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Evaluate carbon stock changes based on the Swedish soil-monitoring program

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Sammanfattning

I den nationella växthusgasinventeringen tillämpar SLU en Tier III metod med hjälp av kolbalansmodellen ICBM inom ett holistiskt ramverk för beräkning av förändringar i kolförråd i åkermark för mineraljordar, vilket Sverige redovisar under sektorn Markanvändning, Markanvändningsförändring och Skogsbruk (LULUCF). Denna metod levererar kolförrådsförändringarna för åtta svenska produktionsområdena (PO8s), som sedan är aggregerade till nationell nivå. Klimatets inverkan på nedbrytningen av kol i marken med ICBM skattas med hjälp av rutnätade dagliga klimatdata från Svenska Meteorologiska Institutet (SMHI). Modellramverket tar aktivitetsdata från årlig jordbruksstatistik avseende användningen av åkermark (areal och avkastning för olika odlingssystem inklusive träda) och andra odlingsåtgärder (halmborttagning och tillförsel av stallgödsel). Dessutom tillämpas olika empiriska funktioner för att skatta den årliga koltillförseln till mark från rötter, samt för att skatta markens densitet för att uttrycka kolkoncentrationer i marken som mängd kol. Funktionerna baseras på litteratursammanställningar och analyser av stora svenska markdatabaser. För att initialisera kolförråden i ICBM används data för kolkoncentrationer från Naturvårdsverkets rikstäckande mark- och grödoinventering. Inventeringen gör provtagningar i svensk åkermark periodvis och analyserar matjordens egenskaper med ungefär 10-års mellanrum. Det första omdrevet (d.v.s. ett heltäckande stickprov av det område som inventeras, i detta fall hela landet) kompletterades mellan 1988 och 1995 och tillhandahåller data för 1990 års baslinje. Det sista av totalt tre kompletta omdrev avslutades 2017. Provtagningspunkterna i inventeringarna har koordinater och data kan kopplas till var och en av de svenska PO8s.

Vi har nu kalibrerat en ny version av ICBM genom att integrera den senaste kunskapen från långliggande fältförsök. Syftet med detta utvecklingsprojekt var att utvärdera förändringarna i kol över tid från inventeringen av svensk åkermark genom att använda exakta koordinater och nya statistiska tester, och jämföra dessa förändringar med skattningar av förändringar i kolförråd med den nya versionen av ICBM. De allmänna trenderna av förändringar i kol beräknade från den nationella inventeringen förblir liknande tidigare analyser och visar konsekventa ökningar över tid. De absoluta ökningarna på nationell nivå är relativt små, kolkoncentrationerna ökade med 0,11 från omdrev 1 till 2, med 0,07 procentenheter från omdrev 2 till 3 och med 0,21 procentenheter från omdrev 1 till 3. Detta representerar en relativ ökning av kolhalten på 9,3 % kol mellan omdrev 3 och 1. Genom att tillämpa exakta

koordinater kunde vi lägga till några punkter i varje PO8 som inte fanns med i vår tidigare analys av de tre inventeringarna.

Användning av andra statistiska tester förbättrade slutsatsen mellan inventeringar på PO8-nivå, där Wilcoxon signed rank test (en icke-parametrisk metod) tillämpad på provtagningspunkterna med samma koordinater i jämförelsen mellan omdrev 3 mot 2 nu visade signifikanta skillnader. Skattningarna med ICBM efterliknar den relativa ökningen av kol på nationell nivå men den relativa ökningen är mycket mindre (dvs. 1,5 %). Jämfört med resultat från den nationella inventeringen, matchar skattningarna med ICBM inte alltid samma trender i kolförändringar för alla PO8. Det kvarstår flera osäkerheter relaterade till båda metoderna som kräver ytterligare överväganden. Exempelvis kan data från den svenska inventeringen vara förknippade med inkonsekvenser relaterade till användningen av olika analysmetoder för kolkoncentrationer eller till möjliga underskattningar av kolkoncentrationer i omdrev 1 på grund av skillnader i provtagningsstrategier. Osäkerheter relaterade till beräkningar med ICBM inkluderar t.ex. skattning av den årliga koltillförseln från rötter och stallgödsel. En fjärde inventering har påbörjats och kommer att ge värdefull information om trender i kolförändringar på nationell nivå, vilket kommer att vara användbart för att utveckla båda metoderna.

Summary

SMED is short for Swedish Environmental Emissions Data, which is a collaboration between IVL Swedish Environmental Research Institute, SCB Statistics Sweden, SLU Swedish University of Agricultural Sciences, and SMHI Swedish Meteorological and Hydrological Institute.

In the national greenhouse gas inventory, SLU is applying a Tier III method using the Introductory Carbon Balance Model (ICBM) in a holistic framework for calculating changes in soil organic carbon (SOC) stocks in arable land for mineral soils, which Sweden is reporting under the Land Use, Land Use Change and Forestry (LULUCF) sector. This method is delivering SOC stock change rates for eight Swedish agricultural production regions (PO8s), which are aggregated to the national level. The effect of the climate on SOC decomposition in ICBM is accounted for using gridded daily weather records from the Swedish Meteorological Institute (SMHI). The model framework is taking agricultural activity data from yearly census records regarding the use of arable land (area and yield of different crops including fallow) and management systems (straw removal and manure applications). In addition, it applies different empirical functions for estimating annual carbon inputs from roots and for estimating dry soil bulk density for expressing carbon concentrations on a mass basis, based on literature reviews and analyses of large Swedish soil databases. For the ICBM model simulations, initial stocks of SOC are derived from data on soil texture and SOC concentrations from the Swedish Environmental Protection Agency (SEPA) national soil-monitoring program (SMP). The national SMP consists of three soil inventories that periodically characterizes the topsoil properties in 10-year cycles across Sweden. The first inventory, conducted between 1988 and 1995 is providing data for the 1990 baseline, while the latest complete inventory ended 2017. The sampling points in the inventories have coordinates, and data can be associated with each of the Swedish PO8s.

We have now been calibrating a new version of the ICBM model by integrating the most recent knowledge gained from long-term field experiments. The objectives of this development project were to evaluate SOC changes from the national SMP by using exact coordinates and new statistical tests and compare these changes to predictions with the new version of ICBM. The general trends in SOC changes calculated from the national SMP remain similar to previous analyses, showing consistent SOC increments over time. The absolute increments at the national level are relatively small, SOC concentrations increased by 0.11, 0.07 and 0.21

percentage units from inventory I to inventory II, from inventory II to inventory III, and from inventory I to inventory III, respectively. This is representing a relative increase of 9.3% between inventory III and I. Applying exact coordinates were allowing us to add a few points in each PO8s that were not present in our previous analysis of the three soil inventories.

