

1 **Title:** Integrating simulation data from a crop model in the development of an agri-
2 environmental indicator for soil cover in Switzerland

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35 **Abstract**

36 Agriculture generates important impacts on the environment, which can be evaluated with
37 agri-environmental indicators. A key element of environment protection in agriculture is the
38 maintenance of a dense soil cover for the longest possible period. Notably, soil cover is
39 known to diminish erosion risks and nitrate leaching. In this study, an agri-environmental
40 indicator for soil cover is presented, which integrates data from the crop model STICS to
41 quantify vegetation growth dynamics. Simulations were conducted with STICS for the major
42 crops cultivated in Switzerland across several contrasting pedoclimatic situations. They were
43 then integrated with data for crop residue cover to evaluate soil cover at the field and farm
44 levels in the framework of a farm network survey. At the field level, for the period from the
45 harvest of the previous crop through the harvest of the main crop, the highest soil cover was
46 achieved by silage maize and winter barley. A high variability between fields was observed,
47 due to the diversity of cultural practices during the period preceding the seeding of the main
48 crops. Some crops, winter wheat in particular, showed a high number of days with insufficient
49 soil cover (under 30%), leading to potential environmental risks. This shows the crucial need
50 of promoting conservation agriculture principles (permanent soil cover, minimum soil
51 disturbance, diversification of crop rotation) in arable systems to better protect the soils and
52 the environment. The soil cover indicator presented here provided a continuous quantification
53 of soil cover, whereas most of the currently used indicators provide qualitative or roughly
54 quantitative results.

55

56

57 **Keywords**

58 soil protection, conservation agriculture, farm network survey, agri-environmental monitoring

59

60 **1. Introduction**

61 Agriculture involves major modifications of the environment and directly influences soil and
62 water quality through crop rotation, tillage practices and crop management. In order to
63 evaluate the impact of agriculture on the environment, many agri-environmental monitoring
64 programs have been set up at the international (e.g. FAO, OECD, UN, EU) and national levels
65 (Giupponi and Carpani, 2006; Piorr, 2003; Yli-Viikari et al., 2007), including Switzerland
66 (FOAG, 2015). In this context, sets of indicators have been developed, aimed at evaluating
67 and quantifying the main pressures exerted by agriculture on natural resources. A decrease in
68 the impact of agriculture on the environment is a crucial issue for a more sustainable
69 development. This objective is at the core of conservation agriculture, which is being
70 promoted more and more as an alternative to intensive and environmentally damaging
71 conventional agriculture (Lahmar et al., 2001; Scopel et al., 2013). Conservation agriculture is
72 based on three main principles: 1. minimization of soil disturbance, 2. diversification of crops
73 in rotation and association, and 3. improvement of soil cover (Scopel et al., 2013). Among
74 these elements, soil cover plays a recognized role for environment protection, through
75 diminished wind and water erosion, limited leaching and run-off, increased weed control and
76 improved soil fertility (Blanchart et al. 2006; Dabney, 1998; Duran and Rodriguez, 2008;
77 Gilley et al. 1986ab; Thorup-Kristensen et al., 2003; Quinton et al., 1997; van Donk, 2010). A
78 minimum threshold value of 30% soil cover is generally recommended in order to achieve
79 this environmental protection role (FAO, 2015)

80 Soil cover embraces the cover offered by the crop itself as well as that provided by the crop
81 residues from the preceding crop. Several factors influence soil cover and have to be taken
82 into account in the development of an accurate soil cover indicator. The crop type determines
83 the amount of live cover as well as the amount of residues after harvest. Residue management
84 and tillage practices influence the proportion of residues incorporated in the soil after each

85 intervention. The pedoclimatic conditions affect the degradation of residues as well as the
86 growth of crops.

87 Soil cover indicators are generally included in monitoring programs such as that set up by the
88 OECD or EU (Piorr, 2003). However, most existing indicators rely on very simplistic
89 assumptions in order to evaluate soil cover (e.g. Bechini and Castoldi, 2009; Eurostat, 2015;
90 OECD, 2001). They usually count the number of days the soil is covered during a year, the
91 soil being fully covered or not at all, without offering any possibility of giving intermediate
92 values. Moreover, they often assume that soil is completely covered by vegetation from crop
93 seeding to harvest without taking into account the dynamics of crop growth, nor the winter
94 pause. A great improvement in these indicators was achieved with the indicator developed for
95 Canadian agriculture (Huffman et al., 2000, 2012, 2015; Lobb et al., 2007). The central idea
96 of this indicator is to evaluate the number of days an area is covered during one year, taking
97 into account that soil cover may continuously vary between 0 and 100%.

98 However, a huge quantity of data needs to be obtained for the computation of such a soil
99 cover indicator. Firstly, concerning the cover provided by residues, information is needed
100 about the degree of soil cover after harvest, the incorporation rate of residues during tillage
101 interventions, and the decomposition rate of residues. Secondly, for the cover provided by
102 crop vegetation, information is needed about emergence time, growth speed and vegetation
103 spatial spread. All this data could potentially be measured directly in the field, but the
104 computation of an indicator at large spatial scales renders direct measurements almost
105 impossible. In the absence of field data, technical literature can be used as a source of general
106 information on soil cover by residues. In contrast, data on the dynamics of soil cover by
107 growing crops is linked to pedoclimatic conditions and thus better assessed regionally. For
108 this reason, an alternative approach is to integrate simulation data from a crop model, taking
109 into account regional variations in crop development dynamics and phenology. Crop models

110 such as STICS (Brisson et al., 1998, 2002, 2003) simulate crop growth day by day, taking into
111 account real daily meteorological data, as well as principal soil characteristics, for a large
112 variety of crops. This model has been validated as a performing crop model in the literature
113 (e.g. Beaudoin et al. 2008; Constantin et al. 2012; Coucheney et al. 2015; Palosuo et al. 2011).
114 This study presents the first quantitative estimation of the soil cover for arable crop rotations
115 at the field and farm levels in Switzerland through the development of a soil cover indicator.
116 Using the model STICS, the dynamics of the main field crops for various Swiss climatic
117 regions and soils were simulated, with the aim of quantifying distinctive values of soil cover.
118 This new approach is expected to produce a large variation of specific results in substitution
119 to constant soil cover data and rough estimations used in current methodologies. These
120 simulations were then integrated with estimations of residue cover for the period before the
121 seeding of the main crop in order to quantify the soil cover for a full crop sequence. This
122 indicator was tested using a database collected by the Swiss agri-environmental data network
123 (SAEDN). It also aimed at evaluating the suitability of the method to explore more thoroughly
124 the differences in soil cover between arable crops, the effects of cropping techniques on soil
125 cover at field scale and the replication of these elements at the farm level.
126 This article presents first the crop soil cover dynamics simulated with the STICS model and
127 second the methodology, application and quantitative evaluation of the soil cover indicator in
128 the framework of the farm network database.

129

130

131 **2. Materials and methods**

132 *2.1. Soil cover indicator principle*

133 The computation principle of the indicator is based on the Canadian soil cover indicator
134 (Huffman et al., 2000, 2012, 2015; Lobb et al., 2007). The unit of computation is the

135 agricultural field. The indicator is expressed as the total number of soil cover days (SCD)
136 achieved over a given period, or as the corresponding average soil cover (ASC). The number
137 of SCD is obtained by summing, over the whole period, the daily soil cover value, which can
138 vary continuously between 0% and 100%. One SCD corresponds thus to a full cover (100%)
139 during one day or to a partial cover during more days, e.g. 2 days at 50%, 10 days at 10%.
140 The soil cover takes into account two main components: the residues left from the preceding
141 crop and the dynamic growth of vegetation. For both elements, databases have been built to
142 provide reference values for different agricultural situations.

143

144 2.2 Data collection

145 2.2.1 Cover by residues

146 The degree of cover by residues depends on the amount of residues after harvest, the
147 decomposition rate of these residues as well as the residue incorporation rate by tillage
148 operations. Quantitative information about these three aspects was obtained from technical
149 literature.

150 Soil cover after harvest for different crop types were collected from US extension services
151 documentation (Shelton et al., 1995; Iowa State University, 2009).

