

1 **Evaluating the Tea Bag Index approach for different management practices in**  
2 **agroecosystems using long-term field experiments in Austria and Sweden**

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24

25 **Abstract**

26 Litter decomposition is an important factor affecting local and global C cycles. It is known that  
27 decomposition through soil microbial activity in ecosystems is mainly influenced by soil type  
28 and climatic conditions. However, for agroecosystems, there remains a need for a better  
29 understanding how management practices influence litter decomposition. This study examined  
30 the effect of different management practices on decomposition at 29 sites with long-term (mean  
31 duration of 38 years) field experiments (LTEs) using the Tea Bag Index (TBI) protocol with  
32 standard litter (Rooibos and Green tea) developed by Keuskamp et al. (2013). The objective  
33 was to determine if the TBI decomposition rate ( $k$ ) and stabilization factor ( $S$ ) are sensitive  
34 enough to detect differences in litter decomposition between management practices, and how  
35 they interact with edaphic factors, crop type and local climatic conditions. Tea bags were buried  
36 and collected after ~90 days in 16 Austrian and 13 Swedish sites. The treatments at Austrian  
37 LTEs focused on mineral and organic fertilizer application, tillage systems and crop residues  
38 management, whereas those in Sweden addressed cropping systems, mineral fertilizer  
39 application and tillage systems. The results showed that in Austria, incorporation of crop  
40 residues and high N fertilizer application increased  $k$ . Minimum tillage had significantly higher  
41  $k$  compared to reduced and conventional tillage. In Sweden, fertilized plots showed higher  $S$   
42 than non-fertilized plots and high N fertilizer had the highest  $k$ . Growing spring cereal lead to  
43 higher  $k$  than forage crops. Random Forest regressions for Austria and Sweden jointly showed  
44 that  $k$  and  $S$  were mainly governed by climatic conditions, which explained more than 70% of  
45 their variation. However, under similar climatic conditions, management practices strongly  
46 influenced decomposition dynamics. It would be appropriate to apply the TBI approach in a  
47 more large-scale network on LTEs for agroecosystems, as an indicator to better assess, which  
48 of the management practices can best promote a higher soil C sink.

49

compared to what?

The next sentences are much clearer because comparisons are made.

so small  $k$  and large  $S$ ? to store C the  $S$  needs to be high and the  $k$  low. or?  
How does the TBI relate to the soil C sink?

## 50 **Introduction**

51 Soil organic carbon (SOC) is one of the most used indicators for soil quality, since its dynamics  
52 is involved in regulating ecosystem functionality through its influences on physical, biological  
53 and chemical soil properties, which are critical for nutrient cycling and soil fertility (Davidson  
54 et al., 2006; Janzen, 2015). Management practices, such as fertilizer application, use of catch-  
55 and cover crops, organic amendments, length of bare fallow periods, permanent surface  
56 protection with perennial crops, tillage practices and aboveground crop residue management,  
57 are impacting SOC balances for agroecosystems (Kätterer and Bolinder, 2022; Sandén et al.,  
58 2018; Paustian et al., 2016).

59 Agricultural soils play a crucial role in the global carbon (C) cycle due to their C sink capacity  
60 (Paustian et al., 2016; Lal, 2004). In this context, improved management practices that maintain  
61 or increase SOC stocks are considered essential in national greenhouse gas reporting systems  
62 (IPCC, 2006), as well as in other international incentives such as the 4 per mille initiative  
63 (Minasny et al., 2017). The SOC balance is dynamic and determined by the difference between  
64 annual C inputs to soil, and the annual C outputs through the decay of existing soil organic  
65 matter and resulting from microbial activity, which is the main contributor to stable SOC  
66 (Tiefenbacher et al., 2021; Bolinder et al., 2007). Management practices have a great impact  
67 on these two factors by affecting either the amount of C inputs or outputs through  
68 decomposition, or both factors simultaneously.

69 Litter decomposition is a complex biogeochemical process controlled by several biotic and  
70 abiotic factors, where the biological activity of decomposers varies with soil properties and is  
71 driven largely by climatic conditions (Daebeler et al., 2022; Bradford et al., 2016; Cleveland  
72 et al., 2014; Gholz et al., 2000). Decomposition and SOC stabilization are long-term processes,  
73 therefore long-term field experiments (LTEs) are among the most useful resources for  
74 quantifying the impact of management practices on litter decomposition, SOC changes, and

75 soil functioning (Sandén et al., 2018; Kätterer et al., 2012; Bergkvist and Öborn, 2011). Within  
76 LTE's, experiments determining litter mass loss over time in situ are important for  
77 understanding SOC dynamics, nutrient cycling and colonization by soil biota under field  
78 conditions. The traditional method that has been used in ecology for more than 50 years consists  
79 of litterbag studies, burying known quantities of various organic materials into the soil, and  
80 retrieving them successively at different intervals (Kampichler and Bruckner, 2009; Burgess et  
81 al., 2002; Bockock and Gilbert, 1957). These studies are not always comparable because they  
82 are subject to variations in e.g., litter type, mesh-size, sample preparation and analytical  
83 methods, and the placement of litterbags may alter the microclimate for decomposers  
84 (Kampichler and Bruckner, 2009).

85 Keuskamp et al. (2013) developed therefore a standardized, low-cost and time-efficient  
86 methodology called Tea Bag Index (TBI), characterizing the decomposition process with  
87 commercially available tea bags, where green tea is representing labile organic material and  
88 rooibos tea as a surrogate for recalcitrant litter. A decomposition rate ( $k$ ) and a stabilization  
89 factor ( $S$ ) are obtained accordingly with their chemical composition and the respective weight  
90 lost at a single point in time after an incubation period of ca 90-days in the soil. The TBI  
91 approach is particularly useful for assessing geographical differences in decomposition  
92 dynamics because results are directly comparable across sites, varying only with local edaphic  
93 and seasonal environmental conditions (Keuskamp et al., 2013).

94 In several studies, the TBI has been used as an indicator for biological (Sandén et al., 2021;  
95 Costantini et al., 2018) and microbial activity (Daebeler et al., 2022; Treharne et al., 2019; Tóth  
96 et al., 2017), ecosystem functioning, nutrient cycling (Zaller et al., 2016), and soil quality  
97 (Tresch et al., 2018; Buchholz et al., 2017). Generally, this follows the concepts of soil quality  
98 as reviewed by Bünemann et al. (2018), where TBI would primarily be a biological soil quality  
99 indicator. According to the TBI community, data collected from networks of researchers and

100 citizen scientists for constructing a global TBI map ([www.teatime4science.org](http://www.teatime4science.org)) shows that  
101 most studies have been using the TBI approach for different forest and grassland ecosystems  
102 or urban soils, studies in agricultural fields represent less than 15% of the TBI database. Indeed,  
103 there are only a few published studies (Daebeler et al., 2022; Dossou-Yovo et al., 2022; Struijk  
104 et al., 2022; Fu et al., 2021; Sandén et al., 2020; Barel et al., 2019; Poeplau et al., 2018; Sievers  
105 and Cook, 2018) that have been using the TBI approach for evaluating agroecosystems, and it  
106 is not clear if this method is sensitive enough to detect differences between management  
107 practices.

108 This study used the TBI approach to investigate the effect of management practices on the  
109 decomposition rate ( $k$ ) and stabilization factor ( $S$ ) at several LTEs in Austria and Sweden, with  
110 different soil characteristics, and climatic conditions, and subjected to various management  
111 practices.

112 To the best of our knowledge, this is the first analysis using the TBI approach for such a large  
113 number of LTEs and management practices for agroecosystems. The management practices  
114 included organic amendments, crop rotations, aboveground crop residue handling, mineral  
115 fertilizer application, and tillage. Our objectives were: (i) to evaluate if the TBI  $k$  and  $S$   
116 parameters are sensitive enough to distinguish litter decomposition between different  
117 management practices; (ii) to quantify the effect of management practices on  $k$  and  $S$ ; and (iii)  
118 to identify the most important local climate and/or soil properties affecting litter decomposition  
119 in Austria and Sweden.

120

## 121 **Materials and Methods**

122

### 123 **Study sites**

124 *Austria*

125 We used sixteen Austrian (AT) sites, by selecting contrasting management practices (as  
126 treatments) from three different categories of LTEs where the management practices had been  
127 in place for 11 to 63 years (see details in Table 1). The TBI measurements were made in 2014,  
128 2015 and 2016. Measurements sometimes took place in more than one year at the same LTE  
129 (e.g., MUBIL), and the sites were abbreviated as AT1 to AT16. Six experiment categories  
130 involved carbon balance practices (CB) focusing on organic matter inputs such as compost and  
131 crop residues, eight sites were studying soil fertility (SF) in terms of differences in mineral N  
132 and P fertilization, and two sites examined tillage systems (TS). The sites are located in several  
133 agricultural areas across the country (Fig. 1), with diverse soil textures (Table S1) and variable  
134 crop types (Table 1) and climatic characteristics (Table 3) during the years of TBI  
135 measurements. More details for some of the sites are available in specific publications: AT3  
136 (Spiegel et al., 2018; Lehtinen et al., 2017; Tatzber et al., 2015; Aichberger and Söllinger,  
137 2009), AT4 to AT6 (Spiegel et al., 2018; Lehtinen et al., 2014), AT15 and AT16 (Tatzber et al.,  
138 2015; Spiegel et al., 2007). In addition, Sandén et al. (2018) puts the Austrian LTEs in the  
139 context of other European LTEs.

