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

Authors

Lucie Büchi[a], Alain Valsangiacomo[b], Enguerrand Burel[a,1], Raphaël Charles[a,]*

Affiliations

[a]Agroscope, Institute for Plant Production Sciences
1260 Nyon 1
Switzerland

[b]Agroscope, Institute for Sustainability Sciences
8046 Zürich
Switzerland

[1]Present address: Centre d'Etudes Spatiales de la Biosphère UMR 5126, 32000 Auch, France

Email addresses

lucie.buchi@agroscope.admin.ch
alain.valsangiacomo@agroscope.admin.ch
enguerrand.burel@iut-tlse3.fr
raphael.charles@agroscope.admin.ch

***Corresponding author**

Raphaël Charles

Agroscope, Institute for Plant Production Sciences
Route de Duillier 50
CP 1012
1260 Nyon 1
Switzerland
Email: raphael.charles@agroscope.admin.ch
Phone: +41 58 460 46 59

Abstract

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

Keywords

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

1. Introduction

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

Soil cover embraces the cover offered by the crop itself as well as that provided by the crop residues from the preceding crop. Several factors influence soil cover and have to be taken into account in the development of an accurate soil cover indicator. The crop type determines the amount of live cover as well as the amount of residues after harvest. Residue management and tillage practices influence the proportion of residues incorporated in the soil after each intervention. The pedoclimatic conditions affect the degradation of residues as well as the growth of crops.

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

However, a huge quantity of data needs to be obtained for the computation of such a soil cover indicator. Firstly, concerning the cover provided by residues, information is needed about the degree of soil cover after harvest, the incorporation rate of residues during tillage interventions, and the decomposition rate of residues. Secondly, for the cover provided by crop vegetation, information is needed about emergence time, growth speed and vegetation spatial spread. All this data could potentially be measured directly in the field, but the computation of an indicator at large spatial scales renders direct measurements almost impossible. In the absence of field data, technical literature can be used as a source of general information on soil cover by residues. In contrast, data on the dynamics of soil cover by growing crops is linked to pedoclimatic conditions and thus better assessed regionally. For this reason, an alternative approach is to integrate simulation data from a crop model, taking into account regional variations in crop development dynamics and phenology. Crop models such as STICS (Brisson et al., 1998, 2002, 2003) simulate crop growth day by day, taking into account real daily meteorological data, as well as principal soil characteristics, for a large variety of crops. This model has been validated as a performing crop model in the literature (e.g. Beaudoin et al. 2008; Constantin et al. 2012; Coucheney et al. 2015; Palosuo et al. 2011). This study presents the first quantitative estimation of the soil cover for arable crop rotations at the field and farm levels in Switzerland through the development of a soil cover indicator. Using the model STICS, the dynamics of the main field crops for various Swiss climatic regions and soils were simulated, with the aim of quantifying distinctive values of soil cover. This new approach is expected to produce a large variation of specific results in substitution to constant soil cover data and rough estimations used in current methodologies. These simulations were then integrated with estimations of residue cover for the period before the seeding of the main crop in order to quantify the soil cover for a full crop sequence. This indicator was tested using a database collected by the Swiss agri-environmental data network (SAEDN). It also aimed at evaluating the suitability of the method to explore more thoroughly the differences in soil cover between arable crops, the effects of cropping techniques on soil cover at field scale and the replication of these elements at the farm level.

This article presents first the crop soil cover dynamics simulated with the STICS model and second the methodology, application and quantitative evaluation of the soil cover indicator in the framework of the farm network database.

2. Materials and methods

2.1. Soil cover indicator principle

The computation principle of the indicator is based on the Canadian soil cover indicator (Huffman et al., 2000, 2012, 2015; Lobb et al., 2007). The unit of computation is the agricultural field. The indicator is expressed as the total number of soil cover days (SCD) achieved over a given period, or as the corresponding average soil cover (ASC). The number of SCD is obtained by summing, over the whole period, the daily soil cover value, which can vary continuously between 0% and 100%. One SCD corresponds thus to a full cover (100%) during one day or to a partial cover during more days, e.g. 2 days at 50%, 10 days at 10%. The soil cover takes into account two main components: the residues left from the preceding crop and the dynamic growth of vegetation. For both elements, databases have been built to provide reference values for different agricultural situations.

2.2 Data collection

2.2.1 Cover by residues

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

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

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

$M_t = M_0 * \exp(-K_D \text{ x } \Delta t)$

$SC = 1\text{-}\exp(-K_m \text{ x } M)$

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

$SC = 1\text{-}\exp[\log(1\text{-}SC_0)*\exp(-K_D \text{ x } \Delta t)]$

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

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

2.2.2 Cover by crops

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

Simulation scenarios were built in order to represent the diversity of Swiss agriculture situations. Simulations were run for the factorial combinations of 10 crops and 3 seeding dates (Table 1), 3 soil textures (Table 2), 3 soil depths (50, 100, 150 cm), 12 climatic regions (Table 3) and 27 cultural years (1982-2009). The climate data came from 12 automatic weather stations in Switzerland operated by the Federal Office of Meteorology and Climatology (MeteoSwiss: www.meteosuisse.admin.ch). For each crop, the seeding dates were set according to standard agricultural practices in Switzerland. Soil textures and depths were chosen to describe the main Swiss agricultural soils. In the same way, the climatic regions were chosen to best represent the whole country. This gave a total of 87480 scenarios which constituted then a reference database used to compute the vegetation component of the soil cover indicator (see section 2.3).

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

$$SC = 1\text{-}\exp(-K \text{ x } LAI)$$

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

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

2.3 Application in the framework of the farm network

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

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

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

Crop soil cover was estimated using the most appropriate dynamics in the STICS dynamics database (see section 2.2.2) in terms of seeding date, field meteorological and geographic situation, and soil type. Median daily soil cover over the 27 years simulated was used to get a more conservative estimate. An exception was done for permanent meadows, which were assumed to fully cover the soil during the whole period considered. To compute the SCD for the vegetation phase, the results from the STICS simulations were adapted in function of the real seeding and harvest dates. When the vegetation period was shorter than the simulated one, the computation of SCD was stopped at the harvest date. In contrast, when the vegetation period was longer, the growth curve simulated by STICS was continued until the harvest date was reached, assuming maximal cover for each added day. For crops not simulated with STICS, the soil cover dynamics was approximated by the most similar crop simulated. Residues still remaining after crop seeding were taken into account by combining residue and vegetation cover fractions.

For each field, the number of soil cover days (SCD) was then obtained by summing the daily soil cover from the harvest of the previous crop to harvest of the main crop. Average soil cover (ASC) was also calculated for each field. In addition, the number and proportion of days with a soil cover below the threshold value of 30% (FAO, 2015) was computed for each field. In the same manner, the proportion of fields with a soil cover below 30% at a given time in year was computed. At the farm level, the indicator was computed as the mean of the soil cover of each field, weighted by its respective area.

