



HUMUS project

Estimation of the soil organic carbon storage potentials in Luxembourg

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Identification of the suitable methodologies and preliminary results

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Abstract: The present study focuses on the localization and quantification of additional carbon storage potentials, that is, carbon stocks that could theoretically be added to existing stocks to maximize the carbon sink role of Luxembourg's soils. Assessing these additional storage potentials help guide public policies related to soil management (agriculture, forestry, urban green space management, spatial planning) toward the most promising opportunities. In this study, six different methodologies for estimating the soil SOC (Soil Organic Carbon) storage potential have been identified and among them, four have been tested. The results obtained show that these four methodologies can be implemented with the data available at national level and provide interested and promising results. However, the results produced are only provisional and must under no circumstances be reused, particularly by policymakers or land managers, due to numerous technical limitations. Moreover, the SOC storage potential values obtained are theoretical values and should not, by default, be considered as targets to be achieved without taking into account other operational aspects, such as agricultural or forestry production, spatial planning or the protection of the environment. In order to obtain reliable estimates of SOC storage potential at the national scale, it is necessary to redo the calculations while addressing the limitations identified in this study.

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1 Introduction

This study is part of the HUMUS project launched in 2021, which aims to provide technical support for quantifying the dynamics of organic carbon stocks in Luxembourg's soils in order to implement the provisions of Regulation (EU) 2018/841 on the inclusion of greenhouse gas emissions and removals from land use, land-use change and forestry (LULUCF).

Indeed, the LULUCF sector faces numerous technical challenges, particularly regarding the carbon pool in mineral soils. These challenges will need to be addressed in the medium term in order to improve inventories as well as projections of CO₂ emissions and sequestration in the LULUCF sector, and above all to meet the sequestration targets set by the regulation for this sector. Among these challenges, the identification and characterization of land management practices that increase soil organic carbon (SOC) stocks were the subject of the first study under the HUMUS project.

The present study focuses on the localization and quantification of additional carbon storage potentials, that is, carbon stocks that could theoretically be added to existing stocks to maximize the carbon sink role of Luxembourg's soils. Assessing these additional storage potentials will help guide public policies related to soil management (agriculture, forestry, urban green space management, spatial planning) toward the most promising opportunities (i.e., those that are the largest and/or most easily achievable potentials), particularly by promoting management practices best suited to local additional storage potentials.

The precise quantification and localization of additional storage potentials will also provide essential information for the development of an effective national strategy within the framework of Luxembourg's CCUS policy.

2 Hypothesis and objectives

The present study is based on the following hypotheses:

- Mineral soils can stably and permanently store a finite maximum amount of organic carbon.
- For a given soil, this finite maximum amount of organic carbon depends on the soil's intrinsic pedological properties as well as on extrinsic factors influencing organic carbon dynamics, such as climate, topography, and biological activity, including human activities.
- In Luxembourg, at least some soils have suboptimal organic carbon stocks, meaning that their current stocks are lower than the theoretical maximum carbon stock they could reach under optimal conditions.
- The theoretical organic carbon deficit of soils can be estimated by calculating the difference between their theoretical maximum stocks and their observed stocks.

Based on these hypotheses, the main objective of this study is to develop and test a methodology capable of quantifying and mapping soil organic carbon (SOC) storage potentials across Luxembourg.

To achieve this, the study begins with a review of the scientific literature in order to establish an overview as comprehensive as possible of existing technical approaches, as well as the main challenges that must be addressed to implement them effectively.

Finally, within the limits of the available resources, the identified methodologies are tested in order to (i) verify their applicability, (ii) precisely identify the resources required for their implementation, and (iii) determine their limitations.

3 State of the art – how to assess the SOC storage potential?

3.1 Basic principles

The SOC storage potential of a soil corresponds to the difference between its maximal SOC stock and its current (observed) SOC stock. From a mathematical perspective, this difference can be expressed by Equation 1.

Equation 1: Basic principle for defining a SOC sequestration potential

$$S_{pot} = S_{max} - S_{obs}$$

With,

S_{pot} , the SOC storage potential ($\text{kgC}\cdot\text{m}^{-2}$) that is the SOC stock that could additionally be stored in the soil, which is referred to as the carbon deficit in some studies,

S_{max} , the maximal SOC stock ($\text{kgC}\cdot\text{m}^{-2}$) that could theoretically be stored in the soil, which is referred to as the maximum reachable SOC stock in some studies,

S_{obs} , the observed SOC stock ($\text{kgC}\cdot\text{m}^{-2}$) that is effectively stored in the soil.

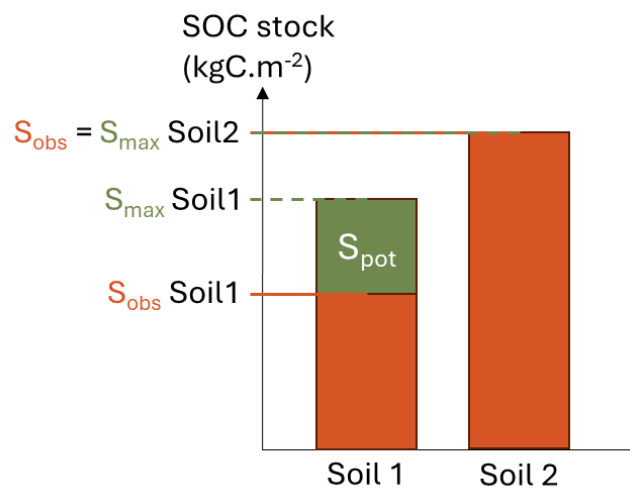


Figure 1: Schematic representation of the SOC storage potential concept

Figure 1 illustrates the concept of SOC storage potential, which corresponds to the difference between the maximum stock that can theoretically be achieved for a soil and the stock that is actually measured (observed) in that same soil. Theoretically, two cases are possible: the soil is in a carbon-deficit state (Soil 1), and therefore its storage potential is positive; or the soil is saturated with carbon (Soil 2), and its storage potential is zero.

The maximal SOC stock of a soil depends on various factors, which are its intrinsic properties (e.g. texture), its environmental conditions (e.g. climate, altitude), its plant cover (e.g. grassland, forest), and its management (e.g. agricultural practices). The maximal SOC stock can be divided into two fractions. A fraction is related to the influence of factors that are not directly modifiable by human activities (i.e. soil types and climatic zones), embodied by the concept of pedoclimatic regions. Another fraction depends on factors directly modifiable by human activities (i.e. plant cover and soil management), embodied by the land use.

Because the maximal SOC stock for a given soil is impossible to measure directly and because, even in the event of the SOC stock of a soil is at its maximum, no evidence can be found to know that it is effectively at its maximum, the maximal SOC stock can only be estimated. Although several methodologies have been developed and tested in the last decades, no standardized methodology exists. To identify and select the most suitable one for our project, we carried out a literature review, whose main findings are presented below.

3.2 Approaches identified to estimate the maximal SOC stock

In the literature, six different approaches able to estimate a value of maximal reachable SOC stock have been identified:

- Modeling of the SOC storage dynamic related to changes in soil management;
- References from soils in good conditions;
- Soil organic carbon storage rates;
- Carbon saturation of the fine fraction;
- Soil organic carbon to clay ratio;
- Expected soil organic carbon content.

3.2.1 Modeling of the SOC storage dynamic

Many mechanistic models have been developed to assess the effects of different biotic and abiotic factors on the SOC contents or stocks in different land uses (Pellegriⁿ et al., 2020). Several literature reviews highlight the high number of models developed and the large diversity of approaches applied (Wutzler et Reichstein, 2007; Manzoni et Porporato, 2009; Campbell et Paustian, 2015; Vereecken et al., 2016), which depend notably on the spatial scale considered, from the aggregate (Vogel et al., 2015) to the whole planet (Todd-Brown et al., 2013). Globally, these models try to model and assess at least one of the three mechanisms that control the SOC stability: OM-mineral phase interaction, chemical recalcitrance and physical protection within aggregates, and consider all the inputs and outputs of carbon that influence the studied system (e.g. aggregate, profile, plot, watershed, region, earth) (Pellegriⁿ et al., 2020).

Multi-compartment models using first-order kinetics are widely and often used to describe and predict the evolution of the OM decomposition, and thus, of the SOC stocks or contents at small scales (plot to planet). Even though first-order kinetics are an over-simplification of the reality, which do not take into account much of the recent knowledge on the OM dynamics (e.g. OM forms continuum, influences of microorganisms, soil heterogeneity, availability of macronutrients N, P, S), these mechanistic models are robust enough to apply them at small spatial scale (Pellegriⁿ et al., 2020). Some models are generic and can be applied to any or several plant covers or land uses (e.g. CENTURY (Parton *et al.*, 1987); STICS (Brisson *et al.*, 1998, 2003); RothC (Coleman et Jenkinson, 1996)), but some others are specific to one land use (e.g. arable land: AMG (Andriulo et al., 1997); Permanent grassland: PaSim (Calanca *et al.*, 2007); Forest: CASTANEA (Dufrêne *et al.*, 2005)).

The existing models have not been designed expressively to assess the SOC storage potential, but to understand and predict the evolution of the SOC contents or stocks, depending on different factors, such as land cover change, agricultural management change or climate change. In order to estimate a SOC storage potential, a model has to be applied twice at a same location, with two different configurations: a first configuration using the existing ongoing environmental and management conditions (baseline configuration), and a second configuration using a hypothetical environmental and management conditions that would be applied in a certain scenario (scenario configuration). Finally, by comparing the results of each model configuration, it is possible to assess the gain or the loss of the response variable (e.g. SOC stocks) due to the tested scenario and thus define if the application of the tested scenario would increase or decrease the response variable after a defined period. In order to increase the total SOC stored in soils, we can state that only the agricultural or forestry management practices can be modified (human actions cannot modify directly, at least over large areas, the other factors, such as the intrinsic soil properties, the elevation or the climate). Thus, the only difference between the baseline configuration and the scenario configuration must be a management practice or a set of management practices, i.e. the other factors that could affect the response variable evolution (e.g. climate) are similarly set in the two model configurations.

If the response variable is the SOC stock, the SOC storage potential at a location is the difference between the SOC that would exist after n years of practice B (scenario configuration) and the SOC that would exist after n years of practice A (baseline configuration, which is the business-as-usual / in-place management) (Figure 2).

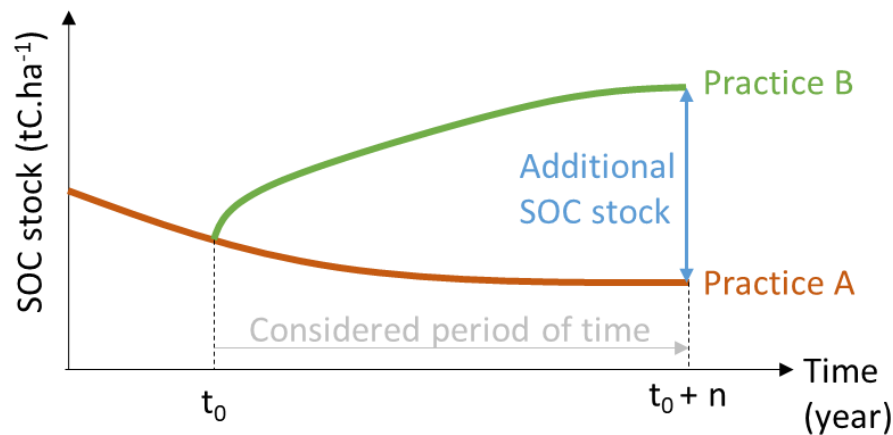


Figure 2 : Schematic representation of SOC storage kinetics for two model configurations for one location: Practice A = business-as-usual soil management = baseline configuration; Practice B = alternative soil management = scenario configuration

This approach requires defining both, a baseline configuration and a relevant scenario configuration, which could be relatively easy for one plot, but appears to be significantly more difficult for an entire country. Furthermore, to assess the maximal SOC storage potential, the “best” practices have to be selected and implemented in the scenario configuration, which is complex to define.

To define a relevant baseline configuration for France, Pellerin et al. (2020) combined data from different sources, such as:

- The main cultural practices for the 8 most cultivated crops, for 2 types of temporary grassland, and 2 types of permanent grassland;
- The typical cultural rotations for each different pedo-climatic regions, including cover crops;
- The mineral and organic fertilization practices;
- The irrigation practices;
- The management of the cultural residues (exported or not);
- The exploitation modes of the grasslands (cutting, grazing, both).