152 The residue decomposition function follows a negative exponential as a function of initial
153 residue mass and time (Steiner et al., 1999; Stott et al., 1995), and soil cover (SC) is
154 exponentially linked to residue mass (M) (Steiner et al., 2000; Stott et al., 1995).

$$155 M_t = M_0 * \exp(-K_D \times \Delta t)$$

$$156 SC = 1 - \exp(-K_m \times M)$$

157 where K_D is the decomposition coefficient and K_m a coefficient linking residue mass to
158 residue cover. The combination of these two equations allows an estimation of the soil cover
159 at any time:

$$160 SC = 1 - \exp[\log(1 - SC_0) * \exp(-K_D \times \Delta t)]$$

161 The use of calendar days to estimate residue decomposition is a simplistic assumption as its
162 rate, in fact, depends also on temperature, humidity, pH or soil biological activity. This
163 simplification leads to an overestimation of decomposition rate and should be considered as a
164 worst case scenario estimation.

165 The incorporation rate of residues, depending on specific tillage implements and field
166 operations, was obtained from US extension services documentation (Natural Resources
167 Conservation Service Ohio, 2002; Iowa State University, 2009), and adapted for Swiss
168 machinery.

169

170 2.2.2 Cover by crops

171 The daily cover provided by the crops is dependent on the dynamics of crop growth. The crop
172 model STICS v. 6.9 (Brisson et al., 1998, 2002, 2003) was used to simulate the growth and
173 evolution of soil cover of the main crops cultivated in a range of different pedoclimatic
174 conditions in Switzerland. This model was chosen because it is both robust and generic, and
175 has been thoroughly validated (e.g. Beaudoin et al. 2008; Constantin et al. 2012; Coucheney
176 et al. 2015; Palosuo et al. 2011). It also allows the simulation of many different crops. The
177 main inputs required by STICS are meteorological data (e.g. temperature, rainfall, solar
178 radiation, humidity, wind speed), pedological data (e.g. soil structure and depth, organic
179 nitrogen content, wilting point, field capacity, bulk density, organic matter, carbon/nitrogen
180 ratio) and data linked to crop management (e.g. crop type, seeding date, timing and rate of
181 fertilization, tillage methods).

182 Simulation scenarios were built in order to represent the diversity of Swiss agriculture
183 situations. Simulations were run for the factorial combinations of 10 crops and 3 seeding dates
184 (Table 1), 3 soil textures (Table 2), 3 soil depths (50, 100, 150 cm), 12 climatic regions (Table
185 3) and 27 cultural years (1982-2009). The climate data came from 12 automatic weather

186 stations in Switzerland operated by the Federal Office of Meteorology and Climatology
187 (MeteoSwiss: www.meteosuisse.admin.ch). For each crop, the seeding dates were set
188 according to standard agricultural practices in Switzerland. Soil textures and depths were
189 chosen to describe the main Swiss agricultural soils. In the same way, the climatic regions
190 were chosen to best represent the whole country. This gave a total of 87480 scenarios which
191 constituted then a reference database used to compute the vegetation component of the soil
192 cover indicator (see section 2.3).

193 The model output considered in this study was the daily evolution of leaf area index (*LAI*)
194 from seeding to harvest. An estimation of soil cover (*SC*) was obtained from *LAI* data using
195 the following relationship, derived from Beer's law:

$$196 \quad SC = 1 - \exp(-K \times LAI)$$

197 where *K* is the crop specific extinction coefficient (Adams and Arkins, 1977). Crop *K* values
198 were those used in STICS, except for winter wheat, winter barley and sugar beet whose *K*
199 were adjusted to match observed maximal soil cover.

200 To investigate the influence of the different crop species and conditions simulated (seeding
201 date, climate, soil) on crop soil cover, the cumulative and average crop soil cover was
202 computed over the whole vegetation period from seeding to harvest. For crops for which
203 harvest is determined by the grain maturity stage, STICS was able to simulate a realistic
204 harvest date. In contrast, the harvest of tuber, root and late maturing grain crops is determined
205 by other criteria and was not adequately simulated by STICS. For these crops, a default
206 harvest date was set (1st September for potato and silage maize, 1st November for grain maize
207 and sugar beet).

208

209 *2.3 Application in the framework of the farm network*

210 The soil cover data simulated with STICS and collected from technical literature were used to
211 compute the soil cover indicator for a dataset obtained from the Swiss agri-environmental data
212 network (SAEDN). Data collection began in 2009 and is currently ongoing. About 300 farms,
213 distributed over the whole country, participate in this survey and provide detailed calendars of
214 field operations with specific information about machines and production inputs.

215 Complete data was available for the years 2010, 2011 and 2012 for respectively 266, 272 and
216 266 farms, and a total of 5912, 6323 and 6100 fields. Soil cover was computed for each field
217 independently, for the period ranging from the harvest of the previous crop to harvest of the
218 main crop. This period could potentially also include the presence of cover crops before the
219 seeding of the main crop, which were also taken into account. For each field, information
220 about harvest, tillage and seeding interventions (dates and implements) were extracted from
221 the dataset.

222 Residue cover at the beginning of the computation phase was defined by the identity of the
223 preceding crop and the residue management adopted (left on the field or exported). Evolution
224 of residue soil cover was then estimated using the information about timing and incorporation
225 rates of the tillage interventions (see section 2.2.1). Crops with no specific data on residue
226 cover were assimilated to the most similar crop with available information.

227 Crop soil cover was estimated using the most appropriate dynamics in the STICS dynamics
228 database (see section 2.2.2) in terms of seeding date, field meteorological and geographic
229 situation, and soil type. Median daily soil cover over the 27 years simulated was used to get a
230 more conservative estimate. An exception was done for permanent meadows, which were
231 assumed to fully cover the soil during the whole period considered. To compute the SCD for
232 the vegetation phase, the results from the STICS simulations were adapted in function of the
233 real seeding and harvest dates. When the vegetation period was shorter than the simulated
234 one, the computation of SCD was stopped at the harvest date. In contrast, when the vegetation

235 period was longer, the growth curve simulated by STICS was continued until the harvest date
236 was reached, assuming maximal cover for each added day. For crops not simulated with
237 STICS, the soil cover dynamics was approximated by the most similar crop simulated.
238 Residues still remaining after crop seeding were taken into account by combining residue and
239 vegetation cover fractions.
240 For each field, the number of soil cover days (SCD) was then obtained by summing the daily
241 soil cover from the harvest of the previous crop to harvest of the main crop. Average soil
242 cover (ASC) was also calculated for each field. In addition, the number and proportion of
243 days with a soil cover below the threshold value of 30% (FAO, 2015) was computed for each
244 field. In the same manner, the proportion of fields with a soil cover below 30% at a given time
245 in year was computed. At the farm level, the indicator was computed as the mean of the soil
246 cover of each field, weighted by its respective area.
247 Computations were performed using R 3.0.1 (R Core Team, 2013).

248

249

250 **3. Results**

251 *3.1 Crop soil cover dynamics with STICS*

252 The soil cover dynamics simulated with STICS gave different results depending on the crop,
253 seeding dates and pedoclimatic conditions (Figure 1). The cumulative soil cover was strongly
254 dependent on the duration of the vegetation period from seeding to harvest (Figure 2A).
255 Winter rapeseed reached the highest cumulative soil cover, especially with early seeding.
256 Among winter crops, winter barley also showed a high cumulative soil cover. The seeding
257 date had a strong influence on soil cover dynamics for winter crops, especially on the degree
258 of cover reached at the beginning of winter and persisting throughout this season (Figure 1),
259 and thus on the total cumulative soil cover achieved (Figure 2A). As expected, summer crops

260 achieved a lower cumulative soil cover than winter crops. Sugar beet and grain maize had the
261 highest cumulative soil cover among the summer crops. However, in terms of average soil
262 cover, some summer crops (e.g. grain maize, sugar beet, potato) achieved a soil cover similar
263 to the highly covering winter rapeseed (Figure 2B). In contrast, winter wheat and pea
264 performed less well, with an average soil cover (late seeding case) as low as 29% and 31%,
265 respectively, for a long vegetation period (Figure 2B).