Computations were performed using R 3.0.1 (R Core Team, 2013).

3. Results

3.1 Crop soil cover dynamics with STICS

The soil cover dynamics simulated with STICS gave different results depending on the crop, seeding dates and pedoclimatic conditions (Figure 1). The cumulative soil cover was strongly dependent on the duration of the vegetation period from seeding to harvest (Figure 2A). Winter rapeseed reached the highest cumulative soil cover, especially with early seeding. Among winter crops, winter barley also showed a high cumulative soil cover. The seeding date had a strong influence on soil cover dynamics for winter crops, especially on the degree of cover reached at the beginning of winter and persisting throughout this season (Figure 1), and thus on the total cumulative soil cover achieved (Figure 2A). As expected, summer crops achieved a lower cumulative soil cover than winter crops. Sugar beet and grain maize had the highest cumulative soil cover among the summer crops. However, in terms of average soil cover, some summer crops (e.g. grain maize, sugar beet, potato) achieved a soil cover similar to the highly covering winter rapeseed (Figure 2B). In contrast, winter wheat and pea performed less well, with an average soil cover (late seeding case) as low as 29% and 31%, respectively, for a long vegetation period (Figure 2B).

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

3.2 Soil cover indicator

3.2.1 Agricultural field level

The use of the SAEDN data enabled successful computation of the soil cover indicator for 4538, 4981 and 4894 fields, for the years 2010, 2011 and 2012, respectively, representing about 79% of the total fields considered. The discarded fields were ones not belonging to grassland or cropland categories. Of the fields retained, about 78% were exclusively permanent grassland fields, 20% had an annual crop as the main crop, and 2% were temporary meadows. The six most frequent crops were winter wheat (28%), silage maize (17%), winter barley (9%), winter rapeseed (8%), sugar beet (5%) and potato (5%), representing a total of 72% of the annual crop fields.

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

Six simulated scenarios with different pre-sowing period managements (with grain maize as main crop and winter wheat as preceding crop) showed the effect of cropping techniques on soil cover (grey lines in Figure 6). In the first scenario S1, no cover crop was seeded between the harvest of the wheat and the seeding of the maize. The other scenarios integrated a non-legume cover crop (e.g. mustard) with varying seeding and destruction dates. In scenarios S2 (late seeding) and S3 (early seeding) the cover crop was destroyed before winter. In contrast, the cover crop was maintained until seeding of the grain maize for scenarios S4 (late seeding), S5 (early seeding) and S6 (early seeding). The cover crop was destroyed by plough in all scenarios except scenario S6 for which a mulch seeding of maize was simulated. The soil cover achieved by each scenario was then computed with the indicator presented in this study. A key factor influencing the soil cover was the presence or absence of a cover crop during the intercrop period (Figure 6). The destruction date of the cover crop also strongly impacted soil cover, with cover ranging from 36% to 77% (scenarios S2 to S4). The estimated soil cover values obtained for the grain maize fields in the study dataset were then compared to these six simulated scenarios to infer possible explanations for the variability in soil cover (dark bars in Figure 6). The observed values formed two rather distinct clusters, the first with cover levels similar to the scenarios with no cover crops or with a cover crop destroyed before winter, and the second one close to the scenarios with overwintering cover crops.

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

3.2.2 Farm level

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

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

4. Discussion

4.1 Evaluation of soil cover

The use of a crop model to generate data about the dynamics of vegetation development, and hence soil cover, proved to be an interesting way of taking into account different crops and pedoclimatic conditions. The soil cover achieved at the field scale was strongly dependent on the choice of the crop and on the cultural practices adopted. Among the six most frequent crops, the mean of the soil cover ranged from 46% to 69%. In comparison, Bechini & Castoldi (2009), with a simpler computation method, obtained lower values for various crop successions in northern Italy (mean soil cover ranging from 34% to 51%). For summer crops, the long pre-sowing period, ranging from the harvest of the previous crop to the seeding of the main crop, allowed large differences in the soil cover achieved, depending on the application of specific management practices. In particular, the simulation of six pre-sowing period management scenarios showed the crucial importance of cover crops on soil cover. The effect of cover crops was maximized by an early establishment of the cover and by a late destruction. These results highlighted the crucial role of cover crop management. Studies have shown that cover crops can in turn improve soil protection and quality (Dabney et al., 2001; Thorup-Kristensen et al., 2003).

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

4.2 Consequences for the environment

Soil cover indicators are generally classified in the driving forces category in the DPSIR (driving forces – pressures – state – impact - responses) classification from the European Environment Agency. Soil cover is thus not considered a direct measure of the impact of agriculture on the environment, but rather a key element in the prevention of damage. Indeed, soil cover is directly or indirectly linked to important processes such as soil erosion, water run-off, nutrient leaching, soil fertility, biodiversity (Blanchart et al., 2006; Dabney, 1998; Duran and Rodriguez, 2008; Gilley et al., 1986ab, Thorup-Kristensen et al., 2003; Quinton et al., 1997). Although these risks tend to diminish continuously with increased soil cover, a soil cover of 30% is often chosen as a threshold value for risk assessment, especially concerning erosion and run-off (Lilley and Moore, 2009). A threshold of 30% cover is also used in the definition of conservation agriculture (FAO, 2015). In the European statistics, less than 30% annual mean soil cover is considered as low, whereas a cover between 50% and 75% is considered as a moderate coverage (Eurostat, 2015). So the quantification of the number of days and fields under this threshold allowed assumptions relative to environmental consequences. Our results showed two periods poorly covered and potentially at risk, corresponding to the initial stage of both winter and summer crop growth. When pooling together the results for the six most frequent crops in the database, the period ranging from September to the end of February presented the highest number of fields under 30% soil cover. In Switzerland, rainfall is substantial and distributed more or less evenly over the year (monthly rainfall from 72 mm to 132 mm, median value over all meteorological stations, MeteoSwiss data). Our results show thus that winter would be a crucial period for soil erosion and nutrient leaching. This outcome is largely due to the high proportion of fields cultivated with winter wheat in the database, reflecting the Swiss situation where winter wheat represents 32% of the field crop area (FOAG, 2014). At the European level, soil cover during winter is also given a particular focus, showing that this period is particularly at risk (Eurostat, 2015). The seeding date of winter crops, and especially wheat, showed a significant influence on the soil cover reached at the beginning of winter, when growth pauses. However in most cases early seeding alone does not allow to reach 30% soil cover before winter. Short cycle cover crops associated with reduction of the intensity of tillage would be a way to increase soil protection and to reduce environmental risks.

