₄ and their impact on climate change. Intensification
72 of agriculture due to technological advancement has doubled crop yields between 1970–2010,
73 but also posed severe environmental problems (Pimentel *et al.*, 1995; FAOSTAT, 2017).
74 Cultivation of agricultural land has caused a historical loss of 50 Pg of soil organic carbon
75 (SOC) (Houghton, 1999). Soil and manure management, enteric fermentation, biomass
76 burning, and rice cultivation have become the largest anthropogenic source of N₂O and CH₄,
77 although there are regional differences in importance of these emissions sources (Smith *et al.*,
78 2014). In 2010, agriculture accounted for 5.0–5.8 Pg CO₂eq yr⁻¹, i.e., 10 – 12% of total global
79 anthropogenic GHG emissions (Tubiello *et al.*, 2013; FAOSTAT, 2017). Switzerland is small,
80 but a large part of its area (1522.7 km²) is used for agriculture. In 2015, agriculture accounted
81 for 12.6% (6.07 Tg CO₂eq yr⁻¹) of total Swiss GHG emissions (FOEN, 2017). Soil
82 management, which is the second largest source, induces N₂O emissions that account for
83 30.9% of Swiss agricultural GHG emissions (FOEN, 2017). Reduction of these emissions
84 therefore constitutes an important part of agriculture's GHG mitigation potential concerning
85 climate change as well as achieving Swiss GHG reduction targets aiming to limit global
86 climate warming below 2°C by 2100 in line with the RCP2.6 scenario (Kyoto Protocol, Lima
87 2014 and Paris 2015 agreements).
88 Research proposed a number of management options that can significantly contribute to
89 reducing soil GHG emissions from cropping systems, such as more efficient use of fertilizers
90 (Bouwman *et al.*, 2002; Venterea *et al.*, 2012), organic farming (Gattinger *et al.*, 2012;
91 Skinner *et al.*, 2014), reduced tillage intensity or no-tillage (West and Marland, 2002; Six *et*
92 *al.*, 2004; van Kessel *et al.*, 2013; Cooper *et al.*, 2016), residue retention, cover cropping
93 (Poeplau and Don, 2015; Kaye and Quemada, 2017), improved water and rice management.

94 The biophysical mitigation potential of these practices need to be evaluated for individual
95 cropping systems under specific pedo-climatic conditions, historical land use and
96 management (Smith, 2012). Previous research on Swiss cropping systems has been designed
97 to investigate the influence of a range of soil management practices on agronomic
98 performance, SOC and soil fertility (Mäder *et al.*, 2002; Fließbach *et al.*, 2007; Berner *et al.*,
99 2008; Krauss *et al.*, 2010; Wittwer *et al.*, 2017). Yet, relatively little is known about effects of
100 these practices on soil GHG emissions. Identification and quantification of GHG mitigation
101 potentials associated with soil managements is key to designing effective agricultural
102 mitigation strategies. In addition to evaluation of mitigation options on an area basis, more
103 attention has been recently paid to assessment of GHG intensity (GHGI) per agricultural
104 product unit that indicates the GHG efficiency of production (Burney *et al.*, 2010). This
105 assessment has been allied to the concept of sustainable intensification (Godfray *et al.*, 2010;
106 Tilman *et al.*, 2011; Smith, 2013) and promotes management practices that increase
107 production without a commensurate increase in emissions (Smith *et al.*, 2014).

108 Net potential of soil management practices to contribute to GHG mitigation depends on the
109 direction and magnitude of changes in SOC, N₂O and CH₄ emissions associated with their
110 implementation compared to conventional practices. Direction and magnitude of soil GHG
111 emissions and thus mitigation potentials might change over time in response to the
112 management and climate change (Smith, 2012). Long-term field experiments (LTE) suggest
113 that rates of SOC change in response to soil management are the greatest in the first 10 years
114 and then attenuate when reaching a new steady-state (Johnston *et al.*, 2009; Gattinger *et al.*,
115 2012). Six *et al.* (2004) and van Kessel *et al.* (2013) found a noticeable time dependency in
116 no-tillage and reduced tillage effects on N₂O emissions. Nevertheless, there is a lack of long-
117 term observations. Most GHG studies are based on a sampling period over one to two
118 growing seasons that does not even cover the entire crop rotation length. Soil management

119 and crop interaction effects on soil GHG emissions can be complex and cannot be entirely
120 identified in a short-term. This is most pronounced in complex cropping systems, like those in
121 organic farming leading to a pronounced temporal decoupling of N input und corresponding
122 N₂O emission (Skinner *et al.*, 2014). Therefore, there is an urgent need for long-term
123 monitoring of management-specific GHG emissions over entire crop rotations preferably
124 across a wide range of pedo-climatic conditions to elucidate long-term N and C dynamics in
125 response to changes in management. However, the spatial and temporal resolution and the
126 extent of GHG measurements are generally limited by cost and time constraints.

127 Alternatively, ecosystem process-based models that are capable of capturing complex long-
128 term dynamics in soil-crop-atmosphere systems, when correctly integrated with empirical
129 data, provide effective and robust tools to bridge data gaps, to understand and quantify soil
130 GHG emissions responses to changes in soil management. Furthermore, these models can be
131 used to identify and evaluate long-term effects and strengths of selected GHG mitigation
132 options and thus support climate change strategies. DayCent (Del Grosso *et al.*, 2001;
133 Campbell and Paustrian, 2015) is a dominant coupled soil-plant dynamic model that has been
134 widely used to simulate long-term ecosystem responses to changes in soil management and
135 climate in the US (Parton and Rasmussen, 1994; Del Grosso *et al.*, 2008b; De Gryze *et al.*,
136 2011; Lee *et al.*, 2015). However, its application to European cropping systems has been
137 limited (e.g., Foereid *et al.* (2012), Alvaro-Fuentes *et al.* (2017)). Hence, if DayCent is to be
138 reliably used to address agriculture GHG mitigation under Swiss conditions, it requires robust
139 parameterization for common Swiss crops and management practices and evaluation across a
140 range of management practices and pedo-climatic conditions. Accordingly, this study was
141 designed with the following objectives: i) to parameterize DayCent for common crops and
142 management practices using long-term empirical data collected under various pedo-climatic
143 conditions in Switzerland; ii) to evaluate the model's ability to simulate long-term crop

144 productivity, SOC dynamics and soil N₂O emissions in diverse Swiss cropping systems; and
145 iii) to examine the long-term impact of management practices and their interactions on soil
146 GHG emissions and GHGI at each experimental site.

147

148 **2. Materials and methods**

149 2.1 LTE descriptions

150 The empirical data was derived from four Swiss LTEs located in **Changins (P29C LTE),**
151 **Therwil (DOK LTE), Reckenholz (FAST LTE) and Frick (Frick LTE),** Table 1). These LTEs
152 have evaluated effects of various farming systems and soil management practices (Table 2).
153 **DOK LTE** compares farming systems differing with respect to fertilization and plant
154 protection management: a) biodynamic (D2) and organic (O2) systems fertilized with
155 farmyard manure (FYM) and slurry at the typical intensity of Swiss organic farms (Mäder *et*
156 *al.*, 2006); b) conventional system (K2) with the same organic fertilizer input and additional
157 mineral fertilization up to recommended plant-specific levels; c) mineral conventional system
158 (M2) fertilized with mineral fertilizers, representing a stockless system; and d) unfertilized
159 system (N) (Mäder *et al.*, 2006). The N, P and K inputs in D2 and O2 were 34-51% lower
160 than in K2 and M2 systems (Mäder *et al.*, 2002). Organic (D, O) and the conventional system
161 (K) were managed at two fertilization levels, corresponding to 100% and 50% of typical
162 fertilization. Systems were arranged in a split-split-plot design with four replicates. Seven-
163 year crop rotation consisted of potatoes (*Solanum tuberosum*), green manure, winter wheat
164 (*Triticum aestivum*), fodder intercrop, white cabbage (*Brassica oleracea*), winter wheat,
165 winter barley (*Hordeum vulgare*) and a two-year grass-clover ley (*Trifolium pratense*,
166 *Trifolium repens*, *Dactylis glomerata*, *Festuca rubra*, *Phleum pratense*, *Lolium perennne*, *Poa*
167 *pratensis*, *Festuca pratensis*) (Fließbach *et al.*, 2007). White cabbage was replaced with
168 beetroot (*Beta vulgaris*) and soybeans (*Glycine max*), and one winter cereal with silage maize

169 (*Zea mays*) in later years. As fodder intercrops, rye and vetch or sunflower and vetch mixtures
170 were planted. Crop rotation was planted with a temporal shift on three rotation subplots (later
171 referred to a rotation A, B and C) so that three crops were grown simultaneously in each
172 system each year. Soils were managed under conventional tillage and cereal straw was
173 removed. SOC at 0-20 cm was measured annually after crop harvest (Fließbach *et al.*, 2007).
174 Climate data (1977-2013) were recorded at the Basel-Binningen weather station. Symbiotic
175 N₂ fixation by soybeans, and red (*Trifolium pratense*) and white clover (*Trifolium repens*) in
176 grass-clover ley was measured using ¹⁵N natural abundance methods (Oberson *et al.*, 2007;
177 Oberson *et al.*, 2013). Weekly soil N₂O and CH₄ emissions and mineral N (NO₃⁻ and NH₄⁺ at
178 0-20 cm) from K2, M2, O2 and N systems were measured during August 2012–March 2014
179 (Gattinger *et al.*, 2017).

180 **Frick LTE** compares the following management factors: i) tillage practices (conventional
181 (CT) vs. reduced (RT)); ii) type of organic fertilization (slurry alone (SL) vs. manure compost
182 (MC)); and iii) without vs. with biodynamic compost and field preparations (Berner *et al.*,
183 2008). Treatments were arranged in a split-split-plot design with four replicates. Six-year crop
184 rotation consisted of winter wheat, oat-clover (*Trifolium alexandrinum*), sunflower
185 (*Helianthus annuus*), spelt (*Triticum spelta*), a two-year grass-clover ley (*Trifolium*
186 *campestre*, *Dactylis glomerata*, *Festuca pratensis* Huds., *Phleum pratense*, *Lolium perenne*),
187 winter pea green manure (*Pisum sativum*) and silage maize (*Zea mays*) (Krauss *et al.*, 2010).
188 Winter pea was grown only under RT following the grass-clover incorporation. Cereal straw
189 and intercrop were harvested (Berner *et al.*, 2008; Gadermaier *et al.*, 2012); sunflower stalks
190 were removed only in 2010. Organic matter (OM) inputs were higher in MC than in SL,
191 partially due to straw content. Differences in N inputs between MC and SL were driven by
192 differences in N content of solid and liquid organic manures and N losses during the storage
193 (Gadermaier *et al.*, 2012). The SOC at 0-10 and 10-20 cm was measured in 2002, 2005 and

194 2008 (Berner *et al.*, 2008; Gadermaier *et al.*, 2012). Climate data (2002-2013) were recorded
195 at the FiBL vineyard weather station.

196 **FAST LTE** compares conventional (CON) and organic (ORG) farming systems with different
197 tillage intensity (intensive tillage by mouldboard ploughing (IT) vs. no-tillage (NT) and
198 reduced tillage (RT) in CON and ORG systems, respectively) and four cover crop treatments
199 (legume (VETCH), non-legume (MUST), mixture of several species (MIX), and a control
200 without cover crops (CONT)) (Wittwer *et al.*, 2017). Six-year crop rotation consisted of
201 winter wheat, maize, field bean (*Vicia faba*), winter wheat and a two-year grass-clover
202 mixture (*Trifolium pratense*, *Trifolium album*, *Dactylis glomerata*, *Festuca pratensis*, *Lolium*
203 *perenne*, *Phleum pratense*). Due to a lack of data only first four years of the rotation were
204 considered in the analysis. Cover crops were sown before winter wheat and maize. Crop
205 residues (cover crops, maize and field bean) remained on plots, except for the winter wheat
206 straw. Climate data (1981-2014) were downloaded from MeteoSwiss (2016).

207 **P29C LTE** compares four tillage practices: i) plough (PL), ii) chisel (CH), iii) cultivator (CL)
208 and iv) rototiller (RT) on two contrasting soil textures. The CH treatment was converted to
209 direct seeding with no-tillage after 2007. Although data from the whole experimental period
210 were considered for model parametrization, GHG predictions only for 1978-2007 were
211 included in analyses. SOC at 0-20 cm was measured in all treatments on 15 occasions (Büchi
212 *et al.*, 2017). Four-year crop rotation consisted of rapeseed (*Brassica napus*), winter wheat,
213 grain maize and winter wheat. Climate data (1969-2013) were recorded at the site.

214 The number of treatments, factorial design and long-term duration of LTEs provided **a rich**
215 **dataset** for DayCent parameterization and evaluation across a range of management practices
216 and pedo-climatic conditions in Switzerland, **although only single site measurements on soil**
217 **mineral N and N₂O emissions were available for evaluation of the model's ability to simulate**

218 **soil N processes.** Due to a limited model representation of biodynamic amendments,
219 biodynamic systems/treatments were neglected.

220

221 2.2 DayCent model

222 DayCent (version 2012)(Del Grosso *et al.*, 2001) is a fully resolved terrestrial ecosystem
223 model of intermediate complexity that simulates C and N biogeochemical processes in
224 various soil-plant systems. It includes sub-models for plant productivity, decomposition of
225 dead plant material and soil organic matter (SOM), soil water and temperature dynamics, N
226 gas fluxes and CH₄ oxidation. Net primary productivity is a function of genetic potential,
227 plant phenology, nutrient availability, soil water, temperature, shading and solar radiation.
228 The SOM, represented by plant litter and three conceptual pools (active, slow, and passive), is
229 simulated for the upper 20 cm. N gas sub-model represents both denitrification and
230 nitrification. Denitrification rates are calculated for each soil layer based on soil NO₃⁻,
231 available labile C, water content, texture, and temperature; while nitrification rates are
232 calculated based on soil NH₄⁺, water content, texture, and temperature. CH₄ oxidation is a
233 function of soil temperature, water content, porosity, and field capacity. **DayCent has been**
234 **shown to accurately simulate crop yields, soil C and N dynamics, and N₂O emissions when**
235 **rigorously calibrated and evaluated against empirical data representing various ecosystems**
236 **and pedo-climatic conditions (Paustian *et al.*, 1997; Del Grosso *et al.*, 2005; Del Grosso *et al.*,**
237 **2008a).**

238 2.3 Modeling approach

239 Model parameterization: Model parameterization was accomplished using an inverse
240 modeling package PEST (version 13.0) (Doherty and Hunt, 2010) that iteratively estimates
241 parameter values using a nonlinear regression method based on the principle of least-squares

242 minimization. Details on coupling DayCent with PEST have been reported by Necpalova *et*
243 *al.* (2015).

244 Parametrization dataset comprised time series of crop yields ($n = 2618$) and SOC contents (n
245 $= 1284$) collected across 46 treatments and 19 crops at four sites. Model integration with
246 empirical data was evaluated using a weighted multicomponent objective function represented
247 by weighted least-squared difference between measured and simulated values. Crop-specific
248 and SOC data formed independent components of the objective function. The inter-
249 component weighting strategy was defined such that each component contributed equally to
250 the objective function at the start of parametrization, regardless of the number of
251 measurements per component, units, and other confounding factors. Individual measurements
252 within each component were weighted equally.

253 Initially, a local sensitivity analysis of model parameters at their default values identified
254 parameters sensitive to the parametrization dataset. The sensitivity was derived from the first-
255 order partial derivatives of simulated values corresponding to available empirical data with
256 respect to selected uncertain parameters. Temperature response functions and nutrient
257 limitations were parametrized at the crop-species level, while the genetic growth potential and
258 maximum harvest index were adjusted at the crop cultivar level. A list of selected model
259 parameters and their uncertainty ranges are listed in Table A.1.

260 Default parameter values were considered as initial values, their uncertainty ranges were
261 derived from the literature review and our prior knowledge. All parameters were log-
262 transformed to strengthen linear relationships between parameters and simulated values. Prior
263 to the parameterization, we observed a large number of correlations between parameters in the
264 correlation coefficient matrix. Therefore, the parameterization was achieved in several
265 independent stages. Firstly, crop parameters were inferred from crop productivity data
266 collected under conventional management practices. Secondly, tillage decomposition

267 multipliers for individual SOM pools were inferred from long-term SOC data collected under
268 various tillage managements and under mineral fertilization. Lastly, bio-chemical
269 composition of organic fertilizers was inferred from long-term crop productivity and SOC
270 data collected under organic fertilization. Each stage was based on a specific subset of the
271 parametrization dataset, while remaining data were assigned 0 weights, and thus did not
272 contribute to the overall objective function computed for the individual stages of
273 parametrization. Model parameters adjusted in the initial stages were frozen at their values for
274 the later stages of parametrization. Parameterization runs across numerous treatments and four
275 sites reduced uncertainty ranges for selected parameters and delivered arithmetic means and
276 confidence intervals considered in the model application. Due to a lack of yield data, Persian
277 and red clover intercrops, green manures at DOK, winter rye, sunflower-summer vetch, and
278 clover-mustard mixtures remained represented by default values in the model application. To
279 retain the model widely applicable, the parameterization was kept as general as possible
280 across the sites.

281

282 Spin-up simulations: Distribution of modeled SOM pools was initialized using spin-up
283 simulations of native temperate deciduous forest (0-1399), already strongly influenced by
284 human activities (Pfister, 1995), that brought SOM pools into equilibrium with OM inputs.
285 Simulations proceed from equilibrium with base simulations of historical land use
286 management in the following periods (Bürgi *et al.*, 2015; Bürgi, 2016): 1) appearance of
287 agriculture (1400 - 1750; winter grain - summer grain - fallow rotations and limited manure
288 inputs), 2) agricultural revolution (1751 - 1850; introduction of improved seeds, planting
289 clover in fallow fields, replacement of summer grains by potatoes, cultivation of formerly
290 uncultivated land due to excessive drainage and higher availability of organic manures due to
291 higher number of animals), 3) agricultural intensification (1851 - 1950; manufacturing of

292 mineral fertilizer that provided supplemental fertilization), and 4) modern agriculture (from
293 1950; introduction of maize and diverse crop rotations with three grass-clover ley years). Due
294 to a scarcity of site-specific data, the land use history was assumed to be identical for all sites,
295 although the last period finished in different years depending on the LTE establishment year.
296 Initial measurements of site-specific SOC content were used by an inverse modeling
297 algorithm to adjust the forest radiation use efficiency for calculating potential productivity to
298 reach pre-experimental SOC content at each site. For these simulations, site-specific climate
299 data was used recursively. Following base simulations, the model simulated long-term soil
300 management effects as imposed in treatments established in LTEs. These simulations started
301 when the actual LTEs were established and continued until the end of the experimental
302 period.