140 The purpose of the Austrian C balance LTEs was threefold: i) to assess the sustainability of  
141 stockless vs. livestock-keeping organic farming management on soil and crop traits (AT1, AT2),  
142 ii) to investigate the effects of compost amendments on soil and crops (AT3), and iii) to  
143 compare crop residue incorporation and removal (AT4-AT6). Compost amendment LTE and  
144 crop residue incorporation LTEs also included mineral fertilizer application, whereas AT1 and  
145 AT2 only focused on different organic fertilizer treatments.

146 The eight soil fertility LTEs (AT7-AT14) were all focusing on the effect of mineral fertilizer on  
147 soil and crop properties. In most cases, treatments studied different amounts of mineral nitrogen  
148 fertilizer, whereas AT9 and AT12 also investigated the effect of different amounts of K fertilizer

149 application. Nitrogen fertilizer was applied in four stages and potassium in three stages,  
150 according to Austrian guidelines for fertilizer (BMLFUW, 2017).

151 For the tillage system experiments, conventional tillage (CT) was compared to reduced tillage  
152 (RT) and minimum tillage (MT). Regular mouldboard ploughing to 25–30 cm soil depth was  
153 applied in CT treatment, whereas cultivator in autumn to a depth of 15–20 cm was used in RT  
154 treatment and a rotary driller that loosened the soil to a depth of 5–8 cm was used in MT  
155 treatment. The soil was turned over only in the CT treatment, where inversion tillage was  
156 incorporating the crop residues. Fertilizer application was crop specific according to the  
157 Austrian guidelines for fertilizing (BMLFUW, 2017).

158

#### 159 *Sweden*

160 We used thirteen Swedish (SE) sites by selecting contrasting treatments from three different  
161 categories of LTEs, where the management practices had been in place for 11 to 59 years (see  
162 details in Table 2). The TBI measurements at these sites were made only in one year (2016)  
163 and were abbreviated as SE1 to SE13. Six sites involving combined management practices  
164 (CMP), four studying the effect of rotations (ROT), and three sites with tillage systems (TS).  
165 The sites are located in several agricultural areas across the country (Fig. 1), with diverse soil  
166 textures and variable crop types (Table 2) and climatic characteristics (Table 3) during the year  
167 of TBI measurements. Bergkvist and Öborn (2011) give a general description of all these LTEs.  
168 Only a brief description of treatments are provided below, more details on the sites with  
169 combined management practices is given by Carlgren and Mattson (2001), and for tillage  
170 systems by Arvidsson et al. (2014), while Poeplau et al. (2015) provide some more insight on  
171 the rotation experiments.

172 The initial purpose of the six LTEs with combined management practices (SE1-SE6) was to  
173 compare a change from the traditional mixed farm production system including crops and

174 livestock into a pure cash crop system, by studying their effects on the sustainability of crop  
175 production and soil properties (entitled soil fertility experiments). The dairy production  
176 treatments contain exclusively perennial grass-clover leys and receive one farmyard manure  
177 (FYM) application per rotation. The cash crop treatments consist of annual crops (i.e., oilseed  
178 is replacing leys in the rotation) without manure applications (0 FYM) only receiving mineral  
179 fertilizers application (NPK). The PK applications in all treatments we selected were aimed at  
180 achieving rapid build-up of the soil PK status, i.e., the amount applied was first replacing that  
181 exported in harvested products (i.e., maintenance principle), to which an extra amount was  
182 added (corresponding to the max treatment). The N-rates in all NPK treatments were also  
183 corresponding to max application rate, and were adapted depending on crop type, where spring  
184 cereals, oilseeds, and leys received 125 kg, while sugar beet received 210 kg N ha<sup>-1</sup> yr<sup>-1</sup>. We  
185 were also using the control plots receiving no NPK (0 NPK). As a third factor, aboveground  
186 crop residue removal takes place in all FYM treatments, simulating use of harvest residues for  
187 fodder or bedding material that are recycled as manure. The southern sites have 4-year rotations  
188 and those in central Sweden have 6-year rotations. The north site (SE5) is slightly different  
189 from the others, consisting of a 7-year rotation and is studying only the livestock-based  
190 production system.

191 For rotation experiments purposes, we were comparing extreme treatments representing two  
192 rotations from four LTEs (SE7-SE10) with the main objective to study changes in SOC (named  
193 humus balance experiments), i.e., a continuous spring cereal (SC) system and a ley-dominated  
194 rotations (L). The straw was removed from the plots every year in the SC treatments, and L  
195 consisted of a grass-clover mixture re-established every fourth year. Both rotations were  
196 receiving P and K accordingly with the maintenance principle, and SC and L were receiving  
197 120 and 150 kg N ha<sup>-1</sup> yr<sup>-1</sup>, respectively.



198 In the three tillage experiments (SE11-SE13), the conventional tillage (CT) and direct seeding  
199 (DS) treatments were the same for all sites, consisting of inversion plowing to a depth of 20-  
200 23 cm and by using a disc seed drill, respectively. The shallow (5-7 cm) and deep (~12 cm)  
201 reduced tillage treatments (SRT and DRT, respectively), consisted of primary tillage operations  
202 made in the autumn and most commonly with a chisel plough. The main crops in all the tillage  
203 system experiments were winter and spring cereals (occasionally oilseed), fertilized  
204 accordingly with local recommendations and with the aboveground residues chopped and left  
205 in the field.

206

### 207 **TBI method and sampling design**

208 The TBI method was used according to the protocol established by Keuskamp et al. (2013) to  
209 determine litter decomposition using two types of commercial tetrahedron-shaped tea bags by  
210 Lipton Unilever (Green tea and Rooibos tea). The green tea (*Camellia sinensis*; EAN:  
211 8722700055525) has high cellulose content, higher soluble fraction, and lower C:N ratio; while  
212 rooibos tea (*Aspalathus linearis*; EAN: 8722700188438) has high lignin content, lower soluble  
213 fraction, and higher C:N ratio, which is expected to slow down decomposition (Keuskamp et  
214 al., 2013). The synthetic tea bag material has a mesh size opening of 0.25 mm allowing access  
215 to microorganisms, very fine roots and root hairs.

216 The initial mass of the tea bag contents was determined on 20 randomly selected bags for each  
217 tea type from different boxes, oven-dried at 70°C for 48 hours and weighed separately; the  
218 mean dry mass for green tea was  $1.717 \pm 0.048$  g and that for rooibos tea was  $1.835 \pm 0.027$  g.  
219 For both countries, close to seeding of annual crops, from end of April to mid-June depending  
220 on location, each tea bag was properly identified and buried in the soil at 8 cm depth.

221 For Austria, four bags of each tea were used and placed side by side at a distance of 2 to 3 cm.

222 Each tea bag was properly identified and buried in the soil at 8 cm depth. The TBI incubation

223 period from placement to last retrieval averaged  $80\pm 13$  days (Table 3) due to logistic issues for  
224 collection. After collecting, the tea bags were oven-dried at  $70^{\circ}\text{C}$  for 48 hours after removal of  
225 adhered soil particles according to the standardized protocol by Keuskamp et al. (2013). After  
226 drying, the tea bags were opened, and the tea content was weighted. The ash content was not  
227 determined.

228 The same TBI protocol was used for the Swedish sites. As in Austria, four bags of each tea  
229 were used per experimental unit, placed side-by-side at a distance of 2 to 3 cm. Each tea bag  
230 was properly identified and buried in the soil at 8 cm depth. The mean TBI incubation period  
231 from placement to last retrieval date averaged  $91\pm 1$  day (Table 3). In addition to the removal  
232 of adhering soil particles, the ash content was determined (i.e., both for green and rooibos tea  
233 on mixed samples of the four replicates) in a muffle oven at  $550^{\circ}\text{C}$  for 16 hours. The rationale  
234 for measuring the ash content was that three of the Swedish sites had a high clay content (Table  
235 S1), where the complete removal of adhering soil particles may be more difficult. However,  
236 the ash content was on average quite low, representing  $15\pm 6\%$  and  $10\pm 4\%$  for the Green and  
237 Rooibos tea bags, respectively (data not shown).

238 After measuring the remaining dry matter, the decomposition rate ( $k$ ) and stabilization factor  
239 ( $S$ ) for both countries were calculated according to the TBI presented by Keuskamp et al.  
240 (2013). This standardized method that is using single measurements after an incubation period  
241 in the soil of 90-days have received some criticism. For instance, Mori (2022) and Mori et al.  
242 (2023) showed that this incubation period is not always long enough for the mass loss of green  
243 tea to reach a plateau, and further suggested that time-series mass loss data of rooibos tea is  
244 also required to respect the underlying assumptions of the TBI method. Time-series (15, 30, 60  
245 and 90-days) of green and rooibos tea were available for all the Swedish sites but only at one  
246 Austrian site (16, 26, 62 and 91-days at AT16). The incubation period was consistently always  
247 90-days for the Swedish sites, and only shorter than that (i.e., about 60-days incubation period)

248 for a few of the Austrian sites (Table 3). To have as uniform comparisons as possible between  
249 the two datasets, we only used the last measurement for both countries for calculating  $k$  and  $S$ .  
250 The purpose of using the time-series for testing the underlying TBI assumptions was beyond  
251 the scope of this paper.