To avoid over-complication of the baseline configuration, several simplifications were made, and to deal with missing information, several assumptions were also made.

To define the scenario configuration, Pellerin et al. (2020) selected, for each land use considered (i.e. cropland and permanent grassland), a set of 9 practices, identified as the most promising ones, on the basis of a literature review and expert knowledge. These practices are:

- Surface and time expansion of cover crops;
- Direct sowing;
- Surface and time expansion of temporary grassland in the rotation;
- Organic fertilization with new organic materials;
- Substitution of the cutting with grazing in permanent grassland;
- Moderate intensification of the extensive permanent grassland management;
- Development of agroforestry;
- Development of hedges;
- Greening of inter-rows in perennial crops.

Then, they combined these practices to create 6 practice change scenarios, based on the identified promising management practices, and run the models (STICS (Brisson *et al.*, 1998, 2003) for the arable lands, and PaSim (Calanca *et al.*, 2007) for the permanent grasslands) with these scenarios.

At the European scale, Lugato *et al.* (2014) used the CENTURY model (Parton *et al.*, 1987) in order to assess the potential carbon sequestration of arable soils. As a baseline scenario (called BAU for Business-as-usual), they also combined information on cultural practices for eighteen different crops (rotation, irrigation, fertilization...) and on crop distributions, for the European pedo-climatic zones. Thanks to a literature review, they identified 6 common and feasible management practices that may increase the SOC sequestration, and they used these practices to define 3 plausible practice change scenarios at European scale. For each model simulation (BAU + 3 scenarios), they applied two versions of climate change and estimated the SOC stocks evolution over the period 2013-2100.

Whichever the existing model, they all need three kinds of data:

- Calibration data to fit the model parameters with the local conditions where the model is applied. This data must cover the output variables, such as SOC content or SOC stocks, but also the input variables, such as soil properties, plant biomass production, or weather information.
- Initialization data that enables the model to start a prediction. This data must contain all the required variables used by the model (input, output) at the initial time ($t = 0$), and for a certain period before. For instance, Lugato *et al.* (2014) applied four successive spin-up sequences for a total of 2000 years before the modeling initial time.
- Validation data that enables to assess the quality of the modeling prediction. This data relates mainly to output variables of the model.

Since calibration data is required to develop a model, this data is systematically available for at least the geographical zone where the model has been developed. Calibration data come mainly from long-time field experiments that have been finely studied over decades. But, this makes the model developed site-specific, at least theoretically. Thus, to use a model outside its initial geographical zone or the environmental conditions in which it was designed, a new calibration is theoretically required. To our knowledge, no such model has been developed using data from Luxembourg, and therefore, any selected model that would be applied in the Luxembourg conditions should be first calibrated with local data. However, some models are robust enough to be applied outside of their initial validity domain (Pellerin *et al.*, 2020). Thus, it could be possible to select an existing robust model and implement it with the Luxembourgish conditions. Initialization data is often missing, and assumptions are used to overcome it (e.g. Lugato *et al.*, 2014). Most of the time, conditions at the initial time are assumed to be at equilibrium. This assumption is the simplest one and, so, is widely used in different initialization protocols (Pellegrin *et al.*, 2020). Validation data might be available, but it is scarce. However, this data is not strictly necessary to run a model and get predictions. The lack of validation data affects only the capacity to assess the prediction reliability and the interpretation of the results.

In conclusion, even if the modeling of the SOC storage dynamic is able to estimate a maximal SOC stock and, therefore, to estimate a potential additional SOC stock, this approach shows several drawbacks (Table 1) that make its use unrealistic in the HUMUS project.

Table 1: Advantages and drawbacks of the use of prediction models in order to estimate the maximal SOC stock

Advantages	Drawbacks
<ul style="list-style-type: none"> • Models can take into account many parameters that affect the SOC stocks and the SOC storage dynamics. Thus, the predictions may be a realistic description of the reality. • Model configurations include scenarios (baseline and alternative scenario) depending on management practices. Therefore, based on the results of the model simulations, it is relatively easy to identify the best practices and to bring out policies that promote them. • Once the model is calibrated and initialized, it is relatively easy to test a multitude of scenarios, to take into account all the potential management practices, but also any other changes in the factors that the model can deal with (climate change, land use change, soil properties change, new crops...). 	<ul style="list-style-type: none"> • Even the most advanced models cannot take into account all the parameters that affect the SOC stocks and the SOC storage dynamics. Thus, the predictions are never completely reliable and might be deeply biased. • Model predictions depend on scenarios (baseline and alternative scenarios) that are difficult to define (lack of data, high complexity, uncertainties, high number of plausible scenarios). • No model has been developed in Luxembourg, therefore, we have the choice either to design and develop our own model or to use an existing one. However, adapting an existing model or designing and developing our own model would require many resources (time, expert knowledge, available calibration data, and money). • Up to three different models may be needed, one for each main land use (arable land, permanent grassland, forest). • No existing model is designed to deal with urban soils. • Difficulties to adapt an existing model to the Luxembourgish conditions due to a lack of calibration data (i.e. data from long-time field experiments). • Difficulties to initialize the model, because of methodological issues and of a lack of data. • Difficulties to identify the best or most promising management practices, leading difficulties to get the maximal SOC storage potential. • Existing models may not be freely available and require expert knowledge to be implemented and run.

3.2.2 References from soils in good condition

Over the past decades, many regional or national soil monitoring networks have been developed and implemented worldwide in order to assess the soil quality and its evolution over time. Although the collected data and their collection frequency depend on each network and its purposes (e.g. decision support tool for agriculture, environmental survey, biodiversity protection...), soil organic carbon content in surface horizons has been often measured because of the key role of this parameter for soil functioning.

The monitoring-generated data on SOC content or stocks can be used to define references to estimate the maximal SOC stocks of a soil or of a soil type, applying data-driven or statistical approaches (Barré et al., 2017). To do so, an underlying assumption with two conditions is required:

- There are still some soils that are in steady-state conditions and are not or not significantly depleted of SOC due to anthropogenic degradations (i.e. reference soils);
- These soils are included in a soil monitoring and therefore data on their SOC contents or stocks are known and available.

It is therefore sufficient to identify these reference soils and to consider their SOC stocks as the maximal SOC stock (S_{max}). Since the SOC stocks depend on the pedoclimatic conditions, a specific reference soil must be identified for each homogeneous pedoclimatic zones. In this context, a homogeneous pedoclimatic zone must be homogeneous at least for the climate and the soil topology. However, the land use could also be considered, depending on the approach applied. The definition of homogeneous pedoclimatic zones depends on the scale of the study and its objectives.

Specific land use as reference:

It is possible to consider that soils in SOC steady-state conditions and not depleted of SOC are the soils under certain land uses within each homogeneous pedoclimatic zones. Thus, for a given homogeneous pedoclimatic zone, forest soils, permanent grassland soils or soils under natural vegetation can be used as reference soils to define the maximum reachable SOC stock (Conant et al., 2001; Guo and Gifford, 2002; Lugato et al., 2014; Barre, et al., 2017; Chen et al., 2019). In concrete terms, the average or the highest SOC stock values under a specific land-use would be equivalent to the attainable potential of C stocks (Barré et al., 2017). Numerous variants of the approach are reported in the literature:

- Sparling *et al.* (2003) have estimated desirable values of soil organic carbon in New Zealand, which were proposed to be above the lower quartile of SOC stocks in New Zealand pasture soils, for each major soil type;
- Reference values of SOC stocks under natural vegetation have been used to assess soil C storage potential in Nigeria (Apka *et al.*, 2016);
- Chen et al. (2019) suggest that the SOC stocks of forest soils may be used as a reference to estimate the maximum SOC storage potential in France.

Highest statistical values as reference:

Within a homogeneous pedoclimatic zone (climate, soil type, land use), the reference SOC stock corresponds to a SOC stock value observed in the data set that describes this zone. This value can be the maximum observed, but it can also be a quantile of the SOC stock distribution (e.g. P90) (Barré et al., 2017; Martin et al., 2022). Some studies that opted for this approach, decided to set the maximum SOC stock observed as the reference value:

- Stolbovoy & Montanarella (2008) estimated the potential of SOC gain of European soils by subtracting the observed SOC stocks per soil typological unit, with the maximum observed SOC stocks in the same typological unit and under the same climate;
- Lilly & Baggaley (2013) subtracted the calculated median and the observed maximum SOC contents to compute the C storage potential of various Scottish soil series.

and other studies chose to set a quantile of the SOC stock distribution as the reference value:

- Chen et al. (2019) used the P80 of the SOC stock distribution of the available data to estimate the additional potential SOC stock of France;
- Barré et al. (2017) proposed that the highest reachable SOC stock for a given pedoclimatic condition under a given land-use could correspond to the mean of the top 10% of the measured SOC stocks for these conditions.

However, these two approaches have several limitations. First, the observed SOC stock values for given pedoclimatic conditions (maximum or quantiles) might be well below the maximum, if for example all reference land uses are degraded in the considered pedoclimatic condition or if steady-state conditions for SOC stocks are not attained for most soils. Second, this approach allows estimating a soil storage potential value for known practices. If new storing practices are designed or implemented in the considered region, the highest reachable SOC stock value could obviously not be calculated (Barré et al., 2017). In order to deal with the risk that the SOC stocks of the reference soils are below the maximum, it is conceivable that the reference values are periodically re-assessed (e.g. every 10 years) to take into account potential increases of SOC stocks over time due to the application of storing soil management practices. This entails the fact that the reference SOC stock defined the first time is unlikely the maximal SOC stock, and that the maximal SOC stock would be reached, if ever reached, only after several iterations of the process in several decades. Nevertheless, these approaches have several advantages. The main one is that they define real references that are fully reachable since they have been locally observed. Thus, using such references will lead to the definition of feasible SOC gain objectives, adapted to the local soil properties, the local climate, and the local soil management practices (specific context). A list of the main advantages and drawbacks of this approach is described in Table 2.

Table 2: Advantages and drawbacks of the use of reference soils in order to estimate the maximal SOC stock

Advantages	Drawbacks
<ul style="list-style-type: none"> • Reference soils enable to define reachable SOC stocks since they have been locally observed. • This approach takes into account the whole-soil OC stock and does not focus only on a SOC fraction. • When a systematic monitoring network covers the considered area, it is relatively easy to define reference soils and reference SOC stocks. • This approach can handle all kinds of soils, including extreme-textured soils. 	<ul style="list-style-type: none"> • This approach requires data from a systematic soil monitoring that covers the entire area considered, and sufficient relevant data to be able to define robust statistical references for each homogeneous pedoclimatic zones. This approach could not be applied if the soils of a homogeneous pedoclimatic zones are only under agricultural land use. • The choice of the reference soils (reference land use or statistical value) is subjective and arbitrary, and the reference soils may be in unsteady-state conditions and depleted of SOC due to anthropogenic degradations. This would lead to an underestimation of the SOC storage potential. • The reference values are valid only for the historic and existing management practices and could be irrelevant for new or innovative practices. • The reference values depend, amongst others, on the existing soil management practices, but, since they are not clearly defined, this approach does not provide clear management practices to reach the SOC stock objective (S_{max}).

3.2.3 SOC storage rates

The estimation of a maximal SOC stock using this methodology requires two main elements. Firstly, the assumption that as long as a soil is not saturated with OC, and it is subject to a C-storing soil management practice, its SOC stock will increase over time, until it reaches a maximum (i.e. C saturation). Secondly, the SOC storage rates of the soil management practices of interest are known. A soil management practice can be, in this context, a technical soil management (e.g. integration of winter cover crops in the rotation) as well as a land use change (e.g. arable land to permanent grassland).

The SOC storage rates are generally defined following the Equation 2.

Equation 2: Mathematical expression to define a C storage rate related to a considered soil management practice

$$R = \frac{(S_{t2} - S_{t1})}{(t_2 - t_1)}$$

With,

R, the C storage rate (MgC.ha⁻¹.yr⁻¹) that is related to a considered soil management practice, S_{t1} and S_{t2}, the SOC stocks (MgC.ha⁻¹) of the soil under the considered practice at time t₁ and time t₂, respectively,

t₁ and t₂, respectively, the initial and the final time of the period during which the considered soil management practice has been applied.