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

4.3 Strengths and weaknesses of the indicator

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

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

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

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

A comparison of the evaluation presented here with real data about the evolution of soil cover over time would be an important validation step of the developed indicator. This could be achieved in the future thanks to the increasing availability of devices providing aerial images, from which soil cover estimations may be obtained. The pros and cons of both approaches could then be compared, and their respective efficiencies evaluated.

5. Conclusions

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

Acknowledgments

The authors thank Pierluigi Calanca (Agroscope) and the Federal Office of Meteorology and Climatology MeteoSwiss for providing access to the daily weather data used in this study. This study was partly funded by the Federal Office for Agriculture, and by the Swiss National Science Foundation in the framework of the National Research Program NRP 68 'Sustainable Use of Soil as a Resource', grant 406840-143063.

References

Adams, J., Arkin, G., 1977. A light interception method for measuring row crop ground cover. Soil Sci. Soc. Am. J. 41, 789-792.

Bechini, L., Castoldi, N., 2009. On-farm monitoring of economic and environmental performances of cropping systems: Results of a 2-year study at the field scale in northern Italy. Ecol. Indic. 9, 1096-1113.

Beaudoin, N., Launay, M., Sauboua, E., Ponsardin, G., Mary, B., 2008. Evaluation of the soil crop model STICS over 8 years against the "on farm" database of Bruyeres catchment. Eur. J. Agron. 29, 46-57.

Blanchart, E., Villenave, C., Viallatoux, A., Barthès, B., Girardin, C., Azontonde, A., Feller, C., 2006. Long-term effect of a legume cover crop (Mucuna pruriens var. utilis) on the communities of soil macrofauna and nematofauna, under maize cultivation, in southern Benin. Eur. J. Soil. Biol. 42, 136–144.

Brisson, N., Mary, B., Ripoche, D., Jeuffroy, M.H., Ruget, F., Gate, P., Devienne-Barret, F., Antonioletti, R., Durr, C., Nicoullaud, B., Richard, G., Beaudoin, N., Recous, S., Tayot, X., Plenet, D., Cellier, P., Machet, J.M., Meynard, J.M., Delecolle, R., 1998. STICS: a generic model for the simulation of crops and their water and nitrogen balance. I. Theory and parametrization applied to wheat and corn. Agronomie 18, 311-346.

Brisson, N., Ruget, F., Gate, P., Lorgeou, J., Nicoullaud, B., Tayot, X., Plenet, D., Jeuffroy, M.H., Bouthier, A., Ripoche, D., Mary, B., Justes, E., 2002. STICS: a generic model for the simulation of crops and their water and nitrogen balances. II. Model validation for wheat and corn. Agronomie, 22, 69-93.

Brisson, N., Gary, C., Justes, E., Roche, R., Mary, B., Ripoche, D., Zimmer, D., Sierra, J., Bertuzzi, P., Burger, P., Bussière, F., Cabidoche, Y.M., Cellier, P., Debaeke, P., Gaudillère, J.P., Hénault, C., Maraux, F., Seguin, B., Sinoquet, H., 2003. An overview of the crop model STICS. Eur. J. Agron. 18, 309-332.

Constantin, J., Beaudoin, N., Launay, M., Duval, J., Mary, B., 2012. Long-term nitrogen dynamics in various catch crop scenarios: Test and simulations with STICS model in a temperate climate. Agr. Ecosyst. Environ. 147, 36-46.

Coucheney, E., Buis, S., Launay, M., Constantin, J., Mary, B., Garcia de Cortazar-Atauri, I., Ripoche, D., Beaudoin, N., Ruget, F., Andrianarisa, K.S., Le Bas, C., Justes, E., Léonard, J., 2015. Accuracy, robustness and behavior of the STICS soil-crop model for plant, water and nitrogen outputs: Evaluation over a wide range of agro-environmental conditions in France. Environ. Modell. Softw. 64, 177-190.

Dabney, S.M., 1998. Cover crop impacts on watershed hydrology. J. Soil Water Cons. 53, 207–213.

Dabney, S.M., Delgado, J.A., Reeves, D.W., 2001. Using winter cover crops to improve soil and water quality. Comm. Soil Sci. Plant Anal. 32, 1221-1250.

Duran, Z.V.H, Rodriguez, P.C.R., 2008. Soil-erosion and runoff prevention by plant covers. A review. Agron. Sustain. Dev. 28, 65–86.

Epperlein, J., Basch, G., Geraghty, J., Streit, B., Sturny, W.G., 2010. No-Tillage in Europe - State of the Art: Constraints and Perspectives. In: Crabtree, B., Search for Sustainability. Crabtree Agricultural Consulting, 203.

European Environment Agency, 2005. Agriculture and environment in EU-15 – the IRENA indicator report. Publication conjointe de la DG Agriculture et développement rural, de la DG Environnement, d'Eurostat et de l'AEE.

Eurostat, 2015. Agri-environmental indicator – soil cover [online]. Available at: http://ec.europa.eu/eurostat/statistics-explained/index.php/Agri-environmental_indicator_-_soil_cover [Accessed 5 July 2015].

FAO, 2015. Food and Agriculture Organization of the United Nations: Conservation Agriculture [online]. Available at: http://www.fao.org/ag/ca [Accessed 5 July 2015].

FOAG, 2014. Rapport agricole 2014. Swiss Federal Office for Agriculture, Bern, 320 pp.

FOAG, 2015. Swiss Federal Office for Agriculture: Monitoring agro-environnemental [online]. Available at: http://www.blw.admin.ch/themen/00010/00070/index.html?lang=fr [Accessed 5 July 2015].

Gilley, J.E., Finkner, S.C., Spomer, R.G., Mielke, L.N., 1986. Runoff and Erosion as Affected by Corn Residue: Part I. Total Losses. T. ASAE 29, 157-160.

Gilley, J.E., Finkner, S.C., Varvel, G.E., 1986. Runoff and Erosion as Affected by Sorghum and Soybean residue. T. ASAE 29, 1605-1610.

Giupponi, C., Carpani, M., 2006. Recent Developments in Indicators and Models for Agri-environmental Assessment. Ital. J. Agron. / Riv. Agron. 4, 647-664

Huffman, E., Eilers, R.G., Padbury, G., Wall, G., MacDonald, K.B., 2000. Canadian agri-environmental indicators related to land quality: integrating census and biophysical data to estimate soil cover, wind erosion and soil salinity. Agr. Ecosyst. Environ. 81, 113–123.

Huffman, E., Coote, D.R., Green, M., 2012. Twenty-five years of changes in soil cover on Canadian Chernozemic (Mollisol) soils, and the impact on the risk of soil degradation. Can. J. Soil Sci. 92, 471-479.