252 The daily climate data for Austria were retrieved from the Central Institution for Meteorology  
253 and Geodynamics (ZAMG). For Sweden, the daily climate data were gathered through official  
254 data from the most nearby LantMet climate stations, and from the Swedish Meteorological and  
255 Hydrological Institute (SMHI). The climate variables used in this study were air temperature,  
256 precipitation, solar radiation, wind speed and air humidity (Table 3).

257 For Austrian soils, pH was measured electrochemically (pH/mV Pocket Meter pH 340i, WTW,  
258 Weilheim, Germany) in 0.01 M CaCl<sub>2</sub> at a soil-to-solution ratio of 1:5 (ÖNORM L1083). Total  
259 soil organic C (TOC) concentrations were analyzed by dry combustion in a LECO RC-612  
260 TruMac CN (LECO Corp., St. Joseph, MI, United States) at 650°C (ÖNORM L1080). Total N  
261 (N<sub>tot</sub>) was determined according to ÖNORM L1095 with elemental analysis using a CNS  
262 (carbon, nitrogen, sulfur) 2000 SGA-410–06 at 1250°C. Texture was determined according to  
263 ÖNORM L1061-1 and L1062-2. For Sweden the data were gathered from recent archived  
264 analysis protocols (pH was measured in water). Clay content, C content, C:N ratio, and pH  
265 measured from each site in both countries are shown in Table S1 (Supplementary material).

266

## 267 **Data analysis**

268 Analysis of variance (ANOVA) for each experiment category (i.e., CB, SF, TS, CMP and ROT)  
269 was performed to analyze the effects of the treatments and the differences between sites on  $k$   
270 and  $S$  separately for both countries. When the treatments were identical within the same  
271 experiment category, sites were used as a random effect with a mixed ANOVA to test the  
272 average treatment effect, mean values were used as replicates to test the differences between

273 sites. The Tukey's test ( $p < 0.05$ ) was used for comparing the same treatments and the same  
274 sites using R software version 4.2.2. We have treated the data from different years at the same  
275 sites in Austria as independent observations, in the sense they are not a time series of  
276 measurement. Interactions between site and treatment were considered.

277 We calculated a climate-dependent soil biological activity parameter ( $Re_{clim}$ ), by using mean  
278 daily air temperature, total precipitation, and potential evapotranspiration (PET) data in  
279 pedotransfer, soil water balance and biological activity functions. Compared to raw climatic  
280 data alone, this parameter is integrating the effect of climate, soil and crop properties. It is  
281 calculated as the product of a soil temperature ( $Re_{temp}$ ) and relative water content ( $Re_{wat}$ ) factor  
282 with a daily time step (i.e.,  $Re_{clim} = Re_{temp} \times Re_{wat}$ ), which is thereafter averaged to give an  
283 estimate of soil biological activity for a given time period. These two factors are derived from  
284 soil temperature and soil moisture response functions expressing the activity of decomposers  
285 and their relative effect on the decay rates of organic materials in the arable layer of agricultural  
286 soils. Briefly, the  $Re_{temp}$  is calculated from air temperature and leaf area index using an  
287 empirical model (Kätterer and Andrén, 2009), while  $Re_{wat}$  is calculated using pedotransfer  
288 functions for simulating the soil water balance and a function for estimating PET. In addition  
289 to air temperature and leaf area index, calculations of  $Re_{wat}$  also involve the use of daily climatic  
290 data for precipitation, wind speed, air humidity, and solar radiation, as well crop types and  
291 yields, soil texture and SOC content. For details see Bolinder et al., 2008, and Fortin et al.,  
292 2011) and information in the following R package used for the calculations:  
293 <https://github.com/ilmenichetti/reclim> (Please refer to the package documentation). The  $Re_{clim}$   
294 concept can be used for quantifying regional differences in soil biological activity alone  
295 (Bolinder et al., 2013; Andrén et al. 2007) or integrated as a parameter in the ICBM SOC model.  
296 In the latter case, it is adjusting the decomposition rates of both C inputs to soil from crop  
297 residues (e.g., straw) and that of the more stable SOC (Andrén and Kätterer, 1997; Andrén et

298 al., 2004). In this study, we used the concept of  $Re_{clim}$  and the  $Re_{temp}$  and  $Re_{wat}$  factors to test if  
299 the product of soil-temperature and relative water content better explained the variation in  $k$   
300 and  $S$  than the two latter alone, and to determine if they also better explained this variation  
301 compared to using only raw climatic data.

302 We calculated simple correlation between variables mean annual temperature (MAT), mean  
303 temperature during the incubation period ( $MAT_{TBI}$ ), total annual precipitation (TAP), total  
304 precipitation during incubation period ( $TP_{TBI}$ ), potential evapotranspiration (PET), potential  
305 evapotranspiration during incubation period ( $PET_{TBI}$ ), aridity index (AI), aridity index during  
306 incubation period ( $AI_{TBI}$ ), temperature and precipitation factor (TxP),  $Re_{clim}$ ,  $Re_{wat}$ ,  $Re_{temp}$ , pH,  
307 SOC, clay and C:N ratio, using Pearson correlation. For more accurate results, we applied  
308 random forest (RF) regression in order to rank the importance of variables for  $k$  and  $S$ , using  
309 the random forest R package (Liaw and Wiener, 2002). The RF is a machine learning technique  
310 based on decision trees that predicts a certain variable from a set of other variables through a  
311 series of binary splits of the data, where the variables are either continuous or categorical. For  
312 example, in the case of a continuous variable it consists of all the data points above or below a  
313 certain threshold, for a categorical variable it consists of all the data points belonging or not to  
314 a specific class. All these subsequent splits constitute a decision tree. A random forest is a set  
315 of decision trees and it is therefore an ensemble technique. This allowed us to utilize treatment  
316 and crop variables (including N fertilizer) without having to convert them into a ranking.  
317 Another useful asset of an RF regression is that it evaluates the importance of each variable in  
318 defining the predicted variable. There are various possible measurements to do that, but they  
319 are all based on measuring the effectiveness of each subsequent split in each node of a decision  
320 tree in sorting out the information. In our study, we used a measurement called node purity  
321 based on the Gini index, which expresses the probability of one split of the data (i.e., one node  
322 of the tree) defining the predicted variable. The total node purity of a certain variable in a tree

323 is the sum of all the node purity measurements for each node considering that particular  
324 variable, and the higher it is the more that variable is important.

325 We used the following models to predict the two TBI parameters  $k$  and  $S$ :

326  
327  $k_n f(TN, SOC, CN, cl, cr, tr, pH, N, PET, PET_{TBI}, TAP, TP_{TBI}, MAT, MAT_{TBI}, AI, AI_{TBI}, Re_{clim}, Re_{wat}, Re_{temp})$

328  $S_n f(TN, SOC, CN, cl, cr, tr, pH, N, PET, PET_{TBI}, TAP, TP_{TBI}, MAT, MAT_{TBI}, AI, AI_{TBI}, Re_{clim}, Re_{wat}, Re_{temp})$

329

330 where soil variables (continuous) were TN (total N g kg<sup>-1</sup>), SOC (g kg<sup>-1</sup>), CN (C:N ratio), cl  
331 (clay content g 100 g<sup>-1</sup>) and pH. Categorical variables were N (N fertilizer application factor  
332 with 4 levels), cr (crop factor, e.g., barley, ley (establishment), ley (production), oat, spring  
333 oilseeds, sugar beet, maize and winter wheat) and tr (a treatment factor with 30 levels). The  
334 climatic variables ( $PET_{TBI}$ ,  $PET$ ,  $TP_{TBI}$ ,  $TAP$ ,  $MAT_{TBI}$ ,  $MAT$ ,  $AI_{TBI}$  and  $AI$ ) are as defined in  
335 Table 3. The climate response variables  $Re_{clim}$ ,  $Re_{wat}$ ,  $Re_{temp}$  are as described above.

336 Since many of variables in our model are likely to be correlated and carry similar information,  
337 we applied the recursive feature elimination algorithm implemented in the caret R package by  
338 Kuhn et al. (2016), which assess in subsequent iterations the optimal set of predicting variables  
339 (features) to be utilized by the RF model. The procedure starts by fitting a RF model with all  
340 variables, ranking them by importance, and discarding the least important. The algorithm then  
341 iterates. The optimal number and set of features are then defined by a fitness metric (in our  
342 case the model  $R^2$ ), selecting the set with the best model fitness. The selected models were used  
343 to compute the variables' relative importance.

344 In order to better understand the similarities between the sites, we run a principal component  
345 analysis (PCA) in the space composed by the variables pH, SOC, TN, C:N, clay, TAP, MAT,  
346 PET, AI and TxP. The analysis was run with the R command prcomp (Venables and Ripley,  
347 2002), from the base R installation ("Stats" package). Variables were all standardized by  
348 rescaling them to zero mean and unit variance.