Using other statistical tests improved the inference between inventories at the PO8 level, where the Wilcoxon signed rank test (a non-parametric method) applied to the matched points when comparing inventory III against II now showed significant differences. The predictions with ICBM are mimicking the relative increase in SOC at the national level but the relative increase is much less pronounced (i.e., 1.5%). Compared to results obtained with the national SMP, ICBM predictions are not always matching the same trends in SOC changes for all of the PO8s. There remain several uncertainties relating to both methods that needs further considerations. For example, data from the Swedish SMP may be associated with inconsistences relating to the use of different analytical methods for measuring SOC concentrations, or to possible under-estimations of SOC concentrations in inventory I due to differences in sampling strategies. While uncertainties relating to ICBM predictions are including e.g., estimation of the amount of annual carbon inputs from roots and manures. A fourth inventory has been initiated and will provide precious information about trends in SOC changes at the national scale, which will be useful for developing both methods.

Keywords: Soil organic carbon, arable land, mineral soils, soil-monitoring program, ICBM, LULUCF

1. Background & purpose

The soil organic carbon (SOC) balance in agricultural soils is dynamic and mainly determined by the difference between annual carbon inputs and carbon outputs from the decay of existing soil organic matter through soil microbial activity. Since changes in the SOC balance occurs slowly, it usually takes decades before changes become measurable due to both small- and large-scale spatial variability. Consequently, long-term field experiments (LTEs) focusing on specific treatments and well-designed spatial soil-monitoring programs (SMPs) are useful tools for estimating changes in SOC stocks. In particular, LTEs are helpful for calibrating and validating SOC models. SMPs are primarily providing a picture of SOC stocks at larger spatial scales, as well as changes therein if they are running over longer time-periods. However, data from both LTEs and SMPs are also subject to a certain degree of uncertainty depending on various aspects (Kätterer and Bolinder, 2022).

The Swedish University of Agricultural Sciences (SLU) developed the Introductory Carbon Balance Model (ICBM) on data from a LTE in Ultuna, Uppsala (Andrén and Kätterer, 1997) for use at the IPCC Tier III level in the national greenhouse gas inventory. The model is calculating changes in SOC stocks in arable land for mineral soils, which Sweden is reporting within the Land Use, Land Use Change and Forestry (LULUCF) sector (NIR, 2021). We have now been calibrating a new version of the ICBM model by integrating the most recent knowledge gained from LTEs, and we have been validating the new model version on data from selected LTEs (Menichetti et al. 2022). This model is using different sources of information relating to the dynamics of SOC for agroecosystems in a holistic framework (Andrén et al. 2004; 2008). The input data for crop and management systems are coming from agricultural census, and it uses daily gridded climatic data from the Swedish Meteorological Institute (SMHI). ICBM is simulating the changes in SOC stocks for each of the eight Swedish agricultural production regions (PO8s) and results are also scaled up to the national level.

The Swedish Environmental Protection Agency (SEPA) is financing a national SMP for arable land beginning around 1990. It consists of three soil inventories that periodically characterizes the topsoil (0-20 cm) properties in 10-year cycles across Sweden, the latest inventory ended 2017 and a fourth inventory have been initiated. The sampling points have coordinates and data can be associated with each of the Swedish PO8s. Originally, the national SMP was not designed with the specific intention of assessing changes in SOC for arable land. However, it has been allowing successful applications for that purpose in recent publications (Poeplau et al. 2015; Henrysson et al. 2022), and as described in analyses presented in the SEPA reports for each of the inventories (Eriksson et al. 1997; 2010; Eriksson, 2021), addressing issues such as the influence of farm types and land use changes. We are also using the SOC concentrations from the first inventory for initializing the ICBM model, and the SMPs that are completed are currently covering changes in SOC concentrations representing a 20-year period.

The purposes of this development project were to:

- Evaluate SOC changes from the national SMP by using exact coordinates and new statistical tests, and compare these changes to predictions with the new version of ICBM
- We also discuss uncertainties related to the two approaches and potential future improvements.

2. Materials & Methods

2.1. The Swedish soil-monitoring program

The data from the national SMP analyzed in this study are using results for topsoil (0-20 cm) samples from inventory I, II and III. Each of the inventories are covering only arable land and the distribution of sampling points are in proportion to the arable land across different regions in Sweden. The first inventory involved data from 4 sampling campaigns, in 1988 and 1992 (about 15% of the samples), 1994 (about 25% of the samples) and 1995 (about 60% of the samples). Four sampling campaigns were made for the second (2001, 2003, 2005, 2007) and third inventories (2011, 2013, 2015, 2017) with a more or less equal number of samples taken for each sampling campaign. However, there was a difference in the selection and precision of coordinates for the sampling points between the inventories. In the first inventory, coordinates for the sampling points were only representing the center of each farm on which the sampling took place. From 2001 and onwards, Statistics Sweden (SCB) was customizing a new scheme of sampling points, having exact coordinates with a precision of 1 meter. The second inventory is actually a restart of the SMP because SCB was establishing this sampling scheme regardless of the sampling positions used in the first inventory. In the sampling campaigns of the third inventory, samples were taken at the same positions as in inventory II but a few exceptions exist (e.g., new sampling points were included because the same positions became unavailable for various practical reasons). These differences in sampling schemes are influencing the statistical tests used for analyzing trends in SOC between the inventories, as described below.

2.1.1. Data treatment

The arable soil database of inventory I, II and III was requested from the data host in the Department of Soil, Water and Environment, Swedish University of Agricultural Sciences (SLU). They were providing exact coordinates in inventory II and III under the signed confidential user agreement. We also received precious information from Katharina Meurer (SLU) who was involved in the previous analyses of the Swedish SMP (Henryson et al. 2022; Bolinder et al. 2018).

Inventory data were treated to have consistent forms. Coordinates, soil type code and name, and soil texture were involved. Coordinates in

SWEREF99TM were chosen to match other spatial datasets. Soil type, based on soil texture classes, were treated to have both code and explicit names. Because revisited sampling points in inventory III had no texture in the database, thus we filled the texture data from the matched points in inventory II.

The sampling points from inventory II and III were associated with the Swedish PO8s using exact coordinates, while those for inventory I were based on rounded coordinates. This procedure was performed in ArcGIS 10.7, using Spatial Join tool to add production region code and name columns. There were 25 points having no PO8 added because they were out of the coarse boundaries of the agricultural production regions, i.e., fell into the water bodies near land (Fig. 1.). For these 25 points, 13, 7 and 5 points were from the inventory I, II and III, respectively. By thoroughly checking these points one by one, they were manually associated with production regions according to the nearest production region. After this manual editing, we exported the attribute table as an Excel worksheet using the Table to Excel tool in ArcGIS, and we were conducting the statistical analysis on production regions based on this exported worksheet.