303

304 Long-term simulations: Parameterized DayCent was used to simulate crop yields, SOC
305 dynamics, N₂O emissions and CH₄ oxidation capacity for individual treatments under site-
306 specific pedo-climatic conditions at each site over 30 years. The model was driven by
307 recorded management, soil physicochemical properties and daily climate data. If the LTE was
308 shorter than 30 years, the management and climate data were used repeatedly until the end of
309 the simulation period. Simulations were run independently by replicate, as soil profiles were
310 characterized at the plot level, except for P29C and Frick, where only average soil properties
311 were available. Soil hydraulic properties (field capacity, wilting point and saturated hydraulic
312 conductivity) were calculated based on soil texture, bulk density and SOC concentration using
313 pedo-transfer functions (Wosten *et al.*, 1999). Soil physical properties were assumed to be
314 constant over time, i.e., SOC content was computed on an equivalent mass basis using initial
315 bulk densities. For all crops, yields, straw and aboveground biomass was expressed on a C
316 content basis using published crop-specific plant component C concentrations. Crop

317 productivity and SOC content data were equally divided into two independent datasets, for
318 model parameterization and evaluation, based on blocking in the experimental design. Soil
319 properties were available for all plot replicates, thus half of the plot replicates was used for
320 model calibration and the other half for model evaluation with the assumption that blocking
321 was effective and arrangement of the blocks reflected variability in soil properties at each
322 LTE. Additionally, soil NO_3^- , NH_4^+ and N_2O data from DOK were considered for the
323 evaluation of the model's ability to simulate soil N processes.

324

325 2.4 Model evaluation, calculations, and statistical analysis

326 Model's ability to simulate crop productivity, long-term SOC, soil NH_4^+ and NO_3^- , daily and
327 cumulative N_2O emissions was quantified using multiple statistical criteria (Wallach *et al.*,
328 2014): root mean square error (RMSE), relative RMSE (rRMSE), coefficient of determination
329 (r^2) and Willmott's index (WI).

330 Net soil GHG emissions (NSGHGE, $\text{kg CO}_2\text{eq ha}^{-1} \text{yr}^{-1}$) were derived from annual changes in
331 SOC content, N_2O emissions and CH_4 oxidation capacity using 100-year time horizon global
332 warming potentials (IPCC, 2014) as follows:

$$\text{NSGHGE} = \frac{44}{12} \times [\Delta\text{SOC}] + 265 \times [\text{N}_2\text{O}] - 28 \times [\text{CH}_4]$$

333

334 where $[\Delta\text{SOC}]$ is the change in SOC content ($\text{kg C ha}^{-1} \text{yr}^{-1}$), $[\text{N}_2\text{O}]$ is N_2O cumulative flux
335 ($\text{kg N}_2\text{O ha}^{-1} \text{yr}^{-1}$) and $[\text{CH}_4]$ is CH_4 uptake ($\text{kg CH}_4 \text{ha}^{-1} \text{yr}^{-1}$). Indirect N_2O emissions were
336 not considered due to high uncertainties associated with their estimates and a lack of reliable
337 evaluation data for Swiss conditions.

338 Due to an implementation of complex crop rotations causing a discrepancy between the
339 growing season of main crops and a period considered for NSGHGE calculation, GHGI (kg

340 CO₂eq kg⁻¹ yield) was computed as the sum of annual NSGHGE over 30 years, divided by
341 total harvested grain, tuber, vegetables and forages (kg DM ha⁻¹) over 30 years:

$$\text{GHGI} = \frac{\sum_{i=1}^{30} \text{NSGHGE}}{\sum_{i=1}^{30} \text{yield}}$$

342

343 If the experimental period was longer than 30 years, only last 30 years were considered in the
344 analysis. Management effects and their interactions were determined statistically using linear
345 mixed-effects models in SAS (2014) with time included as a random effect and other factors
346 and their interactions as fixed effects. Linear regression analysis was used to compute the
347 annual change in SOC content over time corresponding to a slope of the regression line.

348

349 **3. Results**

350 3.1 Model evaluation

351 Following the parameterization, DayCent reproduced 81% of the measured variation in crop
352 productivity across years, treatments and sites (RMSE = 76 g C m⁻², rRMSE = 0.29).

353 Productivity predictions were more certain for Frick and FAST and less certain for P29C
354 (Fig.1). The model substantially underpredicted the measured variation in productivity due to
355 spatial replication. Mean crop-specific productivity across years, treatments and sites was
356 simulated adequately (Table 3). Nevertheless, the model noticeably underpredicted
357 productivity of winter peas, mixture, white mustard, potatoes and overpredicted rapeseed
358 productivity. As indicated by r², it substantially underpredicted the measured variation in
359 spelt, winter barley, white cabbage, field beans and potatoes productivity. The highest rRMSE
360 was associated with productivity predictions of tuber crops, winter peas, spelt and white
361 cabbage.

362 DayCent predicted treatment-associated crop productivity satisfactorily (Fig.2). Nevertheless,
363 it overpredicted productivity for N system in DOK, PL treatment on loam soil in P29C, and
364 underpredicted productivity for ORG-RT treatments with mixture and vetch cover cropping in
365 FAST. The model reproduced most of the variation in measured productivity within each
366 treatment ($r^2 > 0.6$), except for N system in DOK and CH treatment on clay soil in P29C. The
367 rRMSE associated with productivity predictions was below 0.4 for all modeled treatments,
368 excluding N system in DOK.

369 For SOC content, the model reproduced 76% of the measured variation across years,
370 treatments and sites (RMSE = 504 g C m⁻², rRMSE = 0.13; Fig.3a). It also reproduced 63% of
371 the measured variation in treatment-induced SOC change over time, although it substantially
372 underpredicted higher SOC losses (Fig.3b), particularly for N, M2, K2 and K1 systems, all in
373 rotation A in DOK (Fig.B1), and PL treatment on clay soil in P29C (Fig.B2). Although r^2
374 greatly varied between treatments, rRMSE associated with SOC predictions was consistently
375 below 0.23 (Fig.2).

376 Soil N₂O emissions were evaluated against measured data collected in four main systems in
377 DOK over 1.5 years. DayCent predicted 25% of the measured variation in daily N₂O
378 emissions. Soil N₂O predictions for grass-clover and silage maize were adequate, although
379 less certain for green manure (Fig.4). While the error associated with daily emissions was
380 high (RMSE = 19.89 g N m⁻²; rRMSE = 1.73), the model predicted measured variation and
381 magnitude of cumulative N₂O emissions across all systems satisfactorily (Fig.5).

382 Soil NO₃⁻ and NH₄⁺ data from the same systems were used to evaluate model predictions of
383 soil N dynamics. The model reproduced 73% and 42% of the measured variation in soil NO₃⁻
384 and NH₄⁺ concentrations, respectively, across all systems. However, it substantially
385 overpredicted soil NH₄⁺ and underpredicted soil NO₃⁻, particularly after both mineral and

386 organic fertilization events. This amplified the overall predictive error for soil NO_3^- and NH_4^+
387 (Fig.B3).

388 There was no field data available to validate modeled CH_4 uptake at Swiss LTEs, therefore
389 the magnitude of the model's predictions was evaluated with the results from peer-reviewed
390 studies conducted on temperate agricultural soils (Flessa *et al.*, 1995; Smith *et al.*, 2000;
391 Hütsch, 2001; Skinner *et al.*, 2014).

392

393 3.2 Soil GHG emissions and mitigation potentials

394 Tillage treatments and differences in soil texture did not significantly influence soil CO_2
395 emissions in P29C LTE (Table 4). Soils under all treatments acted as a net CO_2 source
396 (Fig.6). The SOC decrease in response to tillage intensities was consistent across two soil
397 textures and followed the order: PL > CH = CL > RO. The rate of decrease was higher for
398 clay than for loam soil (Table 5). In comparison, soil N_2O emissions exhibited sensitivity to
399 tillage intensities and soil texture (Fig.6, Table 4). They decreased in the order: PL > CH > CL
400 > RO, and were significantly higher from clay than from loam soil (Fig.6). The proportion of
401 N inputs lost as N_2O ranged from 1.24 to 1.35% for loam and from 1.36 to 1.53% for clay. All
402 reduced tillage treatments were more effective in reducing N_2O emissions from clay than
403 from loam soil.

404 NSGHGE for P29C ranged from 989 to 1792 $\text{kg CO}_2\text{eq ha}^{-1} \text{yr}^{-1}$ with a 61% contribution from
405 N_2O (Fig.6). The highest NSGHGE were simulated for PL treatments (Table 5). Under CH
406 relative to PL, NSGHGE from loam decreased by 8%, and from clay by 14% (Table 6). This
407 was mainly attributed to the reduction in soil CO_2 emissions. Similarly, CL decreased soil
408 CO_2 emissions relative to PL treatments and thereby NSGHGE by 10 to 14% depending on
409 soil texture. RO treatments exhibited the highest potential to reduce NSGHGE. This reduction

410 was driven by a 49 to 50% decrease in soil CO₂ emissions and a simultaneous 9 to 11%
411 decrease in soil N₂O emissions.

412 Yields were noticeably higher for loam than for clay soil, with a minor increase under RO
413 treatments (Table 5). The GHGI, ranging from 0.22 to 0.41 kg CO₂eq kg⁻¹ yield, responded to
414 tillage intensities consistently across two soil textures. The highest GHGI was simulated for
415 PL treatments. Reduced tillage decreased GHGI by up to 32%, with RO having the highest
416 mitigation potential (Table 6).

417

418 For DOK LTE, two independent statistical analyses were conducted: a) N and M2 systems
419 were excluded to include the fertilization level as a fixed factor; and b) K1 and O1 were
420 excluded to compare all systems at their typical fertilization.

421 Soils under all systems acted as a net CO₂ source and the rate of SOC decrease was driven by
422 total C inputs (Table 5), which explained 89% of the variation in SOC change. Soil CO₂
423 emissions were significantly higher for N than for O2 and K2 systems (Fig.6). Soil N₂O
424 emissions were influenced by a system and level of fertilization interaction (Table 4), and
425 decreased in the order: K2 > M2 = O2 > N with reduced fertilization reducing N₂O emissions
426 more effectively in K1 than in O1 (Fig.6). Soil N₂O emissions were noticeably driven by total
427 N inputs to the systems and their proportion ranged from 1.01 to 1.42% (Table 5). Soil CH₄
428 oxidation potential was significantly influenced by soil management, not just in DOK (Table
429 4).

430 NSGHGE in DOK ranged from 927 to 1498 kg CO₂eq ha⁻¹ yr⁻¹ and were not significantly
431 different between systems (Fig.6). The average contribution of N₂O to NSGHGE was 60%.
432 The highest NSGHGE were simulated for M2 and decreased in the order: M2 > K2 > N > O2
433 > K1 > O1 (Table 5). Implementation of K2 reduced NSGHGE by 4% relative to M2,
434 resulting from a 64% decrease in soil CO₂ emissions but a simultaneous 44% increase in soil

435 N₂O emissions (Table 6). When fertilizer inputs were reduced to 50% of typical fertilization,
436 K1 decreased both N₂O and CO₂ emissions, and led to a 21% reduction in NSGHGE.
437 Adoption of O2 reduced NSGHGE by 18%, primarily due to a 37% reduction in soil CO₂
438 emissions. In comparison, there was an overall decrease in NSGHGE by 24% for O1, mainly
439 due to a 35% reduction in soil N₂O emissions relative to M2. N system reduced soil N₂O
440 emissions by 59% but increased soil CO₂ emissions by 41% relative to M2, thus the overall
441 reduction in NSGHGE was only 16%.

442 Crop yields were influenced by system and fertilization level (Table 4), and decreased in the
443 order: K2 > M2 > O2 > K1 > O1 > N. The GHGI for these systems ranged from 0.13 to 0.20
444 kg CO₂eq kg⁻¹ yield (Table 5). Implementation of K2 and O2 led to a GHGI reduction by 11
445 and 16%, respectively. The reduction in fertilization intensity in K1 led to a further reduction
446 in GHGI, which was not observed for O1 system (Tables 5 and 6).

447

448 In FAST LTE, soil CO₂ emissions were significantly affected by a system and tillage
449 interaction (Table 4) and decreased in the order: CON-IT > CON-NT = ORG-IT > ORG-RT
450 (Fig.6). Soils under all treatments, except for ORG-RT, acted as a net CO₂ source. Total C
451 inputs controlled rates of SOC change under RT and NT treatments, explaining 95 and 89%
452 variation in SOC changes, respectively. Soil N₂O emissions were influenced by a system and
453 tillage interaction and cover cropping (Table 4), and decreased in the order: ORG-IT > CON-
454 IT = ORG-RT > CON-NT, with NT reducing N₂O emissions more effectively in CON system
455 than RT in ORG system (Fig.6). Soil N₂O emissions under vetch were significantly higher
456 than those from other cover crop treatments, and were strongly correlated with total N inputs
457 for IT treatments. However, there was no relationship observed with total N inputs for NT and
458 RT treatments. The proportion of total N inputs lost as N₂O ranged from 0.80% to 1.09%
459 (Table 5).

460 NSGHGE for FAST ranged from -594 to 1397 kg CO₂eq ha⁻¹ yr⁻¹ and were significantly
461 affected by a system and tillage interaction (Table 4). The average N₂O contribution to
462 positive NSGHGE was 63%. The highest NSGHGE were simulated for CON-IT treatment
463 and decreased in the order: CON-IT > ORG-IT = CON-NT > ORG-RT, with ORG-RT
464 reducing NSGHGE twice more effectively than CON-NT treatment (Table 5). Mustard and
465 mixture cover cropping reduced NSGHGE by 6 to 10% relative to CON-IT-CONT, mainly
466 due to a 10 to 15% reduction in soil CO₂ emissions (Table 6). Vetch cover crop reduced soil
467 CO₂ emissions by 35%, but increased soil N₂O emissions, thus the overall reduction in
468 NSGHGE was only 19% relative to CON-IT-CONT. NT reduced NSGHGE by 58%, relative
469 to CON-IT, through a reduction in soil CO₂ and N₂O emissions by 76% and 22%,
470 respectively. Cover cropping in combination with NT reduced the mitigation potential of NT.
471 Implementation of ORG reduced NSGHGE by 31%, primarily due to a 51% reduction in soil
472 CO₂ emissions. ORG in combination with cover cropping, particularly with vetch, decreased
473 NSGHGE even more. This was mainly attributed to a higher reduction in soil CO₂ emissions.
474 Furthermore, the reduction in CO₂ emissions was doubled when ORG was implemented with
475 RT. This ORG-RT combination led to a 128% reduction in NSGHGE compared to CON-IT
476 and thereby turned the cropping system into a net GHG sink. Additional strengthening of the
477 sink potential induced by ORG-RT management was simulated in combination with vetch
478 cover cropping (Table 6).

479 Yields in FAST were influenced by a system and tillage interaction and cover cropping (Table
480 4), and decreased in the order: CON-IT > CON-NT = ORG-IT > ORG-RT, with lower yield
481 reduction due to NT in CON system than due to RT in ORG system (Table 5). Cover
482 cropping had a positive effect on yields; i.e., mustard and mixture significantly increased
483 yields by 4%, and vetch by 14% on average. The GHGI ranged from -0.19 to 0.35 kg CO₂eq
484 kg⁻¹ yield (Table 5). NT reduced GHGI by 56%, ORG by 20%, and the ORG-RT combination

485 exhibited the highest potential to reduce GHGI relative to CON-IT treatment (Table 6). Use
486 of cover crops, vetch in particular, effectively reduced GHGI when applied with IT.
487 Conversely, no GHGI reduction was observed for cover cropping under NT or RT
488 management.

489

490 In Frick, soil CO₂ emissions were significantly affected by the type of organic fertilization
491 (Table 4); i.e., soil CO₂ emissions from SL were significantly higher than from MC
492 treatments. Soils under all treatments, except for RT-MC, acted as a net CO₂ source. The rate
493 of SOC change was driven by total C inputs. SL treatments received about 42% less C inputs
494 in organic fertilizers (consistent with Berner *et al.* (2008)), but 12% more C in crop residues
495 due to a slightly higher productivity. Soil N₂O emissions were also affected by the type of
496 organic fertilization (Table 4); i.e., soil N₂O emissions from SL were higher than those from
497 MC irrespectively of the tillage management (Fig.6). Total N inputs were comparable
498 between fertilization treatments, i.e., SL received 19% more N in organic fertilizers, while
499 MC received 29% more N through biological fixation. The proportion of N inputs lost as N₂O
500 emissions was 1.75 and 1.96%, for MC and SL treatments, respectively (Table 5).

501 The type of organic fertilization had a significant effect on NSGHGE ranging from 661 to
502 1654 kg CO₂eq ha⁻¹ yr⁻¹ (Table 6). The highest NSGHGE were simulated for CT-SL treatment
503 and decreased in the order: CT-SL > RT-SL > CT-MC > RT-MC (Table 5). The average N₂O
504 contribution to NSGHGE was 80%. Replacement of SL with MC reduced NSGHGE by 46%,
505 through a decrease in both soil CO₂ emissions by 80% and soil N₂O emissions by 13% (Table
506 6). Implementation of RT led to a 13% reduction in NSGHGE relative to CT-SL. This
507 reduction was mainly attributed to a 27% decrease in soil CO₂ emissions. The highest
508 reduction in NSGHGE was observed for the RT-MC combination. This was driven by a 108%

509 decrease in soil CO₂ emissions turning the system into a net CO₂ sink, and a simultaneous
510 13% decrease in N₂O emissions.
511 Yields were mainly affected by tillage management, where RT significantly increased yields
512 by about 4%. The GHGI ranged from 0.09 to 0.23 kg CO₂eq kg⁻¹ yield (Table 5).
513 Replacement of SL with MC reduced GHGI by 45%, and RT reduced GHGI by 16%. The
514 RT-MC combination exhibited the highest mitigation potential by decreasing GHGI by 60%
515 relative to CT-SL treatment (Table 6).