349

## 350 **Results**

### 351 *Effect of management practices*

#### 352 *Austria*

353 Both the TBI parameters  $k$  and  $S$  varied between treatments and sites in Austria, and even  
354 between years at the same site within the C balance category (Fig. 2 and Table S2). In general,  
355 all treatments in AT1 with a lucerne crop under wetter conditions (2014) showed higher  $k$  and  
356 lower  $S$  than in AT2 with a wheat crop under dryer conditions (2015), and the treatment with  
357 municipal compost and green manure (FW) had the highest  $S$  in 2015. The AT3 site did not  
358 show significant differences between the treatments. Crop residue incorporation treatment  
359 (CRI) had higher  $k$  than the crop residue removal (CRR) at the AT4 and AT6 sites, and AT6  
360 showed a higher  $k$  than at AT4. Comparing years for the same experiment site and type with  
361 different crops, AT5 (2015; with wheat) had higher  $S$  than AT6 (2016; with maize).

362 For the soil fertility experiment category (Table 1), AT12 had the highest  $k$  and AT13 had the  
363 highest  $S$ . Sites receiving NPK fertilizer application (AT7, AT8 and AT9) had higher  $k$  and  $S$   
364 even at different N doses than at the AT12, AT13 and AT14 sites receiving only N (i.e., without  
365 P and K). Stabilization was significantly higher in AT9 than in AT7. For potassium trials, AT11  
366 showed significantly higher  $k$  and  $S$  than AT10. Regarding sites receiving only N addition  
367 (AT12, AT13, and AT14), maximum doses (180 kg N) showed the highest  $k$  (0.0095), and no  
368 N addition had the lowest  $k$  (0.0066) (Fig. 2 and Table S2).

369 Regarding the tillage system experiment category (AT15 and AT16 - Table 1),  $k$  was  
370 significantly higher in shallow reduced tillage (SRT) and  $S$  was higher in deep reduced tillage  
371 (DRT) in 2015 (AT15), but no significant differences between treatments were found in 2016  
372 (AT16). Site AT16 had significantly higher  $S$  than AT15 (Fig. 2. and Table S2).

373

374 *Sweden*

375 At the Swedish sites (Table 2), the TBI measurements for the combined management practices  
376 experiment category showed that both  $k$  and  $S$  were significantly higher for the FYM/NPK  
377 treatments maximum amount of farmyard manure and maximum doses of NPK (FYM/NPK)  
378 (Fig. 3, Table S3) compared with the control treatments (0 FYM/0 NPK). Comparing sites, SE5  
379 and SE6 had the highest  $k$  and SE4 had the lowest  $k$ , while SE3 showed the highest  $S$  followed  
380 by SE6, SE5 and SE4. The lowest  $S$  was for SE1 and SE2 (Table S3).

381 Regarding the rotation experiments, the continuous spring cereal rotation showed higher  $k$  than  
382 for ley, but there was no significant difference in  $S$ . Comparing sites, SE9 showed higher  $k$  than  
383 SE7, SE8 and SE10, whereas SE7 and SE8 had the highest  $S$ .

384 For the tillage system experiment category, conventional tillage (CT) had the lowest  $k$  and  $S$ ,  
385 while deep reduced tillage (DRT) had the highest  $k$  and  $S$ . The highest  $S$  was observed for the  
386 SE12 followed by SE11 and SE13. Sites did not show significant differences for  $k$ .

387 Comparing tillage system experiments in Austria and Sweden (2016) for sites (AT16, SE11,  
388 SE12 and SE13) for the treatments that were the same in both countries (CT, SRT and DRT),  
389 deep reduced tillage had the highest  $k$  and shallow reduced tillage had the highest  $S$ . The  
390 Austrian site showed the lowest  $k$  and the highest  $S$  compared to the Swedish sites, which did  
391 not show significant differences among them (Table S3).

392 The field application of the TBI found a clear discrimination of both  $k$  and  $S$  values between  
393 the two countries. The both mean  $k$  and  $S$  values were higher in Sweden (Table 4, Fig. 4). In  
394 general, the variation in  $k$  and  $S$  values were lower in Austria. Indeed, mean  $k$  by site in Austria  
395 varied between 0.0058 and 0.0128 and mean  $S$  varied between 0.113 and 0.442 (Table S2).  
396 Whereas mean  $k$  by site in Sweden was between 0.0084 and 0.0301, and mean  $S$  was between  
397 0.118 and 0.361 (Table S3). All values for  $k$  and  $S$  were within the range of the previous global  
398 TBI investigation (0.005-0.04 for  $k$ ; and 0.05-0.55 for  $S$ ) by Sandén et al. (2020).



399

400 *Influence of climate and soil properties*

401 Using the combined dataset for Austria and Sweden, resulted in significant negative correlation  
402 between  $k$  and MAT, TAP, PET, TxP factor,  $Re_{clim}$  and  $Re_{temp}$ , and significant positive correlation  
403 with the C:N ratio (Table S4). Stabilization factors in Austria and Sweden combined correlated  
404 negatively with MAT<sub>TBI</sub> period,  $Re_{clim}$  and  $Re_{temp}$ .

405 The variable selection procedure with the random forest models (Fig. 5) identified fewer  
406 variables explaining  $k$  and  $S$  values for the combined dataset. The variable explaining  $k$  is low,  
407 but the overall predicting power of the model decreased substantially.

408 According to the optimized random forest model, most of the variance in  $k$  was accounted for  
409 by climatic variables (Fig. 5), with  $Re_{temp}$  ranking the highest, followed by AI and MAT. It was  
410 also showing that treatment, C:N ratio and SOC were important factors as well. The  $S$  was also  
411 influenced by climate-related variables, with  $Re_{temp}$  leading the ranking, and it was followed by  
412 pH and more agronomic variables such as treatment, crop and N fertilizer application.

413 The principal component analysis (Fig. 6) revealed that the data are well divided in two groups,  
414 representing the two countries, which allow us to say that indeed edapho-climatic  
415 characteristics are different between Austria and Sweden. The PC1 showed that points in  
416 Austria are positively related to climatic characteristics, such as MAT, TAP and PET. On the  
417 other hand, points in Sweden are positively influenced by high clay content and high C:N ratio.  
418 High C:N enhancement is related to low TAP and TxP. High clay contents are related to low  
419 MAT and PET, which can be due to an historical influence on soil weathering. The PC2 was  
420 dominated by SOC and TN contents, mainly at two points in Austria (AT7 and AT9: two sites  
421 testing soil fertility with NPK and relatively low TAP and TP<sub>TBI</sub> compared to other sites).  
422 Austria showed more divergent data, having more heterogeneous sites than in Sweden.

423

## 424 **Discussion**

### 425 *Influence of climate and soil properties*

426 In previous studies using the TBI approach, it was shown that climate played a significant role  
427 on decomposition in a temperate biome (Djukic et al., 2018), but when comparing several  
428 different biomes, climatic conditions were of relatively low importance (Fanin et al., 2020). In  
429 Boreal soils, Althuizen et al. (2018) found that increased temperatures enhanced  $k$ , whereas  
430 increased precipitation decreased  $k$  across years. Many studies have shown a positive  
431 correlation between precipitation and decomposition rates (Pimentel et al., 2019; García  
432 Palacios et al., 2016), however precipitation did not show correlation with  $k$  according to the  
433 random forest analysis. On the other hand,  $Re_{wat}$  showed great importance (Fig. 5). It is because  
434 this variable includes nonlinearities due to its shape according to which decomposition  
435 increases with soil moisture and then decreases at high soil water content due to oxygen  
436 limitation of microorganisms (Moyano et al., 2013).

437 In general, higher  $k$  values were observed when the aridity index was lower, and it was  
438 identified by the random forest regression model being an important variable affecting the rate  
439 of decomposition (Fig. 5). This may be related to the observations that in more arid and warmer  
440 sites, the biological processes driving SOC dynamics are impaired which may result in  
441 decreasing soil C and N stocks (Kerr and Ochsner, 2020; Ontl and Schulte, 2012; Jiao et al.,  
442 2016; Reynolds et al., 2007).

443 For practical reasons the teabags in our study were buried in the soil during the growing season,  
444 corresponding to a period when the soil biological activity is highest (Bolinder et al., 2013).  
445 When burying the teabags during the growing season, the difference in climatic variables  
446 between sites are attenuated, in particular with respect to air temperature. For example, the  
447 MAT at the Swedish most northerly (SE5 and SE9) and southerly (SE2) sites are 4.1 and 9.0

448 °C, respectively, whereas the corresponding mean air temperatures during the incubation period  
449 ( $\text{MAT}_{\text{TBI}}$ ) were 14.3 and 16.2 °C, respectively.

450 The TBI  $S$  parameter was also dependent on climate. Indeed, the random forest model identified  
451 climatic parameters as the main factors affecting  $S$  in both Austria and Sweden during all  
452 evaluated periods. In particular,  $Re_{\text{clim}}$  and  $Re_{\text{temp}}$  often showed significant negative  
453 correlations, which implies a negative impact of air temperature on  $S$ . However, raw climatic  
454 variables, such as precipitation and temperature were only weakly correlated with  $S$ . This is  
455 probably due to nonlinear processes, which are considered in the ICBM climate-dependent soil  
456 biological activity calculations such as  $Re_{\text{wat}}$  (as discussed above). Furthermore, since litter  
457 decomposition dynamics is influenced by multiple factors that interact and change over time  
458 (Bradford et al., 2016), the relationships are not always linear. Random forest models that we  
459 fitted to the data are more efficient capturing such combinations and interactions of factors,  
460 and can detect relationships that would not be detectable by linear approaches.