A positive R means that the considered soil management practice stored OC in soil during the period for which it has been defined, and on the contrary, a negative R highlights a destocking effect of the practice.

The C storage rates of the soil management practices of interest (i.e. C-storing practices) are defined using time-series data collected through field trials, commercial or experimental farms networks and regional or national soil surveys (Wiesmeier et al., 2020). The C storage rate related to one soil management practice depends on several factors (Olson et al., 2014):

- The soil properties;
- The soil environmental condition (e.g. climate, altitude, use);
- The succession and the interactions of the historical soil management practices that have been applied to the considered soil;
- The equilibrium state of the OC in the soil, which may be in a steady or a non-steady state;
- The level of SOC already stored in the soil;
- The intensity of the soil management practice applied (e.g. the concept of “reduced tillage” encompasses practices ranging from less tillage intensive tillage to a total absence of tillage);
- The interactions between several practices that are simultaneously applied to the soil for agricultural reasons (e.g. use of fertilizers, use of pesticides, irrigation), for environmental reasons (e.g. soil erosion mitigation), for climate reasons (e.g. another C-storing soil practice), and/or for socioeconomic reasons (e.g. type of production).

These factors make the defining of the C storage rates difficult, and the figures obtained are uncertain and variable from a study to another. For instance, Olson et al (2014) inventoried SOC storage rates for a switch from conventional till to no-till ranging from - 0.07 ± 0.27 MgC.ha⁻¹.yr⁻¹ (North East USA) to 0.48 ± 0.59 MgC.ha⁻¹.yr⁻¹ (North Central USA).

To define the maximal SOC stock (S_{max}), the Equation 2 can be adapted to get the Equation 3.

Equation 3: Mathematical expression to define S_{max} from the C storage rate related for one considered practice

$$S_{max} = R * (t_{final} - t_{initial}) + S_{initial}$$

With,

S_{max} , the maximal SOC stock ($MgC \cdot ha^{-1} \cdot yr^{-1}$) that can be reached applying a considered practice;

R, the C storage rate ($MgC \cdot ha^{-1} \cdot yr^{-1}$) corresponding to the considered soil management practice;

$t_{initial}$, the time from which the considered soil management practice is applied;

t_{final} , the time until which the considered soil management practice is applied, and therefore the expected time from which the S_{max} is reached;

$S_{initial}$, the SOC stock ($MgC \cdot ha^{-1}$) of the soil at $t_{initial}$ (i.e. before the soil management practice is applied).

In the literature, the C storage rates (R) are most of the time presented as assumed to be constant over time (linear evolution), and the effective C-storing period, that is the period during which C is effectively stored in the soil at the rate R, is unknown. By convention, IPCC (2006, 2019) decided to set this period to 20 years. However, these two assumptions are biased, as Guzman and Al-Kaisi (2010) demonstrated for the use change from an arable to a permanent grassland. Indeed, they observed that the SOC storage rate was nonlinear over time (curvilinear function) and that the time needed to reach a maximum was uncertain, between several decades and several centuries. McLauchlan et al. (2006) and Matamala et al. (2008) corroborated these observations. Thus, in order to estimate maximal SOC stocks (S_{max}) using the C storage rate approach, the hypothesis of linearity of the rate over time must be accepted and a fixed period must be set.

To estimate the maximal SOC stock of a soil, it is necessary to know which soil management practices will be applied to it. Therefore, a scenario must be determined. Such a scenario is relatively easy to define for one agricultural plot, but it is much more challenging to create a spatially explicit C storage scenario at national level, including the management of agricultural soils, but also the one of the forest and urban soils, as well as changes in land uses. The difficulty lies in the multitude of the plausible scenarios that could be determined, which depend on:

- The abundant existing soil management practices and land use changes;
- The surface expansion potential of these practices and their spatial allocation;
- The interaction between these practices (e.g. an arable land may be converted into a permanent grassland and subjected simultaneously to agroforestry and organic fertilization);
- The identification of the scenario that stores the highest C quantity among those possible.

The determination of such scenarios is similar to the one that is required to apply the methodology described in part 3.2.1 (Modeling).

For instance, Wiesmeier et al. (2020) determined scenarios for agricultural lands of Bavaria, Germany, including five promising management practices (Expansion of cover cropping, improvement of crop rotations, expansion of organic farming, implementation of agroforestry systems, and conversion of cropland to grassland), based on the expansion potential of each practice in percent of the total area of agricultural land. For example, they decided to extend the current area of cover cropping (12.9 % of the total area of agricultural land observed between 2012 and 2015) to 29.2 % of the agricultural total area. According to the authors, these scenarios

may be the most promising current management options to increase SOC stocks as these practices are commonly applied in temperate agricultural systems, are effective measures to build up SOC due to increased OC inputs, and are congruent with the 4per1000 initiative's aim to maintain food security and avoid trade-off effects. The choices taken depend therefore on expert knowledge of the agricultural local context, which may change over time and in function of policy orientations.

The Tier 1 methodology described in the IPCC guidelines (IPCC, 2006) and its update (IPCC, 2019) for estimation of the annual change in OC stocks in mineral soils and the set default parameters could be used in order to estimate the maximal SOC stocks in Luxembourg. For agricultural soils, data published by ASTA (Chartin et al., 2022) can be used to estimate specific rates for studied good agricultural practices: cover crops, reduced tillage, temporary grassland and some of their interactions.

As for the methodology based on the modeling of the SOC storage dynamic (part 3.2.1), the application of SOC storage rates requires a step of initialization. This step aims to define the initial state of the SOC stocks on which the rates will be applied for the chosen storing period. The initial state that could be used is the current SOC stocks estimated by ASTA (Chartin et al., 2022), but this would raise the question of the equilibrium state of the OC in soils. Indeed, based on the available data, it is impossible to determine if the soils are in a steady or in a non-steady state (increasing or decreasing). The assumptions that would be made, would likely introduce uncertainty in the obtained estimation.

A list of the main advantages and drawbacks of this approach is described in Table 3.

Table 3: Advantages and drawbacks of the use of SOC storage rates in order to estimate the maximal SOC stock

Advantages	Drawbacks
<ul style="list-style-type: none"> • The methodology based on SOC sequestration rates includes scenarios depending on management practices. Therefore, based on the results of the estimations, it is relatively easy to identify the best practices and to bring out policies that promote them. • For some management practices of agricultural soils, Luxembourgish SOC storage rates have been estimated. 	<ul style="list-style-type: none"> • The estimations depend on scenarios that are difficult to define (lack of data, high complexity, uncertainties, high number of plausible scenarios). • Difficulties to identify the best or most promising management practices, leading difficulties to get the maximal SOC storage potential. • SOC storage rates are not available for all possible management practices and their interactions, for Luxembourg but also from abroad experiments. Furthermore, there are many different rate values for one practice (high variations). • Difficulties to initialize the methodology, because of methodological issues and of a lack of data. • The period during which the rates must be applied is unknown and almost impossible to assess. That is why it is necessary to set it arbitrarily, which leads to uncertainties in the estimations. • Due to a lack of data and knowledge, the SOC storage rates are assumed to be linear during the entire period of storage, even if evidence prove that, at least for some management practices, they are not.

3.2.4 Carbon saturation of the fine fraction

Based on the study of permanent grassland topsoil, assumed to be C-saturated, from different part of the world, Hassink (1997) developed an equation to describe the relationship between maximum SOC storage in the fine fraction (clay (< 2µm) + fine silt (2-20 µm)) and the soil fine fraction content. The SOC associated with the fine fraction (protected carbon) is assumed to be more stable than the coarse SOC (Six et al., 2002), and the soil mineral fraction is a key feature for SOC stabilization (Kleber et al., 2015). According to these results, Hassink (1997) proposed the carbon saturation concept, which applies only to the soil fine fraction (< 20 µm) and is theoretically related to the inherent capacity of soils to stabilize SOC in the long term. This concept is based on the idea that the soil mineral fraction has a finite capacity to protect C (Hassink, 1997). Since then, several studies have shown results supporting this carbon saturation concept that is now generally accepted (Six et al., 2002; Stewart et al., 2007; Dignac et al., 2017).

This concept has been used by Wiesmeier et al. (2014) and Chen et al. (2019) to develop a methodology to assess the additional SOC storage potential for the mineral soils, in Bavaria (Germany) and France, respectively. To do so, they used the equation (Equation 4) defined by Hassink (1997), which enables to assess the SOC saturation of soil fine fraction (< 20 µm) from the fine fraction content:

Equation 4: Equation developed by Hassink (1997) to estimate the SOC saturation content

$$SOC_{sat} = 4.09(\pm 1.59) + 0.37(\pm 0.04) * FFC$$

With, SOC_{sat} , the SOC saturation content ($g \cdot kg^{-1}$) of the soil fine fraction, FFC, the fine fraction (< 20 µm: clay+fine silt) content of the soil (%).

By applying the methodology developed by Hassink (1997), Guillaume et al. (2022) adjusted the Hassink's equation (Equation 4) using data of permanent (> 30 years) grassland topsoil (n = 24), assumed to be saturated, from the FRIBO network¹ (Canton of Fribourg, Switzerland). The relationship (Equation 5) between SOC in permanent grasslands and fine fraction content (clay + silt) found by Guillaume et al. (2022) was almost identical to the one found by Hassink (1997) for a mix of temperate and tropical grasslands. These results support the C-saturation concept and the fact that the silt+clay content can be used as a unique factor to determine the saturation level of soils.

Equation 5: Equation developed by Guillaume et al. (2022) to estimate the SOC saturation content

$$MAOM_c = 4.23(\pm 3.89) + 0.372(\pm 0.087) * SC$$

With, $MAOM_c$, the carbon content of the mineral-associated organic matter fraction (< 50 µm) ($mg \cdot C \cdot g^{-1}$ soil) corresponding to the SOC_{sat} parameter in Equation 4, SC, the silt + clay fraction (< 50 µm) content (%), corresponding to the FFC parameter in Equation 4.

Equation 4 and Equation 5 can therefore be used to estimate the maximal SOC content of a soil and then the S_{max} .

¹ The FRIBO network is composed of 250 sites, which were established in 1987 and based on a 2 × 2 km grid

The SOC content in soil fine fraction (SOC_{fine}) has not been measured in the data set used (Soil observation sites in Bavaria² and RMQS³ for Wiesmeier et al. (2014) and Chen et al. (2019), respectively). To overcome this issue, Chen et al. (2019) estimated it, based on previous studies (Balesdent, 1996; Jolivet et al., 2003; Angers et al., 2011). SOC_{fine} of cropland soils was assumed to comprise 85 % of the total SOC content. For the forest and grassland soils, SOC_{fine} were assumed to be, respectively, $66 \pm 2\%$ and $69 \pm 9\%$ of the total SOC (Chen et al., 2018). Wiesmeier et al. (2014) sampled 56 representative sites on which they measured SOC_{fine} and extrapolated the results to the entire data set (516 points). They found that SOC_{fine} is equal to 77 %, 60 % and 38 % (median value) of the total SOC, of cropland soils, grassland soils and forest soils, respectively. Those SOC_{fine} estimations, however, correspond to the estimation of the SOC content in the texture fraction below 20 μm , making them irrelevant for the application of the equation developed by Guillaume et al. (2022), which uses SOC_{fine} from the texture fraction below 50 μm . Rabot et al. (2025) developed a pedotransfer function dedicated to the prediction of the SOC_{fine} of the below-50 μm texture fraction. This function uses a second-degree polynomial relationship between SOC_{fine} and the SOC content (measured on the 2mm-sieved soil) (Equation 6) and was established on French soils (951 observations – at the national level). To improve its prediction accuracy, it is adapted according to the land use (4 levels: Cropland and permanent crop; Grassland; Natural grassland; Forest and shrub).

Equation 6: Equation developed by Rabot et al. (2025) to predict SOC_{fine} of the textural fraction below 50 μm from SOC content

$$SOC_{fine} = \beta_1 * SOC + \beta_2 * SOC^2$$

With, SOC_{fine} , the SOC content of the textural fraction below 50 μm (g.kg^{-1}),
 SOC, the SOC content of the 2mm-sieved soil (g.kg^{-1}),
 β_1 and β_2 , the coefficients of the pedotransfer function (Table 4).