516

517 **4. Discussion**

518 4.1 Model evaluation

519 DayCent's ability to simulate crop yields was comparable with other modeling studies (Grant
520 *et al.*, 2016; Senapati *et al.*, 2016; Dutta *et al.*, 2017). For P29C, a lack of plot-specific soil
521 properties limited simulation of the measured yield variation induced by soil heterogeneity.
522 However, even for sites where plot-specific soil data were available and data per replicate plot
523 were modeled independently, the model underpredicted the measured yield variation due to
524 spatial replication. This suggests that ecosystem factors and processes not represented in the
525 model (e.g., pests, diseases, micronutrient deficiencies, weed infestation and topography)
526 might have a substantial influence on crop yields under field conditions. Nevertheless,
527 DayCent captured the most important sources of variation due to treatment effects and
528 biophysical conditions, such as soil properties and climate.
529 Predictive errors generally originate from either uncertainty in the input data or from the
530 limited representation of mechanisms in the model (Ogle *et al.*, 2006). High errors associated
531 with yield predictions of tuber crops seem to be directly related to a simplistic representation
532 of C allocation to belowground plant components during the growth. Similarly, errors
533 associated with yield predictions of winter crops can be explained by the limited

534 representation of crop vernalization in the crop growth sub-model. Larger predictive errors for
535 cover crops and white cabbage yields, which were planted only in one or two years, can be
536 related to a scarcity of time series data required for sufficiently robust model
537 parameterization.

538 Mäder *et al.* (2002) and Mayer *et al.* (2015) reported that yields in N system in DOK have
539 been limited by N, P and K availability and higher incidence of *Phytophthora infestans*
540 compared to other systems. Lack of model representation of these processes resulted in a
541 higher predictive error and overprediction of yields for N system.

542 **DayCent predicted less variation in SOC content than in yield.** This can be associated with a)
543 high uncertainties in empirical data (Fig.B1); b) default parameterization of cover crops and
544 green manures due to data limitation that might have led to under/overprediction of C inputs;
545 and c) reduced ability to simulate growth and biomass allocation for some crops in the
546 rotations.

547 Treatment-induced changes in SOC content were underpredicted in rotation A in DOK,
548 presumably due to exogenous factors that have not affected SOC dynamics in rotation B and
549 C, particularly associated with the top row position of these plots in the experimental blocking
550 (e.g., soil erosion (Siegrist *et al.*, 1998)). Underprediction of SOC change in response to PL in
551 clay soil in P29C can be attributed to a prolonged effect of deep tillage disturbance in clays
552 (La Scala *et al.*, 2006) whereas DayCent increases decomposition rates for SOM pools only
553 for one month (Del Grosso *et al.*, 2011).

554 DayCent difficulties to replicate the measured variation in daily N₂O emissions are consistent
555 with other N₂O modeling studies (Fang *et al.*, 2015; Senapati *et al.*, 2016). Soil N₂O
556 emissions are highly variable in time and space due to a complex interaction of biotic and
557 abiotic processes involving multiple drivers (Davidson *et al.*, 2000; Venterea, 2007;
558 Castellano *et al.*, 2010; Venterea *et al.*, 2012; Zhu *et al.*, 2013). Limited representation of

559 some key drivers (e.g., topography and spatial heterogeneity in nutrient availability) might
560 lead to discrepancies in the timing of N₂O peaks (Del Grosso *et al.*, 2011). Additionally,
561 DayCent underpredicted N₂O emissions from green manure crops, which can be directly
562 related to the default crop parametrization that might have led to overprediction of their
563 productivity. Higher error associated with soil NO₃⁻ and NH₄⁺ predictions, particularly after
564 fertilization events, were also reported in other studies (Del Grosso *et al.*, 2008a; Fang *et al.*,
565 2015; Necpalova *et al.*, 2015) suggesting that model representation of fertilization effects on
566 mineral N pools requires further improvements.

567

568 4.2 Soil GHG emissions and mitigation potentials

569 DayCent substantially underpredicted the variation in measured data. Accordingly, the
570 probability of not committing type II error, i.e., detecting statistically significant differences
571 between management practices with the type I error of 0.05 using ANOVA, was expected to
572 be higher for model predictions. Statistical power to detect differences in measured N₂O
573 emissions between systems in DOK was 0.78, while for model predictions the power
574 increased to 0.92. This should, however, not diminish the validity of our statistical analyses.

575

576 Soils under conventional managements at all sites acted as a net soil GHG source, ranging
577 from 1361 to 1792 kg CO₂eq ha⁻¹yr⁻¹. Despite the consistent decrease in SOC content,
578 NSGHGE were dominated by N₂O (50 - 63%), indicating the relative importance of N₂O over
579 CO₂ emissions in soil GHG mitigation from Swiss cropping systems. The same has been
580 observed for cropping systems in Europe, UK (Smith, 2012) and California (De Gryze *et al.*,
581 2010; De Gryze *et al.*, 2011).

582

583 Reduced tillage practices reduced the long-term SOC loss and thus CO₂ emissions by up to
584 50% in P29C, although this decrease was not significant. In comparison, NT significantly
585 reduced long-term CO₂ emissions by 76% in FAST. It has been well established that both
586 reduced tillage and NT decrease disturbance of soil aggregates and therefore lead to higher
587 SOC stabilization compared to conventional tillage (Six *et al.*, 2000; Six and Paustian, 2014).
588 However, recent studies involving deeper sampling depth suggest that SOC sequestration
589 potential in NT and reduced tillage systems may have been over-estimated as the apparent
590 increase in SOC mostly results from a vertical redistribution of C due to allocation of crop
591 residues into the shallower soil layers (Baker *et al.*, 2007; Angers and Eriksen-Hamel, 2008;
592 Luo *et al.*, 2010; Powlson *et al.*, 2014). Since the SOC measurements at the LTE sites were
593 carried out only to 20 cm depth and the DayCent model has been parametrized to represent
594 the evolution of SOC under RT based on this data, our predictions of SOC sequestration in
595 response to reduced tillage and its role in the CO₂ emission mitigation might be
596 overestimated.

597 Furthermore, our results show that reduced tillage and NT led to an 11% and 22% reduction
598 in long-term N₂O emissions, respectively. Consequently, NSGHGE were reduced by 31% and
599 58% due to reduced tillage and NT over 30 years, respectively. These estimates are consistent
600 with meta-analyses conducted on long-term effects of NT and reduced tillage on NSGHGE
601 (Six *et al.*, 2004; van Kessel *et al.*, 2013). Six *et al.* (2004) reported that a short-term adoption
602 of NT increased NSGHGE relative to conventional tillage primarily due to an initial increase
603 in N₂O, but NT adoption over 20 years reduced NSGHGE. Similarly, van Kessel *et al.* (2013)
604 reported that area and yield-scaled N₂O emissions were significantly reduced after a 10 year
605 implementation of NT or reduced tillage relative to conventional tillage. Our results show that
606 GHGI decreased by up to 32% due to reduced tillage and by 56% due to NT, but also a 5%
607 reduction in the yield. Furthermore, reduced fuel consumption strengthens the GHG

608 mitigation potential associated with the adoption of these practices (Kern and Johnson, 1993;
609 West and Marland, 2002).

610

611 Organic farming, represented by organic fertilization, reduced long-term SOC loss and
612 thereby CO₂ emissions by 37 and 51% in DOK and FAST, respectively. These estimates are
613 consistent with a recent meta-analysis of 74 studies reporting that organic management has
614 the capacity to substantially increase SOC sequestration compared with non-organic
615 management (Gattinger *et al.*, 2012). The SOC increase was driven by total C inputs like
616 elsewhere (e.g. Leifeld and Fuhrer (2010); Kong *et al.* (2005); Autret *et al.* (2016)).

617 Consequently, the reduction in C inputs through organic fertilization in O1 led to a reduction
618 in the CO₂ mitigation potential.

619 Although organic farming did have the capacity to reduce CO₂ over 30 years, it did not reduce
620 N₂O emissions relative to systems relying only on mineral fertilizers. This contradicts a meta-
621 analysis based on 12 studies reporting that organic systems reduce soil N₂O emissions relative
622 to non-organic farming systems (Skinner *et al.*, 2014). Authors attributed this reduction to
623 lower external and total N inputs to organic systems and reduced bioavailability of organic
624 fertilizers. External N inputs to organic systems in FAST were, however, higher, whereas in
625 DOK, they were slightly lower than the inputs to systems solely under mineral fertilization.
626 However, due to differences in plant residues and biological N fixation, total N inputs to
627 organic and conventional systems were comparable in these LTEs. Another possible
628 explanation of inconsistency with Skinner *et al.* (2014) can be that the slow release of mineral
629 N from organic fertilizers might lead to soil N₂O emissions after the crop growth period,
630 which is generally not covered by GHG measurements, but accounted in the modeled results.
631 The N₂O emissions from organic systems might be even higher if we considered indirect N₂O
632 emissions associated with ammonia volatilization (Hristov *et al.*, 2011; Petersen and Sommer,

633 2011). In Switzerland, about 24% of animal manure N applied to soils is assumed to be lost as
634 ammonia (FOEN, 2017).

635 Our results further indicate that N₂O emissions from organic systems were driven by total N
636 inputs. Consequently, a 50% reduction in N inputs through organic fertilizers led to a 35%
637 reduction in N₂O emissions, but simultaneously to a reduction in CO₂ mitigation potential,
638 resulting in a small overall effect on NSGHGE.

639 Organic farming in comparison with systems based solely on mineral fertilizers reduced
640 NSGHGE by 18% in DOK and by 31% in FAST. The inability of DayCent to represent
641 ammonia volatilization from organic fertilizers should have also increased the nutrient
642 availability and yield potential, and consequently led to an inferior modeled yield gap
643 compared to results from field experimentation (De Ponti *et al.*, 2012; Seufert *et al.*, 2012).
644 Nevertheless, organic farming led to a yield reduction by 2% in DOK and 14% in FAST, and
645 accordingly reduced GHGI by 16 and 20%, respectively. These results are in line with a
646 recent LCA study for FAST, which indicated that organic farming reduced overall ‘cradle to
647 grave’ GHG emissions (excluding SOC change) by 46% and 26% on an area and a yield-unit
648 basis, respectively (Prechsl *et al.*, 2017).

649

650 The GHG mitigation potential of organic fertilization was strengthened by OM stabilization
651 prior to its application through composting. Replacement of slurries with a FYM composted
652 over 4 months in Frick led to an 80% and 13% reduction in soil CO₂ and N₂O emissions,
653 respectively. This is associated with higher C inputs and lower N availability of the
654 composted FYM compared to the slurry. The positive effect of composted FYM on SOC and
655 N₂O has been previously reported (Fließbach *et al.*, 2007; Powlson *et al.*, 2012). This
656 fertilization strategy had also no effect on yield and thereby reduced GHGI by 45%. However,

657 our assessment took into consideration only soil GHG emissions within the field boundaries
658 and therefore additional GHG emissions associated with the composting process might
659 partially offset the soil GHG mitigation potential on-site (Pardo *et al.*, 2015).
660
661 A strong positive interactive effect of organic farming and reduced tillage in FAST
662 strengthened the mitigation potential of these practices as when they were applied
663 independently. This management combination led to a 200% reduction in CO₂, while its
664 effect on N₂O emissions was negligible. SOC sequestration completely offset N₂O emissions
665 and turned the cropping system into a GHG sink. Consequently, GHGI was reduced by 142%
666 relative to conventional management, despite a substantial yield reduction. Positive
667 interaction of these practices on GHG emissions has been previously reported (De Gryze *et*
668 *al.*, 2011). Nevertheless, soils under organic farming and reduced tillage in Frick did not act
669 as a net GHG sink. This can be a result of i) an implementation of more intensive and deeper
670 tillage practices, and ii) lower C inputs associated with residues removal and lower proportion
671 of legumes in the rotation in Frick than in FAST (Berner *et al.*, 2008; Krauss *et al.*, 2010;
672 Gadermaier *et al.*, 2012).
673
674 Cover crops residues represent a substantial C source that has been reported to increase SOC
675 and thus reduce soil CO₂ emissions (Kong and Six, 2010; Poeplau and Don, 2015; Kaye and
676 Quemada, 2017). In our study, cover cropping did not significantly reduce long-term soil CO₂
677 emissions, although there were some trends of decreasing CO₂ emissions in FAST. Vetch
678 reduced CO₂ under IT by 35%, and had no effect on CO₂ emissions under NT management
679 relative to no-cover cropping. Mustard and mixture reduced CO₂ under IT by up to 15%,
680 while they increased CO₂ emissions by 12% under NT management. This may be due to a
681 slower incorporation of surface residues into the soil under NT than under conventional

682 tillage management (Six *et al.*, 2004). Tillage associated with the incorporation of cover crop
683 residues increases SOM mineralization rates, and accordingly the net reduction in soil CO₂
684 emissions for cover crop and IT was substantially smaller than for the cover crop and NT
685 combinations.

686 Mustard and mixture did not significantly affect long-term N₂O emissions. Vetch significantly
687 increased N₂O emissions by 10%, most likely due to an additional N input through biological
688 N fixation (~ 7 kg ha⁻¹ yr⁻¹). Recent meta-analysis of cover crop effects on N₂O emissions
689 indicated that legumes might increase N₂O emissions at lower N input rates more than non-
690 legume species (Basche *et al.*, 2014). This can be associated with an increased soil mineral N
691 via N fixation (Kaspar and Singer, 2011) and/or an increased soil N availability during
692 decomposition of residues with low C:N ratios (Baggs *et al.*, 2006; Basche *et al.*, 2014).
693 Furthermore, N₂O from vetch cover cropping can be driven by cover crop-derived DOC
694 (Garland *et al.*, 2014). Although cover cropping did not significantly influence NSGHGE,
695 vetch showed a tendency to reduce NSGHGE. Overall, cover cropping increased yields due to
696 an improved nutrient efficiency and an additional N input through biological fixation in case
697 of legumes. Vetch decreased GHGI by 40% on average, while the reduction in GHGI was
698 negligible for mustard and mixture. This suggests that biological N fixation can contribute to
699 the mitigation potential of cover cropping.

700

701 Swiss soils are drained, aerated with low soil water content, thus have limited potential to
702 produce CH₄ emissions (Conrad, 1996). Predictions of CH₄ uptake ranged from 1.1 to 1.6 kg
703 C ha⁻¹yr⁻¹ and offset about 2.3 to 10.1% of NSGHGE across treatments and sites. Although,
704 there was no field data available to validate modeled CH₄ uptake at Swiss LTEs, the
705 magnitude of the model predictions is comparable with those reported for temperate
706 agricultural soils (Smith *et al.*, 2000; Hütsch, 2001), however slightly higher than those

707 reported by Flessa *et al.* (1995) and Skinner *et al.* (2014). This discrepancy can be attributed
708 to insufficient measurements using chamber-based field methodologies (Smith and Dobbie,
709 2001; Parkin, 2008; Barton *et al.*, 2015) and seasonality of the measurements which generally
710 cover only a crop growth period (e.g., Flessa *et al.* (2002)). Another possible explanation of
711 this inconsistency can be the DayCent's inability to represent methanogenesis following the
712 organic manure application (Gattinger *et al.*, 2007; Chadwick *et al.*, 2011; Gattinger *et al.*,
713 2017) and might therefore slightly overestimate annual CH₄ uptake. Due to a small variance
714 around the means, the modeled oxidation potential was shown to be strongly influenced by
715 studied management practices, perhaps through altering soil water and temperature
716 conditions, which drive the model predictions.

717

718 Although N₂O emissions represented a substantial proportion of NSGHGE (60 - 80% across
719 treatments and sites), management practices and their combinations evaluated in this study
720 showed a larger mitigation potential for CO₂ than N₂O emissions, i.e., organic farming with
721 reduced tillage, composting of organic manures, NT, reduced tillage and organic farming
722 only. The CO₂ mitigation through SOC sequestration is considered as time-limited since the
723 capacity of soils to sequester C is limited once it approaches a new equilibrium (Six *et al.*,
724 2004; Johnston *et al.*, 2009). Furthermore, this process is reversible. If the management is not
725 maintained, previously sequestered C can be released back to the atmosphere (Smith *et al.*,
726 2014).

727 A significant GHG mitigation was also achieved through the reduction in N₂O emissions for
728 the following practices: a 50% reduction in N inputs, NT, composting of organic manures,
729 and reduced tillage. This mitigation is, on the other hand, considered permanent as the GHG
730 emissions are avoided (Smith *et al.*, 2014).

731

732 As not only soil management but also pedo-climatic conditions control soil GHG emissions,
733 the extent of the mitigation potential of soil management practices and their combinations
734 should be further evaluated across a wider range of pedo-climatic conditions. Furthermore, a
735 more comprehensive GHG assessment of Swiss cropping systems taking into account all
736 other emissions associated with the production of fertilizers, energy use, manure storage,
737 composting, farm machinery and livestock emissions is needed.

738

739 5. Conclusions

740 This present study was established on the long-term empirical data that was used to
741 parameterize and evaluate the DayCent model for Swiss cropping systems. The model
742 demonstrated adequate ability to simulate long-term yields and SOC dynamics in complex
743 crop rotations, although the evaluation of its ability to simulate soil N₂O emissions and CH₄
744 uptake was compromised by the limited data availability and therefore requires further
745 assessment based on higher resolution data collected over an entire crop rotation period
746 covering a range of pedo-climatic gradients.