461

#### 462 *Effect of management practices*

463 Our results revealed that a large number of management practices significantly affected both  
464 the decomposition rate  $k$  and stabilization factor  $S$  according to the TBI approach used in  
465 several LTEs in Austria and Sweden (Fig. 2, 3 and 5). This is in contrast to the studies by Djukic  
466 et al. (2018) as well as Saint-Laurent and Arsenault-Boucher (2020), who did not find any  
467 significant effect of land use and management practices on early-stage litter decomposition in  
468 a temperate biome.

469 In the C balance trials in Austria, soils receiving green manure + municipal compost had higher  
470  $S$  than soil receiving biogas slurry at the second year (Table S2). This is in agreement with  
471 studies indicating that compost can improve SOC stabilization over time (Mekki et al., 2019;  
472 Eshetu et al., 2013; Ceccanti et al., 2007). The higher  $k$  in the crop residues incorporated

473 treatments (AT4 and AT6; Table S2) can be attributed to the fact that incorporation of crop  
474 residues into the soil can increase the decomposition rate by stimulating microbial activity.  
475 During the early stages of decomposition, soluble C is rapidly utilized by soil biota (Werth and  
476 Kuzyakov, 2010). The higher  $k$  and lower  $S$  at AT6 compared to AT4 were likely due to the  
477 loamy texture, lower potential evapotranspiration resulting in a lower aridity index at the AT4  
478 site (Table 3 and Table S1), corroborated by the PCA analysis (Fig. 6).

479 There were no significant differences in  $k$  and  $S$  found among treatments in the soil fertility  
480 trials in Austria with NPK addition. However, there was a trend towards a higher  $S$  at AT9  
481 compared to AT7, likely related to the higher SOC content in AT9, since the climatic conditions  
482 and soil texture were quite similar for both areas, which suggests that higher SOC content may  
483 have increased  $S$ . Site AT11 had higher  $k$  and  $S$  than AT10. Possible explanations for this trend  
484 are that AT10 had lower clay content, lower precipitation resulting in higher PET (corroborated  
485 by the PCA analysis) and AI, contributing to a lower soil moisture content and thereby lower  
486 decomposition and stabilization.

487 Nitrogen supply may favor microbial activity and thereby litter decomposition (Raiesi, 2004).  
488 This was reflected in the treatments where only N was added, where the high dose of 180 kg  
489 N ha<sup>-1</sup> (AT12, AT13 and AT14) induced a significantly higher  $k$  (Table S2), compared to the  
490 treatments with no N addition, which also had the lowest  $k$ . Furthermore, the significant  
491 difference between sites, in which AT12 had the highest  $k$  could at least partly be explained by  
492 a higher SOC and higher pH at this site (corroborated by the PCA analysis).

493 In the tillage system experiment at Fuchsenbigl in Austria in 2015 (AT15, with maize) and 2016  
494 (AT16; with wheat), the shallow reduced tillage showed significantly higher  $k$  than deep  
495 reduced tillage and conventional tillage, only in 2015, indicating that shallow soil tillage  
496 stimulated decomposition that particular year. This was likely due to climatic conditions, since  
497 2015 was slightly drier and warmer, furthermore maize straw has lower C:N ratio than wheat

498 straw and tends to decompose faster. Some studies showed faster decomposition under  
499 conventional tillage than under reduced tillage practices (e.g., Lupwayi et al., 2004). However,  
500 Kainiemi et al. (2015) found a decrease in soil respiration in conventional tillage compared to  
501 shallow tillage in temperate regions, which directly implies a lower decomposition (and lower  
502  $k$ ). These differences between tillage treatments are attributable to indirect effects on soil  
503 moisture and temperature profiles. We attribute the significantly higher  $S$  in 2016 to the fact  
504 that this year was moister and less warm, compared to 2015, resulting in a lower aridity index  
505 during the TBI incubation period ( $AI_{TBI}$ ).

506 In the Swedish combined management practices trials, treatments receiving organic and  
507 mineral fertilizer application had higher  $k$  and  $S$  (FYM/NPK; Table S3), likely due to the  
508 increase in microbial diversity and activity favored by nutrient and C supply (Stark et al., 2007).  
509 Sites SE5 and SE6 showed the highest  $k$ : SE5 had low evapotranspiration and aridity index,  
510 resulting in more moisture; SE6 had also high  $S$ , due to high clay content and low PET  
511 (corroborated by the PCA analysis). Site SE3 had high  $S$ , which could be related to a higher  
512 C:N ratio, as suggested in another TBI experiment by Althuizen et al. (2018), a study showing  
513 that C:N ratio is positively correlated to  $S$ . The SE1 and SE2 sites had lower  $S$  than SE3 despite  
514 similar climatic conditions, which probably was related to the type of crops growing in these  
515 treatments (i.e., sugar beet in the SE1 and SE2 and grass/clover ley in SE3), since these two  
516 crop types have different effects on soil temperature and moisture.

517 In the Swedish rotation system trials, spring cereal (SC) had higher  $k$  than ley (Table S3). Site  
518 SE9 had higher  $k$  and lower  $S$ , in which the low stabilization may be caused by low clay content,  
519 low pH, and high solar radiation, leading to low SOC (corroborated the PCA analysis). The  
520 highest  $S$  were found in sites SE7 and SE8, in which the former showed high clay and SOC  
521 content, and SE8 had high precipitation and low PET.

522 For the tillage system treatments in Sweden, similar to the Austrian sites, conventional tillage  
523 showed the lowest  $k$ , and also lowest  $S$ . Even when comparing tillage systems in Sweden and  
524 Austria jointly (Table S3) we noticed that conventional tillage also showed the lowest  $k$ , while  
525 deep reduced tillage the highest.

526 As expected, the decomposition rate  $k$  was mostly affected by climatic conditions such as  
527 temperature and aridity or moisture. However agronomic and edaphic factors (i.e., soil  
528 management choice (treatment), soil C:N ratio, SOC, crop type, pH, clay content, soil nitrogen  
529 and others)- proved to be of great relevance for  $k$ . The stabilization factor  $S$  expresses the degree  
530 by which the labile fraction of the plant material is decomposed. We observed that the influence  
531 of pH was the most important edaphic factor, and the agronomic factors as the soil management  
532 treatment, crop type, and N fertilizer application were also identified as good predictors. A  
533 study conducted by Fu et al. (2021) suggested that pH, nutrient availability and soil compaction  
534 were the main reasons contributing to the differences in litter decomposition. The net effect of  
535 pH is not clear since it modifies both SOC decay kinetics and productivity simultaneously  
536 (Paradelo et al., 2015), with a maximum effect at around neutral pH (Liao et al., 2016).  
537 Nevertheless, the impact of pH on litter decomposition using the TBI approach seems clear in  
538 our study.

539

## 540 **Conclusion**

541 Our results show that both the TBI  $k$  and  $S$  parameters were sensitive to management practices  
542 in agroecosystems in Austria and Sweden. We observed significant differences for some of the  
543 treatments in all categories of LTEs. Notably, for the effect of crop residue incorporation,  
544 organic amendments and N fertilizer application, crop types and tillage systems. In the Austrian  
545 LTEs, application of green manure + municipal compost showed a higher  $S$  compared to the  
546 application of other organic amendments. **Incorporation of crop residues and high N fertilizer**

[also here I recommend to make a comparison.](#)

547 application increased  $k$ . In the Swedish LTEs, it was shown that combined management  
548 practices with both farmyard manure and mineral NPK resulted in higher  $k$  and  $S$  compared to  
549 no manure and no NPK applications, whereas growing spring cereals instead of leys increased  
550  $k$  but did not change  $S$ . For both countries, tillage systems with deep reduced tillage practices  
551 had higher  $k$ , and shallow reduced tillage had higher  $S$ . However, these effects were also site  
552 or year dependent within a given country. Climatic conditions had the most important impact  
553 on the decomposition rate  $k$  and the stabilization factor  $S$ , but also pH, treatment, crop types,  
554 SOC, C:N ratio and clay content were good predictors of the TBI parameters. Generally, the  
555 correlations with raw climatic variables such as precipitation and temperature were quite poor.  
556 Better relationships were found when nonlinearities due to interactions between climatic and  
557 edaphic conditions were accounted for. The results highlight how a wide range of management  
558 practices used in agroecosystems affect TBI parameters jointly to soil and climatic conditions.  
559 This also implies the TBI  $k$  and  $S$  parameters could serve as indicators of how different  
560 agricultural management practices influence the global carbon cycle, and is useful to assess  
561 their potential contribution to act as a sink for atmospheric C.

Good to mention this here, to relate the TBI in the Austrian and Swedish LTEs to the timely issue of the potential (or not) to store C in arable soils. However, it is not clear how  $k$  and  $S$  may indicate a potential contribution to the C sink function of arable soils.

562

### 563 **Data availability**

564 Data can be provided by the authors upon request.

565

### 566 **Author contribution**

567 MRG, MB and TS wrote and prepared the manuscript draft; MB, TK and TS supervised and  
568 led the research; MB, OA, HS, JKF, AS, AS and TS developed the methodology; MRG and  
569 LM analyzed the data. All authors reviewed and edited the manuscript.