Table 4: Coefficients of the pedotransfer function of Rabot et al. (2025)

Land use	β_1	β_2
Cropland and permanent crop	0,865	-0,00194
Grassland	0,819	-0,00173
Natural grassland	0,685	-0,00022
Forest and shrub	0,700	-0,00123

This methodology leads to positive and negative SOC storage potential density for the topsoil. Negative values mean that the soil contains more SOC than expected according to the C-saturation concept (over-saturation). This can be explained by several factors, such as climate (temperature and precipitations (Wiesmeier et al., 2014)), mineralogy of clay (e.g. 1:1 or 2:1 clay minerals), land use and soil management (Six et al., 2002, Feng et al., 2014). Positive values are assumed to highlight a deficit in SOC in comparison with the quantity of SOC that could be theoretically stored in the fine fraction. To estimate a SOC storage potential at the regional or national scale, Wiesmeier et al. (2014) and Chen et al. (2019) counted negative SOC storage potential density as zero.

Even though the C-saturation concept based on the Hassink's (1997) equation has often been used to assess the SOC storage potential of different countries or regions (Angers et al., 2011;

² Soil observation sites in Bavaria come from a combination of representative sites (516 sites) managed by the Bavarian Environmental Agency and by the Bavarian State Institute for Forestry.

³ RMQS: Réseau de Mesure de la Qualité des Sols (maillage national systématique par une maille carrée de 16 km, environ 2000 points de mesure)

Wiesmeier et al., 2014; McNally et al., 2017; Chen et al., 2019), Barré et al (2017) state that this carbon saturation of fine soil particles is not relevant for the calculation of the whole-soil OC storage potential. They specify that this concept, at least in its current form and using the Hassink's (1997) equation, is not appropriate alone to quantitatively assess the soil total carbon storage potential from an operational perspective. According to these authors, the main issue of this concept is that by definition, the SOC_{spd} refers to the OC associated with fine soil particles ($< 20 \mu m$), which represent only a fraction of total SOC. Several studies have reported significant (up to 60 %) contribution of the $> 20 \mu m$ SOC fraction to total SOC in various land uses (Balesdent et al., 1998; Besnard et al., 2001; Wiesmeier et al., 2014) and in coarse-textured soils where particulate organic matter is the dominant form of organic matter (Poeplau and Don, 2023). Moreover, several authors observed that increases in SOC stocks following a land management change were mostly due to an increase in sand-size particulate organic matter (e.g. Feng et al., 2014; Cardinael et al., 2015; Chimento et al., 2016). As a result, a significant part of SOC stock increase induced by the implementation of farming methods known to promote soil carbon stocks is expected to occur mostly in the soil $>20 \mu m$ fraction. Thus, C-saturation concept methodology could lead to an underestimation of the SOC sequestration potential assessed. Barré et al (2017) explained however that the C saturation deficit can help evaluating the long-term soil C storage potential as proposed by Wiesmeier et al. (2014) or McNally et al. (2017).

According to Feng et al. (2013), the use of a linear regression approach such as that proposed by Hassink (1997) to estimate the maximal SOC content presents two drawbacks. One is the underestimation of the maximal SOC content induced by the use of the least-square linear regression which is intrinsically designed to identify the average value of the SOC content distribution of a tested dataset. Therefore, it appears that this method is not fully suited to estimating the maximum SOC content, even though, to reduce this problem, Hassink (1997) only used data from soils supposedly at or near saturation (uncultivated soils and permanent grasslands). To avoid this issue, Feng et al. (2013) suggest using the alternative method of the boundary line analysis, that develops a linear regression model only based on the upper tenth percentile of OC contents in fine soil particles. The top 10 SOC contents are considered as samples having reached maximal C stabilization. However, this threshold (upper 10th percentile) is arbitrary and not supported by any technical elements. Like Feng et al. (2013), Breure et al. (2025) tested the statistical boundary line (BL) method, which assumes that the OC content of the fine fraction has a constant maximum across the entire range of fine fraction values, as well as the piece-wise boundary line (PBL), which is based on the same assumptions as BL but includes an adjustment for soils with a low fine fraction. This adjustment makes it possible to account for OC sorption onto organic matter, which can play a relatively important role in coarse-textured soils. Finally, Breure et al. (2025) also tested the non-linear boundary line (NBL), which allows the maximum OC content of the fine fraction to vary as a function of the fine fraction. According to these authors, the NBL showed the most promising results for the LUCAS dataset at the European scale.

The other drawback highlighted by Feng et al. (2013) is the lack of consideration for soil mineralogy in Hassink's equation (1997). Soil mineralogy can indeed strongly influence the OC content and therefore modify the maximum achievable SOC content. To address this problem, Feng et al. (2013) propose alternatively using the OC loading method, which consists of using the apparent maximum amount of carbon that can be sorbed onto mineral surfaces, based on a carbon loading equivalent to a monolayer ($\sim 1 \text{ mgC}\cdot\text{m}^{-2}$). Theoretically, this approach can efficiently estimate the maximal SOC content, but it suffers two limitations: the estimation of the OC loading, which is often assumed to be constant and set to $1 \text{ mgC}\cdot\text{m}^{-2}$, but several studies have proven this to be incorrect in some cases (Feng et al. 2013); the estimation of the mineral specific surface area (SSA), which depends on the mineralogy (1:1 or 2:1 minerals, Fe and Al oxyhydroxides) and is only rarely measured in soil datasets.

Since Equation 4 does not take into account other soil intrinsic characteristics that may influence the SOC_{fine} content, such as clay mineralogy (Six et al., 2002, Feng et al., 2013) or amorphous Fe and Al oxides (Kaiser et al., 2002; Kleber et al., 2005), that can influence the fine particle fraction properties or even make coarser particles able to adsorb SOM (e.g. silt and quartz coating), this equation may be seen as an oversimplification. Nonetheless, Guillaume et al. (2022) proved that, within the relatively large range of pedoclimatic conditions in their study area (The Fribourg Canton), silt + clay content remained by far the variable explaining most of the SOC_{sat} variation in grasslands. Only two other variables significantly explained the SOC_{sat} variability: the $\text{pH}_{\text{H}_2\text{O}}$ and the rate of SOC changes in the past 30 years, but with a three time less significance. In their study, differences in climate (mean average temperature (2.5 °C range) and precipitations (400 mm rain range)) driven by elevation (± 400 m range) were not significant in the multiple regression model used to describe the SOC_{sat} variability (Guillaume et al., 2022), suggesting that the SOC saturation level is independent from climate.

However, to apply the C saturation concept and the Hassink's (1997) equation to assess the SOC storage potential in Luxembourg, we would face uncertainties that would make the results suboptimal.

- Hassink's (1997) equation (Equation 4) has been developed using data from soils from both temperate and tropical regions (The Netherlands, Germany, Africa, The USA, Canada, Central and South America). Therefore, it may not be relevant for the Luxembourgish context (calibration using Luxembourgish data would be required);
- SOC_{fine} ($< 20 \mu\text{m}$ or $< 50 \mu\text{m}$) content is unknown in Luxembourgish soils, that would require either an additional sampling and measurement campaign to collect this missing data (just like Wiesmeier et al. (2014) did) or estimate it from existing data and literature (Angers et al., 2011; Chen et al., 2019).

A list of the main advantages and drawbacks of this approach is described in Table 5.

Table 5: Advantages and drawbacks of the use of the carbon saturation concept of the fine soil fraction in order to estimate the maximal SOC stock

Advantages	Drawbacks
<ul style="list-style-type: none"> • The concept of the C saturation of the fine soil fraction is widely accepted, and has been used by several scientists, through the Hassink's (1997) equation and its derivatives, to estimate the SOC storage potential. Thus, there are some references to compare the results we could get to. Particularly, two different studies got results in France and in Germany. • The concept and the Hassink's (1997) equation are relatively simple and could be relatively easily implemented. • The Hassink's (1997) equation and its derivatives are good proxy of the SOC saturation in soil and explain a majority of the variance of the data sets tested in the literature. This suggests that, even if the C saturation concept is not completely relevant from the point of view of the SOC dynamic, it can be a robust and pragmatic approach to estimate a SOC storage potential. • Since the C saturation concept is independent of soil management practices and land use, it enables to estimate an intrinsic theoretical maximal SOC stock only based on the soil properties. 	<ul style="list-style-type: none"> • Even if the Hassink's (1997) equation based on the C saturation concept is widely accepted, some arguments tend to prove that is not completely relevant, especially because it ignores some other significant factors (e.g. clay mineralogy), and because the calibration of the equation depends on the data used and the underlying assumption (i.e. the data used come from soil supposedly saturated with C). • The C saturation of the fine fraction is criticized by some scientists because it gives information only on a fraction of the total SOC stock actually stored. The C associated with the coarse fraction and the one included in the particulate organic matter are not considered, leading to an underestimation of the computed SOC storage potential. • The Hassink's (1997) equation requires data on the soil fine fraction C content, which are generally not measured and are not available in Luxembourg. These data must therefore be estimated, introducing uncertainties into the results. • The Hassink's (1997) equation has not been developed using Luxembourgish soils. • Unlike the modeling approach (part 3.2.1), the maximal SOC stock is independent of soil management practices, which subsequently requires defining practices (additional work) to reach the estimated maximal SOC stock.

3.2.5 Soil organic carbon to clay ratio

Dexter et al. (2008) found that different topsoil physical properties, such as bulk density and water retention characteristics, are better correlated with the SOC:clay ratio than with the SOC content for arable and pasture soils of France and Poland. They got the best prediction results using SOC:clay mass ratios between 1:8 and 1:11. They suggest that a SOC:clay ratio of about 1:10 may be the optimal ratio to define good physical properties related to soil structure. From the point of view of physical properties, a 1:10 ratio would be the carbon optimal saturation threshold: a lower ratio is linked to sub-optimal or even degraded soil physical properties.

Johannes et al. (2017) demonstrated that the topsoil structural quality, assessed by physical assay (CoreVESS scoring (Johannes et al., 2016)) can be estimated by the SOC:clay ratio for arable soils in Switzerland. A SOC:clay ratio of 1:10 seems to be the limit between good structural quality (SOC:clay > 1:10) and to-be-improved structural quality (SOC:clay < 1:10). The authors suggest also that soils with a SOC:clay lower than 1:13 have a bad structural quality (deficit in porosity and/or in aggregation), and soils with a SOC:clay higher than 1:8 have a very good structural quality. Prout et al. (2021) confirmed that SOC:clay ratios of 1:8, 1:10, and 1:13 can be used to identify soils with, respectively, very good, good and bad structural quality, for any given soil in England and Wales. The authors showed that permanent grassland and forest soils have often a SOC:clay ratio higher than 1:10, indicating that these soils are most of the time characterized by an excess of SOC or by a slight deficit in SOC, from a structural point of view. On the contrary, they showed that a significant part of arable soils shows a deficit in SOC content (unsaturated soils). Jensen et al. (2019) observed similar results replacing clay content by the fine (< 20 µm) mineral particles content (Fines₂₀). These authors defined the Fines₂₀:SOC ratio that indicates reduced soil structural stability when it is greater than 20, and corresponds approximatively to the SOC:clay ratio threshold of 10 defined by Dexter et al. (2008).

SOC:clay ratio depends on the soil type and therefore on the soil texture. Prout et al. (2021) highlighted that coarse-textured soil types (i.e. Podzol) tend to have SOC:clay > 1:8, reflecting, at least theoretically, a very good structure condition. But Podzol are naturally characterized by very low clay contents (leached soils) and high OM contents (acidic conditions leading to slow OM mineralization) in surface horizon, and so, high SOC:clay ratios. Moreover, these soils are mainly under forest. On the contrary, the authors showed that fine-textured soil types (i.e. Pelosol) are more likely to have SOC:clay < 1:13, reflecting, at least theoretically, a bad structure condition, as if they had been degraded (e.g. SOC loss due to intensive management). Even if the authors suggest that these results could be engendered by the land use and therefore their management (Pelosol are mostly under arable land use), they point out that the SOC:clay ratio thresholds might not be relevant for extreme textured soils.

To test the validity of the SOC:clay ratio to assess the structural properties of clayey soils (extremely fine-textured soils), Johannes et al. (2023) applied this ratio to soils with clay content ranging from 16 to 52 %. They showed that the clay content of these soils is linearly correlated with the SOC content in the entire studied clay content range. Moreover, they also showed that the SOC:clay ratio is independent from clay content. These results suggest that the SOC:clay threshold values can be used as a target for soil quality management for soils with large clay content (at least up to 52 %), even if the authors specified that reaching the corresponding SOC contents for clayey soils can be considered as very demanding or even unattainable under arable land use.