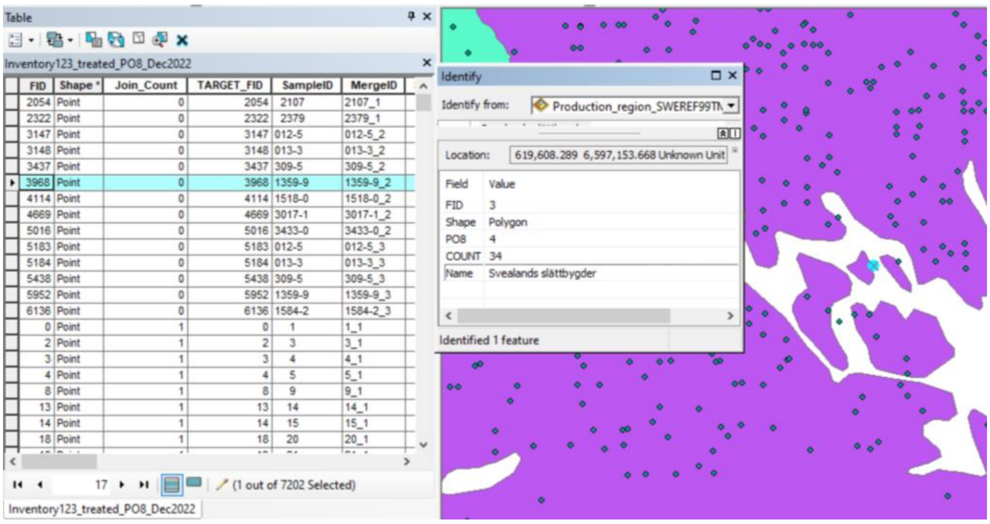


Fig. 1. The highlighted dot is an example of points missing production region information after spatial join because of outside the boundaries of production regions (for details, see the text). The window in the middle showed the production region of the nearest polygon, which was manually added to the attribute table of the highlighted points. A total of 25 points were treated in the same way.

2.1.2. Data analysis

Data analysis was conducted using SAS. The analysis focused on the mineral soils that have SOC not higher than 7% (Andrén et al. 2008), and we further excluded data points with missing SOC values. Descriptive statistics on SOC were performed on both the agricultural production region and at the national level, means, standard deviation, median and quantiles were reported.

The SOC concentrations between inventories were compared differently depending on data distribution and dependency of samplings. As inventory I sampled soils at locations different from the inventory II and III, comparison of inventory I and II will use a two sample t test if the SOC contents of mineral soils is normally distributed or data transformation can meet normality requirement, otherwise a non-parametric method, Mann-Whitney U test, will be used. The same principle applies for the comparison of data between inventory I and III. Considering that inventory III revisited most of sampling points from inventory II, a paired-sample analysis is required for these dependent samples. Sampling points from inventory II and III were matched based on sample ID and the difference in SOC calculated for the matched sampling points. When the difference of SOC is normally distributed or data transformation can meet this requirement, then paired sample t test can be used for comparing means of SOC in inventory II and III. Otherwise, a non-parametric method, Wilcoxon signed rank test, will be used for comparing the distribution of SOC between inventory II and III. Means, standard deviation, median and number of points are reported when two sample t test or paired sample t test is chosen. Shift in location, lower and upper 95% confidence limit, interval midpoint and asymptotic standard error are reported when the Mann-Whitney U test or Wilcoxon signed rank test is chosen. Statistical significance is reported at α=0.05 level.

For each inventory, a normality test was performed both at the national level and for each PO8s by choosing a Kolmogorov-Smirnov test when the number of data points is over 2000. Otherwise, Shapiro-Wilk test is used. When SOC is not normally distributed, data transformation is applied, followed by testing normality of logarithm, square root and cubit root transformed SOC.

2.2. Modifications to the ICBM model for use in LULUCF

We are continuously improving the ICBM model in our research activities, including previous development projects. For this year's submission (2023), we implemented a new version (Menichetti et al. manuscript).

The new version of ICBM is not only useful for the national reporting system but also for other applications such as within farm-scale advisory tools and for use within life cycle analyses. The basic structure of the new calibrated ICBM version remains the same in all applications. However, when used for LULUCF, some differences are occurring in the climatic and activity data used relating to the scale of application.

As described in Appendix 5, compared to the ICBM version used in the previous submissions, the values of the first-order decomposition rate are constants and the humification coefficients are reflecting the changes in the new version. The major difference is the inclusion of a specific humification coefficient for roots, which implies a higher contribution of roots to the formation of SOC in the old pool. The half-life and turnover time of the young SOC pool is also slower in the new version.

The other changes we implemented in this year's submission relating to the application of ICBM for LULUCF are as follows:

- The functions used for calculating the ICBM soil climate parameter, which aggregates the influence of soil water content and soil temperature on the first-order decomposition rates, were revised so that they are better reflecting the use of gridded climatic data

- The problem relating to difficulties with the yield data for leys (i.e., yield data for leys were lower from 2002 and onwards because of a methodological change in the collection of census data), which affected the estimated annual carbon inputs to soil from above- and below-ground crop residues, were adjusted by using a constant for the whole time period

- Regarding another problem with activity data, namely high variations in the time series for annual carbon inputs from manure, we were applying a correction from 2007 and onwards, as explained in another development project conducted this year (Bolinder et al. Coordination of common input data for manure in the Agricultural sector and for ICBM in the LULUCF sector).

3. Results & Discussion

3.1. Soil carbon changes in the Swedish soil-monitoring program

The total number of data points are 7202 from three inventories. After excluding three points that missed SOC values, there are 2921 out of 3136 points, 1873 out of 2033 points, and 1870 out of 2030 points are mineral soils in inventory I, II, and III, respectively.

SOC were not normally distributed at both national and production region levels. Square root and cubic root brought data distribution closer to normal distribution, but none of the transformations met the requirements of normal distribution. Therefore, we were using non-parametric approaches when comparing distribution of SOC between inventories.

3.1.1. Descriptive statistics on production regions and country

Overall, means and median of SOC increased continuously from inventory I to inventory II and inventory III at national level. Where averages of SOC increased from 2.48 to 2.63 and 2.70% from inventory I to inventory II and inventory III, respectively. Whereas the median SOC increased from 2.27 to 2.39 and 2.49% from inventory I to inventory II, and inventory III, respectively. Similarly, the trends of incremental increases over time were occurring in most of the PO8s (Table 1; Appendix 1 is showing quantiles of SOC for each of the PO8s and inventories). Histograms of SOC were showing consistent increasing number of samples towards the right tails (Appendix 2).

3.1.2. Testing soil carbon differences between inventories

Inventory I was compared with inventory II and III using the Mann-Whitney U test. At the national level, SOC increased significantly by 0.11 and 0.21 percentage units from inventory I to inventory II and III, respectively (Table 2). At the PO8s level, three out eight regions showed significant increment in SOC from inventory I to inventory II, while seven regions had significant increment of SOC from inventory I to inventory III except for the Övre Norrland region. Shifts of SOC from inventory I to inventory II ranged between 0.05 and 0.32, and ranged between 0.17 and 0.31 from inventory I to inventory III.

Table 1 Descriptive statistics on soil organic carbon (SOC) at national and agricultural production (PO) region level.