570

### 571 **Competing interests**

572 The contact author has declared that none of the authors has any competing interests.

573

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579



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811 **Tables**

812

813 Table 1. Experimental sites in Austria. Site acronym, location name, year of TBI measurements,  
 814 category and type of LTE including its duration, main crop cultivated during the TBI  
 815 measurements and management treatments

Site	Location	Year	Category*	Experiment <sup>†</sup>	Age	Crop	Treatments <sup>§</sup>
AT1	MUBIL	2014	CB	OA	11	Luzerne	GM, FW, FYM, BS
AT2	MUBIL	2015	CB	OA	12	Wheat	GM, FW, FYM, BS
AT3	Ritzlhof	2015	CB	IF-N & OA+N	24	Maize	0, 40, 90, 120 N CFW, CGM, CS, CSS+80N
AT4	Rottenhaus	2016	CB	CR with NPK	31	Maize	CRR, CRI
AT5	Rutzendorf	2015	CB	CR with NPK	34	Wheat	CRR, CRI
AT6	Rutzendorf	2016	CB	CR with NPK	35	Maize	CRR, CRI
AT7	Breitstetten	2015	SF	IF-N with PK	40	Wheat	60, 90, 120, 145 N
AT8	Breitstetten	2016	SF	IF-N with PK	41	Wheat	60, 90, 120, 145 N
AT9	Haringsee	2015	SF	IF-N with PK	40	Wheat	60, 90, 120, 145 N
AT10	Fuchsenbigl	2016	SF	IF-K with NP	61	Maize	0, 150, 300 K
AT11	Rottenhaus	2016	SF	IF-K with NP	63	Maize	0, 150, 300 K
AT12	Haringsee	2016	SF	IF-N without PK	41	Maize	0, 60, 120, 180 N
AT13	Zinsenhof	2016	SF	IF-N without PK	41	Maize	0, 60, 120, 180 N
AT14	Zissersdorf	2016	SF	IF-N without PK	41	Maize	0, 60, 120, 180 N
AT15	Fuchsenbigl	2015	TS	TS	27	Maize	CT, SRT, DRT
AT16	Fuchsenbigl	2016	TS	TS	28	Wheat	CT, SRT, DRT

816 \* CB: carbon balance practices; SF: soil fertility; TS: tillage systems.

817 <sup>†</sup> OA: organic amendments; IF-N & OA+N: N inorganic fertilization and organic amendments plus mineral N;  
 818 CR & IF-P with NK: crop residues and P inorganic fertilization with 90 and 40 kg ha<sup>-1</sup> of N and K, respectively;  
 819 IF-N with PK: N inorganic fertilization with 55 and 180 kg ha<sup>-1</sup> of P and K, respectively; IF-N without PK: N  
 820 inorganic fertilization; IF-K with NP: K inorganic fertilization with 40 and 120 kg ha<sup>-1</sup> of P and K; TS: tillage  
 821 system.

822 <sup>§</sup> GM: green manure; FW: municipal compost and green manure; FYM: farmyard manure; BS: biogas slurry;  
 823 CFW: compost food waste with 175 kg N ha<sup>-1</sup>; CGM: compost green manure with 175 kg N ha<sup>-1</sup>; CS: compost  
 824 slurry with 175 kg N ha<sup>-1</sup>; CSS: compost sewage sludge with 175 kg N ha<sup>-1</sup>; CRR: crop residues removed; CRI:  
 825 crop residues incorporated; CT: conventional tillage; SRT: shallow reduced tillage; DRT: deep reduced tillage.

826

827



828 Table 2. Experimental sites in Sweden. Site acronym, location name, year of TBI measurements  
 829 conducted in 2016, type of LTE including its duration, main crop cultivated during the TBI  
 830 measurements and management treatments

Site	Name	Experiment*	Age	Crop	Treatments†
SE1	Börgeby	CMP	59	Sugar beet	FYM/NPK
				Sugar beet	0 FYM/0 NPK
SE2	Ekebo	CMP	59	Sugar beet	FYM/NPK
				Sugar beet	0 FYM/0 NPK
SE3	Högåsa	CMP	50	Ley production year	FYM/NPK
				Ley production year	FYM/0 NPK
				Spring oilseed	0 FYM/NPK
				Spring oilseed	0 FYM/0 NPK
SE4	Kungsängen	CMP	53	Oat	FYM/NPK
				Oat	0 FYM/0 NPK
SE5	Röbacksdalen	CMP	47	Barley	FYM/NPK
				Barley	FYM/0 NPK
SE6	Vreta Kloster	CMP	50	Ley production year	FYM/NPK
				Ley production year	FYM/0 NPK
				Spring oilseed	0 FYM/NPK
				Spring oilseed	0 FYM/0 NPK
SE7	Lanna	ROT	35	Oat	SC
				Ley production year	L
SE8	Lönnstorp	ROT	36	Barley	SC
				Ley establish. year	L
SE9	Röbacksdalen	ROT	36	Barley	SC
				Ley establish. year	L
SE10	Säby	ROT	46	Wheat	SC
				Ley establish. year	L
SE11	Lanna	TS	34	Winter wheat	CT, DS
SE12	Säby	TS	11	Barley	CT, SRT, DRT, DS
SE13	Ultuna	TS	19	Barley	CT, DRT

831 \* CMP: combined management practices; ROT: rotation systems; TS: tillage systems.

832 † FYM/NPK: maximum amount of farmyard manure and maximum doses of NPK; 0 FYM/0 NPK: no manure  
 833 and no NPK application; FYM/0 NPK: maximum amount of farmyard manure and no NPK application; 0  
 834 FYM/NPK: no manure and maximum doses of NPK; SC: spring cereal; L: ley; CT: conventional tillage; DS:  
 835 direct seeding; SRT: shallow reduced tillage; DRT: deep reduced tillage.

836

837

838

839 Table 3. Annual climatic characteristics for the Austrian and Swedish sites during the entire  
840 year of measurements and only during the TBI period (days) corresponding to the period  
841 between the date of placement and the last retrieval date of the tea bags.

842

Site	TBI period	TAP	TP <sub>TBI</sub>	MAT	MAT <sub>TBI</sub>	PET	PET <sub>TBI</sub>	AI	AI <sub>TBI</sub>
	days	mm		°C		mm			
<i>Austria</i>									
AT1	99	756	294	12.5	20.3	811.4	414.0	1.07	1.4
AT2	61	516	65	12.6	18.8	605.1	141.3	1.17	2.2
AT3	80	622	161	12.2	20.0	682.9	295.1	1.09	1.8
AT4 & 11	84	939	384	11.2	20.5	763.4	306.1	0.81	0.8
AT5	63	516	82	12.6	19.4	605.1	148.6	1.17	1.8
AT6	96	735	226	12.0	21.6	854.2	394.0	1.16	1.7
AT7	59	516	81	12.6	19.3	605.1	137.4	1.17	1.7
AT8	84	735	240	12.0	17.1	854.2	334.2	1.16	1.4
AT9	60	516	81	12.6	19.2	605.1	139.6	1.17	1.7
AT10 & 16	92	735	205	12.0	21.4	851.2	378.9	1.15	1.8
AT12	87	735	203	12.0	21.8	854.2	367.4	1.16	1.8
AT13	84	939	327	11.2	20.5	763.4	304.3	0.81	0.9
AT14	82	735	154	12.0	21.3	854.2	319.6	1.16	2.1
AT15	81	516	103	12.6	22.5	605.1	212.9	1.17	2.1
<i>Sweden</i>									
SE1	92	436	141	9.2	16.7	444.6	235.1	1.02	1.7
SE2	91	681	270	9.0	16.5	578.5	297.8	0.85	1.1
SE3	91	458	142	7.9	13.3	618.0	306.4	1.35	2.1
SE4	93	429	126	7.1	15.3	640.0	367.0	1.48	2.9
SE5 & 9	92	526	164	4.1	14.3	396.2	218.2	0.75	1.3
SE6	91	433	158	7.9	13.3	617.5	301.8	1.16	1.9
SE7 & 11	91	412	115	7.4	12.7	514.2	276.4	1.3	2.4
SE8	90	610	224	9.4	14.4	500.2	265.7	0.82	1.2
SE10 & 12	91	429	126	7.1	15.3	358.5	155.7	0.84	1.2
SE13	92	429	126	7.1	15.3	639.1	377.8	1.5	3.0

843

844 TAP: total annual precipitation; TP<sub>TBI</sub>: total precipitation during TBI period; MAT: mean annual temperature;  
845 MAT<sub>TBI</sub>: mean temperature during TBI period; PET: total annual potential evapotranspiration; PET<sub>TBI</sub>: potential  
846 evapotranspiration during TBI period; AI: annual aridity index (PET divided by TAP); AI<sub>TBI</sub>: aridity index during  
847 TBI period.

848

849

850

851 Table 4 – Mean values of decomposition rate ( $k$ ) and stabilization factor ( $S$ ) for the TBI  
852 approach after the incubation period.