266 As all factorial combinations were considered to establish the scenarios simulated with
267 STICS, a large variability in crop dynamics was obtained. Among these, many limiting and
268 non-realistic situations were simulated. In such situations, soil cover was very low or harvest
269 dates were too early or too late, and sometimes a complete crop failure was simulated. To
270 understand from where this variability arose, the coefficient of variation of cumulative soil
271 cover was computed for each potential source of variation (Table 4). The year of simulation
272 showed a coefficient of variation between 6% and 17%. So to get a standard reference of crop
273 growth in each pedoclimatic condition, and to reduce the influence of the limiting situations
274 simulated, median values over the 27 years of simulation were used for the soil cover
275 indicator. Among the other sources of variation, seeding date had the major influence on the
276 cumulative soil cover for winter crops, while the soil characteristics and the climate had a
277 weaker effect on winter crop growth (Table 4). Concerning summer crops, much less
278 variability in cumulative soil cover was observed. The climatic factor showed here the highest
279 coefficients of variation (Table 4).

280

281 *3.2 Soil cover indicator*

282 3.2.1 Agricultural field level

283 The use of the SAEDN data enabled successful computation of the soil cover indicator for
284 4538, 4981 and 4894 fields, for the years 2010, 2011 and 2012, respectively, representing

285 about 79% of the total fields considered. The discarded fields were ones not belonging to
286 grassland or cropland categories. Of the fields retained, about 78% were exclusively
287 permanent grassland fields, 20% had an annual crop as the main crop, and 2% were temporary
288 meadows. The six most frequent crops were winter wheat (28%), silage maize (17%), winter
289 barley (9%), winter rapeseed (8%), sugar beet (5%) and potato (5%), representing a total of
290 72% of the annual crop fields.

291 Figure 3 shows an example of daily soil cover dynamics simulated for winter rapeseed
292 following winter wheat. During the period from wheat harvest to rapeseed harvest a total of
293 254 soil cover days SCD were accumulated for 343 calendar days, corresponding to an
294 average soil cover ASC of 66%. In the whole dataset, the average soil cover of rapeseed as
295 main crop ranged from about 40% up to 85%. The comparison of the soil cover for the six
296 most frequent main crops showed a wide range of soil cover (Figure 4). Winter barley and
297 silage maize achieved the highest soil cover, with median values of 69% and 75%,
298 respectively, although high variability was observed. The highest variability was observed for
299 summer crops. Summer crops have short duration and so a major part of the indicator
300 computation period (from harvest to harvest) was composed by the pre-sowing period, which
301 can show high variability in soil cover level, depending on the cropping techniques applied
302 (Figure 5). In contrast, the degree of soil cover associated with the crop was far less variable.
303 For winter crops, the relative contribution of the pre-sowing period was small compared to the
304 in-crop period, which explains the smaller variability of average soil cover for winter crops
305 (Figure 5).

306 Six simulated scenarios with different pre-sowing period managements (with grain maize as
307 main crop and winter wheat as preceding crop) showed the effect of cropping techniques on
308 soil cover (grey lines in Figure 6). In the first scenario S1, no cover crop was seeded between
309 the harvest of the wheat and the seeding of the maize. The other scenarios integrated a non-

310 legume cover crop (e.g. mustard) with varying seeding and destruction dates. In scenarios S2
311 (late seeding) and S3 (early seeding) the cover crop was destroyed before winter. In contrast,
312 the cover crop was maintained until seeding of the grain maize for scenarios S4 (late seeding),
313 S5 (early seeding) and S6 (early seeding). The cover crop was destroyed by plough in all
314 scenarios except scenario S6 for which a mulch seeding of maize was simulated. The soil
315 cover achieved by each scenario was then computed with the indicator presented in this study.
316 A key factor influencing the soil cover was the presence or absence of a cover crop during the
317 intercrop period (Figure 6). The destruction date of the cover crop also strongly impacted soil
318 cover, with cover ranging from 36% to 77% (scenarios S2 to S4). The estimated soil cover
319 values obtained for the grain maize fields in the study dataset were then compared to these six
320 simulated scenarios to infer possible explanations for the variability in soil cover (dark bars in
321 Figure 6). The observed values formed two rather distinct clusters, the first with cover levels
322 similar to the scenarios with no cover crops or with a cover crop destroyed before winter, and
323 the second one close to the scenarios with overwintering cover crops.

324 For each crop, the proportion of days with a soil cover below 30% followed a pattern inverse
325 to soil cover (Figure 4). The highest proportion of insufficiently covered days was for winter
326 wheat (median value: 51%) and the lowest for winter barley (14%). High values were also
327 observed for sugar beet (34%) and potato (46%). The analysis of the evolution through time
328 of the proportion of fields under 30% soil cover gave more precise insights (Figure 7). For
329 winter crops, the poorly covered period is the end of summer (pre-sowing) and autumn,
330 during initial phase of crop growth. For winter wheat, this period continued over winter until
331 March as wheat was generally not enough developed at the beginning of the winter growth
332 pause to cover soil properly. For summer crops, the crucial period was also the initial phase of
333 crop growth, mostly in the April and May months. The evolution of the proportion of fields

334 under 30% during the pre-sowing period depended on the timing of tillage interventions and
335 the use of cover crops.

336

337 3.2.2 Farm level

338 The weighted average soil cover was computed at the farm level for a total of 226, 240 and
339 243 farms in 2010, 2011 and 2012, respectively. Farms were classified by using a standard
340 typology classification (FAT99S3 typology as defined in Meier (2000)). The most frequent
341 typology was dairy farming with 28% of the farms, followed by intensive livestock farming
342 (16%), suckler cow farming (11%), combined type dairy/arable farming (11%) and arable
343 farming (7%).

344 Dairy farming exhibited really high cover (median value: 98%) due to the almost exclusive
345 presence of grassland fields. The other two typologies which included livestock had an
346 average soil cover of about 90% (median value). In contrast, arable farming achieved an
347 average soil cover around 61%. As expected, mixed arable/dairy farming achieved a soil
348 cover lying between pure arable and dairy farming (78%). Here again, the proportion of days
349 with a soil cover below 30% followed a pattern inverse to soil cover. Arable farming showed
350 a median of 30% of days, while the median value was 0% for dairy farming and 16% for
351 mixed arable/dairy farming.

352

353

354 **4. Discussion**

355 *4.1 Evaluation of soil cover*

356 The use of a crop model to generate data about the dynamics of vegetation development, and
357 hence soil cover, proved to be an interesting way of taking into account different crops and
358 pedoclimatic conditions. The soil cover achieved at the field scale was strongly dependent on

359 the choice of the crop and on the cultural practices adopted. Among the six most frequent
360 crops, the mean of the soil cover ranged from 46% to 69%. In comparison, Bechini &
361 Castoldi (2009), with a simpler computation method, obtained lower values for various crop
362 successions in northern Italy (mean soil cover ranging from 34% to 51%). For summer crops,
363 the long pre-sowing period, ranging from the harvest of the previous crop to the seeding of the
364 main crop, allowed large differences in the soil cover achieved, depending on the application
365 of specific management practices. In particular, the simulation of six pre-sowing period
366 management scenarios showed the crucial importance of cover crops on soil cover. The effect
367 of cover crops was maximized by an early establishment of the cover and by a late
368 destruction. These results highlighted the crucial role of cover crop management. Studies have
369 shown that cover crops can in turn improve soil protection and quality (Dabney et al., 2001;
370 Thorup-Kristensen et al., 2003).

371 At the farm level, our results revealed that the average soil cover achieved by arable farming
372 was much lower than for dairy farming. Few comparable data exist in the literature, which
373 impedes a proper evaluation of the results obtained at the farm level. Nevertheless, results
374 aggregated at the regional level could be used to give a raw point of comparison. For
375 example, in Canada, with the method from which the present indicator was derived, Huffman
376 et al. (2012) reported mean soil cover ranging from 67% to 85% for different soil zones. At
377 the European level, the IRENA report indicated that approximately 56% of arable land
378 achieved a soil cover of 70% and 24% of land achieved 80% of soil cover throughout the year
379 (European Environment Agency, 2005). At the country level, mean annual soil cover ranged
380 from 11% to 80% in Europe (Eurostat, 2015). These values were, however, based exclusively
381 on cover by crops and did not take into account the pre-sowing period or the potential
382 presence of residue cover.