Huffman, E., Liu, J., Green, M., Coote, D.R., Li, Z., Liu, H., Liu, T., Zhang, X., Du, Y., 2015. Improving and evaluating the soil cover indicator for agricultural land in Canada. Ecol, Ind. 48, 272-281.

Iowa state university. University extension, 2009. Residue management and cultural practices.

Kumar, K., Goh, K.M., 2000. Crop residues and management practices: effects on soil quality, soil nitrogen dynamics, crop yield, and nitrogen recovery. Adv. Agron. 68, 197–319.

Lahmar, R., 2010. Adoption of conservation agriculture in Europe. Lessons of the KASSA project. Land Use Policy 27, 4–10.

Lilley, J.M., Moore A.D., 2009. Trade-offs between productivity and ground cover in mixed farming systems in the Murrumbidgee catchment of New South Wales. Anim. Prod. Sci. 49, 837-851.

Lobb, D.A., Huffman, E., Reicosky, D.C., 2007. Importance of information on tillage practices in the modelling of environmental processes and in the use of environmental indicators. J. Environ. Manage. 82, 377–387.

Meier, B., 2000. Neue Methodik für die Zentrale Auswertung von Buchhaltungsdaten an der FAT. Eidg. Forschungsanstalt für Agrarwirtschaft und Landtechnik (FAT), Switzerland

Natural resources conservation service Ohio, 2002. Estimates of residue cover remaining after single operation of selected tillage operations.

OECD, 2001. Environmental Indicators for Agriculture Volume 3. Methods and Results. Paris, OECD Publishing.

Palosuo, T., Kersebaum, K.C., Angulo, C., Hlavinka, P., Moriondo, M., Olesen, J.E., Patil, R.H., Ruget, F., Rumbaur, C., Takac, J., Trnka, M., Bindi, M., Caldag, B., Ewert, F., Ferrise, R., Mirschel, W., Saylan, L., Siska, B., Rotter, R., 2011. Simulation of winter wheat yield and its variability in different climates of Europe: A comparison of eight crop growth models. Eur. J. Agron. 35, 103-114.

Piorr, H.-P., 2003. Environmental policy, agri-environmental indicators and landscape indicators. Agr. Ecosyst. Environ. 98, 17–33.

Quinton, J.N., Edwards G.M., Morgan, R.P.C., 1997. The influence of vegetation species and plant properties on runoff and soil erosion: results from a rainfall simulation study in south east Spain. Soil Use Manage. 13, 143-148

R Core Team, 2013. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Scopel, E., Triomphe, B., Affholder, F., Da Silva, F.A.M., Corbeels, M., Xavier, J.H.V., Lahmar, R., Recous, S., Bernoux, M., Blanchart, E., de Carvalho Mendes, I., De Tourdonnet, S., 2013. Conservation agriculture cropping systems in temperate and tropical conditions, performances and impacts. A review. Agron. Sustain. Dev. 33:113–130

Shelton, D.P., Smith, J.A., Jasa, P.J., Kanable, R., 1995. Estimating percent residue cover using the calculation method. University of Nebraska, Institute of agriculture and natural resources.

Soane, B.D., Ball, B.C., Arvidsson, J., Basch, G., Moreno, F., Roger-Estrade, J., 2012. No-till in northern, western and south-western Europe: A review of problems and opportunities for crop production and the environment. Soil Till. Res. 118, 66–87

Spycher, S., Badertscher, R., Daniel, O. 2013. Indicateurs de l'utilisation de produits phytosanitaires (PPS) en Suisse. Recherche Agronomique Suisse 4:192-199.

Steiner, J.L., Schomberg, H.H., Unger, P.W., Cresap, J., 1999. Crop residue decomposition in no-tillage small-grain fields. Soil Sci. Soc. Am. J. 63, 1817-1824.

Steiner, J.L., Schomberg, H.H., Unger, P.W., Cresap, J., 2000. Biomass and residue cover relationships of fresh and decomposing small grain residue. Soil Sci. Soc. Am. J. 64, 2109-2114.

Stott, D.E., Alberts, E.E., Weltz, M.A., 1995. Chapter 9. Residue decomposition and management In: D.C. Flanagan and M.A. Nearing (eds.), USDA-Water Erosion Prediction Project hillslope profile and watershed model documentation. NSERL Report No. 10, USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, Indiana.

Thorup-Kristensen, K., Magid., J., Jensen, L.S., 2003. Catch crops and green manures as biological tools in nitrogen management in temperate zones. Adv. Agron. 79, 227–302.

van Donk, S.J., 2010. Value of crop residue for water conservation. Proceedings of the 22nd Annual Central Plains Irrigation Conference, Kearney, NE., February 24-25, 2010.

Yli-Viikari, A., Hietala-Koivu, R., Huusela-Veistola, E., Hyvönen, T., Perälä, P., Turtola, E., 2007. Evaluating agri-environmental indicators (AEIs) - Use and limitations of international indicators at national level. Ecol. Indic. 7, 150–163.