747 In this study, we evaluated the long-term impact of management practices and their
748 interactions on soil GHGE and GHGI in order to identify and quantify potential opportunities
749 for mitigating GHG emissions in the Swiss agricultural sector. Our results demonstrated that
750 organic farming, particularly in combination with reduced tillage management, substantially
751 reduced long-term NSGHGE and GHGI, but it simultaneously led to a decrease in crop
752 yields. In contrast, composting of organic manures, reduced tillage and NT managements
753 effectively reduced long-term NSGHGE and GHGI without a noticeable crop yield reduction
754 (up to 5%). The least GHG mitigation potential was associated with cover cropping
755 management, which had a minor impact on NSGHGE. Despite the relative importance of N₂O
756 over CO₂ emissions in soil GHG mitigation, SOC sequestration accounted, on average, for

757 89% of GHG mitigation potentials. Thus, the conversion to the above soil management
758 practices have a considerable potential for climate change mitigation in Swiss agriculture,
759 without affecting the overall production levels, however this potential is not permanent.

760

761 **Acknowledgements**

762 This research is part of international collaborative projects COMET-Global [grant
763 40FA40_154247] and CLIMATE-Café [grant 40FA40_158394], funded by the Swiss
764 National Science Foundation (SNSF) within the framework of the National Research
765 Programme “Sustainable Use of Soil as a Resource” (NRP 68), and the Joint Programming
766 Initiative on Agriculture, Food Security and Climate Change (FACCE-JPI).

767 **List of Tables**

768 **Table 1** Soil and climate characteristics of Swiss long-term field experimental (LTE) sites.

769 **Table 2** Description of management factors and levels studied in long-term field experiments
770 (LTEs) in Switzerland. FYM refers to farm yard manure. LU refers to livestock unit.

771 **Table 3** Mean (\pm standard deviation) measured and modeled crop productivity by crop across
772 all treatments, years and sites, and error associated with model predictions. N,
773 RMSE, rRMSE, r^2 and WI refer to the number of observations, root mean squared
774 error, relative root mean squared error, coefficient of determination and Willmott's
775 index calculated for each simulated crop across all treatments, years and sites.

776 **Table 4** Analysis of variance for the effects of management practices and their interactions on
777 soil greenhouse gas emissions and yield at each long-term experimental (LTE) site.
778 NSGHGE refers to net soil GHG emissions. For DOK, two independent analyses
779 were conducted: a) we excluded unfertilized (N) and mineral (M2) treatments in
780 order to include the level of fertilization as a fixed factor in the model statement; b)
781 treatments at 50% fertilization (i.e., K1 and O1) were excluded, in order to compare
782 all farming systems at their typical fertilization levels.

783 **Table 5** Greenhouse (GHG) emissions, changes in soil organic C (SOC) content, total N and
784 C inputs and yield calculated for the main treatments at four long-term experimental
785 (LTE) sites over 30 years. Standard errors (SE) were computed by linear mixed
786 effects models in SAS. Positive change in SOC indicates SOC sequestration, while a
787 negative change indicates a decrease in SOC. Positive values of soil CH₄ oxidation
788 refer to CH₄ uptake. Positive values for net soil GHG emissions (NSGHGE) denote
789 net GHG source, while negative values denote a net sink for GHG emissions. GHGI
790 refers to GHG intensity.

791 **Table 6** Relative (%) and absolute (kg CO₂eq ha⁻¹ or kg CO₂eq kg⁻¹) changes in annual soil
792 GHG emissions in response to studied soil management combinations compared with
793 the baseline treatment in four long-term experiments (LTEs). GHGI refers to GHG
794 intensity. The baseline represented by the treatment with the highest soil GHG
795 emissions on an area basis at each LTE site is denoted by underlining. Mean
796 differences (± standard error) relative to the baseline were calculated as differences
797 of least squares means by linear mixed effects models in SAS.

798 **List of Figures**

799 **Figure 1** Modeled vs. measured grain, straw, tuber, forage yields by crop across various
800 years, and treatments at four long-term field experimental sites in Switzerland. Each
801 point represents a crop-specific mean of two spatial replications for a year. The
802 horizontal error bars refer to standard deviations around measured yields due to
803 spatial replication, while the vertical error bars refer to standard deviations around
804 modeled yields. N, r^2 , RMSE, rRMSE, WI refer to the number of observations,
805 coefficient of determination, root mean squared error, relative root mean squared
806 error and Willmott's index calculated for each experimental site across all
807 treatments, crops and years, respectively. RMSE has the same unit as the variable
808 shown. The solid line is the 1:1 line and the dashed line is the linear regression line.

809 **Figure 2** Mean measured and modeled crop productivity and changes in soil organic C
810 content at the 0 to 20 cm depth by long-term experimental site and treatment across
811 all crops and years, and error associated with model predictions. Productivity
812 comprises of grain, straw, tuber, vegetable, forages such as silage maize and grass-
813 clover, and cover crop biomass. The error bars refer to standard deviations around
814 measured and modeled means. rRMSE refers to the relative root mean squared error
815 and r^2 refers to the coefficient of determination. The annual change in soil organic C
816 content was calculated as a slope of the linear regression over time. For FAST, no
817 soil C data were available. For Frick, soil organic C data from three sampling
818 occasions in 2002, 2005 and 2008 were available, and these were considered to be
819 insufficient for the linear regression analysis.

820 **Figure 3** Modeled vs. measured (a) soil organic C content at 0 to 20 cm across various
821 treatments, years and four long-term field experimental sites in Switzerland. Each
822 point represents a mean soil organic C content of two spatial replications; (b) annual

823 changes in soil organic C content over time for each individual treatment. Each point
824 represents a slope of the linear regression against time. N , r^2 , RMSE, rRMSE and WI
825 refer to the number of observations, coefficient of determination, root mean squared
826 error, relative root mean squared error and Willmott's index calculated across all
827 sites, treatments and years. RMSE has the same unit as the variable shown. The solid
828 line is the 1:1 line and the dashed line is the linear regression line.

829 **Figure 4** Measured and modeled daily soil N₂O emissions over time for four farming system
830 treatments in DOK. The dashed error bars refer to standard deviations around
831 measured daily emissions due to spatial replication. The solid error bars refer to
832 standard deviations around modeled daily emissions. The following crops were
833 planted during this period: grass-clover lay until 13th May 2013, silage maize
834 between 28th May and 25th September 2013 and green manure after 9th October 2013.
835 The measured N₂O data is unpublished data obtained through Pers. Comm. with Dr.
836 Andreas Gattinger and Colin Skinner.

837 **Figure 5** Modeled vs. measured cumulative soil N₂O emissions by treatment in DOK. Each
838 point represents a cumulative treatment mean. The horizontal error bars refer to
839 standard deviations around measured emissions due to spatial replication, while the
840 vertical error bars refer to standard deviations around modeled emissions. r^2 , RMSE,
841 rRMSE and WI refer to the coefficient of determination, root mean squared error,
842 relative root mean squared error and Willmott's index calculated across all
843 treatments at this site. RMSE has the same unit as the variable shown. The solid line
844 is the 1:1 line and the dashed line is the linear regression line.

845 **Figure 6** Mean modeled net soil greenhouse gas (GHG) emissions, as calculated from soil
846 CO₂, N₂O and CH₄ emissions for individual treatments at four long-term
847 experimental sites over a 30 years period. Net soil GHG emissions and individual

848 components of net soil GHG balance are expressed in CO₂ equivalents. The error
849 bars represent standard errors of the least squares means calculated by linear mixed
850 effects models. Letters next to the error bars indicate which treatment means are
851 significantly different from each other within the site-specific analysis of variance
852 represented by the color coding. Positive soil CO₂ emissions indicate a decrease in
853 soil organic C, while negative soil CO₂ emissions indicate soil C sequestration from
854 the atmosphere. Negative CH₄ emissions indicate CH₄ oxidation potential.

855

856 **References**

- 857 Alvaro-Fuentes, J., Arrue, J.L., Bielsa, A., Cantero-Martinez, C., Plaza-Bonilla, D., Paustian,
858 K., 2017. Simulating climate change and land use effects on soil nitrous oxide
859 emissions in Mediterranean conditions using the Daycent model. *Agr Ecosyst Environ*
860 238, 78-88.
- 861 Ammann, C., Flechard, C.R., Leifeld, J., Neftel, A., Fuhrer, J., 2007. The carbon budget of
862 newly established temperate grassland depends on management intensity. *Agr Ecosyst*
863 *Environ* 121, 5-20.
- 864 Angers, D.A., Eriksen-Hamel, N.S., 2008. Full-Inversion Tillage and Organic Carbon
865 Distribution in Soil Profiles: A Meta-Analysis. *Soil Science Society of America Journal*
866 72, 1370.
- 867 Armengot, L., Berner, A., Blanco-Moreno, J.M., Mader, P., Sans, F.X., 2015. Long-term
868 feasibility of reduced tillage in organic farming. *Agron Sustain Dev* 35, 339-346.
- 869 Autret, B., Mary, B., Chenu, C., Balabane, M., Girardin, C., Bertrand, M., Grandeau, G.,
870 Beaudoin, N., 2016. Alternative arable cropping systems: A key to increase soil organic
871 carbon storage? Results from a 16 year field experiment. *Agriculture, Ecosystems &*
872 *Environment* 232, 150-164.
- 873 Baggs, E.M., Rees, R.M., Smith, K.A., Vinten, A.J.A., 2006. Nitrous oxide emission from
874 soils after incorporating crop residues. *Soil Use Manage* 16, 82-87.
- 875 Baker, J.M., Ochsner, T.E., Venterea, R.T., Griffis, T.J., 2007. Tillage and soil carbon
876 sequestration—What do we really know? *Agriculture, Ecosystems & Environment* 118,
877 1-5.

878 Barton, L., Wolf, B., Rowlings, D., Scheer, C., Kiese, R., Grace, P., Stefanova, K.,
879 Butterbach-Bahl, K., 2015. Sampling frequency affects estimates of annual nitrous
880 oxide fluxes. *Sci Rep* 5, 15912.

881 Basche, A.D., Miguez, F.E., Kaspar, T.C., Castellano, M.J., 2014. Do cover crops increase or
882 decrease nitrous oxide emissions? A meta-analysis. *J. Soil Water Conserv.* 69, 471-482.

883 Berner, A., Hildermann, I., Fließbach, A., Pfiffner, L., Niggli, U., Mader, P., 2008. Crop
884 yield and soil fertility response to reduced tillage under organic management. *Soil Till*
885 *Res* 101, 89-96.

886 Bouwman, A.F., Boumans, L.J.M., Batjes, N.H., 2002. Emissions of N₂O and NO from
887 fertilized fields: Summary of available measurement data. *Global Biogeochemical*
888 *Cycles* 16, 1058–1070.

889 Büchi, L., Gebhard, C.A., Liebisch, F., Sinaj, S., Ramseier, H., Charles, R., 2015.
890 Accumulation of biologically fixed nitrogen by legumes cultivated as cover crops in
891 Switzerland. *Plant and Soil* 393, 163-175.

892 Büchi, L., Wendling, M., Amossé, C., Jeangros, B., Sinaj, S., Charles, R., 2017. Long and
893 short term changes in crop yield and soil properties induced by the reduction of soil
894 tillage in a long term experiment in Switzerland. *Soil Till. Res.*, 120-129.

895 Büchi, L., Wendling, M., Amossé, C., Nepalova, M., Charles, R., 2018. Importance of cover
896 crops in alleviating negative effects of reduced soil tillage and promoting soil fertility in
897 a winter wheat cropping system. *Agriculture, Ecosystems and Environment*, 256, 92-
898 104.

899 Bürgi, M., 2016. Agricultural history of Switzerland. Historical approach – Land Use History
900 and Historical Ecology. ETH, Zürich.

901 Bürgi, M., Salzmann, D., Gimmi, U., 2015. 264 years of change and persistence in an
902 agrarian landscape: a case study from the Swiss lowlands. *Landscape Ecol* 30, 1321-
903 1333.

904 Burney, J.A., Davis, S.J., Lobell, D.B., 2010. Greenhouse gas mitigation by agricultural
905 intensification. *Proc Natl Acad Sci U S A* 107, 12052-12057.

906 Campbell, E.E., Paustrian, K., 2015. Current developments in soil organic matter modeling
907 and the expansion of model applications: a review. *Environmental Research Letters* 10.

908 Castellano, M.J., Schmidt, J.P., Kaye, J.P., Walker, C., Graham, C.B., Lin, H., Dell, C.J.,
909 2010. Hydrological and biogeochemical controls on the timing and magnitude of nitrous
910 oxide flux across an agricultural landscape. *Global Change Biology* 16, 2711-2720.

911 Chadwick, D., Sommer, S., Thorman, R., Fangueiro, D., Cardenas, L., Amon, B.,
912 Misselbrook, T., 2011. Manure management: Implications for greenhouse gas
913 emissions. *Anim Feed Sci Tech* 166-167, 514-531.

914 Conrad, R., 1996. Soil microorganisms as controllers of atmospheric trace gases (H₂,CO,
915 CH₄, OCS, N₂O, and NO). *Microbiol Mol Biol Rev* 60, 609-640.

916 Cooper, J., Baranski, M., Stewart, G., Nobel-de Lange, M., Bàrberi, P., Fließbach, A., Peigné,
917 J., Berner, A., Brock, C., Casagrande, M., Crowley, O., David, C., De Vliegheer, A.,
918 Döring, T.F., Dupont, A., Entz, M., Grosse, M., Haase, T., Halde, C., Hammerl, V.,
919 Huiting, H., Leithold, G., Messmer, M., Schloter, M., Sukkel, W., van der Heijden,
920 M.G.A., Willekens, K., Wittwer, R., Mäder, P., 2016. Shallow non-inversion tillage in

921 organic farming maintains crop yields and increases soil C stocks: a meta-analysis.
922 Agron Sustain Dev 36, 22.

923 Davidson, E.A., Keller, M., Erickson, H.E., Verchot, L.V., Veldkamp, E., 2000. Testing a
924 conceptual model of soil emissions of nitrous and nitric oxides. *Bioscience* 50, 667-680.

925 De Gryze, S., Lee, J., Ogle, S., Paustian, K., Six, J., 2011. Assessing the potential for
926 greenhouse gas mitigation in intensively managed annual cropping systems at the
927 regional scale. *Agric. Ecosyst. Environ.* 144, 150-158.

928 De Gryze, S., Wolf, A., Kaffka, S.R., Mitchell, J., Rolston, D.E., Temple, S.R., Lee, J., Six,
929 J., 2010. Simulating greenhouse gas budgets of four California cropping systems under
930 conventional and alternative management. *Ecol Appl* 20, 1805-1819.

931 De Ponti, T., Rijk, B., van Ittersum, M.K., 2012. The crop yield gap between organic and
932 conventional agriculture. . *Agricultural Systems*, 1–9.

933 Del Grosso, S.J., Halvorson, A.D., Parton, W.J., 2008a. Testing DAYCENT model
934 simulations of corn yields and nitrous oxide emissions in irrigated tillage systems in
935 Colorado. *J Environ Qual* 37, 1383-1389.

936 Del Grosso, S.J., Parton, W.J., Keough, C.A., Reyes-Fox, M., 2011. Special Features of the
937 DayCent Modeling Package and Additional Procedures for Parameterization,
938 Calibration, Validation, and Applications. In: Ahuja L.R., L., M. (Eds.), *Methods of*
939 *Introducing System Models into Agricultural Research*. American Society of
940 *Agronomy*, Madison, USA., pp. 155-176.

941 Del Grosso, S.J., Parton, W.J., Mosier , A.R., Hartman, M.D., Brenner, J., Ojima, D.S.,
942 Schimel, D.S., 2001. Simulated Interaction of Carbon Dynamics and Nitrogen Trace

943 Gas Fluxes Using the DAYCENT Model. In: Hansen , S., Shaffer , M.J., Liwang, M.
944 (Eds.), Modeling Carbon and Nitrogen Dynamics for Soil Management. CRC Press.

945 Del Grosso, S.J., Parton, W.J., Ojima, D.S., Keough, C.A., Riley, T.H., 2008b. DAYCENT
946 simulated effects of land use and climate on county level N loss vectors in the USA. In:
947 Follett, R.F., J.L., H. (Eds.), Nitrogen in the Environment: Sources, Problems, and
948 Management, 2nd ed. . Elsevier Science Publishers, The Netherlands.

949 Doherty, J.E., Hunt, R.J., 2010. Approaches to Highly Parameterized Inversion: A Guide to
950 Using PEST for Groundwater-Model Calibration. U.S. Geological Survey Scientific
951 Investigations Report 2010–5169. U.S. Geological Survey, Reston, Virginia, p. 59.

952 Dutta, B., Grant, B.B., Campbell, C.A., Lemke, R.L., Desjardins, R.L., Smith, W.N., 2017. A
953 multi model evaluation of long-term effects of crop management and cropping systems
954 on nitrogen dynamics in the Canadian semi-arid prairie. *Agricultural Systems* 151, 136-
955 147.

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

959 Fang, Q.X., Ma, L., Halvorson, A.D., Malone, R.W., Ahuja, L.R., Del Grosso, S.J., Hatfield,
960 J.L., 2015. Evaluating four nitrous oxide emission algorithms in response to N rate on
961 an irrigated corn field. *Environmental Modelling & Software* 72, 56-70.

962 FAOSTAT, 2017. FAOSTAT database. . Food and Agriculture Organization of the United
963 Nations. , Rome, Italy Available at: <http://www.fao.org/faostat>.

964 Flessa, H., Dorsch, P., Beese, F., 1995. Seasonal-Variation of N₂o and Ch₄ Fluxes in
965 Differently Managed Arable Soils in Southern Germany. *J Geophys Res-Atmos* 100,
966 23115-23124.

967 Flessa, H., Ruser, R., Schilling, R., Loftfield, N., Munch, J.C., Kaiser, E.A., Beese, F., 2002.
968 N₂O and CH₄ fluxes in potato fields: automated measurement, management effects and
969 temporal variation. *Geoderma* 105, 307-325.

970 Fließbach, A., Mader, P., Niggli, U., 2000. Mineralization and microbial assimilation of C-14-
971 labeled straw in soils of organic and conventional agricultural systems. *Soil Biol*
972 *Biochem* 32, 1131-1139.

973 Fließbach, A., Oberholzer, H.R., Gunst, L., Mader, P., 2007. Soil organic matter and
974 biological soil quality indicators after 21 years of organic and conventional farming.
975 *Agr Ecosyst Environ* 118, 273-284.