383

384 *4.2 Consequences for the environment*

385 Soil cover indicators are generally classified in the driving forces category in the DPSIR
386 (driving forces – pressures – state – impact - responses) classification from the European
387 Environment Agency. Soil cover is thus not considered a direct measure of the impact of
388 agriculture on the environment, but rather a key element in the prevention of damage. Indeed,
389 soil cover is directly or indirectly linked to important processes such as soil erosion, water
390 run-off, nutrient leaching, soil fertility, biodiversity (Blanchart et al., 2006; Dabney, 1998;
391 Duran and Rodriguez, 2008; Gilley et al., 1986ab, Thorup-Kristensen et al., 2003; Quinton et
392 al., 1997). Although these risks tend to diminish continuously with increased soil cover, a soil
393 cover of 30% is often chosen as a threshold value for risk assessment, especially concerning
394 erosion and run-off (Lilley and Moore, 2009). A threshold of 30% cover is also used in the
395 definition of conservation agriculture (FAO, 2015). In the European statistics, less than 30%
396 annual mean soil cover is considered as low, whereas a cover between 50% and 75% is
397 considered as a moderate coverage (Eurostat, 2015). So the quantification of the number of
398 days and fields under this threshold allowed assumptions relative to environmental
399 consequences. Our results showed two periods poorly covered and potentially at risk,
400 corresponding to the initial stage of both winter and summer crop growth. When pooling
401 together the results for the six most frequent crops in the database, the period ranging from
402 September to the end of February presented the highest number of fields under 30% soil
403 cover. In Switzerland, rainfall is substantial and distributed more or less evenly over the year
404 (monthly rainfall from 72 mm to 132 mm, median value over all meteorological stations,
405 MeteoSwiss data). Our results show thus that winter would be a crucial period for soil erosion
406 and nutrient leaching. This outcome is largely due to the high proportion of fields cultivated
407 with winter wheat in the database, reflecting the Swiss situation where winter wheat
408 represents 32% of the field crop area (FOAG, 2014). At the European level, soil cover during

409 winter is also given a particular focus, showing that this period is particularly at risk (Eurostat,
410 2015). The seeding date of winter crops, and especially wheat, showed a significant influence
411 on the soil cover reached at the beginning of winter, when growth pauses. However in most
412 cases early seeding alone does not allow to reach 30% soil cover before winter. Short cycle
413 cover crops associated with reduction of the intensity of tillage would be a way to increase
414 soil protection and to reduce environmental risks.

415 At farm level, for arable farming, about 30% of the time period showed soil cover below the
416 30% threshold, for a median soil cover of about 60%. On an annual basis this is equivalent to
417 about 110 days at risk. The median annual rainfall over all Swiss meteorological stations
418 (MeteoSwiss data) is 1237 mm distributed in 133 rain days (>1 mm) and each month has
419 between 10 and 13 rain days,. The probability that rain and even heavy rain days occur during
420 the 110 days not sufficiently covered is thus really high. This shows that in terms of soil
421 protection, arable farming is still far from providing enough soil cover compared to other
422 farming systems. Increasing soil cover and duration of covered period appeared to be
423 beneficial for the environment, and is thus strongly promoted in the framework of
424 conservation agriculture (Scopel et al., 2013). In 2005, about 15% of arable land was
425 cultivated in conservation agriculture and a further increase is expected (Epperlein et al.,
426 2010). A wider adoption of conservation agriculture principles is crucial in order to improve
427 long-term sustainability of soils. Nevertheless, permanent soil cover could also present some
428 disadvantages for crop cultivation and requires proper management (Soane et al., 2012).

429

430 *4.3 Strengths and weaknesses of the indicator*

431 Most existing indicators rely on very simplistic assumptions about soil cover by crops (e.g.
432 Bechini and Castoldi, 2009; EU; OECD). They are thus less sensitive to regional variations in
433 crop growth dynamics. In the present study, the use of simulation data from the crop model

434 STICS enabled consideration of the influence of pedoclimatic conditions and growth
435 dynamics on the amount of soil cover achieved. In addition, the huge quantity of data
436 collected from the farm network survey, which provided very precise data at the field level,
437 enabled computation of a very fine-grained indicator, while at the same time including many
438 particular cases. The validity of the indicator thus strongly relies on the precision and quality
439 of data collected at the farm level.

440 In this study, a bottom-up approach was adopted, starting at the field level, then aggregating
441 the values obtained at the main crop, farm and farming category levels. Thus, the
442 extrapolation of results to the whole country depends on the representativeness of the farms
443 included in the survey relative to the Swiss farming situation. As the farmers took part in this
444 survey on a voluntary basis, there is a potential bias in the farm sampling. However, the
445 proportion of the different crops observed in the database was similar to that observed at the
446 Swiss level (Spycher et al., 2013). Another possible approach to estimate the indicator on a
447 wide scale would have been to directly use statistical data for the crop surfaces and link them
448 with cultural practices at the regional or national scale (e.g. Huffman et al., 2012). The
449 disadvantage of such a method is the obligation to establish standard scenarios of crop
450 cultivation, discarding important information about crop sequence and rotation, crop specific
451 tillage method or climatic region particularities.

452 An important improvement in the accuracy of the indicator would be to run simulations with
453 STICS for each field independently, using the real data from the farm dataset and from local
454 meteorological stations. However, this would necessitate additional data collection and
455 handling far beyond the scope of this study and the relevance of the model.

456 A comparison of the evaluation presented here with real data about the evolution of soil cover
457 over time would be an important validation step of the developed indicator. This could be
458 achieved in the future thanks to the increasing availability of devices providing aerial images,

459 from which soil cover estimations may be obtained. The pros and cons of both approaches
460 could then be compared, and their respective efficiencies evaluated.

461

462

463 **5. Conclusions**

464 Using the crop model STICS, we have provided the first quantitative estimation of soil cover
465 at the field and farm level in Switzerland. We showed that 1. the use of a crop model to
466 account for crop growth dynamics provided a detailed description of the evolution of soil
467 cover through time, 2. the total soil cover provided by residues and crops is strongly
468 dependent on the crop choice and on cultural practices, 3. soil cover during the pre-sowing
469 period, from harvest of the preceding crop to seeding of the main crop, can be increased using
470 alternative management, 4. depending on the crop, a high number of days show insufficient
471 soil cover to prevent environmental risk 5. in Switzerland, arable farming achieves an
472 average soil cover of 61%, a very low value compared to almost full cover for dairy farming.
473 The modelling approach used in this study provides a more versatile tool than the application
474 of constant reference values or a direct measurement approach. The present indicator could
475 help as a decision support tool to better design crop rotation and innovative management
476 strategies to maximise soil protection. From the information so far obtained, a substantial
477 increase in soil cover could already be achieved, thanks to adapted crop management,
478 considering the low levels attained in arable farms and the large variations observed among
479 crops. This improvement could be consolidated by the adoption of innovative cropping
480 techniques within the framework of conservation agriculture, such as systematic use of cover
481 crops properly managed over winter, introduction of short cycle cover crops, reduction of soil
482 tillage intensity, relay intercropping adoption, crop rotation intensification in time.

483

484

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663 **Table and figure legends**

664

665 **Table 1:** Crops simulated with STICS and corresponding seeding dates.

666

667 **Table 2:** Soil textures used for the simulations and corresponding soil classification according
668 to the USDA and Swiss texture triangles.

669

670 **Table 3:** Meteorological stations used for the simulations with STICS, with their main
671 characteristics: altitude (asl), average monthly temperature, and average cumulated annual
672 rainfall during the 27 cultural years 1982-2009.

673

674 **Table 4:** Coefficient of variation of the cumulative soil cover for different sources of
675 variation. Year: year of simulation, Seeding: seeding date, Climate: meteorological station,
676 Soil: combination of soil texture and depth.

677

678 **Figure 1:** Daily soil cover as a function of time for the six principal crops. A. winter wheat,
679 B. winter rapeseed, C. winter barley, D. silage maize, E. sugar beet, F. potato. Each line
680 corresponds to the median value over the 27 years of simulation for 1 seeding date in 1
681 specific soil and 1 meteorological station. For late summer crops, the harvest date is fixed
682 relatively to technical considerations not taken into account by STICS (in grey the part not
683 taken into account in the computation).