Table and figure legends

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

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

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

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

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

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

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

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

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

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

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

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

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

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%

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

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

Figure 1

Click here to download Figure: figure1.eps

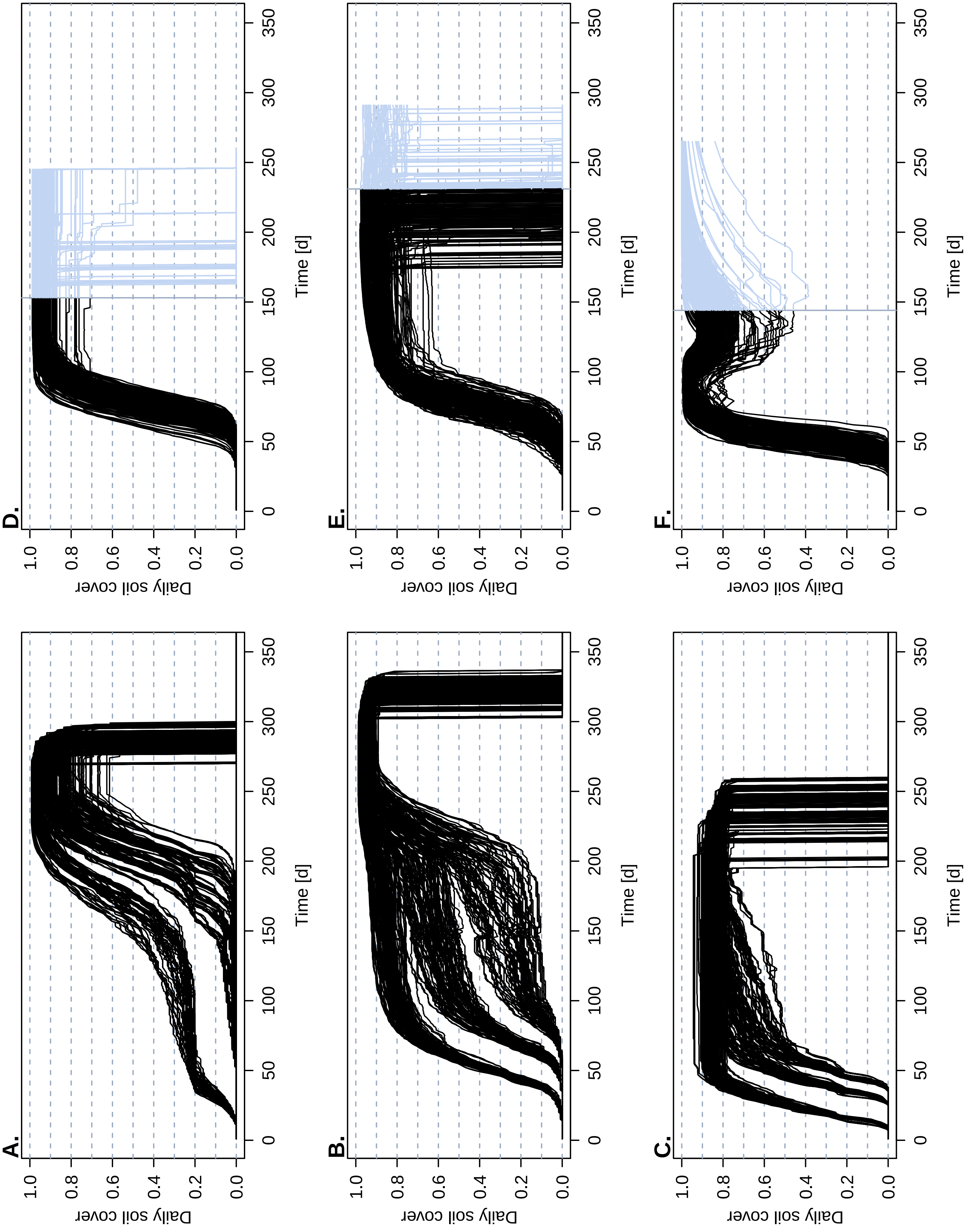


Figure 2

Click here to download Figure: figure2.eps

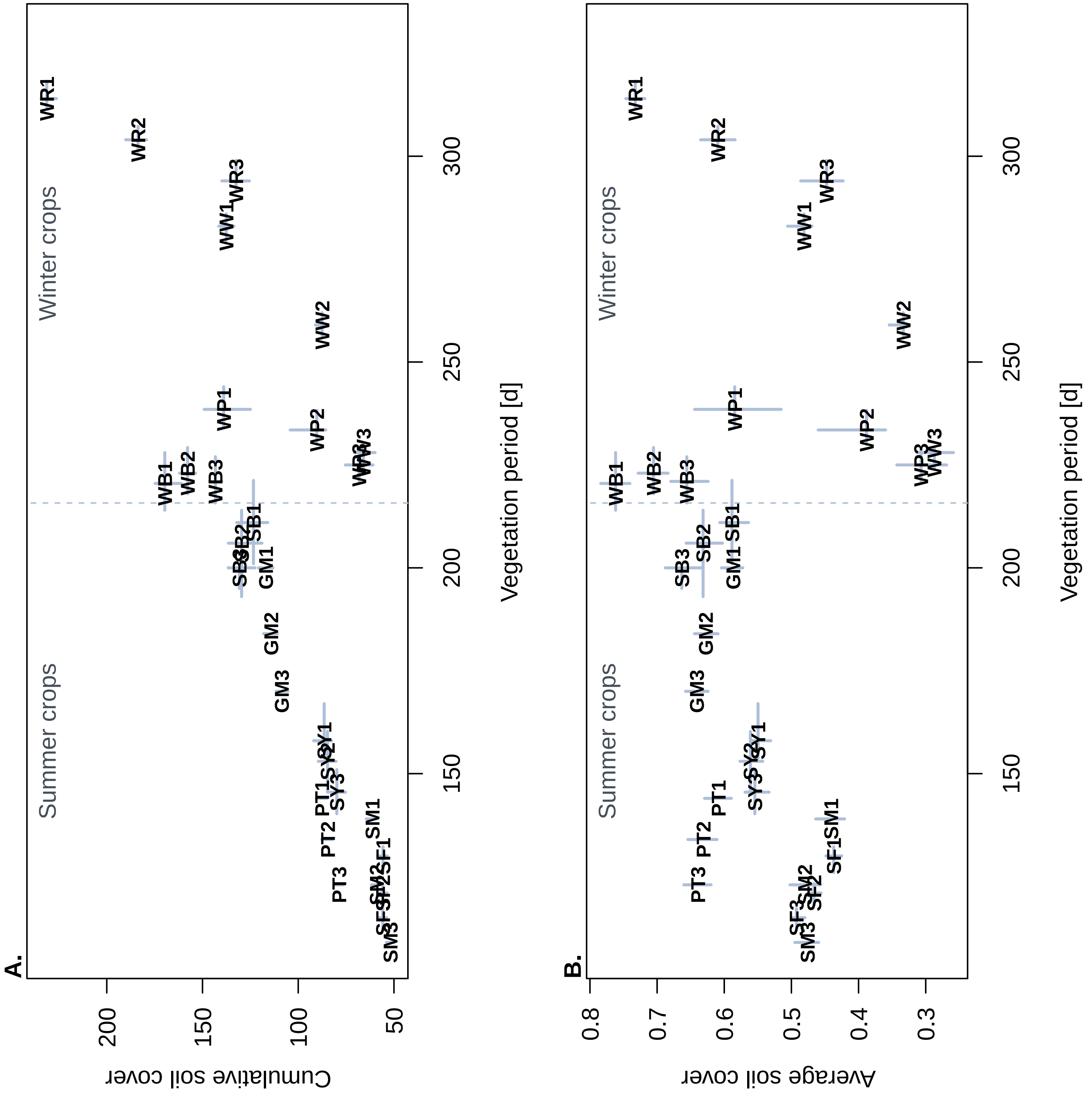


Figure 3

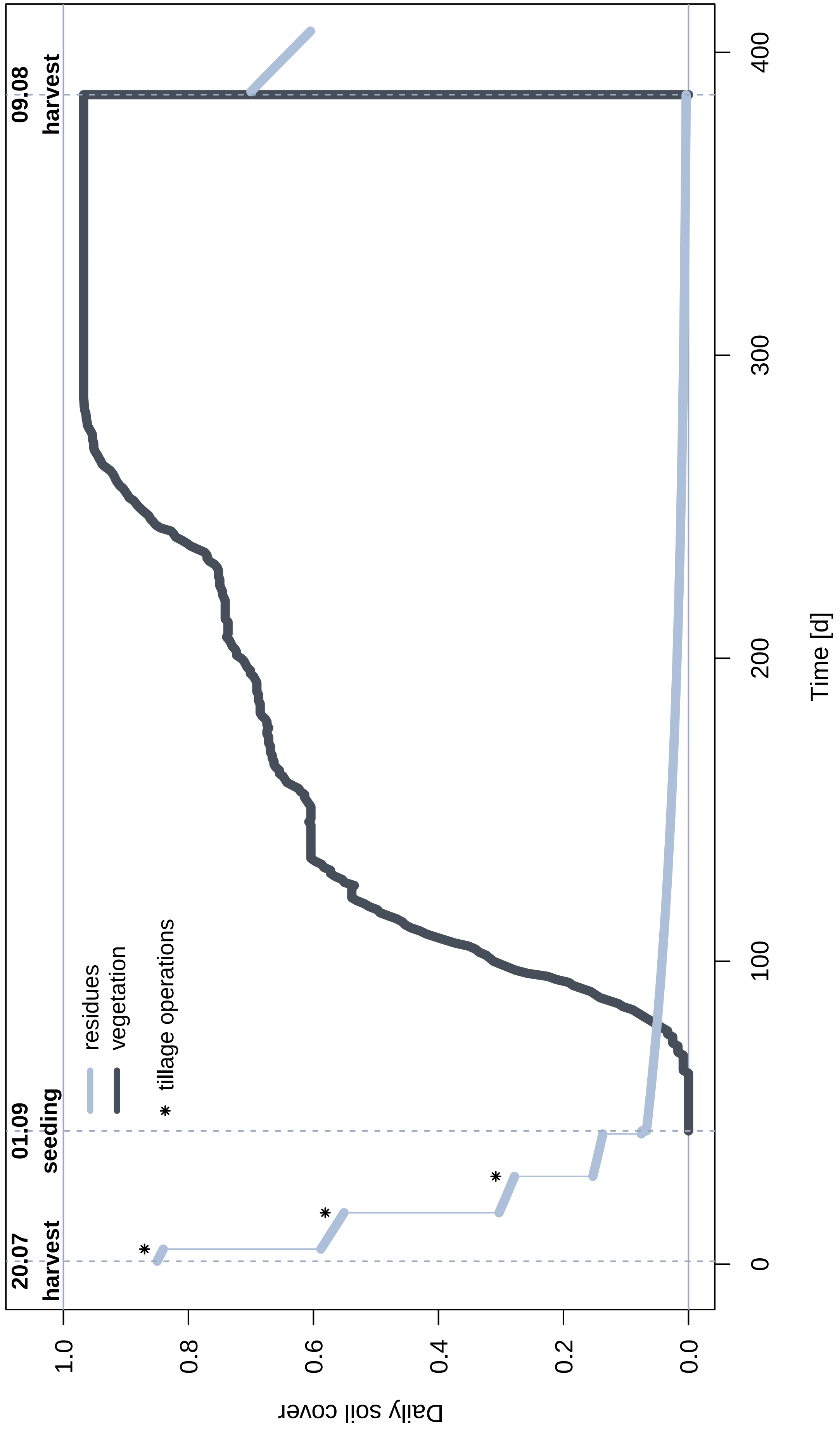

20.07
harvest
01.09
seeding
09.08
harvest
residues
vegetation
* tillage operations
*
*
*
0
100
200
300
400
Time [d]
0.0
0.2
0.4
0.6
0.8
1.0
Daily soil cover

Figure 4

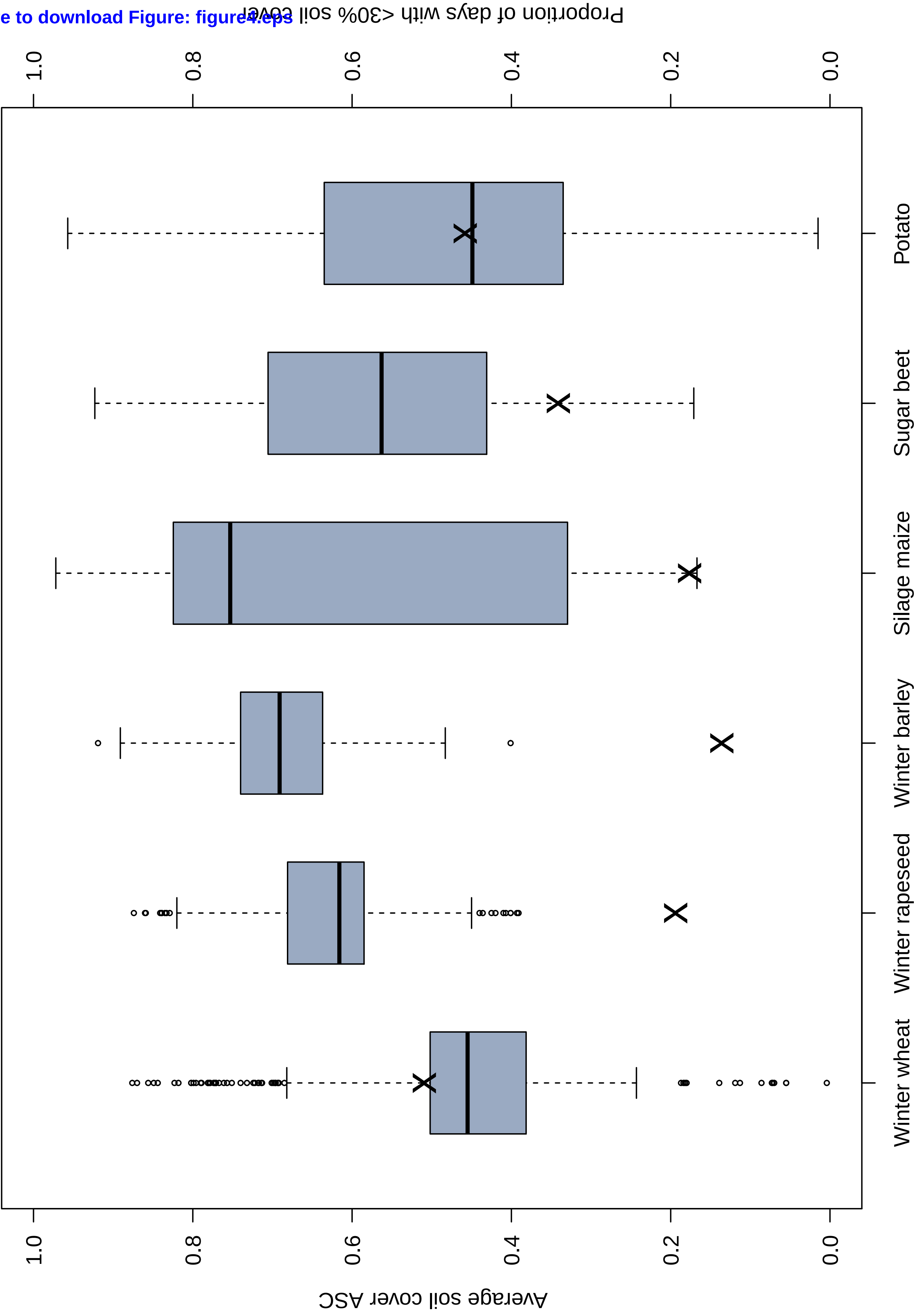

Proportion of days with <30% soil cover
1.0
0.8
0.6
0.4
0.2
0.0
Winter wheat
Winter rapeseed
Winter barley
Silage maize
Sugar beet
Potato
1.0
0.8
0.6
0.4
0.2
0.0
Average soil cover ASC