853

	Mean TBI parameters	
	$k$	$S$
<i>Sweden</i>	$0.0160 \pm 0.01$	$0.247 \pm 0.14$
<i>Austria</i>	$0.0115 \pm 0.004$	$0.228 \pm 0.11$

854

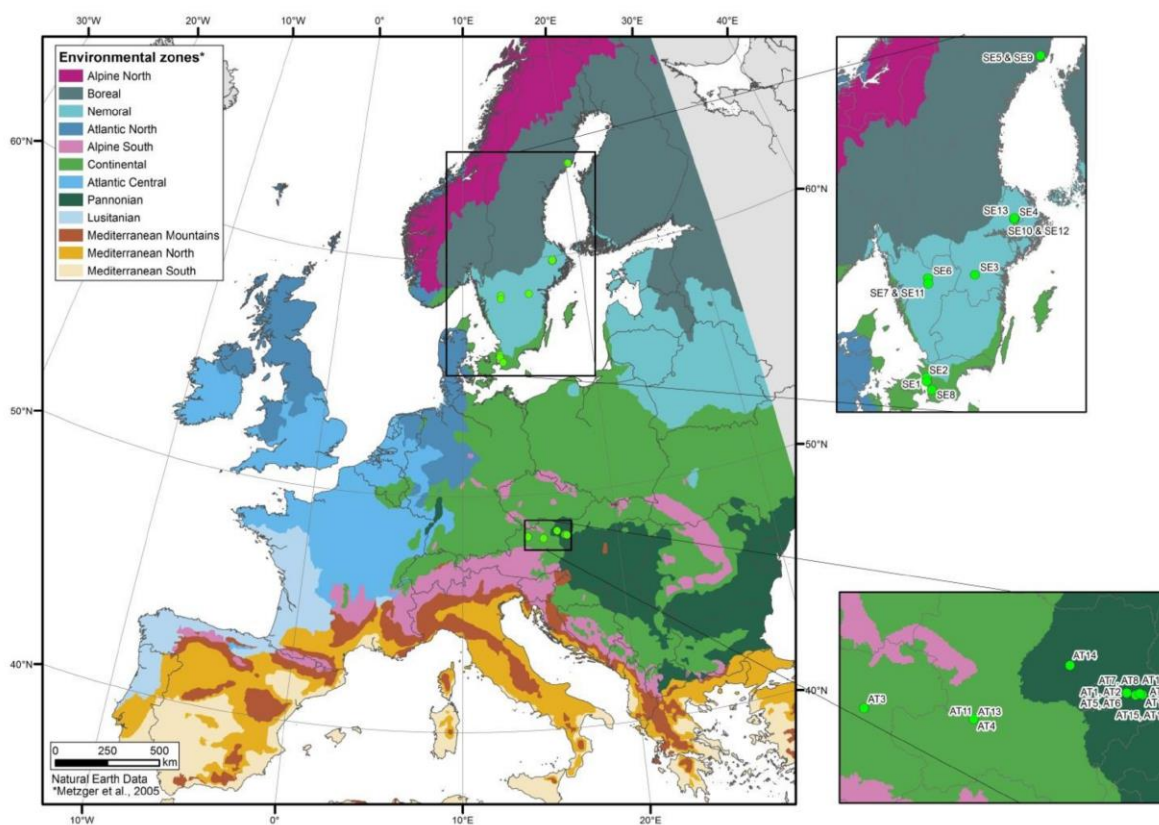
855

856 **Figures**

857

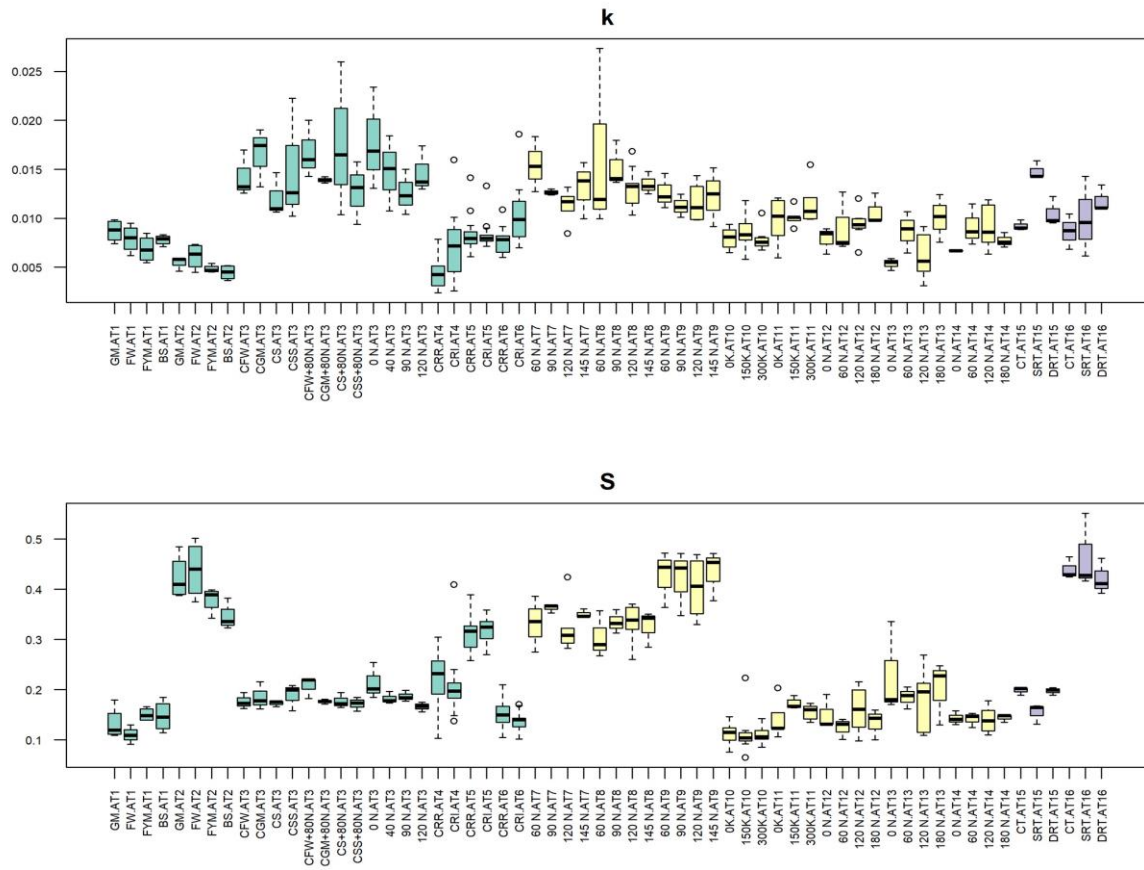
858 **FIGURE 1**

859



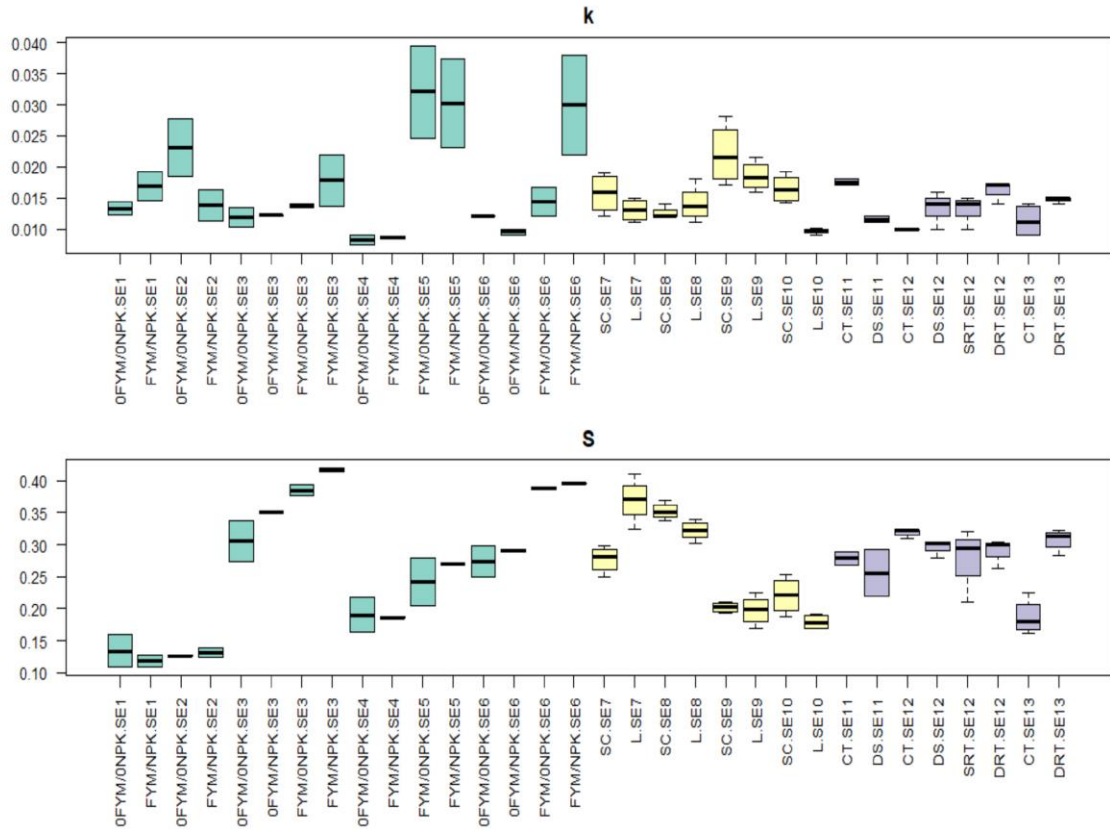
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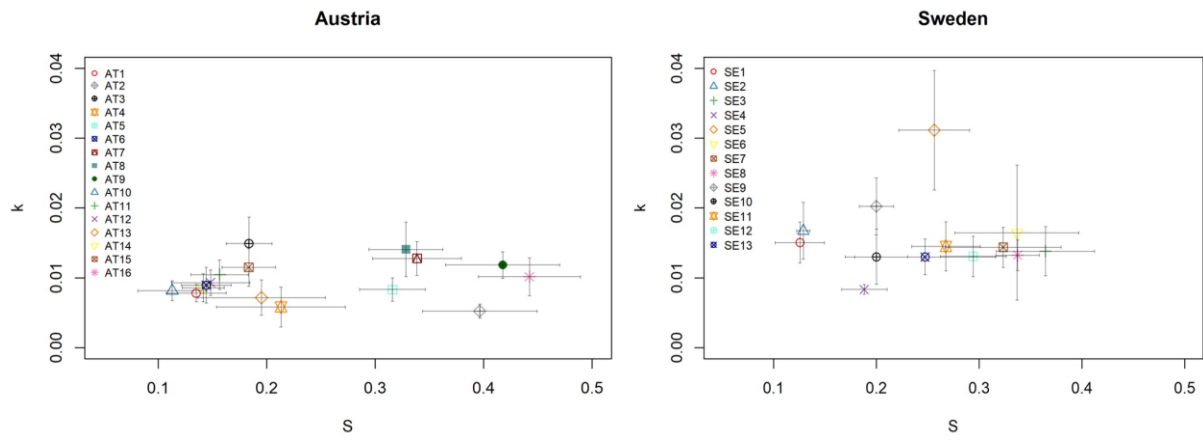
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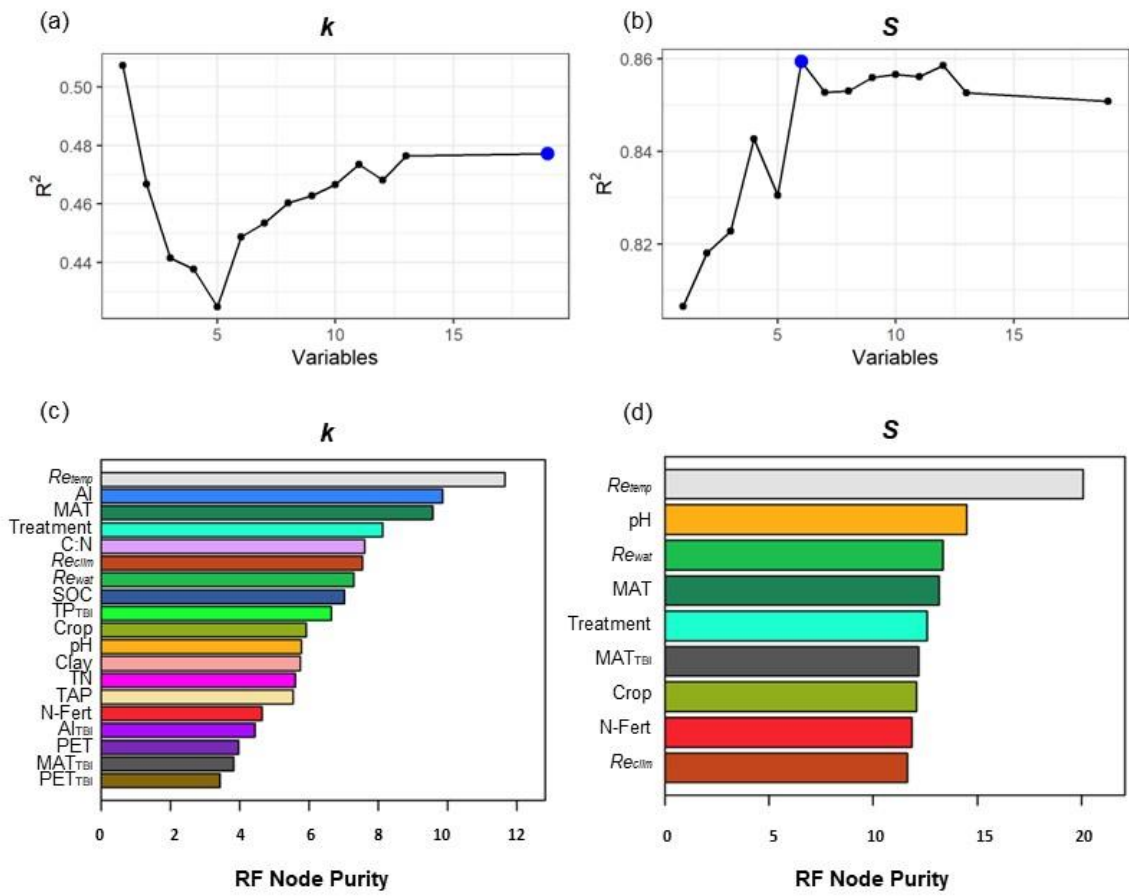




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872 **FIGURE 5**

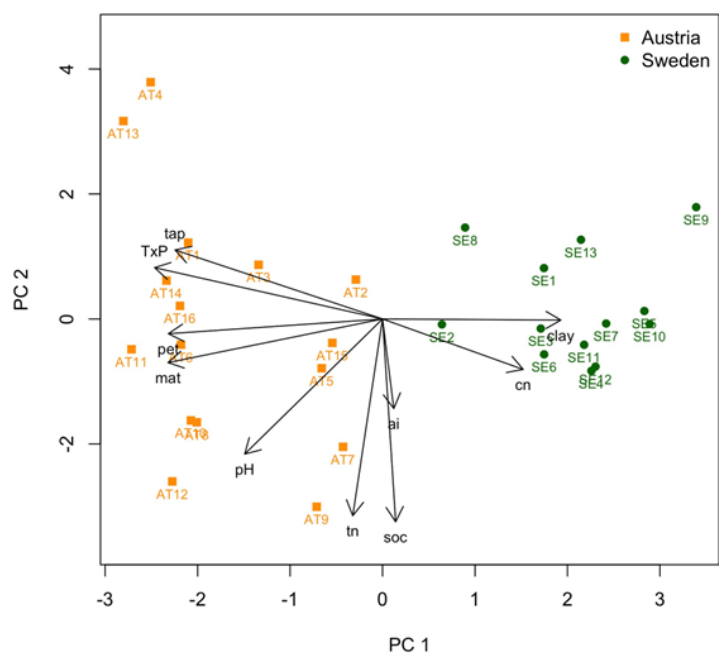


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874



875 **FIGURE 6**



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877

878 **Figure caption**

879

880 Figure 1 - Location and environmental zone of the Austrian and Swedish sites.

881

882 Figure 2 - Average decomposition rate ( $k$ ) and stabilization factor ( $S$ ) for each treatment and  
883 site in Austria. The extents of the box indicate 25<sup>th</sup> and 75<sup>th</sup> percentiles, and the lines represent  
884 the 50<sup>th</sup> percentile. Whiskers represent the 10<sup>th</sup> and 90<sup>th</sup> percentiles and outliers are given as  
885 open symbols. Green boxes: Carbon balance (CB) experiment; yellow boxes: Soil fertility (SF)  
886 experiment; purple boxes: tillage systems (TS) experiment. Site AT1 shows results from 2014.  
887 Sites AT2, AT3, AT5, AT7, AT9, and AT15 show results from 2015. And sites AT4, AT6, AT8,  
888 AT10, AT11, AT12, AT13, AT14, and AT16 show results from 2016.

889

890 Figure 3 - Average decomposition rate ( $k$ ) and stabilization factor ( $S$ ) for each site and treatment  