976 FOEN, 2017. Switzerland's Greenhouse Gas Inventory 1990–2015. National Inventory
977 Report Including reporting elements under the Kyoto Protocol Submission of April
978 2017 under the United Nations Framework Convention on Climate Change and under
979 the Kyoto Protocol. Federal Office for the Environment, FOEN, Climate Division, 3003
980 Bern, Switzerland

981 Foereid, B., Bellamy, P.H., Holden, A., Kirk, G.J.D., 2012. On the initialization of soil carbon
982 models and its effects on model predictions for England and Wales. *Eur J Soil Sci* 63,
983 32-41.

984 Gadermaier, F., Berner, A., Fliessbach, A., Friedel, J.K., Mader, P., 2012. Impact of reduced
985 tillage on soil organic carbon and nutrient budgets under organic farming. *Renew Agr*
986 *Food Syst* 27, 68-80.

987 Garland, G.M., Suddick, E., Burger, M., Horwath, W.R., Six, J., 2014. Direct N₂O emissions
988 from a Mediterranean vineyard: Event-related baseline measurements. *Agriculture,*
989 *Ecosystems & Environment* 195, 44-52.

990 Gattinger, A., Hofle, M.G., Schloter, M., Embacher, A., Bohme, F., Munch, J.C., Labrenz,
991 M., 2007. Traditional cattle manure application determines abundance, diversity and
992 activity of methanogenic Archaea in arable European soil. *Environ Microbiol* 9, 612-
993 624.

994 Gattinger, A., Muller, A., Haeni, M., Skinner, C., Fliessbach, A., Buchmann, N., Mader, P.,
995 Stolze, M., Smith, P., Scialabba Nel, H., Niggli, U., 2012. Enhanced top soil carbon
996 stocks under organic farming. *Proc Natl Acad Sci U S A* 109, 18226-18231.

997 Gattinger, A., Skinner, C., Krauss, M., Mayer, J., van der Heijden, M., Mäder, P., 2017.
998 Lower area-scaled and equal yield-scaled nitrous oxide emissions in organically than in
999 non-organically managed soils. submitted.

1000 Godfray, H.C., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J.,
1001 Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food security: the challenge of feeding
1002 9 billion people. *Science* 327, 812-818.

1003 Grant, B.B., Smith, W.N., Campbell, C.A., Desjardins, R.L., Lemke, R.L., Krobel, R.,
1004 McConkey, B.G., Smith, E.G., Lafond, G.P., 2016. Comparison of DayCent and DNDC
1005 Models: Case Studies Using Data from Long-Term Experiments on the Canadian
1006 Prairies. In: DelGrosso, S.J., Ahuja, L.R., Parton, W.J. (Eds.), *Synthesis and Modeling*
1007 *of Greenhouse Gas Emissions and Carbon Storage in Agricultural and Forest Systems*
1008 *to Guide Mitigation and Adaptation*, pp. 21-57.

1009 Houghton, R.A., 1999. The annual net flux of carbon to the atmosphere from changes in land
1010 use 1850-1990. *Tellus B* 51, 298-313.

1011 Hristov, A.N., Hanigan, M., Cole, A., Todd, R., McAllister, T.A., Ndegwa, P.M., Rotz, A.,
1012 2011. Review: Ammonia emissions from dairy farms and beef feedlots¹. *Canadian*
1013 *Journal of Animal Science* 91, 1-35.

1014 Hütsch, B.W., 2001. Methane oxidation in non-flooded soils as affected by crop production
1015 — invited paper. *Eur J Agron* 14, 237-260.

1016 IPCC, 2014. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II,*
1017 *and III to the Fifth Assessment Report of the Intergovernmental Panel of Climate*
1018 *Change.* In: Team, C.W., Pachauri, R.K., Meyer, L.A. (Eds.), Geneva, Switzerland, p.
1019 151.

1020 Johnston, A.E., Poulton, P.R., Coleman, K., 2009. Soil Organic Matter: Its Importance in
1021 Sustainable Agriculture and Carbon Dioxide Fluxes. *Adv Agron* 101, 1-57.

1022 Kaspar, T.C., Singer, J.W., 2011. The use of cover crops to manage soil. In: Hatfield, J.L.,
1023 Sauer, T.J. (Eds.), *Soil Management: Building a Stable Base for Agriculture.*, American
1024 Society of Agronomy and Soil Science Society of America, Madison, WI.

1025 Kaye, J.P., Quemada, M., 2017. Using cover crops to mitigate and adapt to climate change. A
1026 review. *Agron Sustain Dev* 37, 4.

1027 Kern, J.S., Johnson, M.G., 1993. Conservation Tillage Impacts on National Soil and
1028 Atmospheric Carbon Levels. *Soil Science Society of America Journal* 57, 200-210.

1029 Kong, A.Y.Y., Six, J., 2010. Tracing Root vs. Residue Carbon into Soils from Conventional
1030 and Alternative Cropping Systems. *Soil Science Society of America Journal* 74, 1201.

- 1031 Kong, A.Y.Y., Six, J., Bryant, D.C., Denison, R.F., van Kessel, C., 2005. The relationship
1032 between carbon input, aggregation, and soil organic carbon stabilization in sustainable
1033 cropping systems. *Soil Science Society of America Journal* 69, 1078-1085.
- 1034 Krauss, M., Berner, A., Burger, D., Wiemken, A., Niggli, U., Mader, P., 2010. Reduced
1035 tillage in temperate organic farming: implications for crop management and forage
1036 production. *Soil Use Manage* 26, 12-20.
- 1037 Krauss, M., Ruser, R., Muller, T., Hansen, S., Mader, P., Gattinger, A., 2017. Impact of
1038 reduced tillage on greenhouse gas emissions and soil carbon stocks in an organic grass-
1039 clover ley - winter wheat cropping sequence. *Agric Ecosyst Environ* 239, 324-333.
- 1040 Külling, D.R., Dohme, F., Menzi, H., Sutter, F., Lischer, P., Kreuzer, M., 2002. Methane
1041 emissions of differently fed dairy cows and corresponding methane and nitrogen
1042 emissions from their manure during storage. *Environmental Monitoring and Assessment*
1043 79 (2), 129-150.
- 1044 Külling, D.R., Menzi, H., Sutter, F., Lischer, P., Kreuzer, M., 2003. Ammonia, nitrous oxide
1045 and methane emissions from differently stored dairy manure derived from grass- and
1046 hay-based rations. *Nutrient Cycling in Agroecosystems* 65 (1), 13-22.
- 1047 Kuntz, M., Berner, A., Gattinger, A., Scholberg, J.M., Mäder, P., Pfiffner, L., 2013. Influence
1048 of reduced tillage on earthworm and microbial communities under organic arable
1049 farming. *Pedobiologia* 56, 251-260.
- 1050 La Scala, N., Bolonhezi, D., Pereira, G.T., 2006. Short-term soil CO₂ emission after
1051 conventional and reduced tillage of a no-till sugar cane area in southern Brazil. *Soil and*
1052 *Tillage Research* 91, 244-248.

1053 Lee, J., Pedroso, G., van Kessel, C., Six, J., 2015. Potential regional productivity and
1054 greenhouse gas emissions of fertilized and irrigated switchgrass in a Mediterranean
1055 climate. *Agriculture, Ecosystems & Environment* 212, 64-74.

1056 Leifeld, J., Fuhrer, J., 2010. Organic farming and soil carbon sequestration: What do we really
1057 know about the benefits? *Ambio* 39, 585-599.

1058 Leifeld, J., Reiser, R., Oberholzer, H.-R., 2009. Consequences of Conventional versus
1059 Organic farming on Soil Carbon: Results from a 27-Year Field Experiment. *Agronomy*
1060 *Journal* 101, 1204.

1061 Luo, Z., Wang, E., Sun, O.J., 2010. Can no-tillage stimulate carbon sequestration in
1062 agricultural soils? A meta-analysis of paired experiments. *Agriculture, Ecosystems &*
1063 *Environment* 139, 224-231.

1064 Mäder, P., Edenhofer, S., Boller, T., Wiemken, A., Niggli, U., 2000. Arbuscular mycorrhizae
1065 in a long-term field trial comparing low-input (organic, biological) and high-input
1066 (conventional) farming systems in a crop rotation. *Biology and Fertility of Soils* 31,
1067 150-156.

1068 Mäder, P., Fliessbach, A., Dubois, D., Gunst, L., Fried, P., Niggli, U., 2002. Soil fertility and
1069 biodiversity in organic farming. *Science* 296, 1694-1697.

1070 Mäder, P., Fliessbach, A., Dubois, D., Gunst, L., Jossi, W., Widmer, F., Oberson, A.,
1071 Frossard, E., Oehl, F., Wiemken, A., Gattinger, A., Niggli, U., 2006. The DOK
1072 experiment (Switzerland). In: Raupp J, Pekrun C, Oltmanns M, U, K. (Eds.), *Long term*
1073 *field experiments in organic farming*. Dr. Köster, Berlin, pp. 41-58.

1074 Mayer, J., Gunst, L., Mäder, P., Samson, M.-F., Carcea, M., Narducci, V., Thomsen, I.K.,
1075 Dubois, D., 2015. "Productivity, quality and sustainability of winter wheat under long-
1076 term conventional and organic management in Switzerland". *Eur J Agron* 65, 27-39.

1077 MeteoSwiss, 2016. Historic measured meteorological data of the Swiss National Basic
1078 Climatological Network. In: MeteoSwiss, F.O.o.M.a.C. (Ed.),
1079 <http://www.meteoswiss.admin.ch/home/measurement-and-forecasting->
1080 [systems/datenmanagement/historic-measured-meteorological-data.html](http://www.meteoswiss.admin.ch/home/measurement-and-forecasting-systems/datenmanagement/historic-measured-meteorological-data.html).

1081 Necpalova, M., Anex, R.P., Fienen, M.N., Del Grosso, S.J., Castellano, M.J., 2015.
1082 Understanding the DayCent model: Calibration, sensitivity, and identifiability through
1083 inverse modeling. *Environmental Modelling and Software* 66, 110-130.

1084 Oberson, A., Frossard, E., Buhlmann, C., Mayer, J., Mader, P., Luscher, A., 2013. Nitrogen
1085 fixation and transfer in grass-clover leys under organic and conventional cropping
1086 systems. *Plant and Soil* 371, 237-255.

1087 Oberson, A., Nanzer, S., Bosshard, C., Dubois, D., Mäder, P., Frossard, E., 2007. Symbiotic
1088 N₂ fixation by soybean in organic and conventional cropping systems estimated by 15N
1089 dilution and 15N natural abundance. *Plant and Soil* 290, 69-83.

1090 Ogle, S.M., Breidt, F.J., Paustian, K., 2006. Bias and variance in model results associated
1091 with spatial scaling of measurements for parameterization in regional assessments.
1092 *Global Change Biology* 12, 516-523.

1093 Pardo, G., Moral, R., Aguilera, E., Del Prado, A., 2015. Gaseous emissions from management
1094 of solid waste: a systematic review. *Glob Chang Biol* 21, 1313-1327.

- 1095 Parkin, T.B., 2008. Effect of sampling frequency on estimates of cumulative nitrous oxide
1096 emissions. *J Environ Qual* 37, 1390-1395.
- 1097 Parton, W.J., Rasmussen, P.E., 1994. Long term effects of crop management in wheat fallow:
1098 II. CENTURY model simulations. . *Soil Science Society of America Journal*. 58, 530-
1099 536.
- 1100 Paustian, K., Andren, O., Janzen, H.H., Lal, R., Smith, P., Tian, G., Tiessen, H., Van
1101 Noordwijk, M., Woomer, P.L., 1997. Agricultural soils as a sink to mitigate CO₂
1102 emissions. *Soil Use Manage* 13, 230-244.
- 1103 Peigné, J., Messmer, M., Aveline, A., Berner, A., Mäder, P., Carcea, M., Narducci, V.,
1104 Samson, M.-F., Thomsen, I.K., Celette, F., David, C., 2013. Wheat yield and quality as
1105 influenced by reduced tillage in organic farming. *Org. Agr.* 4, 1-13.
- 1106 Peltre, C., Christensen, B.T., Dragon, S., Icard, C., Katterer, T., Houot, S., 2012. RothC
1107 simulation of carbon accumulation in soil after repeated application of widely different
1108 organic amendments. *Soil Biol Biochem* 52, 49-60.
- 1109 Petersen, S.O., Lind, A.M., Sommer, S.G., 1998. Nitrogen and organic matter losses during
1110 storage of cattle and pig manure. *J Agr Sci* 130, 69-79.
- 1111 Petersen, S.O., Sommer, S.G., 2011. Ammonia and nitrous oxide interactions: Roles of
1112 manure organic matter management. *Anim Feed Sci Tech* 166-167, 503-513.
- 1113 Pfister, C., 1995. Geschichte des Kantons Bern seit 1798. Band IV. Im Strom der
1114 Modernisierung., Bevölkerung, Wirtschaft und Umwelt 1700–1914, Bern.

1115 Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., McNair, M., Crist, S.,
1116 Shpritz, L., Fitton, L., Saffouri, R., Blair, R., 1995. Environmental and economic costs
1117 of soil erosion and conservation benefits. *Science* 267, 1117-1123.

1118 Poeplau, C., Don, A., 2015. Carbon sequestration in agricultural soils via cultivation of cover
1119 crops – A meta-analysis. *Agriculture, Ecosystems & Environment* 200, 33-41.

1120 Powlson, D.S., Bhogal, A., Chambers, B.J., Coleman, K., Macdonald, A.J., Goulding,
1121 K.W.T., Whitmore, A.P., 2012. The potential to increase soil carbon stocks through
1122 reduced tillage or organic material additions in England and Wales: A case study.
1123 *Agriculture, Ecosystems & Environment* 146, 23-33.

1124 Powlson, D.S., Stirling, C.M., Jat, M.L., Gerard, B.G., Palm, C.A., Sanchez, P.A., Cassman,
1125 K.G., 2014. Limited potential of no-till agriculture for climate change mitigation.
1126 *Nature Climate Change* 4, 678-683.

1127 Prechsl, U.E., Wittwer, R., van der Heijden, M.G.A., Lüscher, G., Jeanneret, P., Nemecek, T.,
1128 2017. Assessing the environmental impacts of cropping systems and cover crops: Life
1129 cycle assessment of FAST, a long-term arable farming field experiment. *Agricultural
1130 Systems* 157, 39-50.

1131 Sans, F.X., Berner, A., Armengot, L., Mader, P., 2011. Tillage effects on weed communities
1132 in an organic winter wheat-sunflower-spelt cropping sequence. *Weed Res* 51, 413-421.

1133 SAS, 2014. SAS System for Windows, version 9.4 TS Level 1M2. SAS Institute Inc., Cary,
1134 NC, USA

1135 Senapati, N., Chabbi, A., Giostri, A.F., Yeluripati, J.B., Smith, P., 2016. Modelling nitrous
1136 oxide emissions from mown-grass and grain-cropping systems: Testing and sensitivity

1137 analysis of DailyDayCent using high frequency measurements. *Sci. Total Environ.* 572,
1138 955-977.

1139 Seufert, V., Ramankutty, N., Foley, J.A., 2012. Comparing the yields of organic and
1140 conventional agriculture. *Nature* 485, 229-232.

1141 Siegrist, S., Schaub, D., Pfiffner, L., Mader, P., 1998. Does organic agriculture reduce soil
1142 erodibility? The results of a long-term field study on loess in Switzerland. *Agric.*
1143 *Ecosyst. Environ.* 69, 253-264.

1144 Six, J., Elliott, E.T., Paustian, K., 2000. Soil macroaggregate turnover and microaggregate
1145 formation: a mechanism for C sequestration under no-tillage agriculture. *Soil Biol*
1146 *Biochem* 32, 2099-2103.

1147 Six, J., Ogle, S.M., Jay breidt, F., Conant, R.T., Mosier, A.R., Paustian, K., 2004. The
1148 potential to mitigate global warming with no-tillage management is only realized when
1149 practised in the long term. *Global Change Biology* 10, 155-160.

1150 Six, J., Paustian, K., 2014. Aggregate-associated soil organic matter as an ecosystem property
1151 and a measurement tool. *Soil Biol Biochem* 68, A4-A9.

1152 Skinner, C., Gattinger, A., Muller, A., Mader, P., Fließbach, A., Stolze, M., Ruser, R., Niggli,
1153 U., 2014. Greenhouse gas fluxes from agricultural soils under organic and non-organic
1154 management--a global meta-analysis. *Sci Total Environ* 468-469, 553-563.

1155 Smith, K.A., Dobbie, K.E., 2001. The impact of sampling frequency and sampling times on
1156 chamber-based measurements of N₂O emissions from fertilized soils. *Global Change*
1157 *Biology* 7, 933-945.

1158 Smith, K.A., Dobbie, K.E., Ball, B.C., Bakken, L.R., Sitaula, B.K., Hansen, S., Brumme, R.,
1159 Borken, W., Christensen, S., Priemé, A., Fowler, D., Macdonald, J.A., Skiba, U.,
1160 Klemedtsson, L., Kasimir-Klemedtsson, A., Degórska, A., Orlanski, P., 2000. Oxidation
1161 of atmospheric methane in Northern European soils, comparison with other ecosystems,
1162 and uncertainties in the global terrestrial sink. *Global Change Biology* 6, 791-803.

1163 Smith, P., 2012. Agricultural greenhouse gas mitigation potential globally, in Europe and in
1164 the UK: what have we learnt in the last 20 years? *Global Change Biology* 18, 35-43.

1165 Smith, P., 2013. Delivering food security without increasing pressure on land Pete Smith.
1166 *Glob Food Secur-Agr* 2, 18-23.

1167 Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E.A., Haberl, H.,
1168 Harper, R., House, J., Jafari, M., Masera, O., Mbow, C., Ravindranath, N.H., Rice,
1169 C.W., Robledo Abad, C., Romanovskaya, A., Sperling, F., Tubiello, F., 2014.
1170 *Agriculture, Forestry and Other Land Use (AFOLU)*. In: Edenhofer, O., Pichs-Madruga,
1171 R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S.,
1172 Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel,
1173 T., Minx, J.C. (Eds.), *Climate Change 2014: Mitigation of Climate Change*.
1174 *Contribution of Working Group III to the Fifth Assessment Report of the*
1175 *Intergovernmental Panel on Climate Change* Cambridge University Press, Cambridge,
1176 United Kingdom and New York, NY, USA.