Although SOC:clay ratio threshold values have been developed to assess the soil structural quality, Johannes et al. (2023) suggest that these values could be used as targets for SOC storage potential evaluation. Since the SOC:clay ratio of 1:8 is considered to be the threshold value from

which a soil is in a very good condition, the maximal SOC content, or rather the optimal SOC content since this threshold value is not a limit, could correspond to (Equation 7):

Equation 7: Equation to estimate S_{max} from the SOC:clay ratio value of 1:8

$$SOC_{max} = \frac{Clay}{8}$$

With,

SOC_{max} , the maximal SOC content ($g.kg^{-1}$) that could theoretically be reached in a soil and from which the S_{max} could be estimated;

Clay, the clay content ($g.kg^{-1}$) of the soil.

A list of the main advantages and drawbacks of this approach is described in Table 6 Table 3.

Table 6: Advantages and drawbacks of the use of the SOC to clay ratio in order to estimate the maximal SOC stock

Advantages	Drawbacks
<ul style="list-style-type: none"> • Since the SOC/clay ratio is independent of soil management practices and land use, it enables to estimate an intrinsic theoretical maximal SOC stock only based on the soil properties. • The SOC/clay ratio is relatively simple and could be relatively easily implemented using the existing soil data. • The validity domain of the SOC/clay ratio application is large, which suggests that the ratio can be applied to most of the Luxembourgish soils. • The SOC/clay ratio thresholds have been developed using soil data from Switzerland and validated using soil data from the United Kingdom, which are close to those of Luxembourg. This suggests that these thresholds could be applied to assess Luxembourg soils. 	<ul style="list-style-type: none"> • Unlike the modeling approach (part 3.2.1), the maximal SOC stock is independent of soil management practices, which subsequently requires defining practices (additional work) to reach the estimated maximal SOC stock. • The validity domain limits of the SOC/clay ratio application are not clear and may lead to irrelevant results for extreme-textured soils (very coarse and very fine textures). • As the SOC/clay ratio and its thresholds have been developed to assess the structure quality of a soil, it might not be relevant to estimate the soil C storage capacity. Thus, the estimated SOC maximal stock might be underestimated.

3.2.6 Expected soil organic carbon

In a recent study, Poeplau and Don (2023) stated that the SOC:clay ratio applied to the data from the first German agricultural soil inventory (n = 2958 samples of mineral topsoils) is not an appropriate indicator for evaluating the SOC level of soils. They suggested that the SOC:clay ratio is not sensitive enough to indicate degradation of extreme-textured soils since all the studied sandy soils (104 Podzols) were far beyond the threshold value of 1:8, and, on the opposite, 97 % of the fine-textured soils (76 Vertisols) were below the threshold value of 1:13. They also highlighted that a major part (61 %) of the 90 studied Chernozems had SOC:clay ratios below 1:13, meaning that these fine-textured but OM-enriched soils would be considered as “degraded” according to the SOC:clay ratio, even though Chernozems are among the most fertile soils on the planet.

To avoid this clay bias, Poeplau et Don (2023) suggested a variant of the SOC:clay ratio by defining the SOC:SOC_{exp} ratio (SOC_{exp} = expected SOC). The SOC_{exp} is calculated using the correlation between SOC and clay contents at national (Germany) level (Equation 8) and is the reference to which compare the SOC content measured in a soil. When the SOC:SOC_{exp} ratio is greater than 1, the SOC content is above expected SOC content and thus above average SOC content, and when the ratio is below 1 the soil is rather SOC-depleted and below average.

Equation 8: Equation developed by Poeplau et Don (2023) for German agricultural topsoils to estimate the expected SOC content

$$SOC_{exp} = 13.674 + 0.0288 * clay$$

With,

SOC_{exp}, the expected SOC content (g.kg⁻¹),

Clay, the clay content (g.kg⁻¹).

The quartiles of the SOC:SOC_{exp} ratio dataset distribution were then defined in a similar way to Johannes et al. (2017) to determine four SOC-level classes and their corresponding threshold values. In this case, the threshold values were not derived in response to any functional properties, contrary to the threshold values defined by Johannes et al. (2017), but according to arbitrary limits (quartiles). Nevertheless, Poeplau and Don (2023) proved that the defined quartile threshold values are able to significantly separate soils according to their porosity (i.e. bulk volume = 1/bulk density (cm³.g⁻¹)), which is an indicator of the soil structure.

Based on this methodology and the studied dataset, the authors suggested threshold values as follows:

- 1st quartile: a SOC:SOC_{exp} < 0.65 corresponds to a degraded soil (SOC-depleted);
- 2nd quartile: A 0.65 ≤ SOC:SOC_{exp} < 0.83 corresponds to a moderate soil;
- 3rd quartile: A 0.83 ≤ SOC:SOC_{exp} < 1.16 corresponds to a good soil;
- 4th quartile: A SOC:SOC_{exp} ≥ 1.16 corresponds to a very good soil (SOC-enriched).

Since a SOC:SOC_{exp} ratio greater than 1.16 corresponds to a soil that is in a very good condition, the maximal (or optimal) SOC content could correspond to (Equation 9):

Equation 9: Equation to estimate S_{max} from the SOC:clay ratio value of 1:8

$$SOC_{max} = SOC_{exp} * 1.16$$

With,

SOC_{max}, the maximal SOC content (g.kg⁻¹) that could theoretically be reached in a soil and from which the S_{max} could be estimated;

SOC_{exp}, the expected SOC content (g.kg⁻¹) of the soil, estimated from the correlation between the SOC and the clay content of the soil data set in which the considered belongs.

Poeplau and Don (2023) suggest refining the estimation of the SOC_{exp} by defining regional SOC~clay relationships, because the relationships used by the authors for their estimation has been defined at national level and then could conceal local variabilities related to the local soil properties. To get more relevant SOC_{exp} contents, they should be calculated for each homogeneous pedoclimatic region. This approach could therefore be considered as a kind of SOC reference, which corresponds to a statistical value that describes a group of soils (see part 3.2.2). Thus, this approach rests upon the underlying assumption that only a fraction of the existing/monitored soils are degraded and a significant part of them are still in good conditions from the SOC content point of view. This assumption may be wrong at least for certain pedoclimatic regions.

A list of the main advantages and drawbacks of this approach is described in Table 7.

Table 7: Advantages and drawbacks of the use of the SOC to SOC_{exp} ratio in order to estimate the maximal SOC stock

Advantages	Drawbacks
<ul style="list-style-type: none"> • The SOC:SOC_{exp} ratio is relatively simple and could be relatively easily implemented using the existing soil data, even if Luxemburgish threshold values should be calculated to interpret the results. • The validity domain of the SOC:SOC_{exp} ratio application seems to be larger than the one of the SOC:clay ratio, suggesting that this ratio can be applied to the majority, or maybe all, of the Luxembourgish soils, including extreme-textured soils. 	<ul style="list-style-type: none"> • Unlike the modeling approach (part 3.2.1), the maximal SOC stock is independent of soil management practices, which subsequently requires defining practices (additional work) to reach the estimated maximal SOC stock. • The SOC:SOC_{exp} ratio is a new recent concept that has not been tested in other contexts. • The expected SOC (SOC_{exp}) depends on the assumption that only a fraction of studied soils is degraded from a SOC content point of view. The methodology developed to estimate it depends on the scale and the homogeneity of area considered. • The threshold values proposed by Poeplau and Don (2023) are only valid for the German agricultural topsoil. Luxemburgish thresholds values should be estimated. • The definition of the threshold values is arbitrary, derived from statistical approach (quartiles).

3.3 Selection of the best approaches to be used in the project

Theoretically, it is possible to distinguish at least four different SOC storage potentials (Figure 3):

- The biophysical and environmental SOC storage potential: it depends mainly on the intrinsic (chemical, physical and biological) pedological properties of the soil and the climate to which it is subjected. This is the storage potential that can be achieved for a certain soil within the limits of the natural chemical, physical and biological processes that affect its SOC dynamics.
- The technical SOC storage potential: it depends mainly on the management practices that are applied on a soil and its land use. This is the storage potential that can be achieved for a certain soil within the limits of the management techniques that can technically be applied. Although this potential is closely related to the biophysical one, the application of human-driven practices can artificially modify it. Thus, these two types of potential overlap, without being strictly identical.
- The economic SOC storage potential: it depends mainly on the economic conditions that govern the soil farming or exploitation that aim to create economic values. This is the storage potential that can be achieved for a certain soil within the limits of the profitability of its exploitation or the public funds that a society is willing to spend (subsidies). The economic potential corresponds to the economically profitable technical potential. Therefore, the economic potential is included within the technical potential.
- The effective SOC storage potential: this potential is the intersection of the three previous potentials (i.e. biophysical, technical and economic potentials). It represents the potential that could be effectively achieved at a location.

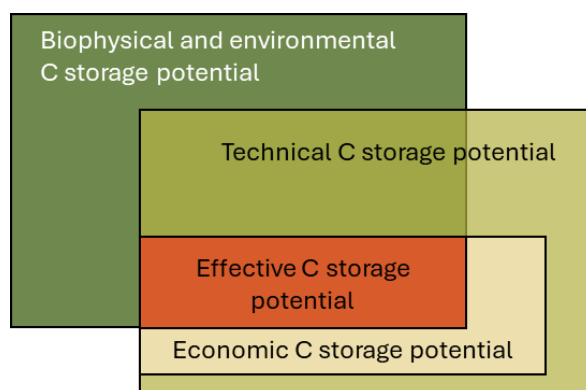


Figure 3: Schematic representation of the four different SOC storage potentials

Table 8 shows that none of the identified approach is able to estimate the effective SOC storage potential. Depending on the model applied and the reference soils chosen, the corresponding approaches can estimate a biophysical potential, a technical potential, an economic potential or a combination of them. The storage rates approach can estimate a technical potential or an economic potential, depending on the considered practices. The three other approaches (i.e. fine fraction saturation, SOC:clay ratio and expected SOC content) can mainly estimate a biophysical potential, even if the expected SOC content approach can also be used to assess a technical potential, depending on the data set used to calculate the expected contents.

Table 8: Relationships between the identified approaches to estimate the S_{max} and the types of SOC storage potential

Approach to estimate the maximal SOC stock (S_{max})	Type of SOC storage potential			
	Biophysical	Technical	Economic	Effective
Modeling - biophysical model	X			
Modeling - management scenario	X	X		
Modeling - management scenario with economic aspects	X	X	X	
Reference soils - natural soil	X			
Reference soils - agricultural soil	X	X		
Reference soils - agricultural soil with economic aspects	X	X	X	
Storage rates		X		
Storage rates with economic aspects		X	X	
Fine fraction saturation	X			
SOC to clay ratio	X			
Expected SOC content	X	X		

The achieved literature review on the different possible approaches capable of estimating the maximal SOC stock (S_{max}) of a soil does not allow us to highlight one optimal approach. Each approach has its own advantages and drawbacks and none of them is able to estimate the effective SOC storage potential. Based on these findings and considering the data available at the national level and the expert knowledge that is available in the project, two approaches (i.e. modeling and storage rates) appear to be inapplicable. These two approaches would require the definition of plausible scenarios at nation level, that is unrealistic in terms of means and resources available in the project. However, it appears that the four other approaches are promising and could be implemented at Luxemburgish level. **We decided then to implement the four identified approaches:**

- **Reference soils** (designated as Methodology 1 or m1),
- **Fine fraction saturation** (designated as Methodology 2 or m2),
- **Soil organic carbon to clay ratio** (designated as Methodology 3 or m3),
- **Expected content** (designated as Methodology 4 or m4),

and to assess and discuss the results they will provide.