684

685 **Figure 2:** A. Cumulative soil cover and B. average soil cover of each crop simulated with
686 STICS, as a function of the duration of the vegetation period (from seeding to harvest), for the
687 three seeding dates (median values over the 27 years of simulation). The labels are positioned
688 at the median values over pedoclimatic conditions and the bars represent the 25% and 75%

689 quantiles. WW: winter wheat, WR: winter rapeseed, WB: winter barley, WP: winter pea, SM:
690 silage maize, GM: grain maize, SB: sugar beet, PT: potato, SY: soybean, SF: sunflower. 1:
691 early seeding, 2: standard seeding, 3: late seeding.

692

693 **Figure 3:** Example of estimated daily soil cover dynamics from the harvest of a winter wheat
694 to the harvest of a winter rapeseed. The pale line represents cover by the residues, the dark
695 line the cover by the crop vegetation.

696

697 **Figure 4:** Average soil cover ASC at the field level (computed from the harvest of the
698 preceding crop to the harvest of the main crop) based on simulations applied to the Swiss
699 agri-environmental data network, for the six main crops cultivated in Switzerland (winter
700 wheat, winter rapeseed, winter barley, silage maize, sugar beet and potato). The crosses
701 represent, for each crop, the median proportion of days below the threshold value of 30% soil
702 cover (secondary y axis).

703

704 **Figure 5:** Total number of soil cover days SCD at the field level achieved respectively by the
705 residues from previous crop and potential cover crops (light boxes) and by the main crop
706 vegetation (dark boxes), for the six principal crops: A. winter wheat, B. winter rapeseed, C.
707 winter barley, D. silage maize, E. sugar beet, F. potato.

708

709 **Figure 6:** Average soil cover ASC for all the fields of grain maize in the dataset (histogram).
710 The horizontal lines represent soil cover values for six simulated scenarios (S1 to S6) of the
711 management of the pre-sowing period between the harvest of a winter wheat and the seeding
712 of a grain maize (seeding 01.05, harvest 15.10; cover crop destroyed by ploughing unless
713 specified).

714

715 **Figure 7:** Proportion of fields with soil cover under the 30% threshold for the six principal
716 crops, for the period from the 1st of August of the first year, to the 1st of October of the
717 second year. A. winter wheat, B. winter rapeseed, C. winter barley, D. silage maize, E. sugar
718 beet, F. potato.

719 **Table 1**

	Seeding date		
	Early	Standard	Late
Winter wheat	01.10	01.11	01.12
Winter rapeseed	15.08	01.09	15.09
Winter barley	15.09	01.10	10.10
Winter pea	01.10	15.10	30.10
Silage maize	15.04	10.05	15.05
Grain maize	15.04	10.05	15.05
Sugar beet	15.03	01.04	15.04
Potato	10.04	20.04	01.05
Soybean	20.04	01.05	15.05
Sunflower	10.04	20.04	01.05

720

721

722 **Table 2**

USDA classification	Swiss classification	Clay	Silt	Sand
Clay	Silty clay	45%	25%	30%
Sandy clay loam	Loamy	25%	25%	50%
Sandy loam	Sandy loam	8%	25%	67%

723

724

725 **Table 3**

	Altitude [m]	T January [°C]	T July [°C]	Rainfall [mm]
Aigle	381	1.3	19.2	1015
Basel	316	1.9	19.9	837
Bern	553	0.2	18.8	1059
Changins	455	1.6	19.9	999
Chur	556	1.1	19.1	855
Luzern	454	0.7	19.5	1191
Magadino	203	1.5	21.8	1822
Payerne	490	0.4	19.1	882
Reckenholz	443	0.3	19.0	1027
Schaffhausen	438	0.3	19.2	893
Sion	482	0.5	20.1	606
Taenikon	539	-0.4	18.1	1169

726

727

728 **Table 4**

	Source of variation			
	Year	Seeding	Climate	Soil
Winter wheat	0.17	0.46	0.08	0.02
Winter rapeseed	0.14	0.27	0.05	0.03
Winter barley	0.06	0.08	0.03	0.02
Winter pea	0.19	0.35	0.12	0.04
Silage maize	0.11	0.08	0.07	0.05
Grain maize	0.06	0.02	0.05	0.04
Sugar beet	0.07	0.01	0.10	0.04
Potato	0.07	0.05	0.06	0.05
Soybean	0.14	0.02	0.14	0.03
Sunflower	0.08	0.00	0.07	0.03