1177 Tilman, D., Balzer, C., Hill, J., Befort, B.L., 2011. Global food demand and the sustainable
1178 intensification of agriculture. *Proc Natl Acad Sci U S A* 108, 20260-20264.

1179 Tubiello, F.N., Salvatore, M., Rossi, S., Ferrara, A., Fitton, N., Smith, P., 2013. The
1180 FAOSTAT database of greenhouse gas emissions from agriculture. *Environmental*
1181 *Research Letters* 8, 1-11.

1182 van Kessel, C., Venterea, R., Six, J., Adviento-Borbe, M.A., Linnquist, B., van Groenigen,
1183 K.J., 2013. Climate, duration, and N placement determine N₂O emissions in reduced
1184 tillage systems: a meta-analysis. *Glob Chang Biol* 19, 33-44.

1185 Venterea, R., Halvorson, A., Newell Kitchen, Mark A Liebig, Michel A Cavigelli, Stephen J
1186 Del Grosso, Peter P Motavalli, Kelly A Nelson, Kurt A Spokas, Bhupinder Pal Singh,
1187 Catherine E Stewart, Andry Ranaivoson, Jeffrey Strock, Collins, H., 2012. Challenges
1188 and opportunities for mitigating nitrous oxide emissions from fertilized cropping
1189 systems. *Front Ecol Environ*.

1190 Venterea, R.T., 2007. Nitrite-driven nitrous oxide production under aerobic soil conditions:
1191 kinetics and biochemical controls. *Global Change Biology* 13, 1798-1809.

1192 Wallach, D., Makowski, D., Waddington, J., 2014. Working with dynamic crop models:
1193 Methods, tools and examples for agriculture and environment. 2nd Edition. . Elsevier
1194 Science. , Oxford, UK.

1195 West, T.O., Marland, G., 2002. A synthesis of carbon sequestration, carbon emissions, and
1196 net carbon flux in agriculture: comparing tillage practices in the United States. *Agr*
1197 *Ecosyst Environ* 91, 217-232.

1198 Wittwer, R.A., Dorn, B., Jossi, W., van der Heijden, M.G., 2017. Cover crops support
1199 ecological intensification of arable cropping systems. *Sci Rep* 7, 41911.

- 1200 Wosten, J.H.M., Lilly, A., Nemes, A., Le Bas, C., 1999. Development and use of a database
1201 of hydraulic properties of European soils. *Geoderma* 90, 169-185.
- 1202 Zhu, X., Burger, M., Doane, T.A., Horwath, W.R., 2013. Ammonia oxidation pathways and
1203 nitrifier denitrification are significant sources of N₂O and NO under low oxygen
1204 availability. *Proc. Natl. Acad. Sci. U. S. A.* 110, 6328-6333.

Table1[Click here to download Tables: Table1.docx](#)**Table 1** Soil and climate characteristics of Swiss long-term field experimental (LTE) sites.

LTE	Location	Coordinates	Soil type	Sand (%)	Clay (%)	Soil bulk density (g m ⁻³)	Soil C (%)	Soil pH	Mean annual temperature (°C)	Mean annual precipitation (mm)
P29C	Changins (Clay)	46°24'N, 06°14'E	Calcaric Cambisol	16	46	1.17	2.92	6.2	10.2	999
	(Loam)			30	26	1.44	1.34	6.8		
DOK	Therwil near Basel	47°30'N, 7°3 3'E	Haplic Luvisol	12	16	1.22	1.66	6.3	9.5	791
FAST	Reckenholz near Zurich	47°26'N, 8°31'E	Calcareous Cambisol	43	23	1.48	1.44	7.3	9.4	1054
Frick	Frick	47°30'N, 8°01'E	Stagnic Eutric Cambisol	22	45	1.58	2.20	7.1	8.9	1000

Table 2 Description of management factors and levels studied in long-term field experiments (LTEs) in Switzerland. FYM refers to farm yard manure. LU refers to livestock unit.

LTE (duration)	Management factors	Levels	Description	Total N input kg N ha ⁻¹	Abbreviation	No. treatments	Reference
P29C (1969-2013)	Tillage	Plough	Plough to 25 cm	90 - 168	PL	8	(Büchi <i>et al.</i> , 2017a; Büchi <i>et al.</i> , 2017b)
		Chisel until 2007, then no-tillage	Chisel to 25 cm, then 0 tillage	90 - 168	CH		
		Reduced tillage - cultivator	Cultivator to 10 to 15 cm	90 - 168	CL		
		Reduce tillage - rototiller	Rototiller or rotary harrow to 8 cm	90 - 168	RO		
DOK (1977-2013)	Farming system	Control	Unfertilized	0	N	18	(Siegrist <i>et al.</i> , 1998; Fließbach <i>et al.</i> , 2000; Mäder <i>et al.</i> , 2000; Mäder <i>et al.</i> , 2002; Mäder <i>et al.</i> , 2006; Esperschütz <i>et al.</i> , 2007; Leifeld <i>et al.</i> , 2009)
		Bio-Organic	FYM and slurry at a level of 1.2, later at 1.4 LU ha ⁻¹ yr ⁻¹ ; 50%/100% fertilization	47/93	O1/O2		
		Conventional	Mixed FYM and slurry at a level of 1.2, later at 1.4 LU ha ⁻¹ yr ⁻¹ + mineral NPK; 50%/100% fertilization	75/149	K1 /K2		
	Mineral	Mineral NPK according to Swiss guidelines	125	M2**			
	Crop rotation		Three crops are planted in each system simultaneously every year		A, B, C		
FAST (2009-2013)	Farming system	Organic	Slurry at a level of 1.4 LU ha ⁻¹ yr ⁻¹	119 - 132	ORG	16	(Prechsl <i>et al.</i> , 2017; Wittwer <i>et al.</i> , 2017)
		Conventional	Mineral fertilizer	90 - 110	CON		
	Tillage	Intensive tillage	Mouldboard plough to 20 cm		IT		
		No-tillage in CON; Reduced tillage in ORG	Crops were seeded directly into the soil Rotary harrow before wheat and rotary harrow before maize, both to 5 cm		NT and RT		
	Cover crop	Legume	Common vetch (<i>Vicia sativa</i>) before winter wheat, hairy vetch (<i>Vicia villosa</i>) before maize		VETCH		
		Non-legume	White mustard (<i>Sinapis alba</i>)		MUST		
Mixture		Mixture of legume and non-legume spp.*		MIX			
	Control	Fallow – natural vegetation		CONT			
FRICK (2002-2013)	Tillage	Conventional	Mouldboard plough to 15 cm followed by rotary harrow to 5 cm		CT	4	(Bernier <i>et al.</i> , 2008; Krauss <i>et al.</i> , 2010; Sans <i>et al.</i> , 2011; Gadermaier <i>et al.</i> , 2012; Kuntz <i>et al.</i> , 2013; Peigné <i>et al.</i> , 2013; Armengot <i>et al.</i> , 2015; Krauss <i>et al.</i> , 2017)
		Reduced	Chisel plough to 15 cm followed by rotary harrow 5 cm		RT		
	Fertilization	Manure compost supplemented with slurry	Composted farmyard manure and slurry at a level of 1.4 LU ha ⁻¹ yr ⁻¹	~90	MC		
		Only slurry	Slurry alone at a level of 1.4 LU ha ⁻¹ yr ⁻¹	~ 85	SL		

*containing 20% phacelia (*Phacelia tanacetifolia*), 30% Persian clover (*Trifolium resupinatum*) and 50% berseem clover (*Trifolium alexandrinum*) before winter wheat and a self-designed mixture containing 15% phacelia, 52% hairy vetch, 32% buckwheat (*Fagopyrum esculentum* Moench) and 1% camelina (*Camelina sativa*) before maize.

** unfertilized during the first crop rotation (1978-1984).

Table3[Click here to download Tables: Table3.docx](#)

Table 3 Mean (\pm standard deviation) measured and modeled crop productivity by crop across all treatments, years and sites, and error associated with model predictions. N, RMSE, rRMSE, r^2 and WI refer to the number of observations, root mean squared error, relative root mean squared error, coefficient of determination and Willmott's index calculated for each simulated crop across all treatments, years and sites.

Crop	Measured	Modeled	N	RMSE	rRMSE	r^2	WI
	productivity (g C m^{-2})			(g C m^{-2})			
Winter wheat	206 \pm 56	207 \pm 71	1032	57	0.27	0.39	0.78
Spring wheat	130 \pm 35	119 \pm 29	40	25	0.20	0.55	0.82
Silage maize	694 \pm 156	689 \pm 191	88	124	0.18	0.58	0.80
Winter barley	172 \pm 48	173 \pm 36	96	46	0.27	0.16	0.64
Rapeseed	134 \pm 34	156 \pm 32	150	30	0.23	0.66	0.80
Beetroot	245 \pm 182	270 \pm 151	108	124	0.50	0.55	0.85
Grain Maize	332 \pm 102	340 \pm 94	176	51	0.15	0.76	0.93
Potatoes	312 \pm 146	357 \pm 70	168	127	0.41	0.34	0.64
White cabbage	108 \pm 32	111 \pm 4	24	33	0.30	0.24	0.13
Sunflower	184 \pm 51	210 \pm 50	20	32	0.17	0.84	0.89
Spelt	129 \pm 39	129 \pm 23	32	48	0.37	0.07	0.21
Winter peas	87 \pm 3	52	4	35	0.40	-	0.10
Soybeans	143 \pm 48	154 \pm 50	144	35	0.25	0.58	0.86
Field beans	193 \pm 42	169 \pm 13	32	42	0.22	0.33	0.55
Mixture	78 \pm 13	62 \pm 13	16	20	0.26	0.37	0.56
Common vetch	88 \pm 24	80 \pm 19	16	11	0.13	0.91	0.93
White mustard	85 \pm 31	71 \pm 22	16	18	0.21	0.91	0.88
Fodder intercrop	157 \pm 81	169 \pm 51	60	42	0.27	0.83	0.89
Grass-clover mixture	478 \pm 134	495 \pm 85	392	93	0.19	0.53	0.80

Table 4 Analysis of variance for the effects of management practices and their interactions on soil greenhouse gas emissions and yield at each long-term experimental (LTE) site. NSGHGE refers to net soil GHG emissions. For DOK, two independent analyses were conducted: a) we excluded unfertilized (N) and mineral (M2) treatments in order to include the level of fertilization as a fixed factor in the model statement; b) treatments at 50% fertilization (i.e., K1 and O1) were excluded, in order to compare all farming systems at their typical fertilization levels.

LTE	Factors and their interactions	df	CO ₂	N ₂ O	CH ₄ oxidation	NSGHGE	Yield
P29C	Tillage	3	0.32	<0.001	0.06	0.16	<0.01
	Soil texture	1	0.14	<0.001	<0.001	<0.05	<0.001
	Tillage x soil texture	3	0.98	0.33	0.86	0.97	0.97
DOK (excluding unfertilized and mineral treatments)	Farming system	1	0.43	<0.001	<0.001	0.53	<0.05
	Level of fertilization	1	0.26	<0.001	<0.001	0.35	<0.01
	Rotation	2	0.47	0.40	<0.001	0.38	0.44
	Farming system x level of fertilization	1	0.90	<0.001	<0.05	0.68	0.97
	Farming system x rotation	2	1.00	0.13	<0.01	0.97	0.98
	Level of fertilization x rotation	2	0.99	0.92	0.9953	0.99	0.98
	Farming system x level of fertilization x rotation	2	1.00	0.80	<0.01	1.00	0.93
DOK (excluding 50% fertilization level treatments)	Farming system	3	<0.05	<0.001	<0.001	0.66	<0.001
	Rotation	2	0.46	0.22	<0.001	0.37	0.56
	Farming system x rotation	6	1	0.70	<0.001	1	1.00
FAST	Farming system	1	<0.001	<0.001	<0.001	<0.001	<0.001
	Tillage	1	<0.001	<0.001	<0.001	<0.001	<0.001
	Cover cropping	3	0.35	<0.001	<0.001	0.52	<0.001
	Farming system x tillage	1	<0.001	<0.001	<0.001	<0.01	<0.001
	Farming system x cover cropping	3	0.95	0.85	<0.001	0.94	0.34
	Tillage x cover cropping	3	0.83	0.97	<0.001	0.79	0.09
	Farming system x tillage x cover cropping	3	0.97	0.93	<0.001	0.96	0.88
Frick	Tillage	1	0.40	0.80	<0.01	0.40	<0.05
	Fertilization	1	<0.05	<0.001	0.13	<0.01	0.15
	Tillage x fertilization	1	0.99	0.89	0.85	0.98	0.86

Table 5 Greenhouse (GHG) emissions, changes in soil organic C (SOC) content, total N and C inputs and yield calculated for the main treatments at four long-term experimental (LTE) sites over 30 years. Standard errors (SE) were computed by linear mixed effects models in SAS. Positive change in SOC indicates SOC sequestration, while a negative change indicates a decrease in SOC. Positive values of soil CH₄ oxidation refer to CH₄ uptake. Positive values for net soil GHG emissions (NSGHGE) denote net GHG source, while negative values denote a net sink for GHG emissions. GHGI refers to GHG intensity.

LTE	Treatment		N ₂ O	N inputs*	N ₂ O proportion**	Δ SOC	C inputs***	CO ₂	CH ₄ oxidation	NSGHGE	Yield****	GHGI
			kg N ha ⁻¹ y ⁻¹ ± SE	kg N ha ⁻¹ y ⁻¹ ± SD	%	g C m ⁻² y ⁻¹ ± SE	g C m ⁻² y ⁻¹ ± SD	g C m ⁻² y ⁻¹ ± SE	g CH ₄ m ⁻² y ⁻¹ ± SE	kg CO ₂ eq ha ⁻¹ yr ⁻¹ ± SE	kg ha ⁻¹ yr ⁻¹ ± SE	kg CO ₂ eq kg ⁻¹ yield ± SE
P29C‡	Clay	CL	2.06 ± 0.08	141.59 ± 29.56	1.45	-19.90 ± 15.83	184 ± 148	730 ± 581	0.148 ± 0.002	1545 ± 594	4365 ± 351	0.35 ± 0.000
		CH	2.09 ± 0.08	141.56 ± 29.57	1.48	-19.21 ± 15.83	180 ± 145	704 ± 581	0.148 ± 0.002	1534 ± 594	4322 ± 351	0.35 ± 0.000
		PL	2.16 ± 0.08	141.53 ± 29.57	1.53	-25.49 ± 15.83	179 ± 144	934 ± 581	0.148 ± 0.002	1792 ± 594	4339 ± 351	0.41 ± 0.000
		RT	1.92 ± 0.08	141.48 ± 29.60	1.36	-12.84 ± 15.83	187 ± 140	471 ± 581	0.147 ± 0.002	1230 ± 594	4385 ± 351	0.28 ± 0.000
	Loam	CL	1.83 ± 0.08	141.50 ± 29.58	1.30	-14.11 ± 15.83	172 ± 138	518 ± 581	0.189 ± 0.002	1228 ± 594	4452 ± 351	0.28 ± 0.000
		CH	1.88 ± 0.08	141.50 ± 29.59	1.33	-14.17 ± 15.83	168 ± 136	520 ± 581	0.190 ± 0.002	1249 ± 594	4402 ± 351	0.28 ± 0.000
		PL	1.91 ± 0.08	141.47 ± 29.59	1.35	-16.86 ± 15.83	168 ± 135	618 ± 581	0.190 ± 0.002	1361 ± 594	4418 ± 351	0.31 ± 0.000
		RT	1.75 ± 0.08	141.41 ± 29.60	1.24	-8.57 ± 15.83	175 ± 131	314 ± 581	0.189 ± 0.002	989 ± 594	4484 ± 351	0.22 ± 0.000
DOK	K1	1.66 ± 0.07	134.50 ± 42.89	1.23	-12.83 ± 7.31	244 ± 223	471 ± 268	0.207 ± 0.003	1103 ± 264	8799 ± 549	0.13 ± 0.001	
	K2	2.81 ± 0.07	198.22 ± 70.09	1.42	-6.42 ± 7.31	313 ± 264	235 ± 268	0.205 ± 0.003	1347 ± 264	9907 ± 549	0.14 ± 0.001	
	M2	1.95 ± 0.07	164.03 ± 47.08	1.19	-17.62 ± 7.31	185 ± 203	646 ± 268	0.208 ± 0.003	1402 ± 264	9169 ± 549	0.15 ± 0.001	
	N	0.79 ± 0.07	78.30 ± 49.97	1.01	-24.78 ± 7.31	155 ± 193	908 ± 268	0.205 ± 0.003	1182 ± 264	6049 ± 549	0.20 ± 0.001	
	O1	1.27 ± 0.07	112.65 ± 44.10	1.13	-16.20 ± 7.31	236 ± 224	594 ± 268	0.208 ± 0.003	1064 ± 264	7924 ± 549	0.13 ± 0.001	
	O2	1.94 ± 0.07	150.46 ± 64.33	1.29	-11.10 ± 7.31	306 ± 266	407 ± 268	0.208 ± 0.003	1156 ± 264	9009 ± 549	0.13 ± 0.001	
FAST	CON - IT	CONT	1.36 ± 0.06	131.02 ± 79.25	1.04	-23.98 ± 13.93	191 ± 182	879 ± 511	0.171 ± 0.003	1397 ± 511	5048 ± 465	0.35 ± 0.002
		MUST	1.38 ± 0.06	131.13 ± 79.46	1.05	-21.53 ± 13.93	208 ± 200	789 ± 511	0.176 ± 0.003	1314 ± 511	5255 ± 465	0.31 ± 0.002
		MIX	1.35 ± 0.06	131.35 ± 79.67	1.03	-20.28 ± 13.93	210 ± 204	744 ± 511	0.176 ± 0.003	1258 ± 511	5292 ± 465	0.30 ± 0.002
		VETCH	1.48 ± 0.06	138.03 ± 75.74	1.07	-15.55 ± 13.93	243 ± 252	570 ± 511	0.176 ± 0.003	1136 ± 511	5787 ± 465	0.25 ± 0.002
	CON - NT	CONT	1.05 ± 0.06	131.04 ± 79.91	0.80	-5.75 ± 13.93	184 ± 163	211 ± 511	0.214 ± 0.003	590 ± 511	4829 ± 465	0.15 ± 0.002
		MUST	1.07 ± 0.06	131.08 ± 79.96	0.82	-8.74 ± 13.93	197 ± 172	320 ± 511	0.167 ± 0.003	721 ± 511	4832 ± 465	0.19 ± 0.002
		MIX	1.08 ± 0.06	131.03 ± 79.87	0.83	-8.54 ± 13.93	198 ± 173	313 ± 511	0.167 ± 0.003	718 ± 511	4816 ± 465	0.19 ± 0.002
		VETCH	1.17 ± 0.06	138.04 ± 76.43	0.85	-6.20 ± 13.93	217 ± 195	227 ± 511	0.166 ± 0.003	667 ± 511	5087 ± 465	0.16 ± 0.002
	ORG - IT	CONT	1.40 ± 0.06	135.48 ± 77.25	1.03	-11.67 ± 13.93	237 ± 211	428 ± 511	0.171 ± 0.003	962 ± 511	4344 ± 465	0.28 ± 0.002
		MUST	1.45 ± 0.06	134.60 ± 75.70	1.08	-7.72 ± 13.93	260 ± 235	283 ± 511	0.176 ± 0.003	837 ± 511	4694 ± 465	0.22 ± 0.002
		MIX	1.45 ± 0.06	134.60 ± 75.66	1.08	-6.56 ± 13.93	265 ± 243	241 ± 511	0.176 ± 0.003	794 ± 511	4700 ± 465	0.21 ± 0.002
		VETCH	1.53 ± 0.06	141.32 ± 72.94	1.09	-1.98 ± 13.93	297 ± 291	73 ± 511	0.177 ± 0.003	662 ± 511	5251 ± 465	0.16 ± 0.002
	ORG - RT	CONT	1.31 ± 0.06	130.12 ± 69.07	1.01	24.04 ± 13.93	255 ± 217	-882 ± 511	0.171 ± 0.003	-384 ± 511	3310 ± 465	-0.15 ± 0.002
		MUST	1.39 ± 0.06	129.94 ± 68.61	1.07	21.94 ± 13.93	280 ± 239	-805 ± 511	0.176 ± 0.003	-275 ± 511	3450 ± 465	-0.10 ± 0.002
		MIX	1.35 ± 0.06	129.98 ± 68.80	1.04	22.76 ± 13.93	284 ± 246	-834 ± 511	0.175 ± 0.003	-322 ± 511	3497 ± 465	-0.11 ± 0.002
		VETCH	1.43 ± 0.06	136.87 ± 66.48	1.05	31.13 ± 13.93	328 ± 312	-1142 ± 511	0.175 ± 0.003	-594 ± 511	3939 ± 465	-0.19 ± 0.002
Frick	CT	MC	1.86 ± 0.10	107.35 ± 44.21	1.73	-4.36 ± 22.14	206 ± 96	160 ± 812	0.168 ± 0.003	886 ± 797	7142 ± 762	0.12 ± 0.002
		SL	2.14 ± 0.10	110.18 ± 47.16	1.94	-22.05 ± 22.14	191 ± 99	808 ± 812	0.168 ± 0.003	1654 ± 797	7345 ± 762	0.23 ± 0.002