Production region		Inventory I SOC (%)				Inventory II SOC (%)				Inventory III SOC (%)			
		mean	standard deviation	median	n	mean	standard deviation	median	n	mean	standard deviation	median	n
PO1	Götalands södra slättbygder	2.03	0.93	1.76	410	2.21	1.02	1.96	234	2.25	0.93	2.00	242
PO2	Götalands mellanbygder	2.31	1.06	2.11	361	2.48	1.17	2.25	213	2.52	1.03	2.41	223
PO3	Götalands norra slättbygder	2.42	0.97	2.21	436	2.47	0.98	2.21	357	2.58	0.92	2.39	352
PO4	Svealands slättbygder	2.41	0.94	2.18	653	2.51	1.08	2.27	426	2.62	1.04	2.34	436
PO5	Götalands skogsbygder	2.81	1.07	2.62	551	3.04	1.14	3.04	329	3.11	1.1	2.99	309
PO6	Mellersta Sveriges skogsbygder	2.55	0.87	2.43	214	2.63	0.92	2.45	145	2.75	0.97	2.63	138
PO7	Nedre Norrland	2.85	0.99	2.68	181	3.24	1.34	3.06	102	3.22	1.28	3.00	107
PO8	Övre Norrland	2.94	1.31	2.75	115	3.08	1.23	2.96	67	3.14	1.12	2.96	63
	Country	2.48	1.03	2.27	2921	2.63	1.12	2.39	1873	2.70	1.07	2.49	1870

Table 2. Changes of SOC (%) from inventory I to inventory II and III, using Mann-Whitney U Test.

Production region		SOC_{II}-SOC_{I} (Inventory II-inventory I, %)					SOC_{III}-SOC_{I} (Inventory III-inventory I, %)				
		Location shift	95% confidence limit-Lower	95% confidence limit-Upper	Interval midpoint	Asymptotic standard error	Location shift	95% confidence limit-Lower	95% confidence limit-Upper	Interval midpoint	Asymptotic standard error
PO1	Götalands södra slättbygder	0.14*	0.03	0.26	0.14	0.06	0.21*	0.10	0.31	0.21	0.05
PO2	Götalands mellanbygder	0.13	-0.01	0.28	0.13	0.08	0.24*	0.10	0.39	0.24	0.07
PO3	Götalands norra slättbygder	0.05	-0.06	0.16	0.05	0.06	0.19*	0.08	0.30	0.19	0.06
PO4	Svealands slättbygder	0.07	-0.03	0.16	0.07	0.05	0.18*	0.09	0.27	0.18	0.05
PO5	Götalands skogsbygder	0.23*	0.09	0.37	0.23	0.07	0.30*	0.16	0.44	0.30	0.07
PO6	Mellersta Sveriges skogsbygder	0.05	-0.12	0.23	0.06	0.09	0.17*	0.00	0.33	0.17	0.08
PO7	Nedre Norrland	0.32*	0.05	0.60	0.32	0.14	0.31*	0.04	0.58	0.31	0.14
PO8	Övre Norrland	0.17	-0.17	0.54	0.19	0.18	0.28	-0.06	0.59	0.27	0.17
	Country	0.11*	0.06	0.17	0.11	0.03	0.21*	0.16	0.26	0.21	0.03

*Represents significant difference between two groups in a two-sided test at $\alpha=0.05$ level. Positive values are increment and negative values are decrement of SOC

4. Future Prospects & Conclusions

Applying exact coordinates were allowing us to add a few points in each PO8s that were not present in our previous analysis of the three soil inventories, and to make sure assigning correct PO8s to each sampling point in inventory II and III. Using other statistical tests were also improving the inference between inventories at the PO8 level, where the Wilcoxon signed rank test (a non-parametric method) applied to the matching points when comparing inventory III against II now showed significant differences. However, the general trends remain similar compared with the previous analysis. Although data analysis of the inventories showed consistent SOC increment over time, the absolute increment is relatively small, e.g. at national level SOC concentrations increased by 0.11, 0.07 and 0.21 percentage units from inventory I to inventory II, from inventory II to inventory III, and from inventory I to inventory III, respectively. The predictions with ICBM are mimicking the relative increase in SOC at the national level but the relative increase is much less pronounced, compared to that obtained with the national SMP, and ICBM predictions are not always matching the same trends for all of the PO8s.

Regardless of the methods used, for several reasons it remains a challenge estimating changes in SOC over time for arable land at a national and particularly at regional scale. The two methods addressed in this report both have uncertainties, not only for estimating changes in SOC for Sweden but also for national estimates for other countries.

For the Swedish SMP, we have for the moment been identifying a few aspects, discussed below, which we believe are particularly important and that needs to be considered when assessing spatio-temporal changes in SOC with these data. Other uncertainties also exist.

There is a possible bias in C concentrations depending on the use of different analysis methods, which have changed over time between the three inventories. We are currently examining this in another SMED development project, by re-analyzing selected sub-samples from each of the inventories in the same batch.

The sampling strategy in inventory I was different from inventory II and III. In many cases, soil samples in inventory I were coming from fields on farms that were part of the official objective yield estimate surveys. This survey was focusing on farms specialized growing small-grain cereals. Although it also included farms with ley crops in their rotations, accordingly with the description in Eriksson et al. (1997, and references cited therein), there is an indication that the fields were mostly fields with annual crops (spring barley and oats, winter wheat) at the time of sampling. Consequently, there is a possibility that the C concentrations may have been under-estimated in inventory I. However, these thoughts need further investigations.

With the exception of a few sampling points, Inventories II and III have the advantage of having identical and more precise coordinates, which offers a better possibility of obtaining detailed information for each sampling point, and is helpful in the interpretation. Analyses of the data from the Swedish SMP have already been considering this (Eriksson et al. 2010; Eriksson, 2021; Henryson et al. 2022), by using data from the Swedish farm register on, for example, the type of farms and the respective proportion of leys. It is possible exploring the usefulness of precise coordinates further and obtaining other type of information's (e.g., on crop yields and climate) from other databases.

The comparisons between inventory II and III are more uniform and allow the application of stronger statistical methods. However, as discussed in Henryson et al. (2022), the matched points from these two inventories are sometimes showing extreme SOC concentration changes, and they were applying a filtering process to remove outliers. In our analysis, we did not filter out these data. We concur that this is problematic and needs consideration; it is also possible further improving the statistical analysis by considering other modern and alternative approaches, e.g., using permutation/randomization tests and bootstrap confidence intervals.

The comparisons between inventory III vs II are only representing changes in C concentrations over a 10-year period. This is a short time perspective with respect to changes in C concentrations that occurs slowly, the fourth inventory has been started and will provide precious information concerning the trends discussed in this report. We are continuing this work in close collaboration with the persons at SLU responsible for the Swedish SMP. Notably regarding the re-analysis of selected sub-samples mentioned above.