4 Methodologies applied

4.1 Data required

Ideally, the implementation of the selected methodologies should have been based on national point data ensuring pedological consistency between the parameters required for the calculations. However, such point data could not be made available for this study. By default, the methodologies were implemented using available rasterized national data (extrapolated to the national level). In the absence of available national data, the data for parameter coarse fragment were extracted from data extrapolated to European scale and published by ESDAC. In this study, the following data were used:

- **Soil organic carbon content** ($SOC_{content_ASTA}$) [%] (Appendix 1): this data was published by ASTA - Service pédologique, in the form of a raster characterized by:
 - Projection: EPSG = 2169 (LUREF)
 - Resolution: 100m x 100m
 - Dimensions: 818 x 572 = 467896 cells
 - Extent: Luxembourg⁴
- **Clay content** (clay_ASTA) [%]: (clay = < 2 μ m) this data was published by ASTA - Service pédologique, in the form of a raster characterized by:
 - Projection: EPSG = 2169 (LUREF)
 - Resolution: 100m x 100m
 - Dimensions: 818 x 572 = 467896 cells
 - Extent: Luxembourg⁴
- **Sand content** (sand_ASTA) [%]: (50 μ m < sand < 2000 μ m) this data was published by ASTA - Service pédologique, in the form of a raster characterized by:
 - Projection: EPSG = 2169 (LUREF)
 - Resolution: 100m x 100m
 - Dimensions: 818 x 572 = 467896 cells
 - Extent: Luxembourg⁴
- **Bulk density** (BD) [g.cm⁻³]: this data was published by ASTA - Service pédologique, in the form of a raster characterized by:
 - Projection: EPSG = 2169 (LUREF)
 - Resolution: 100m x 100m
 - Dimensions: 818 x 572 = 467896 cells
 - Extent: Luxembourg⁴
- **Coarse fragments** (CF) [%]: this data was published by ESDAC, in the form of a raster characterized by:
 - Projection: EPSG = 9820
 - Resolution: 500m x 500m
 - Dimensions: 8045 x 7781 = 62598145 cells
 - Extent: Europe⁵
- **Soil association map** (soil): this data was published by ASTA - Service pédologique, in the form of a vector (shapefile), characterized by:
 - Projection: EPSG = 2169 (LUREF)
 - Scale: 1/100000
 - Extent: Luxembourg
 - Categorical : 12 soil associations
- **Land use 2018** (landuse): this data was published by DATer, in the form of a vector (shapefile), characterized by:

⁴ 48884.25, 106084.2, 56964.25, 138764.2 (xmin, xmax, ymin, ymax)

⁵ 2635700, 6526200, 1399700, 5422200 (xmin, xmax, ymin, ymax)

- Projection: EPSG = 2169 (LUREF)
- Extent: Luxembourg
- Categorical: 45 land use classes

Data published by the EcoDataCube project (<https://ecodatacube.eu>) (EDC) was also collected and tested for the implementation of the selected methodologies. However, these data, developed at the European level, prove to be unsuitable for national use, in particular because the variability of these data on the territory of Luxembourg appears to be completely flattened compared to the variability measured in the national data. Thus, only the data presented above from ASTA, DATer and ESDAC were used for the implementation of the selected methodologies.

4.2 Homogeneous zones

The maximal SOC stock of a given soil depends on various soil intrinsic properties and on external biotic and abiotic factors. At the national level, due to the natural variation in these properties and factors and the possible interactions between them, the maximal SOC stock can vary strongly from one soil to another. These variations make the assessment of this soil property irrelevant and unrepresentative at the national scale. On the contrary, estimating this maximal SOC stock at the plot level would require the necessary data for all plots. Such a comprehensible data coverage is not currently available for agricultural, forest and urban soils. Therefore, as a compromise, homogeneous zones have been used. These zones represent different regions in which the variability in factors affecting the SOC stock is assumed to be minimized, based on the data available. Although a statistical approach, such as a stratified clustering, would allow defining geographical regions with minimized variability, this solution appears to be too data-intensive and time-consuming for this study. It has been assumed that homogeneous zones defined as the intersect between soil associations and land uses is an optimized and efficient approach for the purposes of this study. Indeed, the combinations of soil associations and land uses take implicitly into account most of the factors that drive the SOC stock dynamics (e.g. climate, geology, soil properties, management practices, plant cover), while being applicable at large scale such as the national level.

This kind of zones are used in various studies (Barré et al., 2017), especially for the application of the Reference soil approach (m1). Poeplau and Don (2023) also recommend applying their approach (i.e. Excepted SOC: m4) to such homogeneous zones, since the SOC-clay relationship on which their entire methodology is based, is strongly dependent on pedoclimatic conditions. For the two other approaches (i.e. fine texture saturation (m2) and SOC to clay ratio (m3)), the use of zones of homogeneous texture appears also necessary. To simplify the application of the four identified approaches and to make it easier to compare the results obtained, the same homogeneous zones have been used for all the approaches.

In the present study, the national territory was divided into 72 homogeneous units, referred to as “soilscape”. These soilscape correspond to the topological intersection of the land use aggregated classes of the Land use map 2018 (DATer, 2025) and the soil associations at 1:100 000 of ASTA (2016). To simplify the land use classes and stick to the 6 classes used in the LULUCF regulation (OJEU, 2018), the 45 land use classes of the national land use map 2018 were aggregated into 6 land use classes: settlement (code = 1), cropland (code = 2), grassland (code = 3), forest (code = 4), wetland (code = 5) and other (code = 6). The applied aggregation key is presented in the Table 9.

Table 9: Aggregation key followed to establish the 6 land use classes from the 45 classes of the DATer's land use map 2018

DATER's land use classes (2018)	Land use classes
Settlement 111, 112, 113, 114, 115, 131, 132, 133, 134, 141, 142, 143, 144, 151, 152, 160	Settlement 1
Transport 611, 612, 620, 631, 632, 640, 650	
Agriculture – arable land 210	Cropland 2
Agriculture – special crops 231, 232, 233, 234	
Agriculture – Grassland 220	Grassland 3
Natural surfaces – natural grassland 430	
Natural surfaces – heathland 440	
Natural surfaces – bushes 450	Forestland 4
Forest 311, 312, 313, 314, 323, 321, 322	
Natural surfaces – wetland 460	Wetland 5
Natural surfaces – gravel 410	Other 6
Natural surfaces –Rocks 420	
Water 511, 512, 521, 522	

In the original soil associations map at 1:100 000 published in 1969 listed 32 soil associations. Due to relatively small differences between some soil associations, ASTA (2016) published a simplified version of this map, retaining only 12 soil associations. This simplification is based on the regrouping of some of the original soil associations, according to expert knowledge. Details of the original and simplified soil associations can be found in Table 10, and the simplified map can be visualized in Appendix 3.

The soilscape vector (topological intersection of 6 land use classes and 12 soil associations) comprises 72 classes (Appendix 4). After rasterization according to a 150m square grid, the national territory is divided into 115 247 cells. The surface proportion of each soilscape is available in Table 10: Details of the original and simplified soil associations, according to

geoportail.lu (Carte des sols au 1:100 000)

Soil associations (original)	
Code	Name
1	Sols limoneux peu caillouteux, non gleyifiés à modérément gleyifiés, à horizon B structural
2	Sols limono-caillouteux à charge schisto-phylladeuse, non gleyifiés, à horizon B structural
3	Sols limono-caillouteux à charge schisto-phylladeuse altérée, non gleyifiés, à horizon B structural
4	Sols limono-caillouteux à charge schisto-phylladeuse, faiblement à modérément gleyifiés, à horizon B structural
5	Sols limono-caillouteux à charge schisto-gréseuse, non gleyifiés, à horizon B structural
6	Sols limono-caillouteux à charge schisto-gréseuse altérée, non gleyifiés, à horizon B structural
7	Sols limono-caillouteux à charge schisto-gréseuse, faiblement à modérément gleyifiés, à horizon B structural
8	Sols limono-caillouteux à charge argilo-schisto-gréseuse, faiblement à modérément gleyifiés, à horizon B structural
9	Sols limono-caillouteux à charge schisteuse, non gleyifiés, à horizon B structural
10	Sols limono- et argilo-caillouteux à charge de galets quartzitiques, non gleyifiés à modérément gleyifiés, à horizon B structural ou textural
11	Sols argilo-caillouteux à charge dolomitique, non gleyifiés, à horizon B structural
12	Sols argilo-caillouteux à charge calcaireuse, non gleyifiés, à horizon B structural
13	Sols sableux, limono-sableux et sablo-limoneux, non gleyifiés, à horizon B structural ou textural, sur substrat de grès calcaire, de sable, de calcaire
14	Sols sableux, limono-sableux et sablo-limoneux, faiblement à modérément gleyifiés, à horizon B textural, sur substrat d'argiles
15	Sols sablo-limoneux et sablo-argileux, non gleyifiés, à horizon B structural ou textural, sur substrat de grès bigarré
16	Sols sablo-limoneux et limoneux, non gleyifiés à modérément gleyifiés, à horizon B textural
17	Sols sablo-limoneux et limoneux, fortement à très fortement gleyifiés, à horizon B textural
18	Sols argileux et argileux lourds, non gleyifiés, à horizon B structural ou textural, sur substrat de calcaires
19	Sols argileux, non gleyifiés, à horizon B structural ou textural, sur substrat de macigno
20	Sols argileux, faiblement à modérément gleyifiés, à horizon B textural, sur substrat de macigno
21	Sols argileux, faiblement à modérément gleyifiés, à horizon B textural, sur substrat d'argiles
22	Sols argileux, non gleyifiés à modérément gleyifiés, à horizon B textural, sur substrat de grès coquillier
23	Sols argileux et argileux lourds, non gleyifiés à modérément gleyifiés, à horizon B structural ou textural, sur substrat de marnes et de calcaires
24	Sols argileux et argileux lourds, non gleyifiés, à horizon B structural, sur substrat de marnes
25	Sols argileux lourds, faiblement à fortement gleyifiés, à horizon B structural ou textural, sur substrat de marnes
26	Colluvions et alluvions
27	Zones de suintement
32	Non sol - Surface en eau

Table 11. Due to the chosen grid (150m), which is relatively wide, 4 soilscapes are not represented (5_32, 5_9, 6_27, 6_8), and due to the lack of sufficient data for settlement areas (land use code = 1) and other areas (land use code = 6), soilscapes derived from these two land uses were excluded from the estimations made in this study. Thus, only 46 soilscapes were finally considered. It has been decided to keep the soil association 32 (non-soil, water surface) because of its relative importance within wetland land use, although it is expected that a significant part of the soilscapes x_32 only result from edge effects caused by the coarse resolution of the soil association map relative to the land use map.

Table 10: Details of the original and simplified soil associations, according to geoportail.lu (Carte des sols au 1:100 000)

Soil associations (original)		Soil associations (simplified)
Code	Name	
1	Sols limoneux peu caillouteux, non gleyifiés à modérément gleyifiés, à horizon B structural	1
2	Sols limono-caillouteux à charge schisto-phylladeuse, non gleyifiés, à horizon B structural	1
3	Sols limono-caillouteux à charge schisto-phylladeuse altérée, non gleyifiés, à horizon B structural	1
4	Sols limono-caillouteux à charge schisto-phylladeuse, faiblement à modérément gleyifiés, à horizon B structural	1
5	Sols limono-caillouteux à charge schisto-gréseuse, non gleyifiés, à horizon B structural	1
6	Sols limono-caillouteux à charge schisto-gréseuse altérée, non gleyifiés, à horizon B structural	1
7	Sols limono-caillouteux à charge schisto-gréseuse, faiblement à modérément gleyifiés, à horizon B structural	1
8	Sols limono-caillouteux à charge argilo-schisto-gréseuse, faiblement à modérément gleyifiés, à horizon B structural	1
9	Sols limono-caillouteux à charge schisteuse, non gleyifiés, à horizon B structural	1
10	Sols limono- et argilo-caillouteux à charge de galets quartzitiques, non gleyifiés à modérément gleyifiés, à horizon B structural ou textural	2
11	Sols argilo-caillouteux à charge dolomitique, non gleyifiés, à horizon B structural	3
12	Sols argilo-caillouteux à charge calcaireuse, non gleyifiés, à horizon B structural	9
13	Sols sableux, limono-sableux et sablo-limoneux, non gleyifiés, à horizon B structural ou textural, sur substrat de grès calcaire, de sable, ou d'argiles d'altération	5
14	Sols sableux, limono-sableux et sablo-limoneux, faiblement à modérément gleyifiés, à horizon B textural, sur substrat d'argiles	5
15	Sols sablo-limoneux et sablo-argileux, non gleyifiés, à horizon B structural ou textural, sur substrat de grès bigarré	2
16	Sols sablo-limoneux et limoneux, non gleyifiés à modérément gleyifiés, à horizon B textural	7
17	Sols sablo-limoneux et limoneux, fortement à très fortement gleyifiés, à horizon B textural	7
18	Sols argileux et argileux lourds, non gleyifiés, à horizon B structural ou textural, sur substrat de calcaires	9
19	Sols argileux, non gleyifiés, à horizon B structural ou textural, sur substrat de macigno	6
20	Sols argileux, faiblement à modérément gleyifiés, à horizon B textural, sur substrat de macigno	6
21	Sols argileux, faiblement à modérément gleyifiés, à horizon B textural, sur substrat d'argiles	6
22	Sols argileux, non gleyifiés à modérément gleyifiés, à horizon B textural, sur substrat de grès coquillier	8
23	Sols argileux et argileux lourds, non gleyifiés à modérément gleyifiés, à horizon B structural ou textural, sur substrat de marnes et de calcaires	6
24	Sols argileux et argileux lourds, non gleyifiés, à horizon B structural, sur substrat de marnes	4
25	Sols argileux lourds, faiblement à fortement gleyifiés, à horizon B structural ou textural, sur substrat de marnes	4
26	Colluvions et alluvions	26
27	Zones de suintement	27
32	Non sol - Surface en eau	32