RT	MC	1.86 ± 0.10	105.95 ± 42.11	1.76	1.82 ± 22.14	226 ± 104	-67 ± 812	0.169 ± 0.003	661 ± 797	7428 ± 762	0.09 ± 0.002	* Total N inputs
	SL	2.16 ± 0.10	108.82 ± 44.33	1.98	-16.12 ± 22.14	209 ± 106	591 ± 812	0.169 ± 0.003	1443 ± 797	7586 ± 762	0.19 ± 0.002	

comprise of organic and mineral fertilizers, biological N fixation, and atmospheric deposition.

** Refers to a proportion of total N inputs lost as soil N₂O emissions.

*** Total C inputs comprise of plant litter (above-, belowground) and organic fertilizers.

**** Yield comprises of harvested grain, tuber, vegetable and forages such as silage maize and grass-clover.

‡ Due to a lack of plot-specific soil properties, only one simulation was run per treatment at this LTE site.

Table6

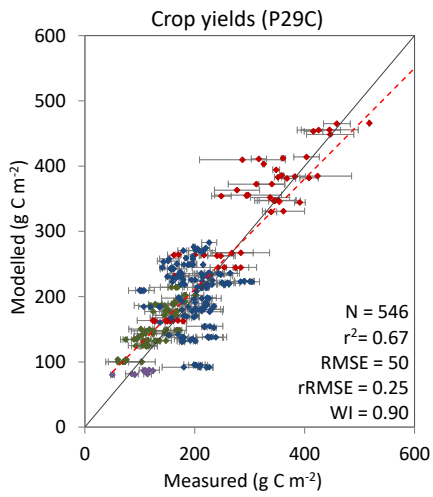
[Click here to download Tables: Table6.docx](#)

Table 6 Relative (%) and absolute (kg CO₂eq ha⁻¹ or kg CO₂eq kg⁻¹) changes in annual soil GHG emissions in response to studied soil management combinations compared with the baseline treatment in four long-term experiments (LTEs). GHGI refers to GHG intensity. The baseline represented by the treatment with the highest soil GHG emissions on an area basis at each LTE site is denoted by underlining. Mean differences (\pm standard error) relative to the baseline were calculated as differences of least squares means by linear mixed effects models in SAS.

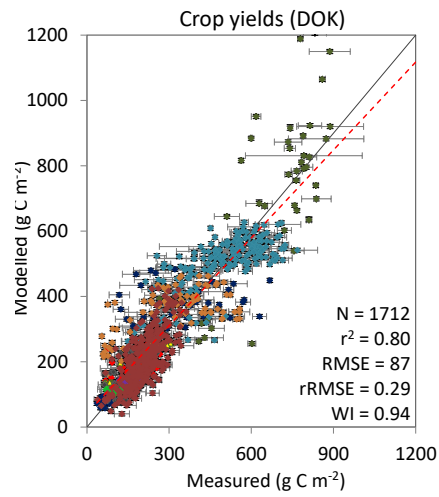
LTE	Treatment		NSGHGE		CO ₂		N ₂ O		GHGI	
			kg CO ₂ eq ha ⁻¹ yr ⁻¹	%	kg CO ₂ eq ha ⁻¹ yr ⁻¹	%	kg CO ₂ eq ha ⁻¹ yr ⁻¹	%	kg CO ₂ eq kg ⁻¹ yield	%
P29C	Clay	<u>PL</u>								
		CH	-258 \pm 295	-14	-230 \pm 291	-25	-28 \pm 12	-3	-0.06 \pm 0.000	-14
		CL	-247 \pm 295	-14	-205 \pm 291	-22	-42 \pm 12	-5	-0.06 \pm 0.000	-14
		RT	-563 \pm 295	-31	-464 \pm 291	-50	-99 \pm 12	-11	-0.13 \pm 0.000	-32
	Loam	<u>PL</u>								
		CH	-112 \pm 295	-8	-99 \pm 291	-16	-13 \pm 12	-2	-0.02 \pm 0.000	-8
		CL	-133 \pm 295	-10	-101 \pm 291	-16	-33 \pm 12	-4	-0.03 \pm 0.000	-10
		RT	-372 \pm 295	-27	-304 \pm 291	-49	-68 \pm 12	-9	-0.09 \pm 0.000	-28
DOK	<u>M2</u>									
	K1	-299 \pm 230	-21	-176 \pm 237	-27	-124 \pm 31	-15	-0.03 \pm 0.002	-18	
	K2	-55 \pm 230	-4	-411 \pm 237	-64	355 \pm 31	44	-0.02 \pm 0.002	-11	
	O1	-338 \pm 230	-24	-52 \pm 237	-8	-286 \pm 31	-35	-0.02 \pm 0.002	-12	
	O2	-246 \pm 230	-18	-239 \pm 237	-37	-6 \pm 31	-1	-0.02 \pm 0.002	-16	
	N	-220 \pm 230	-16	262 \pm 237	41	-483 \pm 31	-59	0.04 \pm 0.002	28	
FAST	<u>CON - IT</u>	<u>CONT</u>								
		MUST	-83 \pm 275	-6	-90 \pm 287	-10	8 \pm 24	1	-0.03 \pm 0.003	-10
		MIX	-140 \pm 275	-10	-136 \pm 287	-15	-3 \pm 24	0	-0.05 \pm 0.003	-14
		VETCH	-261 \pm 275	-19	-309 \pm 287	-35	49 \pm 24	9	-0.10 \pm 0.003	-29
	CON - NT	<u>CONT</u>								
		MUST	-807 \pm 275	-58	-668 \pm 287	-76	-127 \pm 24	-22	-0.19 \pm 0.003	-56
		MIX	-677 \pm 275	-48	-559 \pm 287	-64	-119 \pm 24	-21	-0.16 \pm 0.003	-46
		VETCH	-680 \pm 275	-49	-566 \pm 287	-64	-115 \pm 24	-20	-0.16 \pm 0.003	-46
	ORG - IT	<u>CONT</u>								
		MUST	-730 \pm 275	-52	-652 \pm 287	-74	-80 \pm 24	-14	-0.18 \pm 0.003	-53
		MIX	-436 \pm 275	-31	-451 \pm 287	-51	16 \pm 24	3	-0.07 \pm 0.003	-20
		VETCH	-560 \pm 275	-40	-596 \pm 287	-68	38 \pm 24	7	-0.12 \pm 0.003	-36
	ORG - RT	<u>CONT</u>								
		MIX	-603 \pm 275	-43	-639 \pm 287	-73	37 \pm 24	7	-0.13 \pm 0.003	-39
		VETCH	-735 \pm 275	-53	-806 \pm 287	-92	73 \pm 24	13	-0.19 \pm 0.003	-54
		MUST	-1782 \pm 275	-128	-1761 \pm 287	-200	-21 \pm 24	-4	-0.49 \pm 0.003	-142
	<u>CONT</u>									
	MIX	-1672 \pm 275	-120	-1684 \pm 287	-192	13 \pm 24	2	-0.45 \pm 0.003	-129	
	VETCH	-1719 \pm 275	-123	-1714 \pm 287	-195	-4 \pm 24	-1	-0.46 \pm 0.003	-133	
	MUST	-1991 \pm 275	-143	-2021 \pm 287	-230	31 \pm 24	5	-0.53 \pm 0.003	-154	
Frick	<u>CT</u>	<u>SL</u>								
		MC	-768 \pm 363	-46	-649 \pm 373	-80	-119 \pm 25	-13	-0.10 \pm 0.003	-45
	RT	SL	-211 \pm 363	-13	-217 \pm 373	-27	7 \pm 25	1	-0.03 \pm 0.003	-16
		MC	-992 \pm 363	-60	-875 \pm 373	-108	-117 \pm 25	-13	-0.14 \pm 0.003	-60

Figure1

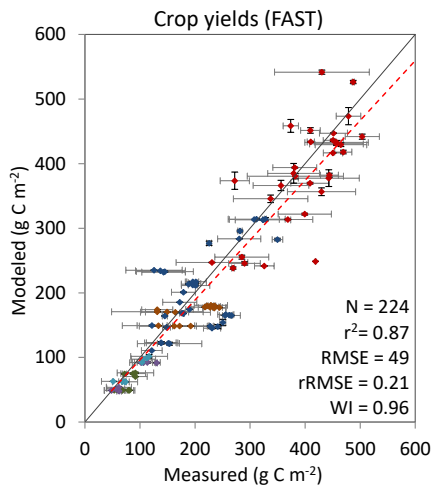
[Click here to download Figure: Figure1.pdf](#)



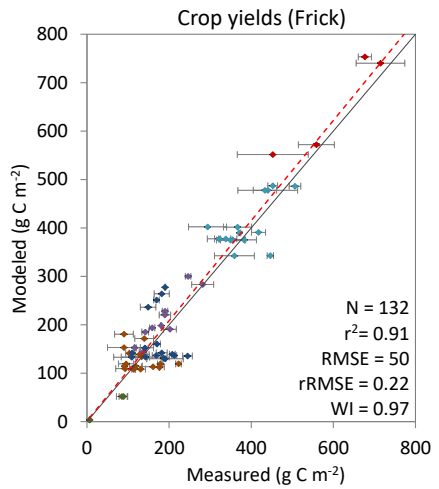
- ◆ Grain maize
- ◆ Winter rapeseed
- ◆ Spring wheat
- ◆ Winter wheat



- ◆ Beetroot
- ◆ Winter barley
- ◆ Silage maize
- ◆ Fodder intercrop
- ◆ Grass-clover
- ◆ Potatoes
- ◆ Soybean
- ◆ White cabbage
- ◆ Summer wheat
- ◆ Winter wheat



- ◆ Field beans
- ◆ Grain maize
- ◆ Phacelia based mixture
- ◆ White mustard
- ◆ Common vetch
- ◆ Winter wheat



- ◆ Spelt
- ◆ Silage maize
- ◆ Winter pea
- ◆ Sunflower
- ◆ Grass-clover
- ◆ Winter wheat

Figure2

[Click here to download Figure: Figure2.pdf](#)

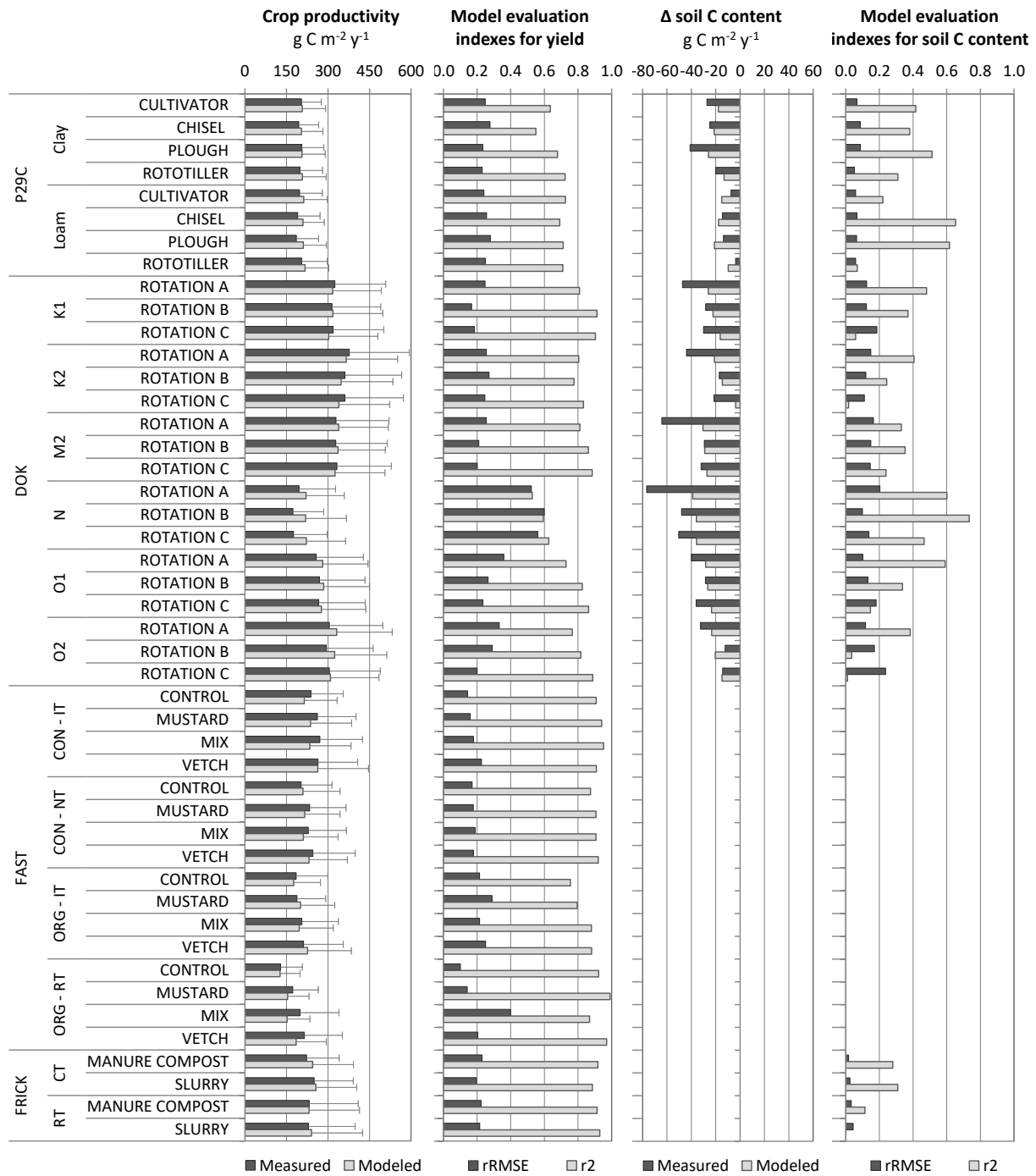


Figure3

[Click here to download Figure: Figure3.pdf](#)