Regarding the application of ICBM with the Tier III approach; although we have been improving the new version with a new calibration by better accounting for the contribution of roots to the formation of stable SOC, the problem of accurately estimating some of the input data used remain. In particular, the amount of annual C inputs to soil from roots is problematic. This constitutes an important source of uncertainty not only for ICBM but also for all SOC models (Keel et al. 2017). For example, when using different approaches for leys (Bolinder et al. 2007; Palosuo et al. 2015; Taghizadeh-Toosi et al. 2020), the variation in estimates of root-derived C inputs is at least ±0.2 Mg C ha-1 yr-1, which is not negligible considering that about one third of this C contributes to the formation of stable SOC. Similarly, although we are now using an improved time series with C inputs from manures, uncertainty in these estimates also remain high, in the same order of magnitude or even higher as that for leys mentioned above, and this needs further improvement (Bolinder et al. 2022).

Concerning the ICBM parameter values as such (i.e., SOC decay rates and humification coefficients), including more Swedish long-term experiments in a multi-site calibration would make the model parameters less uncertain and more generally applicable for the national level. In the new calibration presented in this report, we have been using more than two decades of additional data from the original calibration site (i.e., the Ultuna frame trial), as well as data from a long-term sister experiment at Lanna. However, more than ten other Swedish long-term experiments could be included in a multi-site calibration. We are currently working on developing such a calibration within a research project.

References

Andrén O, Kätterer T, Karlsson T, Eriksson J. 2008. Soil C balances in Swedish agricultural soils 1990-2004, with preliminary projections. Nutr. Cycl. Agroecosyst. 81: 129-144.

Andrén O, Kätterer T, Karlsson T. 2004. ICBM regional model for estimations of dynamics of agricultural soil carbon pools. Nutr. Cycl. Agroecosyst. 70: 231-239.

Andrén, O., Kätterer, T. 1997. ICBM: The introductory carbon balance model for exploration of soil carbon balances. Ecol. App. 7: 1226-1236.

Bolinder MA, Hytteborn J, Lang R, Lundblad M, Kätterer T. 2022. Coordination of common input data for manure in the agricultural sector and for ICBM in the LULUCF sector. SMED Rapport Nr 19 2022.

Bolinder MA, Menichetti L, Meurer K, Lundblad M, Kätterer T. 2018. New calibration of the ICBM model & analysis of soil organic carbon concentrations from Swedish soil monitoring programs. SMED Report 20, 2018.

Bolinder MA, Janzen HH, Gregorich EG, Angers DA. Vandenbyggart AJ. 1997. An approach for estimating net primary productivity and annual carbon inputs to soil for common agricultural crops in Canada. Agriculture, Ecosystems and Environment. 118: 29-42.

Eriksson J. 2021. Tillståndet i svensk åkermark och gröda. Data från 2011-2017. Uppsala (Sweden): Ekohydrologi 168. Swedish University of Agricultural Sciences; 2021. [In Swedish].

Eriksson J, Mattsson L, Söderström M. 2010. Tillståndet i svensk åkermark och gröda. Stockholm, Swedish Environmental Protection Agency, Report 6349. [In Swedish].

Eriksson J, Andersson A, Andersson R. 1997. Tillståndet i svensk åkermark. Stockholm, Swedish Environmental Protection Agency, Report 4778. [In Swedish].

Henryson K, Meurer KHE, Bolinder MA, Kätterer T, Tidåker P. 2022. Higher carbon sequestration on Swedish dairy farms compared with other farm types as revealed by national soil inventories. Carbon Management. 13: 266-278. https://doi.org/10.1080/17583004.2022.2074315

Keel SG, Leifeld J, Mayer J, Taghizadeh-Toosi A, Olesen JE. 2017. Large uncertainty in soil carbon modelling related to method of calculation of plant carbon input in agricultural systems. European Journal of Soil Science. doi: 10.1111/ejss.12454

Kätterer T, Bolinder MA. 2022. Chapter 15: Agriculture practices to improve soil carbon sequestration in upland soil, In: Understanding and fostering soil carbon sequestration (ed. Dr Cornelia Rumpel). https://dx.doi.org/10.19103/AS.2022.0106.15

Menichetti L, Bolinder MA, Kätterer T. 2022. Bayesian calibration of the ICBM soil organic carbon model to include multiple uncertainty sources. (manuscript).

NIR (National Inventory Report Sweden), 2021. Greenhouse Gas Emission Inventories 1990-2019 submitted under the United Nations Framework Convention on Climate Change and the Kyoto Protocol.

Palosuo T, Heikkinen J, Regina K. 2015. Method for estimating soil carbon stock changes in Finnish mineral cropland and grassland soils. Carbon Management. 6: 207-220.

Poeplau C, Bolinder MA, Eriksson J, Lundblad M, Kätterer T. 2015. Positive trends in organic carbon storage in Swedish agricultural soils due to unexpected socio-economic drivers. Biogeosciences. 12: 3241-3251.

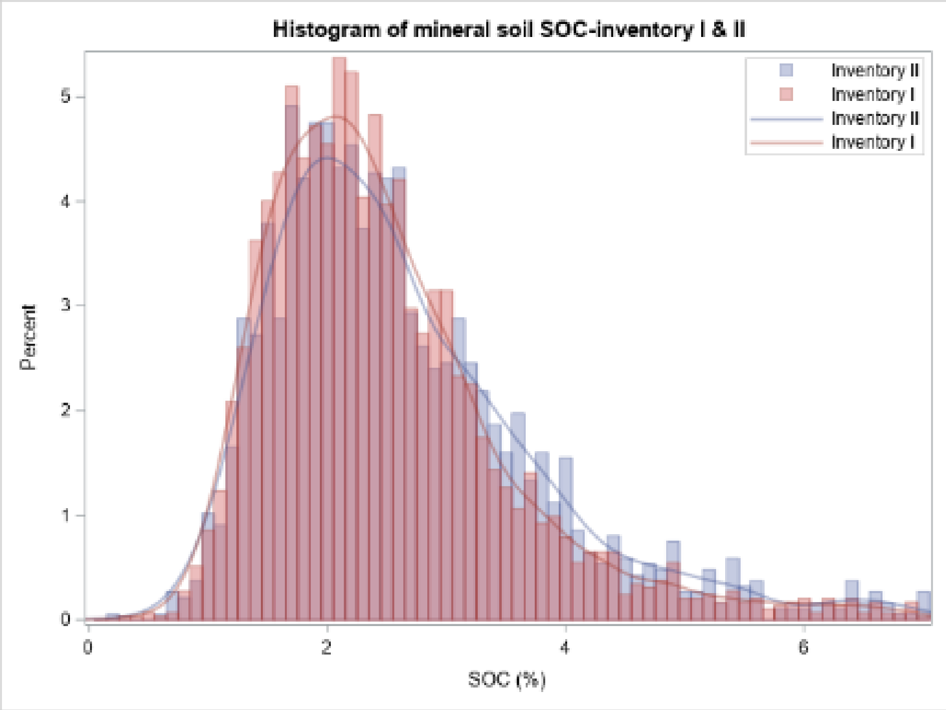
Taghizadeh-Toosi A, Cong W-F, Eriksen J, Mayer J, Olesen JE, Keel SG, Glendining M, Kätterer T, Christensen BT. 2020. Visiting dark sides of model simulation of carbon stocks in European temperate agricultural soils: allometric function and model initialization. Plant and Soil. 450: 255-272.