891 in Sweden. The extents of the box indicate 25<sup>th</sup> and 75<sup>th</sup> percentiles, and the lines represent the  
892 50<sup>th</sup> percentile. Whiskers represent the 10<sup>th</sup> and 90<sup>th</sup> percentiles. Green boxes: combined  
893 management practices (CMP) experiment; yellow boxes: rotation (ROT) experiment; purple  
894 boxes: tillage systems (TS) experiment.

895

896 Figure 4 - Distribution of the mean decomposition rate constant ( $k$ ) and the stabilization factor  
897 ( $S$ ) for each site in Austria and Sweden. Errors bars represent standard deviation.

898

899 Figure 5 - a and b) Variables selection procedure to identify the optimal number of variables to  
900 explain the variance of  $k$  and  $S$  with a Random Forest model. The blue point represents the  
901 optimal model. c and d) Relative importance of the variables used by each optimized Random

902 Forest model to predict the variance in the  $k$  and  $S$  parameters in Austria and Sweden jointly.

903 The higher the Node purity, the higher the importance of such variable.

904

905 Figure 6 - Principal component analysis showing how the sites in Austria and Sweden differ

906 based on the variables. PC1 and PC2 are the first two components, explaining most variance.

907 The loadings (black arrows) are the weight of each variable in defining each principal

908 component. The size of the arrows can tell how much they contribute defining this space, while

909 the direction is their contribution on each axis. Tap: total annual precipitation; TxP: temperature

910 x precipitation factor; pet: potential evapotranspiration; mat: mean annual temperature; tn: total

911 soil nitrogen; soc: total soil organic carbon; cn: soil C:N ratio; ai: aridity index.