Table 11 : List of the 72 soilscapes and their surface proportions in the country surface (cell = 150m x 150m)

Soilscape	Landuse class	Soil ass.	Count of cells	Proportion in the national surface (%)	Surface (ha)	Soilscape	Landuse class	Soil ass.	Count of cells	Proportion in the national surface (%)	Surface (ha)	Soilscape	Landuse class	Soil ass.	Count of cells	Proportion in the national surface (%)	Surface (ha)
1_1	1	1	2432	2,11	5472	3_1	3	1	6735	5,84	15153,75	5_1	5	1	9	0,01	20,25
1_2	1	2	557	0,48	1253,25	3_2	3	2	1539	1,34	3462,75	5_2	5	2	1	<0,01	2,25
1_26	1	26	3054	2,65	6871,5	3_26	3	26	6114	5,31	13756,5	5_26	5	26	73	0,06	164,25
1_27	1	27	22	0,02	49,5	3_27	3	27	106	0,09	238,5	5_27	5	27	1	<0,01	2,25
1_3	1	3	591	0,51	1329,75	3_3	3	3	2050	1,78	4612,5	5_3	5	3	1	<0,01	2,25
1_32	1	32	26	0,02	58,5	3_32	3	32	10	0,01	22,5	5_32	5	32	0	0	0
1_4	1	4	1190	1,03	2677,5	3_4	3	4	5141	4,46	11567,25	5_4	5	4	5	<0,01	11,25
1_5	1	5	1933	1,68	4349,25	3_5	3	5	1689	1,47	3800,25	5_5	5	5	4	<0,01	9
1_6	1	6	2597	2,25	5843,25	3_6	3	6	4933	4,28	11099,25	5_6	5	6	9	0,01	20,25
1_7	1	7	852	0,74	1917	3_7	3	7	2232	1,94	5022	5_7	5	7	3	<0,01	6,75
1_8	1	8	865	0,75	1946,25	3_8	3	8	881	0,76	1982,25	5_8	5	8	2	<0,01	4,5
1_9	1	9	254	0,22	571,5	3_9	3	9	316	0,27	711	5_9	5	9	0	0	0
2_1	2	1	10211	8,86	22974,8	4_1	4	1	15458	13,41	34780,5	6_1	6	1	125	0,11	281,25
2_2	2	2	2016	1,75	4536	4_2	4	2	1965	1,71	4421,25	6_2	6	2	15	0,01	33,75
2_26	2	26	1742	1,51	3919,5	4_26	4	26	1807	1,57	4065,75	6_26	6	26	204	0,18	459
2_27	2	27	54	0,05	121,5	4_27	4	27	56	0,05	126	6_27	6	27	0	0	0
2_3	2	3	1779	1,54	4002,75	4_3	4	3	1790	1,55	4027,5	6_3	6	3	16	0,01	36
2_32	2	32	6	0,01	13,5	4_32	4	32	93	0,08	209,25	6_32	6	32	125	0,11	281,25
2_4	2	4	2438	2,12	5485,5	4_4	4	4	3383	2,94	7611,75	6_4	6	4	2	<0,01	4,5
2_5	2	5	2499	2,17	5622,75	4_5	4	5	8470	7,35	19057,5	6_5	6	5	17	0,01	38,25
2_6	2	6	3583	3,11	8061,75	4_6	4	6	2533	2,2	5699,25	6_6	6	6	5	<0,01	11,25
2_7	2	7	2529	2,19	5690,25	4_7	4	7	3768	3,27	8478	6_7	6	7	5	<0,01	11,25
2_8	2	8	306	0,27	688,5	4_8	4	8	391	0,34	879,75	6_8	6	8	0	0	0
2_9	2	9	250	0,22	562,5	4_9	4	9	1370	1,19	3082,5	6_9	6	9	9	0,01	20,25

4.3 Data treatment

To harmonize all the required data and enable the calculations, all the data were rasterized, resampled, cropped and reprojected to meet the following characteristics:

- Raster format
- Resolution: 150 x 150m
- Dimensions: 545 x 378 = 206010 cells, including 95549 empty cells (NAs)
- Extent: Luxembourg (4014630, 4071330, 2933840, 3015590 (xmin, xmax, ymin, ymax)
- Projection: EPSG = 3035

Initially, a resolution of 30m was considered, based on the resolution of the EDC's data, but the limiting computing capacity was not suitable for managing the generated large files of raw data and resulted in very long computing times. The resolution of 150m was chosen as a compromise between computation capacity and data accuracy.

4.4 SOC stocks estimation

Although soil organic carbon stock can be estimated following different calculations, it was estimated following Equation 10.

Equation 10 : Equation to estimate SOC stock

$$SOC_{Stock} = SOC_{content} \times BD \times (1 - RM) \times d$$

With,

SOC_{stock} , the SOC stock ($t \cdot ha^{-1}$);

$SOC_{content}$, the SOC content ($g \cdot kg^{-1}$) in the fine fraction (≤ 2 mm);

BD, the bulk density of the fine fraction ($g \cdot cm^{-3}$);

RM, the mass proportion of rock fragment (> 2 mm) in the total mass of soil ($g \cdot g^{-1}$);

d, the considered soil depth or thickness (cm).

In order to ensure comparability of the study results with those already produced by ASTA or within the framework of the LULUCF regulation, the conventional depth of 0.3 m was applied and the result are expressed in tons of SOC per hectare ($t \cdot ha^{-1}$).

4.5 Estimation of the maximal organic carbon concentrations (C_{max})

The estimation of the SOC storage potential of a soil requires a reference value (S_{max}) as stated in Equation 1 (part 3.1), to which is compared the observed value of SOC stock. This reference value corresponds to the maximum reachable SOC stock that is theoretically possible to store in a given soil. To estimate this reference value, four methodologies were identified thanks to the state of the art carried out in part 3.2 : **m1: references from soils in good condition; m2: carbon saturation of the fine fraction; m3: soil organic carbon to clay ratio; m4: expected soil organic carbon**. Each approach is based on its own concept and assumptions, which make the estimation of S_{max} different from one approach to another. For each methodology (m1, m2, m3 and m4), the S_{max} values are considered as unmeasurable and their estimations require a preliminary estimation of C_{max} , (maximal SOC content) which are then converted to S_{max} according to Equation 10 : Equation to estimate SOC stock(part 4.4).

4.5.1 Methodology m1: References form soils in good condition

The concept underlying the methodology m1 is that in a given area, the maximal reachable SOC stock does exist and can be directly measured on soils in good condition, i.e. soils that have not been significantly depleted in SOC due to human activities. Thus, in order to estimate S_{max} values according to methodology m1, two elements must be defined and identified:

- The area of interest to be considered, which may range from the plot to the national level,
- The soils in good condition (not depleted in SOC) within the area of interest.

In this study, the soils in good condition were assumed to be the fraction of existing soils with the highest measured SOC content, within two types of areas of interest: the land use types (6 classes), and the soilscapes (46 classes). As it is subjective to define relevant fraction of the highest SOC stocks, and following the fact that there is no scientific consensus on this aspect according to the carried-out state of the art, two options were studied for each area of interest:

- the value of the 80th percentile (p80) of the measured SOC content distribution,
- the value of the 90th percentile (p90) of the measured SOC content distribution.

Thus, within each area of interest, the C_{max} corresponds to the 80th percentile or the 90th percentile of the SOC content distribution.

4.5.2 Methodology m2: Carbon saturation of the fine fraction

The concept underlying the methodology m2 is that for a given soil, the maximal reachable SOC stock can be estimated based on the maximal concentration of SOC (C_{max}) that can be stabilized by its fine fraction at saturation. To estimate the C_{max} , the Equation 5 adjusted by Guillaume et al. (2022) was used. In comparison with the Equation 4, developed by Hassink (1997), the Guillaume's et al. (2022) equation requires as input data, a fine fraction defined as the sum of the clay content (0-2 μm) and the silt content (2-50 μm), which is available among the data available for this study (from ASTA), while the silt fraction used by Hassink (1997) is the 0-20 μm fraction, which is not available. Moreover, the equation adjusted by Guillaume et al. (2022) was calibrated on agricultural topsoil of a temperate region (Switzerland), which is theoretically closer to the Luxembourgish context than the soils used by Hassink (1997) (mix of soils from temperate and tropical regions).

Applying the Equation 5, C_{max} was calculated for each cell of the raster based on the fine fraction content, established on the silt fraction itself estimated according to Equation 11 :

Equation 11 : Estimation of the silt content

$$\text{Silt} = 100 - \text{Sand} - \text{clay}$$

With, silt, the silt content (%) of the soil,
sand, the sand content (%) of the soil,
and clay, the clay content (%) of the soil.

This C_{max} , expressed in g.kg^{-1} , corresponds to theoretical SOC content at saturation in the fine fraction (< 50 μm) in each cell of the raster.

Since the SOC of the fine fraction were not measured (unavailable data for this study), the observed SOC content in the fine fraction (C_{obs}), expressed in g.kg^{-1} , were estimated using the pedotransfer function developed by Rabot et al. (2025) (Equation 6).

4.5.3 Methodology m3: Soil organic carbon to clay ratio

The concept underlying the methodology m3 is that for a given soil, the maximal reachable SOC stock can be estimated based on the optimal concentration of SOC that a soil with very good structural properties contains depending on its clay content. According to Johannes et al. (2017), soils with a SOC:clay greater than 1:8 have a very good structural quality. Thus, a soil having a SOC content greater or equal to its clay content divided by 8, is assumed to have an optimal SOC content, which is considered as the C_{max} of this soil (Equation 7).

Applying the Equation 7, C_{max} was calculated for each cell of the raster based on the clay content.

4.5.4 Methodology m4: Expected soil organic carbon

The concept underlying the methodology m4 is that for a given soil, the maximal reachable SOC stock can be estimated based on the optimal concentration of SOC that a soil with very good SOC content (SOC-enriched) contains depending on its clay content and its level of SOC content in comparison with other soils in a given area.

Poeplau et Don (2023) defined the expected SOC content (SOC_{exp}) of soils of a given area, according to their clay content, establishing a linear regression of the type of $SOC = a * clay + b$. In this study, the areas of interest were the 6 land use classes. Thus, for each land use class, a linear regression was established between SOC and clay contents. Table 12 shows the parameters of the established linear regressions. All the coefficients are significant and the R^2 adjusted are all greater than 0,55, indicating solid linear relationships between those soil parameters, within each land use.

Table 12: Parameters of the linear regressions established between SOC and clay contents for the 6 land use classes.

Land use class	Coefficient		P-value		R2 adjusted
	a	b	a	b	
1	0,598593122	20,29506857	0	0	0,71
2	0,582068557	20,81648498	0	0	0,55
3	0,496858966	23,17113666	0	0	0,58
4	0,696891924	19,47645559	0	0	0,65
5	0,489843718	23,74152464	6,71E-21	4,83E-37	0,56
6	0,825142986	17,02207524	1,02E-75	4,70E-74	0,60

The areas of interest used to establish the linear regressions were only the land use classes. The national level was considered too broad to apprehend the variabilities in the soil types and their corresponding managements. The soilscales were also tested as areas of interest to determine the linear relationships, but the low availability of data in certain soilscales did not allow these relationships to be established in a significant way (moreover, in some soilscales, the relationship between SOC content and clay appears non-linear).