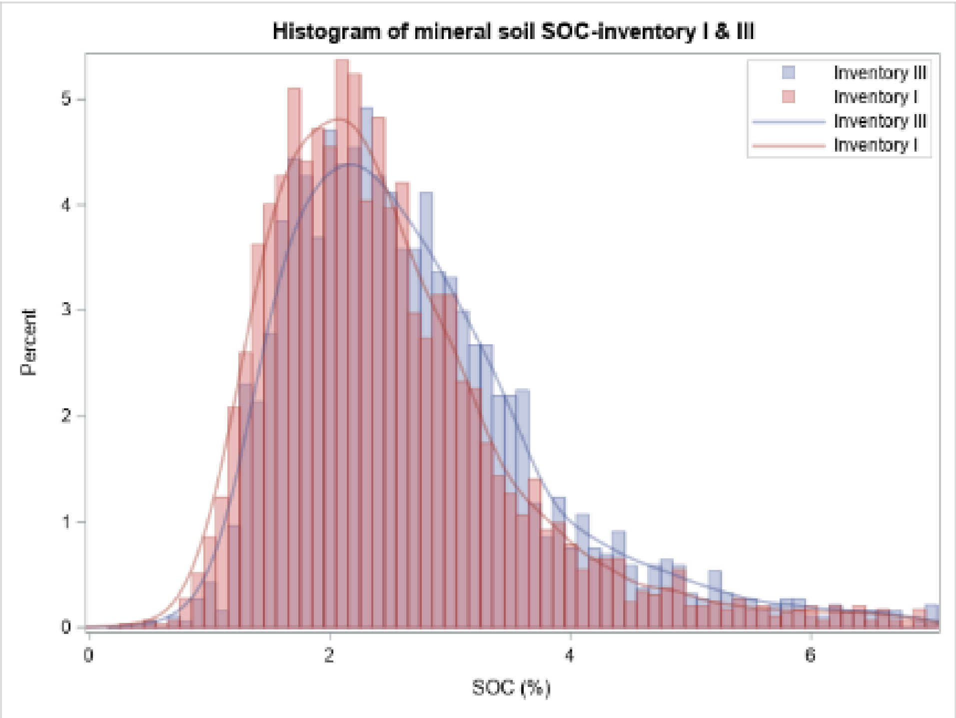
Appendix 1. Quantiles of SOC for each of the PO8s for the three inventories.

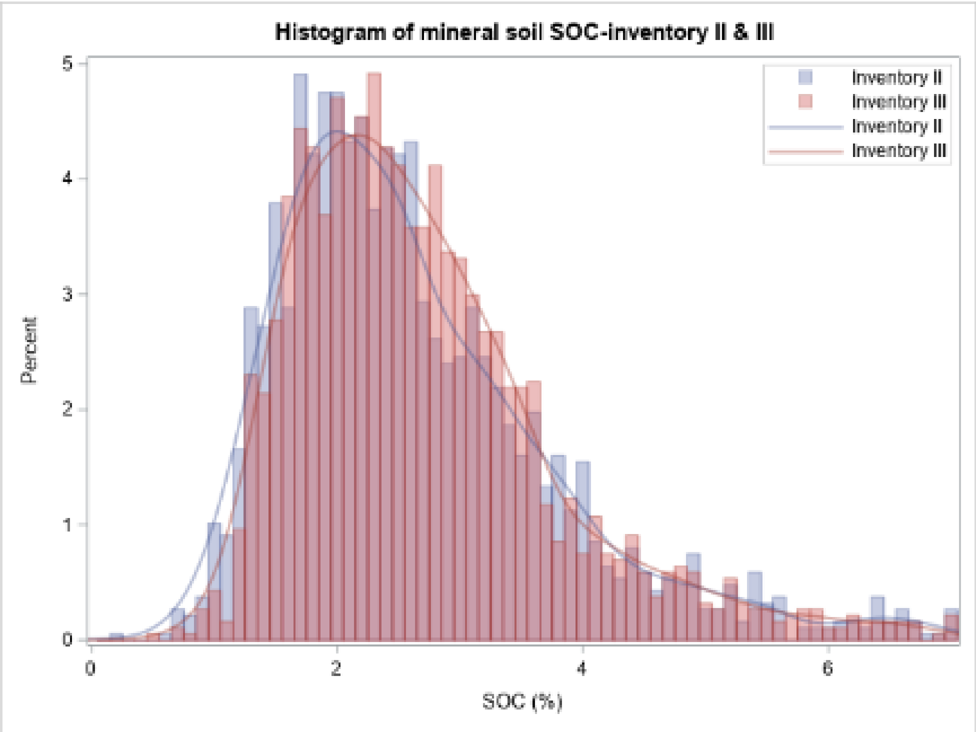
		Production region								
Inventory	**Level**	**PO1**	**PO2**	**PO3**	**PO4**	**PO5**	**PO6**	**PO7**	**PO8**	**Country**
Inventory I	**100% Max**	6.76	6.79	6.94	6.97	6.91	6.42	6.22	6.88	6.97
	99%	5.64	6.58	5.96	5.86	6.45	6.19	5.97	6.62	6.22
	95%	3.72	4.32	4.38	4.31	4.88	4.04	4.81	5.96	4.50
	90%	3.23	3.54	3.66	3.57	4.20	3.68	4.23	4.77	3.79
	75% Q3	2.41	2.68	2.83	2.78	3.34	2.93	3.40	3.42	2.94
	50% Median	1.76	2.11	2.21	2.18	2.62	2.43	2.68	2.75	2.27
	25% Q1	1.41	1.64	1.77	1.78	2.10	2.00	2.13	1.98	1.75
	10%	1.18	1.25	1.43	1.49	1.69	1.64	1.74	1.66	1.41
	5%	1.05	1.10	1.28	1.36	1.43	1.44	1.55	1.41	1.24
	1%	0.92	0.78	1.04	1.17	0.96	1.11	1.20	1.03	0.95
	0% Min	0.47	0.44	0.79	0.79	0.50	0.97	0.85	0.27	0.27
Inventory II	**100% Max**	6.93	6.69	6.96	6.98	6.96	6.12	6.54	6.65	6.98
	99%	5.49	6.54	5.65	6.61	6.61	5.60	6.41	6.65	6.45
	95%	4.26	4.97	4.65	4.63	5.15	4.31	6.05	5.41	4.89
	90%	3.70	3.98	3.87	3.76	4.64	3.87	5.24	4.52	4.06
	75% Q3	2.65	3.11	2.90	2.90	3.60	3.10	3.88	3.81	3.17
	50% Median	1.96	2.25	2.21	2.27	2.92	2.45	3.06	2.96	2.39
	25% Q1	1.47	1.67	1.81	1.81	2.27	1.91	2.28	2.07	1.83
	10%	1.23	1.26	1.50	1.43	1.70	1.66	1.66	1.62	1.44
	5%	1.09	1.11	1.34	1.30	1.42	1.51	1.41	1.44	1.28
	1%	0.99	0.84	1.00	1.03	1.04	0.94	0.99	0.97	0.96
	0% Min	0.74	0.66	0.65	0.19	0.71	0.89	0.56	0.97	0.19
Inventory III	**100% Max**	6.93	6.98	6.28	6.97	6.96	6.70	6.62	6.19	6.98
	99%	5.19	5.31	5.93	6.52	6.36	6.44	6.48	6.19	6.32
	95%	4.02	4.70	4.38	4.84	5.23	4.76	5.51	5.74	4.84
	90%	3.56	3.93	3.64	3.80	4.65	4.13	5.17	4.45	4.12
	75% Q3	2.75	2.94	3.10	2.98	3.65	3.16	4.05	3.62	3.21