729

730

Figure 1
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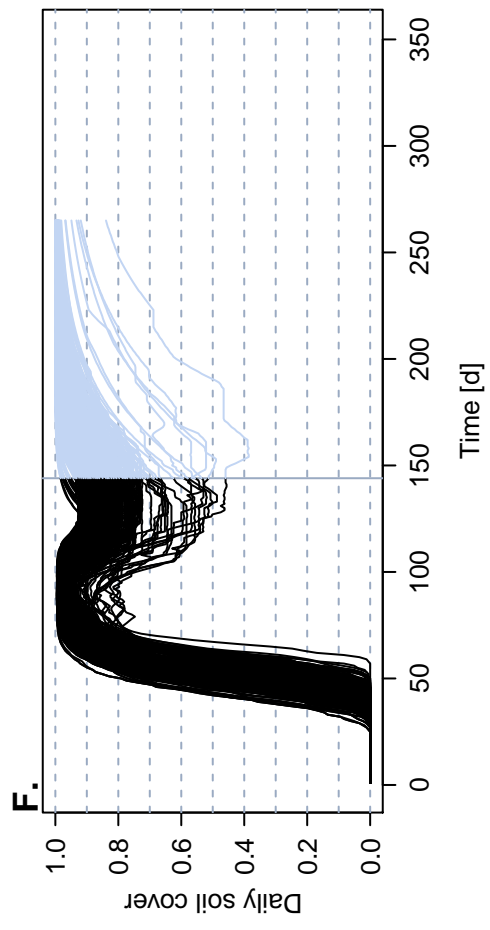
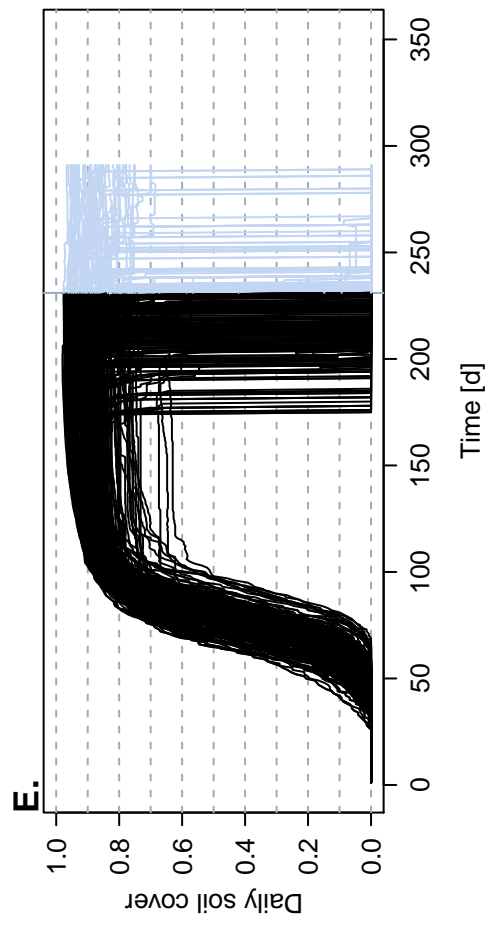
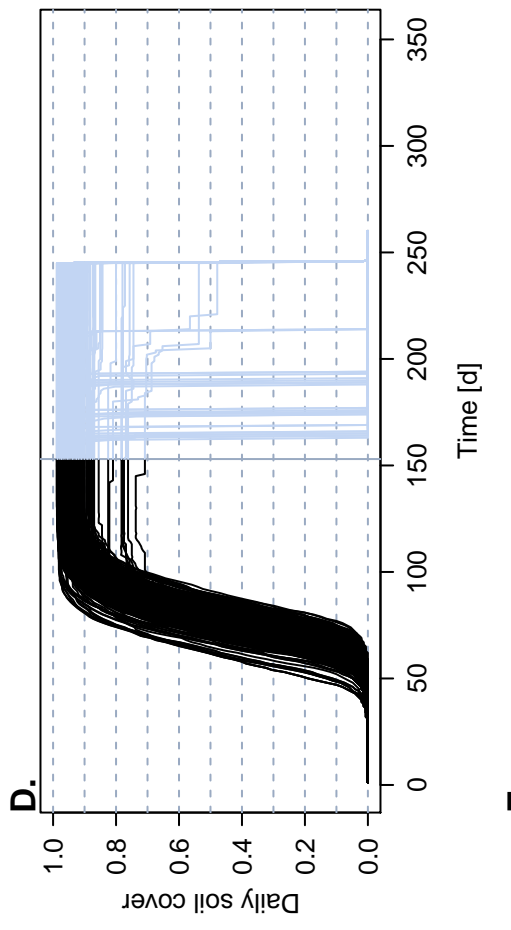
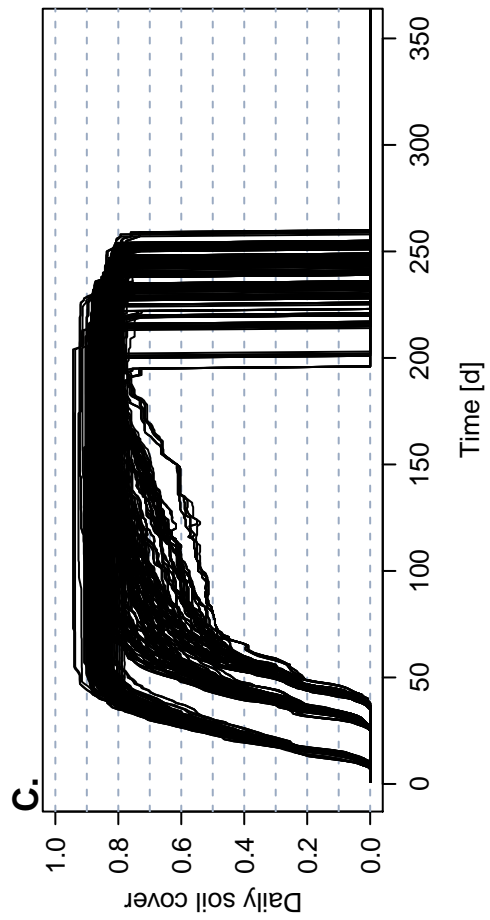
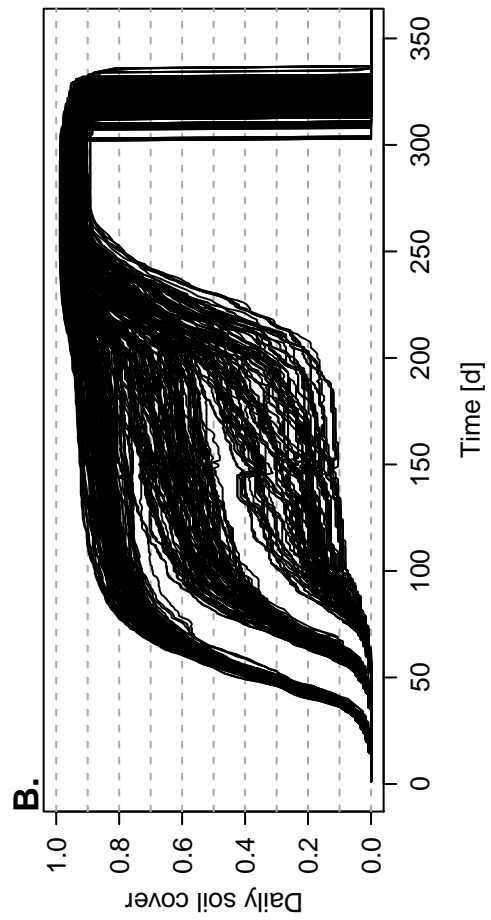
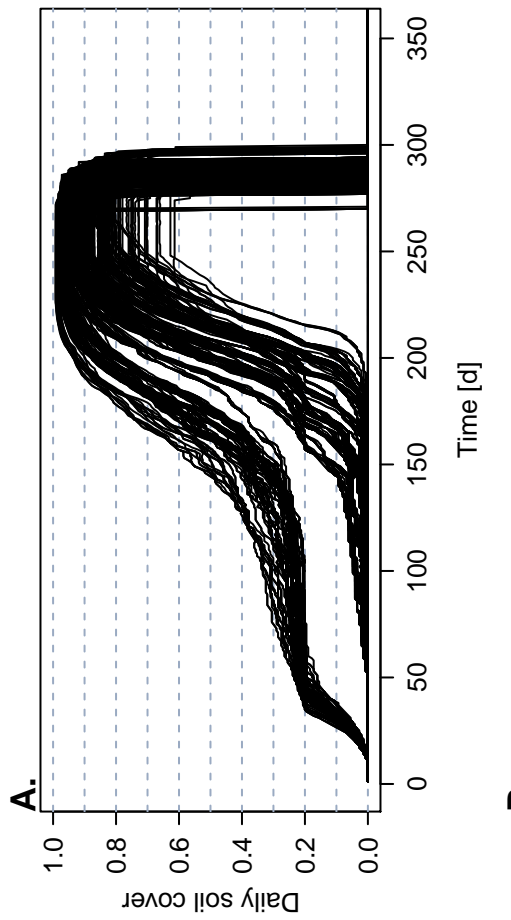


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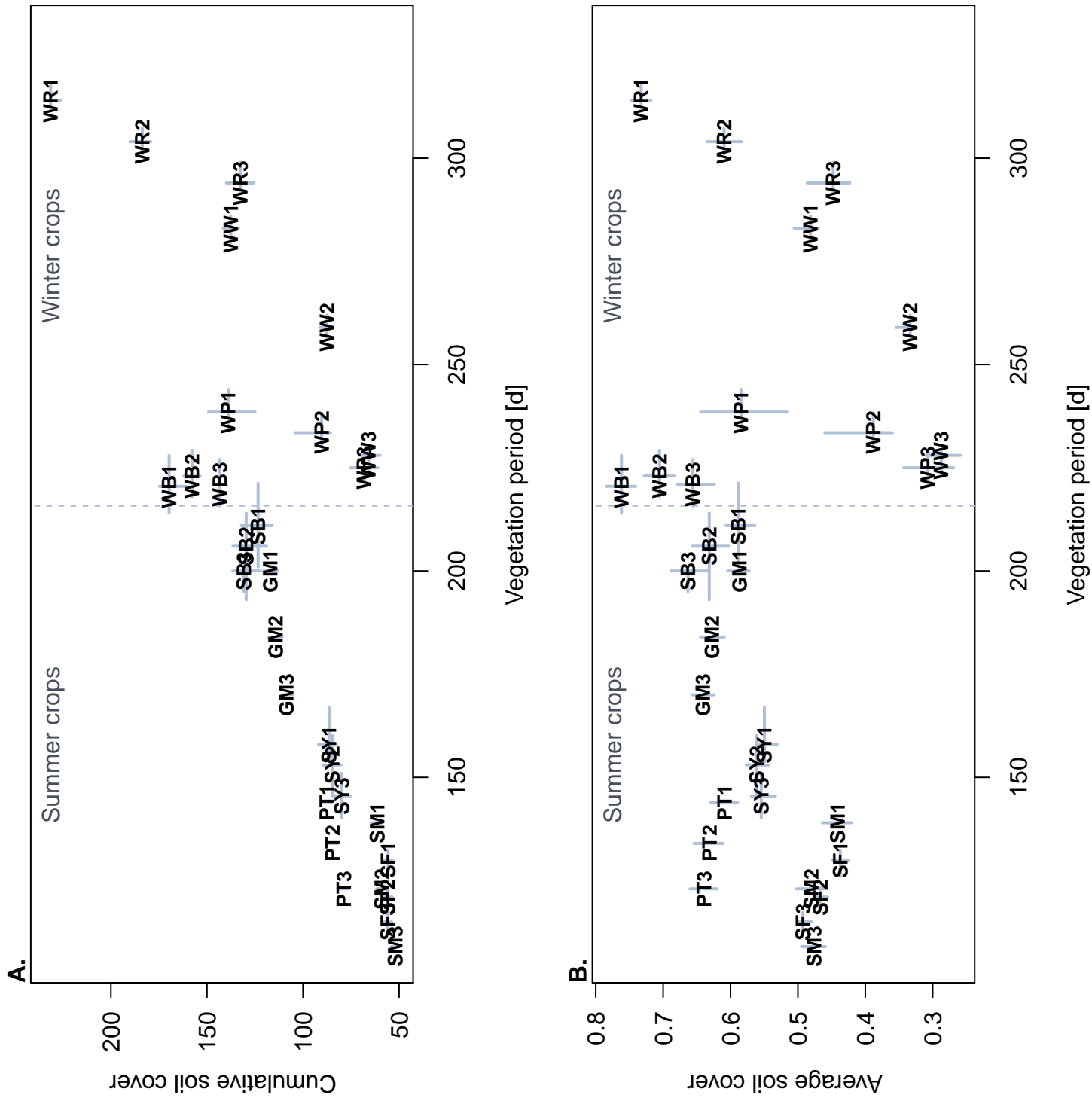