Figure 5

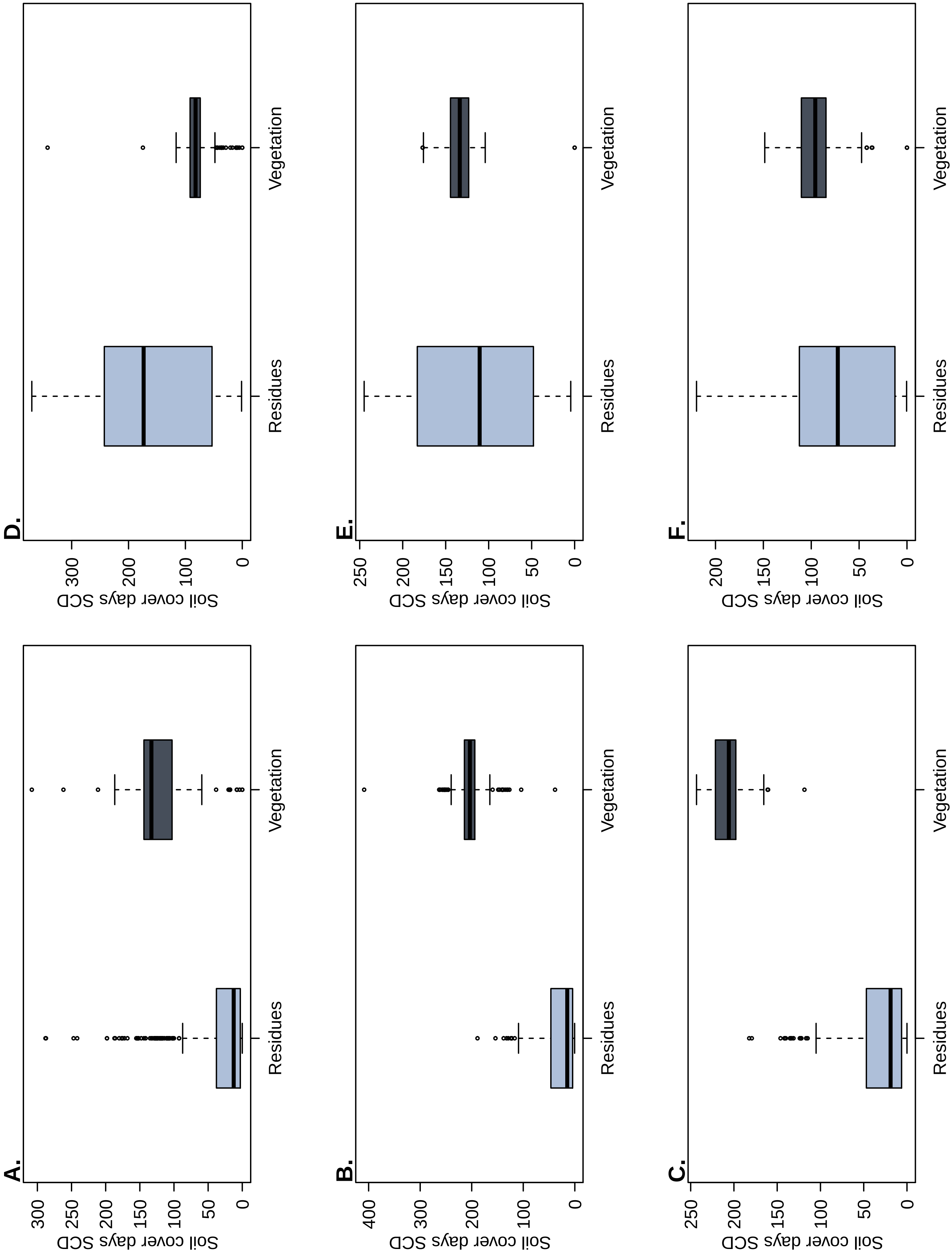

A.
B.
C.
D.
E.
F.
Soil cover days SCD
Residues
Vegetation
0
50
100
150
200
250
300
400

Figure 6

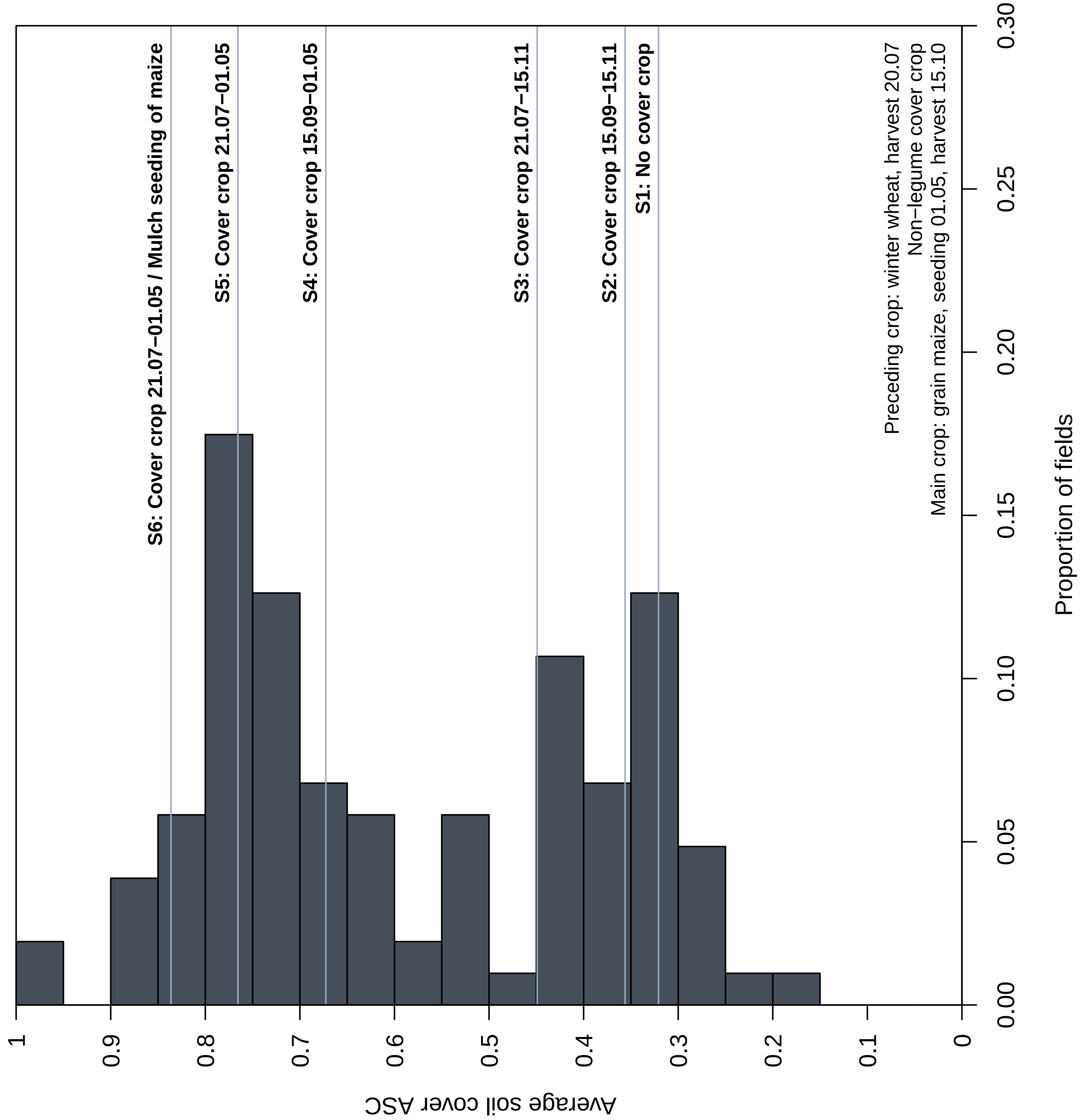
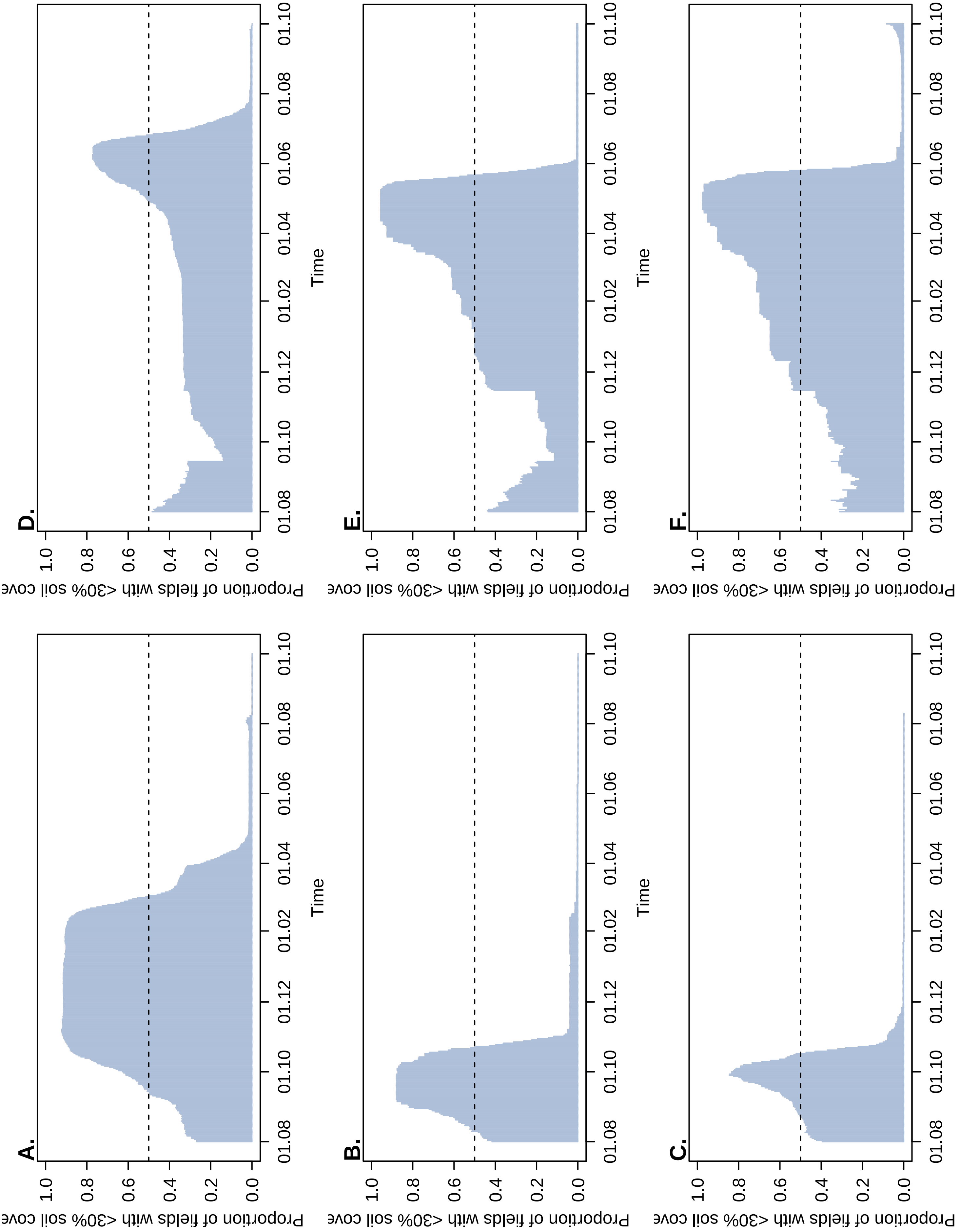

S6: Cover crop 21.07−01.05 / Mulch seeding of maize
S5: Cover crop 21.07−01.05
S4: Cover crop 15.09−01.05
S3: Cover crop 21.07−15.11
S2: Cover crop 15.09−15.11
S1: No cover crop
Preceding crop: winter wheat, harvest 20.07
Non−legume cover crop
Main crop: grain maize, seeding 01.05, harvest 15.10
Proportion of fields
0.00
0.05
0.10
0.15
0.20
0.25
0.30
Average soil cover ASC
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

Figure 7


A.
B.
C.
D.
E.
F.
Proportion of fields with <30% soil cove
1.0
0.8
0.6
0.4
0.2
0.0
01.08
01.10
01.12
01.02
01.04
01.06
01.08
01.10
Time