50% Median	2.00	2.41	2.39	2.38	2.99	2.63	3.00	2.96	2.49
25% Q1	1.59	1.77	1.92	1.95	2.37	2.10	2.34	2.43	1.94
10%	1.37	1.39	1.63	1.64	1.75	1.67	1.77	1.82	1.57
5%	1.23	1.27	1.45	1.42	1.56	1.58	1.64	1.59	1.38
1%	1.03	0.89	1.24	1.24	1.28	1.42	0.98	1.17	1.09
0% Min	1.01	0.74	0.84	0.47	1.25	1.35	0.90	1.17	0.47

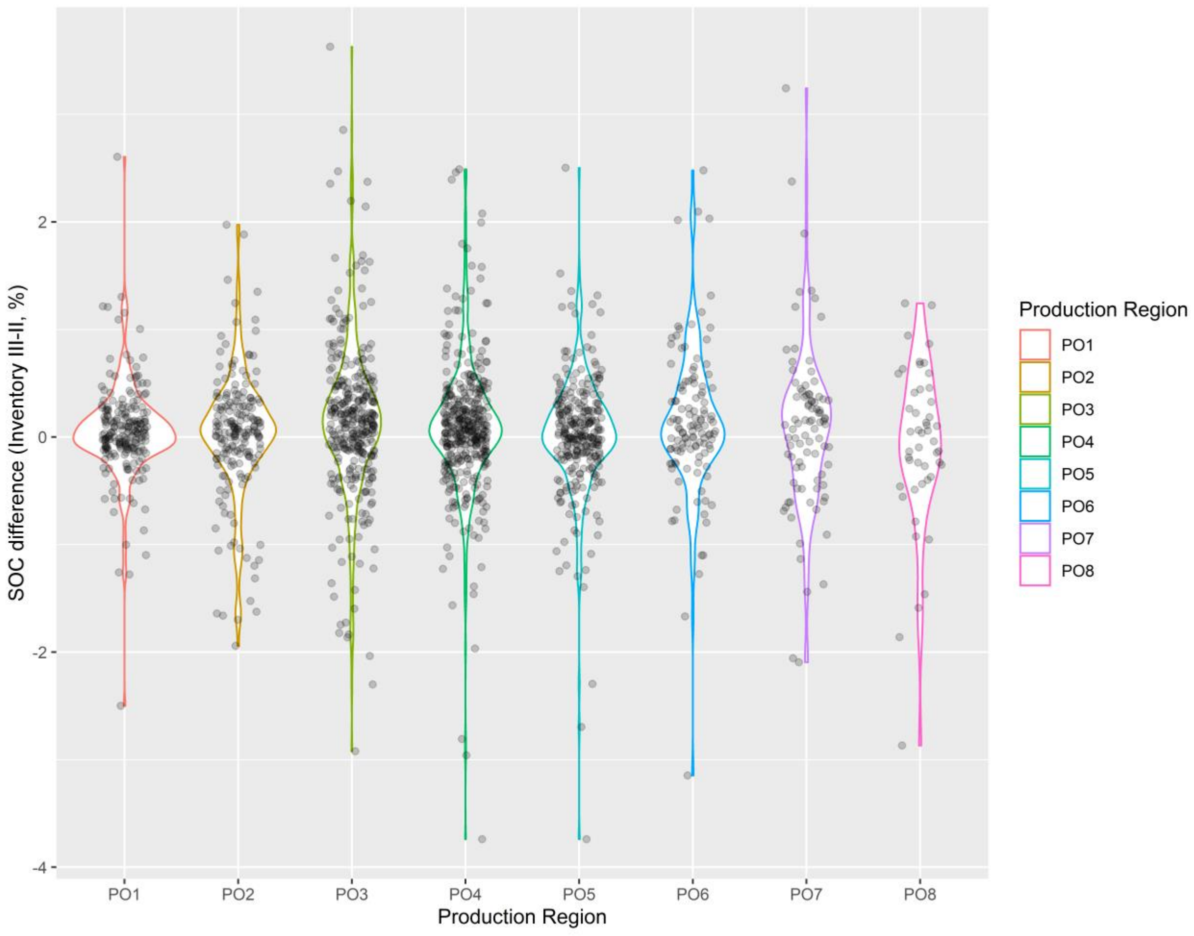
Appendix 2. Histograms of SOC comparing the three inventories at the national level (inventory I & II, inventory I & III and inventory II & III).




Histogram of mineral soil SOC-inventory I & III
Inventory III
Inventory I
Inventory III
Inventory I
Percent
0
1
2
3
4
5
0
2
4
6
SOC (%)