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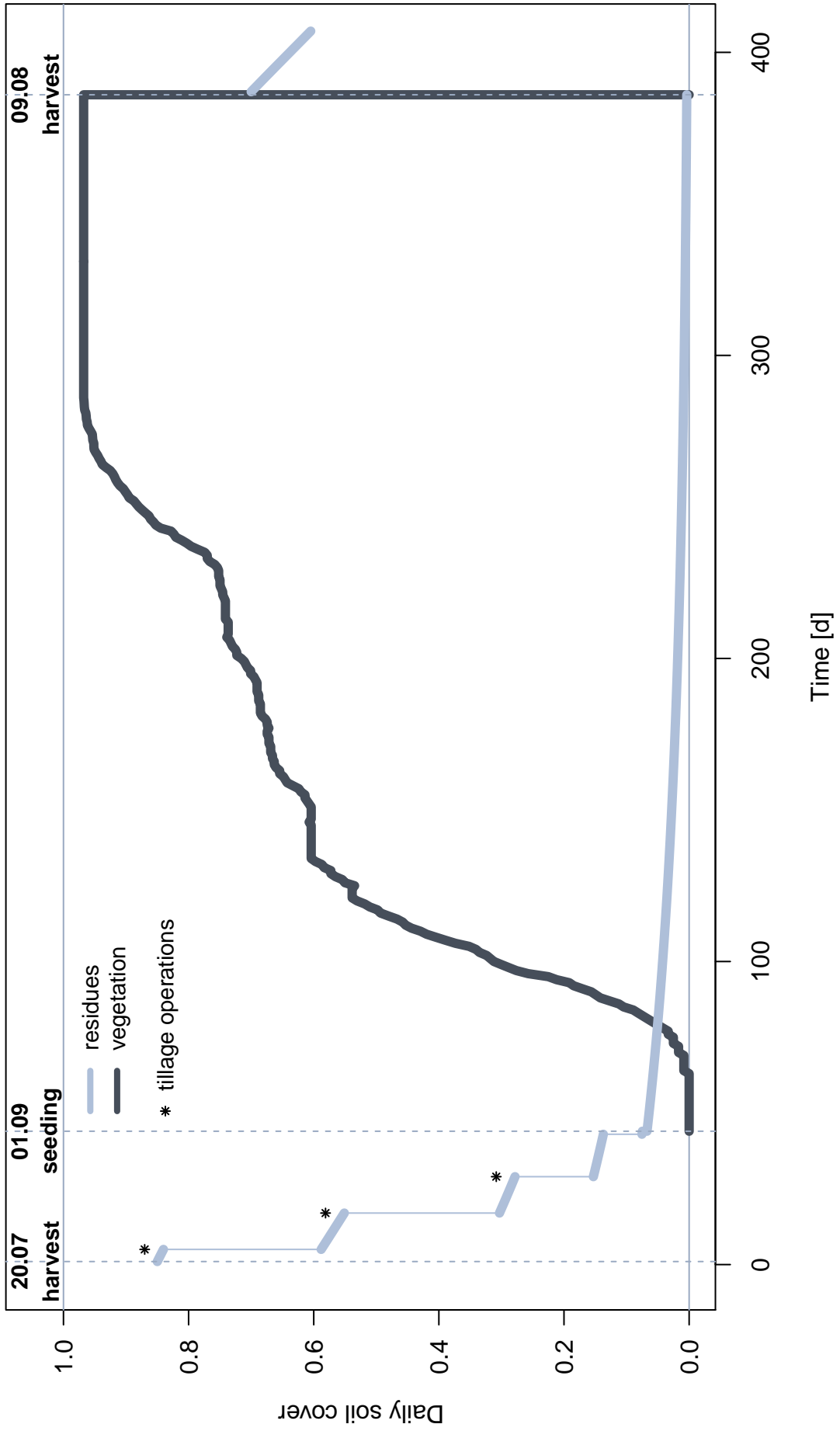


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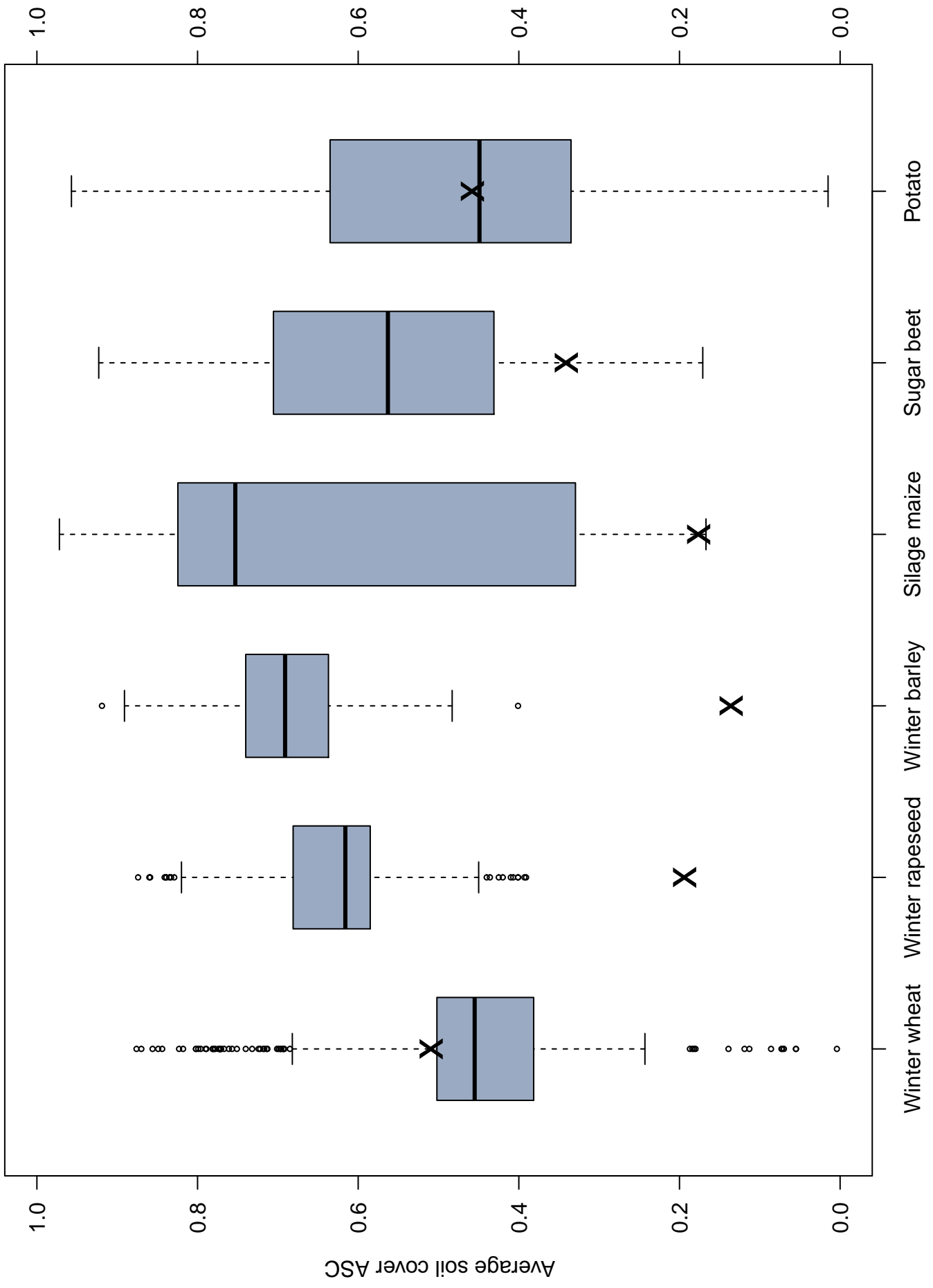