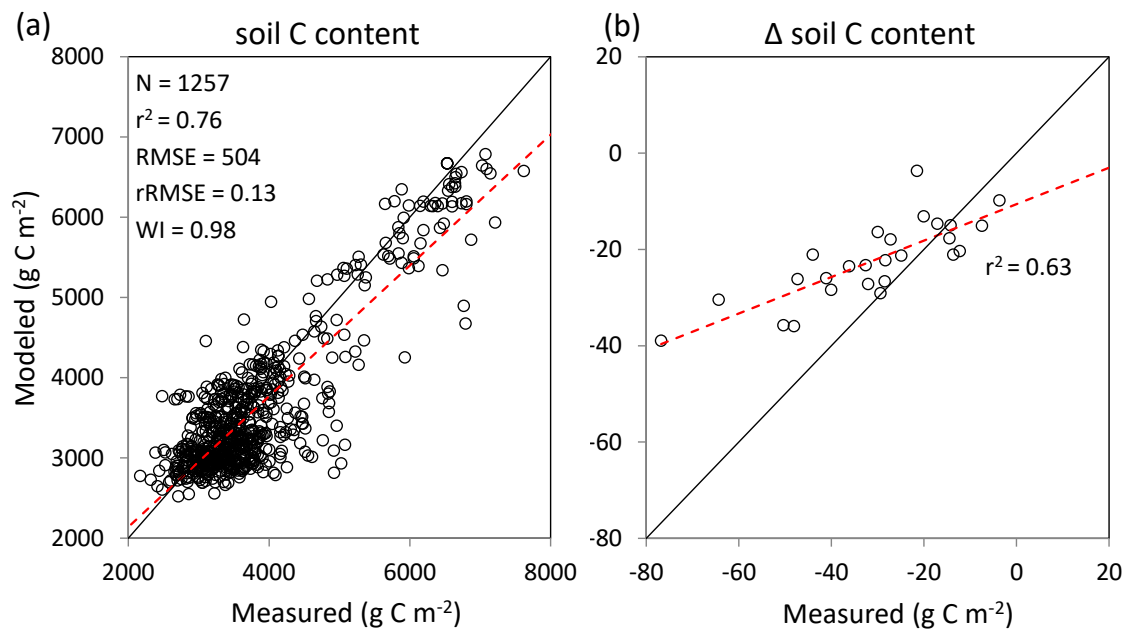


Figure4

[Click here to download Figure: Figure4.pdf](#)

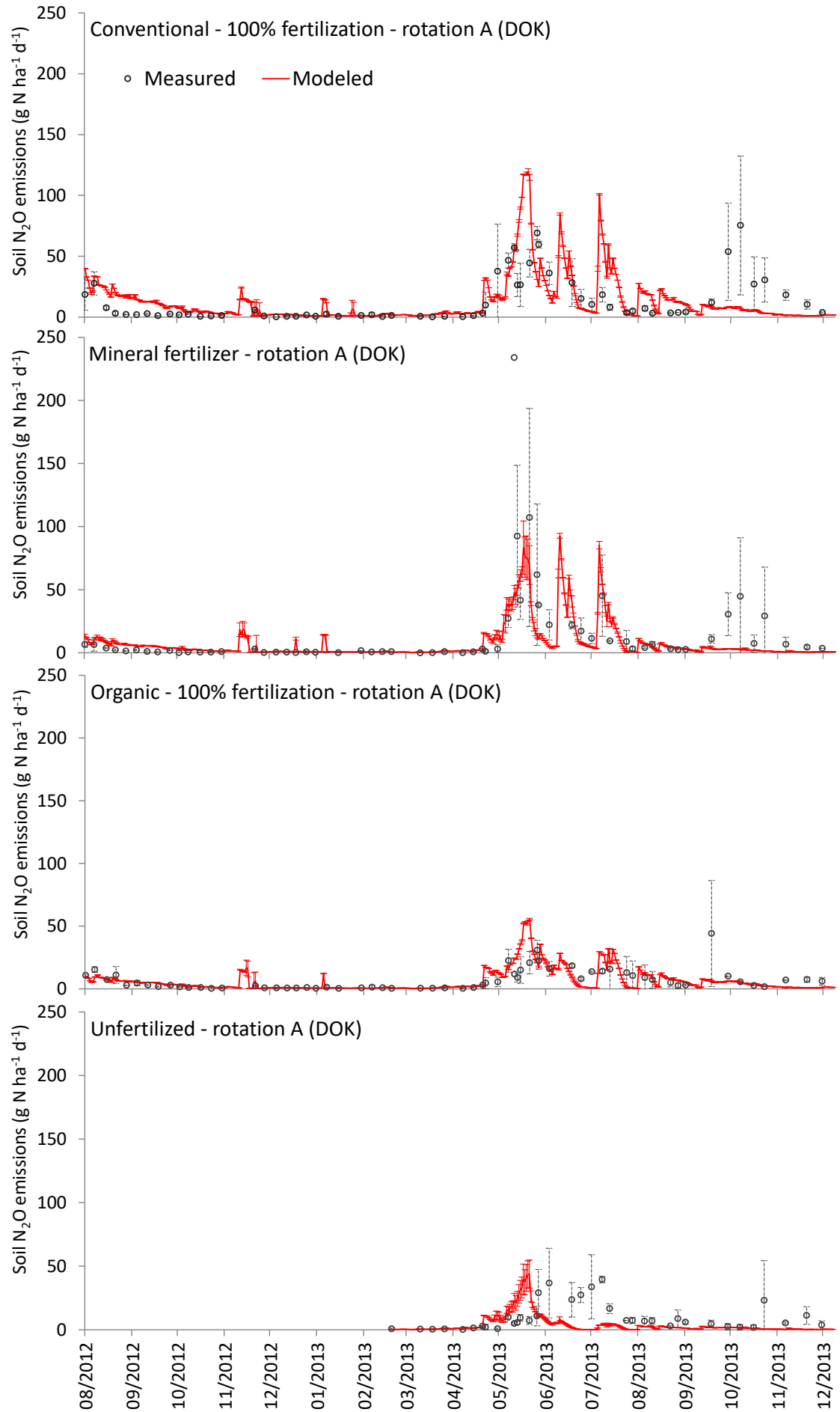
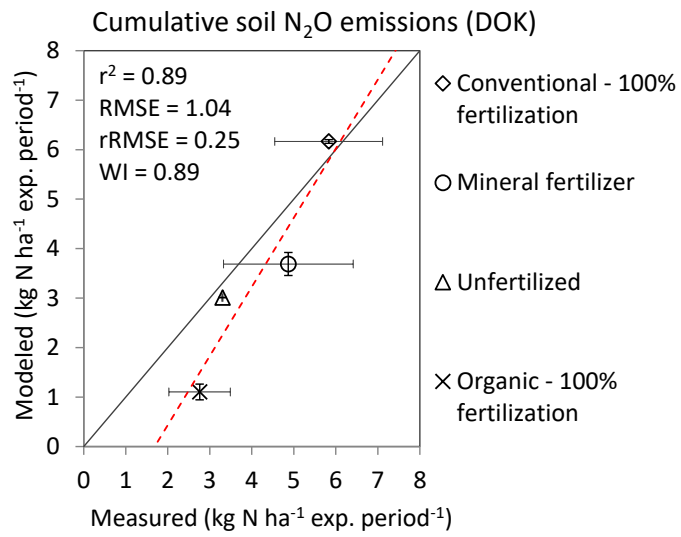


Figure5

[Click here to download Figure: Figure5.pdf](#)



Figure

[Click here to download Figure: Figure6.pdf](#)

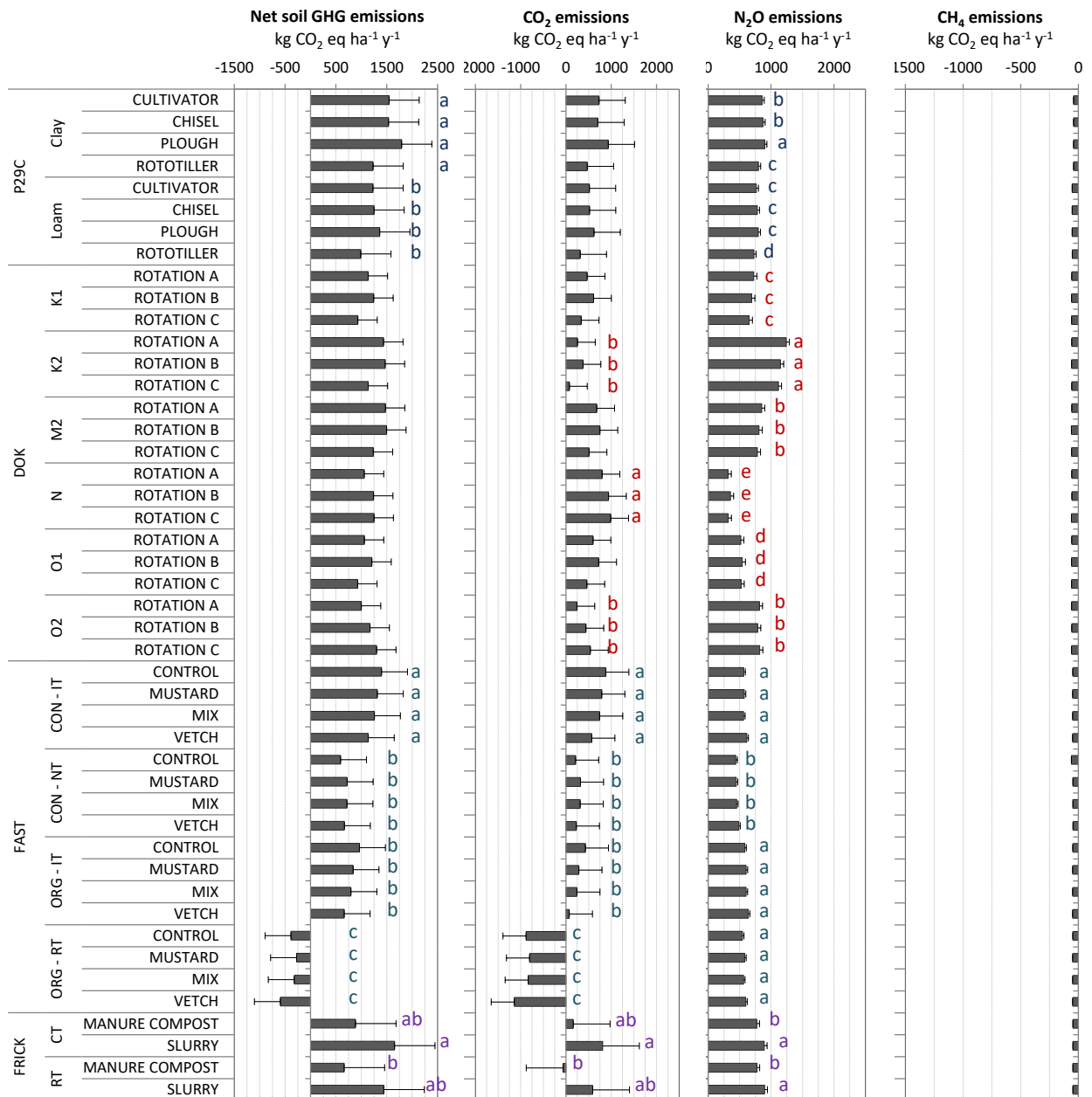


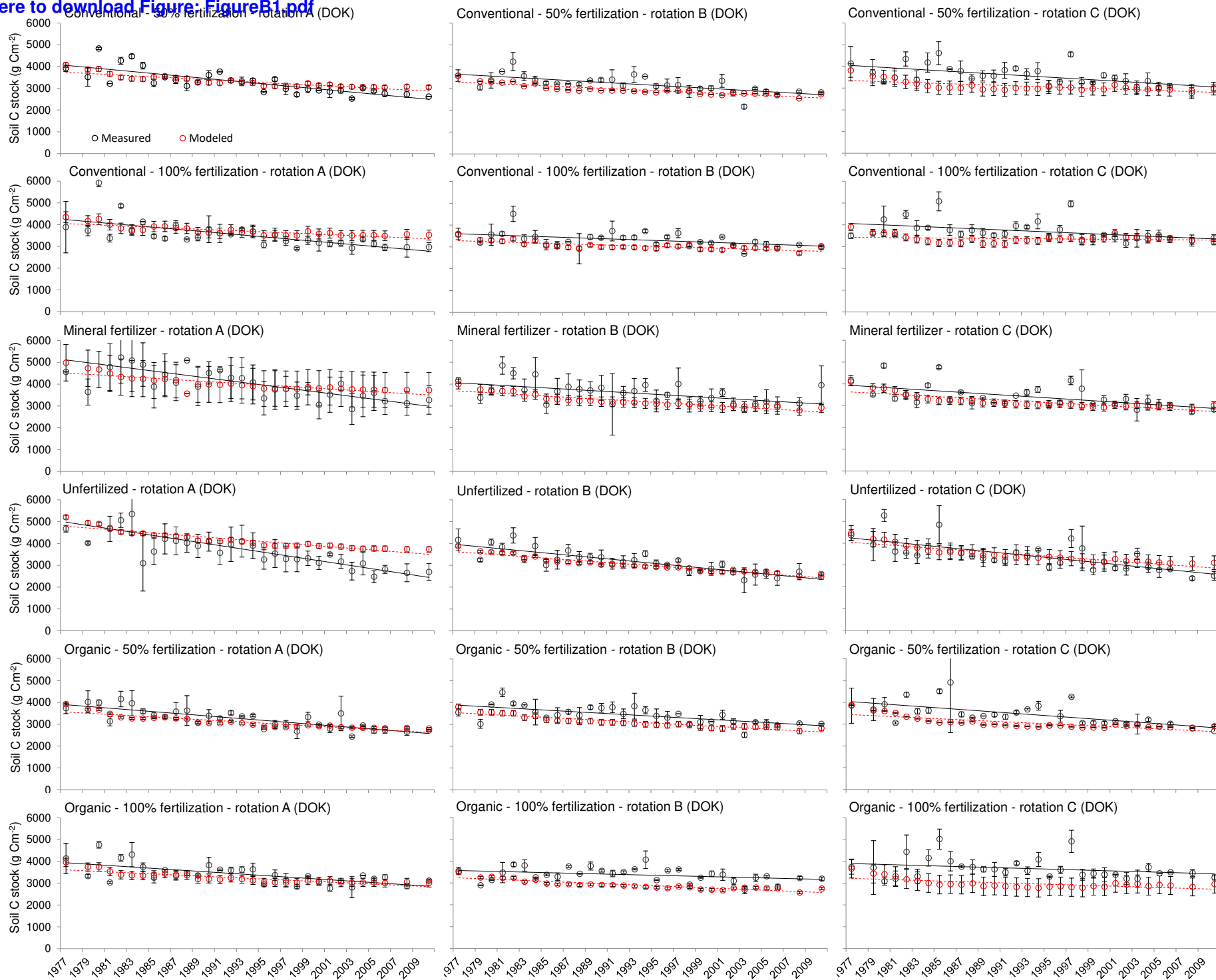
Figure B.1[Click here to download Figure - FigureB1.pdf](#)

Figure B.2

[Click here to download Figure: FigureB2.pdf](#)

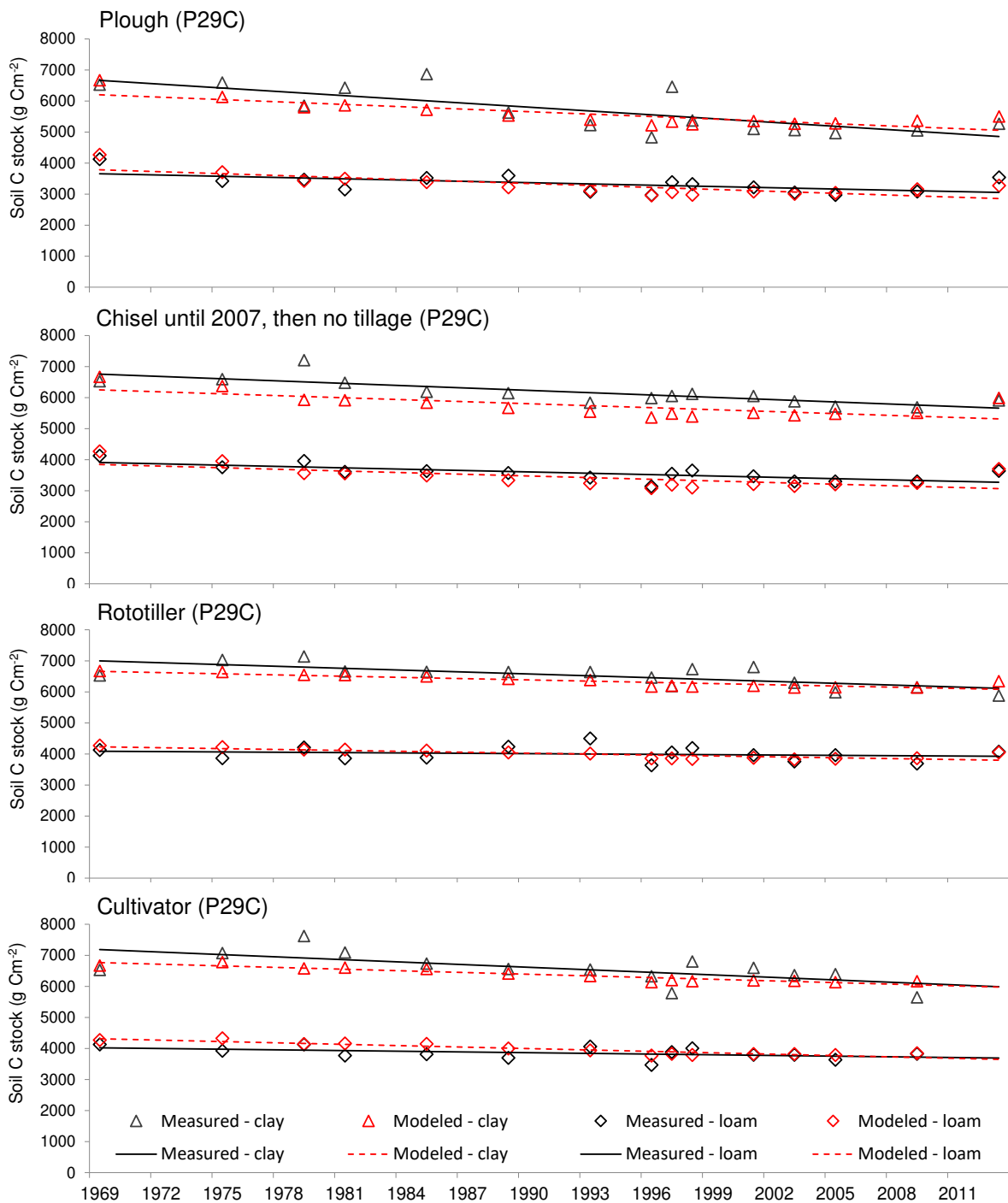


Figure
[Click here to download Figure: FigureB3.pdf](#)