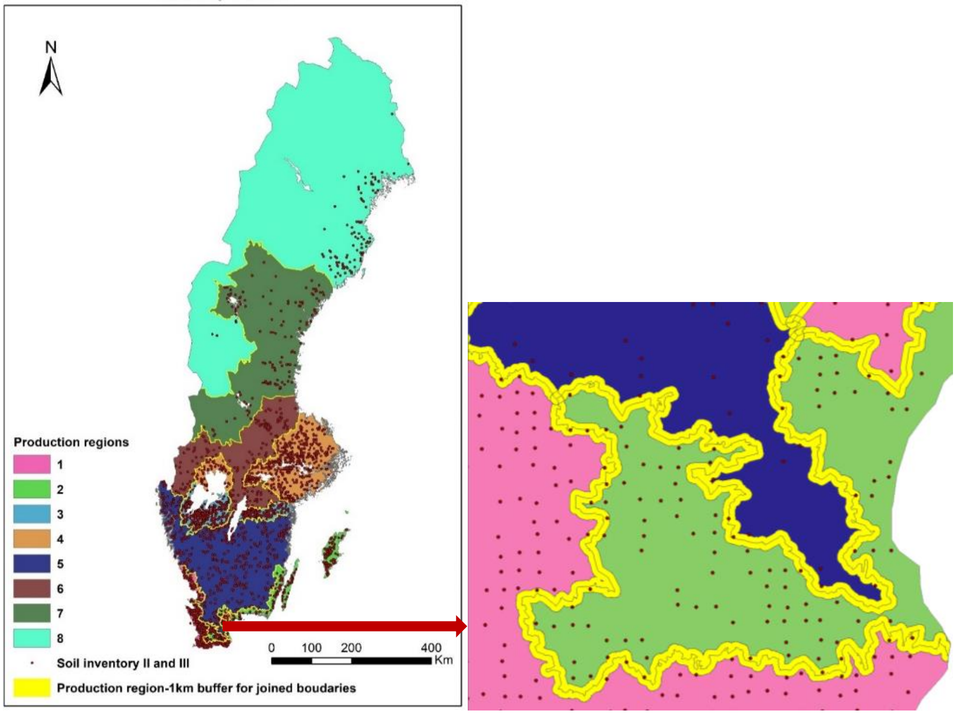

Histogram of mineral soil SOC-inventory II & III
Inventory II
Inventory III
Inventory II
Inventory III
Percent
0
1
2
3
4
5
0
2
4
6
SOC (%)

Appendix 3. Distribution of the SOC difference in each PO8s from matched points in inventory II and III (SOC_{III}-SOC_{II}).

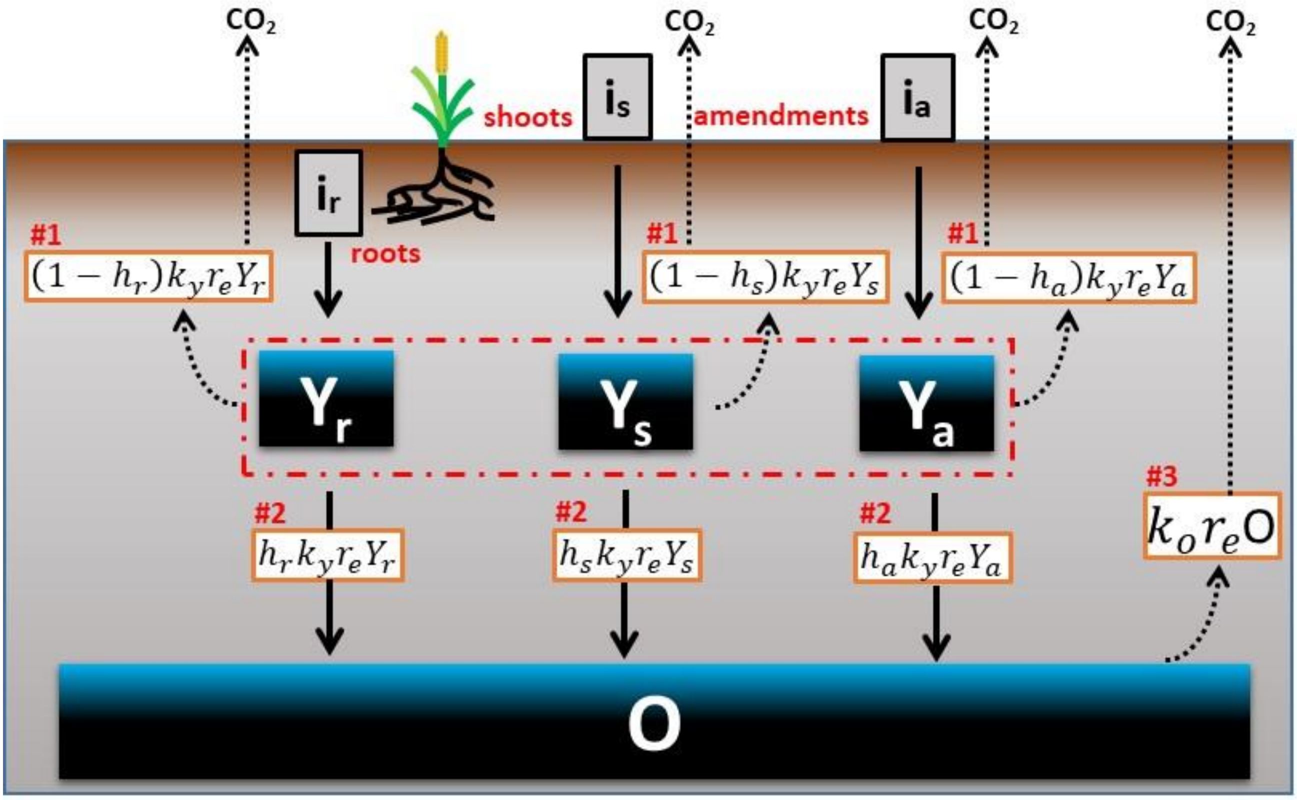


Appendix 4. Distribution of sampling points in inventory II and III.

The points falling into 1-km buffer of joined boundaries of production regions could be allotted to the wrong production region when rounded coordinates (rounded to 1000 meter) are used in spatial join procedure. Current analysis is using the exact coordinates.



Appendix 5. Description of the new version of the ICBM model used in LULUCF.



The ICBM model calculates temporal changes in soil organic carbon (SOC) stocks with annual discrete time steps based on first-order kinetics. The model applied for this year's submission (2023) is dividing total SOC stocks into three Young (Y) pools, where the subscripts r, s and a are referring to roots (debris derived from belowground crop residues), shoots (aboveground crop residues) and amendments (organic amendments), and one old SOC pool (O). Each of the three Y-pools has specific humification coefficients (h_r, h_s and h_a parameters, respectively). These humification coefficients are determining the fraction of each Y-pool (i.e., in equation #2) that enters the O-pool, representing the more stabilized form of SOC, while (1 –h) in equation #1 is determining the respective losses of CO_2 during the decomposition process of each Y-pool. The parameters K_Y and K_O are first-order decomposition rate constants, where K_Y is the same for each Y-pool. There are four driving variables, the amount of annual carbon input to each of the three Y-pools (I_r, I_s and I_a, respectively) and a soil climate parameter (r_e) that aggregates the influence of soil water content and soil temperature on decomposition. The climate parameter multiplies the decay rates of the different SOC pools (i.e., in equation #1, 2 and #3), a higher r_e implies faster decomposition. For the moment, we are running the ICBM model by using a weighted average of the three humification coefficients (i.e., considering the three Y-pools as only one as indicated by the dashed red line), and for organic amendments we are presently only considering carbon from animal manures. The difference in parameter values compared to the ICBM model version used in previous submissions are h_r = 0.36 (instead of 0.13), h_s = 0.14 (instead of 0.13), h_a = 0.31 (instead of 0.35), K_Y = 0.37 (instead of 0.8) and K_O = 0.010 (instead of 0.006).