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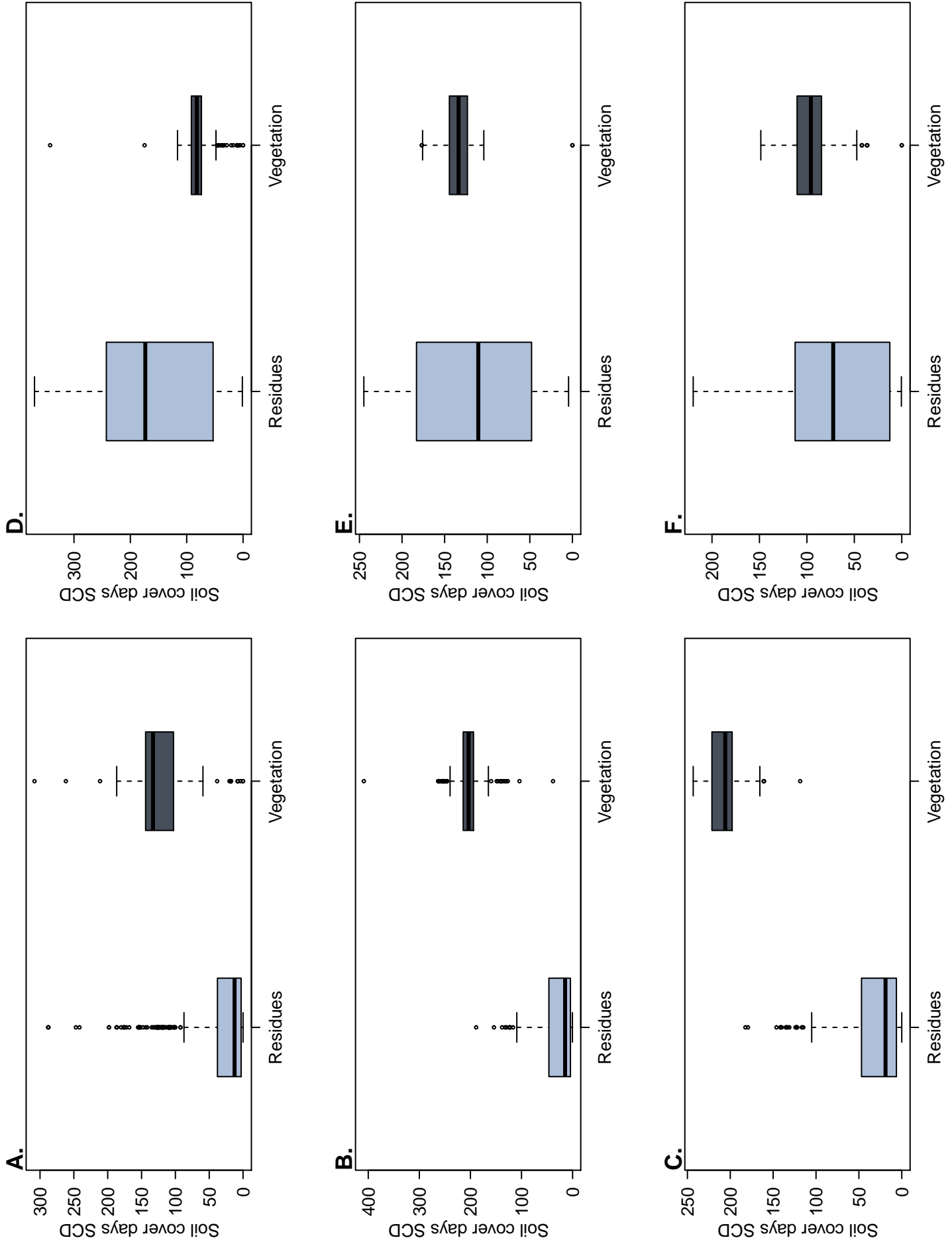


Figure 6

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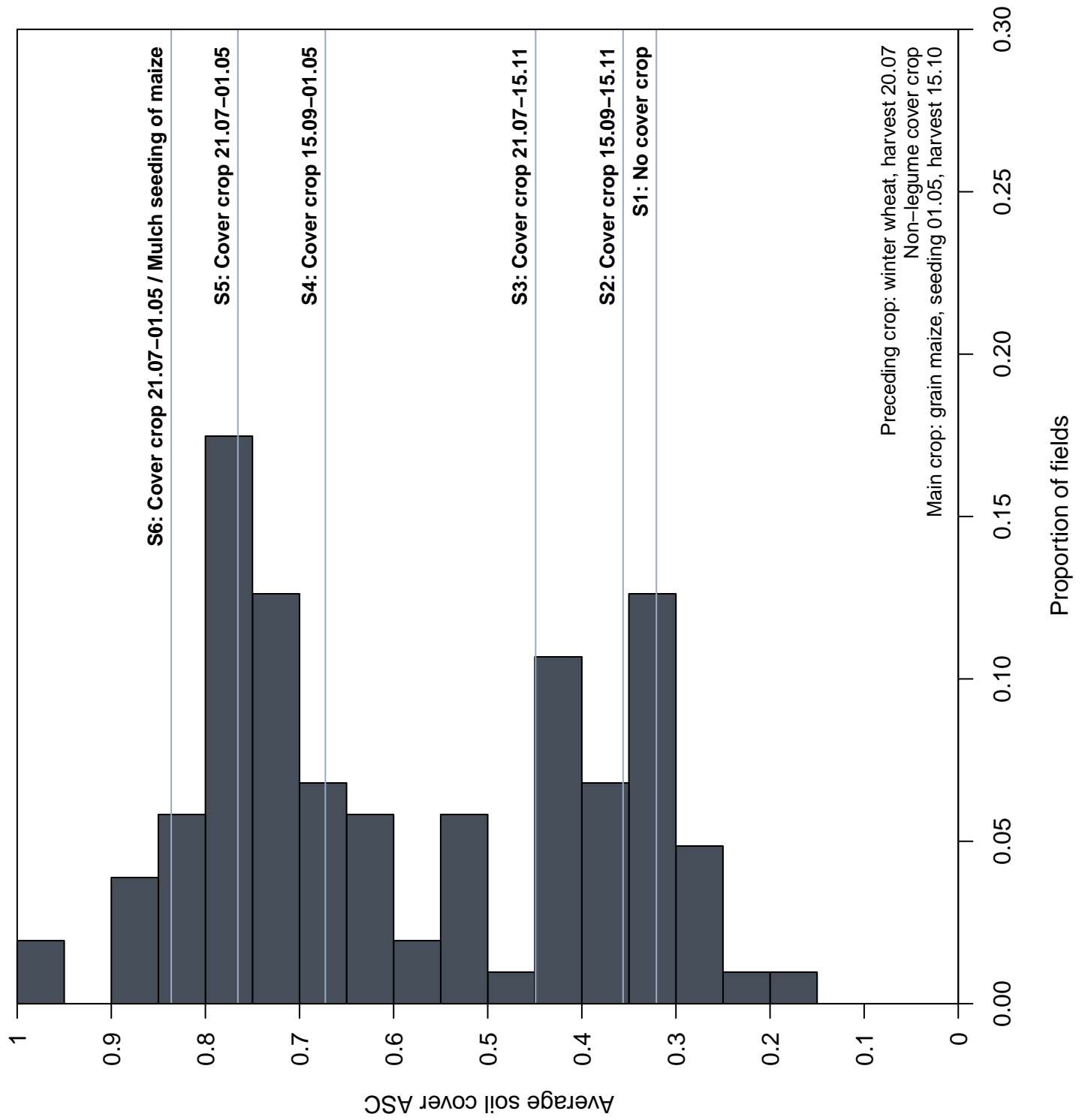


Figure 7
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