Once the relationship between SOC and clay contents established, the coefficient a and b were used to estimate the SOC_{exp} of each cell according to the clay content, following Equation 12:

Equation 12: Linear regression developed for each land use class to estimate the expected SOC content

$$SOC_{exp} = a * clay + b$$

Then, for each cell, the SOC content to the expected SOC content (SOC: SOC_{exp}) ratio was calculated. A ratio greater than 1 indicates that the SOC content of the soil is above expected SOC content and thus above average SOC content within a land use class, and a ratio below 1 means that the soil is rather SOC-depleted and below average.

For each land use class, the distribution of the SOC: SOC_{exp} ratio values were analyzed, and the values of the 3rd quartile (q3) were defined (Table 13).

Table 13: Values of the 3rd quartile of the SOC:SOExp ratio for each land use class

Land use class	Q3 of the SOC:SOExp
4	1,119609966
3	1,077258132
2	1,106499497
1	1,064737629
5	1,071508147
6	1,07626191

Applying Equation 13, C_{max} was calculated for each land use class based on the $SOExp$.

Equation 13: Equation to estimate C_{max} from the $SOExp$ and q3

$$C_{max} = SOExp * q3$$

4.6 Estimation of carbon deficit

In application of the Equation 14, a SOC content deficit is calculated from the C_{max} established using the four different methodologies.

Equation 14: Determination of the difference between the maximal SOC content and the observed SOC content

$$\Delta_{pot} = C_{max} - C_{obs}$$

With,

Δ_{pot} , the SOC content deficit ($g.kg^{-1}$) that could additionally be stored in the soil,

C_{max} , the maximal SOC content ($g.kg^{-1}$) that could theoretically be reached in the soil, and determined according to the four tested methodologies,

C_{obs} , the observed SOC content ($g.kg^{-1}$) that is effectively present in the soil.

To limit the bias introduced into the calculations by the use of surface data derived from the interpolation of initial point soil data (unavailable for the study), the determination of the Δ_{pot} is not performed at the raster cell level but at aggregated levels (soilscape or land use) and based on the median values of C_{max} and C_{obs} . Indeed, the use of individual raster cell values leads to unrealistic results skewed towards extreme values produced by interpolated surface data. The use of average values results in the same issue. Thus, for each area of interest (soilscape or land use), a median value of the SOC content deficit (Δ_{pot}) is estimated.

To apprehend the variability of the SOC content deficit that is encountered in each area of interest, the median value of the C_{max} was flanked by the 1st quartile and the 3rd quartile values, except for the estimation resulting from the methodology 1, since this methodology intrinsically allows only one value of C_{max} per area of interest (i.e. 80th percentile or 90th percentile of the C_{obs} distribution).

Once the Δ_{pot} estimated for each area of interest, the median SOC storage potential (ΔS_{pot}), expressed in $tC.ha^{-1}$, was calculated using Equation 10, with Δ_{pot} as a substitute for $SO_{content}$.

Thanks to the application of the four methodologies m1, m2, m3 and m4, the maximal reachable SOC stock of each group of soils (grouped by land use class or by soilscape) were estimated.

A positive ΔS_{pot} expresses a deficit in SOC stock in the area of interest in comparison with the reference (S_{max}). The soils of this area are (median value) considered as depleted in SOC in comparison to the applied reference, and it expresses a carbon deficit, and therefore, the

maximal theoretical additional stock of SOC that could be stored in these soils. A negative ΔS_{pot} expresses an excess of SOC stock. The soils of this area are (median value) SOC-enriched in comparison with the applied reference, and it expresses a carbon excess.

4.7 Extrapolation at national level

To extrapolate the results at the national level, the negative SOC storage potentials (ΔS_{pot}) were replaced by 0 as they have by definition no potential to store additional SOC.

Then the SOC storage potential value of each soilscape or land use class, expressed in $\text{tC}\cdot\text{ha}^{-1}$, were multiplied by the total area of each soilscape or land use class, respectively, and expressed in kt of carbon.

Finally, the obtained results of SOC storage potentials were also expressed in percent of the total maximal reachable SOC stocks, for each soilscape or land use class. The total maximal reachable SOC stocks correspond to the sum of the existing observed SOC stocks and the estimated SOC storage potentials.

5 Results and discussion

5.1 SOC storage potentials estimated at the soilscape level

At the soilscape level, the estimated SOC storage potentials depend strongly on the applied methodology and differ widely from one soilscape to another (detailed results in Appendix 5).

According to methodology m1, the SOC storage potentials range from 0 (3 soilscares are estimated saturated: 5_2, 5_27, 5_3 - all under wetland land use) to 149.6 kt of carbon for soilscape 4_5 (forest land use and sandy soils developed on sandstone).

When scaled to the national area, the SOC storage potential is estimated at 1,703 kt, with an average soil carbon deficit of 7.6 t/ha. At the scale of the four land-use types considered, the highest average deficit is observed in grassland soils (8.5 t/ha), closely followed by cropland soils (8.05 t/ha). Forest soils show a lower deficit (6.5 t/ha), similar to that of wetland soils (6.93 t/ha) (Figure 4). In terms of carbon deficit relative to the maximum soil storage capacity, the average national deficit is estimated at 7.0%, ranging from 5.7% in wetlands to 7.3% in croplands. Finally, in absolute terms (i.e. when accounting for the area of each land-use type) the largest deficit is found in grasslands (606 kt), whereas only 2 kt could be stored in wetlands. It should be noted that the deficits of the three most widespread land-use types are relatively similar (496 kt, 606 kt, and 599 kt for croplands, grasslands, and forests, respectively) (Table 14).

According to methodology m2, the SOC storage potentials range from 0 (1 soilscape is estimated saturated: 5_8 – under wetland land use) to 404.8 kt of carbon for soilscape 4_1 (forest land use in Oesling).

When scaled to the national area, the SOC storage potential is estimated at 2,958 kt, with an average soil carbon deficit of 13.1 t/ha. At the scale of the four land-use types considered, the highest average deficit is observed in forest soils (16.8 t/ha). Grassland soils show a lower deficit (11.6 t/ha), close to that of cropland soils (9.4 t/ha) (Figure 5). In terms of carbon deficit relative to the maximum soil storage capacity, the average national deficit is estimated at 15.2%, ranging from 5.7% in wetlands to 21.4% in forest soils. Finally, in absolute terms (i.e. when accounting for the area of each land-use type) the largest deficit is found in forest (1550 kt), which represent about half of the national deficit, whereas only 1 kt could be stored in wetlands. It should be noted that the deficits of cropland and grassland are relatively similar (578 kt and 829 kt, respectively) (Table 15).

According to methodology m3, the SOC storage potentials range from 0 (39 soilscares are estimated saturated: see Appendix 5) to 86.49 kt of carbon for soilscape 3_4 (grassland land use and clay-stony soils).

When scaled to the national area, the SOC storage potential is only estimated at 280 kt, with an average soil carbon deficit of 1.2 t/ha. At the scale of the four land-use types considered, the highest average deficit is observed in grassland soils (2.6 t/ha), followed by cropland soils (1.4 t/ha). Forest soils show a lower deficit (0.06 t/ha) and would be almost totally at saturation (Figure 6). In terms of carbon deficit relative to the maximum soil storage capacity, the average national deficit is estimated at 1.2%, ranging from 0.5% in wetlands to 2.4% in grassland. Finally, in absolute terms (i.e. when accounting for the area of each land-use type) the largest deficit is found in grasslands (187 kt), whereas only 6 kt could be stored in forest (non in wetlands), and 87 kt could be stored in cropland (Table 16).

According to methodology m4, the SOC storage potentials range from 0 (8 soilscares are estimated saturated: see Appendix 5) to 335 kt of carbon for soilscape 4_5 (forest land use and sandy soils).

When scaled to the national area, the SOC storage potential is estimated at 2,296 kt, with an average soil carbon deficit of 10.2 t/ha. At the scale of the four land-use types considered, the highest average deficit is observed in cropland soils (11.2 t/ha), closely followed by grassland soils (11.05 t/ha). Forest soils show a lower deficit (8.0 t/ha) (Figure 7). In terms of carbon deficit relative to the maximum soil storage capacity, the average national deficit is estimated at 9.2%, ranging from 5.6% in wetlands to 10.6% in forest soils. Finally, in absolute terms (i.e. when accounting for the area of each land-use type) the largest deficit is found in forest (1030 kt), which represent about half of the national deficit, whereas only 2 kt could be stored in wetlands. It should be noted that the deficits of cropland and grassland are relatively similar (693 kt and 572 kt, respectively) (Table 17Table 14).

The results obtained show a certain degree of consistency among the different methodologies. At the national scale, the average carbon deficit relative to the maximum soil storage capacity ranges from 1.2% (methodology m3) to 15.2% (methodology m2), with intermediate values of 7.0% and 9.2% for methodologies m1 and m4, respectively. Although these results remain relatively close, the different methodologies reveal substantial disparities in carbon deficits at the soilscape and land-use type scales. Specifically, for methodologies m1 and m3, carbon deficits are greater in cropland and grassland soils, whereas methodologies m2 and m4 indicate that forest soils are the most depleted in carbon relative to their storage potential.

By expressing SOC storage potentials in tons per hectare and per soilscape (Figures 4 to 7, Appendix 5), the soils of the Oesling appear to be mostly carbon-saturated or close to saturation according to methodologies m1, m3, and m4. These results reinforce the idea that soils in this region are already well supplied with carbon, notably due to the region's relatively cool and wet climate.

However, the results obtained using methodology m2, which is based on the fine fraction of soil texture, show that the soils of the Oesling are not carbon-saturated and exhibit a moderate carbon deficit (2.5 to 10 t/ha) in the soils of this region.

For methodology m2, the sandy soils (soil association 5) developed on Luxembourg sandstone are the only soils close to carbon saturation, whereas all the others show a carbon deficit ranging from moderate to high (between 2.5 t/ha and 40 t/ha). The influence of soil texture is also visible, to a lesser extent, in the results of the other methodologies. Indeed, for all four methodologies, soils with a clayey to heavy clayey texture (mainly soil associations 6 and 7) show the highest carbon deficits. For methodology m3, these soils are even almost the only soils that are not saturated with carbon, with a moderate deficit between 10 and 20 t/ha. For these soils, methodology m1 shows a carbon deficit similar to that estimated with methodology m3. With methodologies m2 and m4, these clayey soils have an even greater SOC additional storage potential (between 20 and 40 t/ha).

The large carbon deficits in clayey soils highlighted by the tested methodologies (mainly m2, m3, and m4) could be explained by a methodological bias. Indeed, these methodologies directly take soil texture into account and may overestimate the theoretical storage capacity of very clay-rich soils, while conversely underestimating the storage capacity of very sandy soils. For example, according to Poeplau and Don (2023), methodology m3, based on the SOC:clay ratio, would not be relevant for soils with extreme textures (i.e. heavy clay or sandy textures). Although, in this case, Johannes et al. (2023) demonstrated that methodology m3 remains relevant for a wide range of textures (between 16 and 52% of clay), it cannot be ruled out that this methodology is not applicable to textures lying outside this range.

Moreover, Johannes et al. (2023) as well as Sauzet et al. (2024) emphasize that one should not confuse the pedological carbon storage potential, which depends on the intrinsic properties of soils such as texture, with the agronomic and agro-environmental carbon storage potential, which depends on soil management practices, agronomic production objectives, and the climatic conditions to which soils are subjected. Thus, it is possible that a soil with an extreme texture has a given pedological storage potential, estimated using methodologies m2, m3, or m4, but that this potential is not realistically achievable for a given agronomic production objective (e.g. intensive maize or potato cultivation) and/or under a given climate (e.g. a relatively dry and warm climate).

The independence of methodology m1 from intrinsic soil properties allows it to partially circumvent this issue of extreme textures, since the references used in methodology m1 are real and measured. However, this raises the question of the relevance of the chosen reference. Indeed, this reference may also prove to be inappropriate for a given soil subjected to a particular climate and/or managed under certain practices and for a specific agronomic objective, if these conditions differ significantly from those applying to the reference.

Table 14: SOC storage potentials derived from methodology m1 estimated by soilscape and then aggregated by land use at the national scale

Landuse	Surface area		Existing stock		Stock deficit			Stock deficit - low estimation (q1)			Stock deficit - high estimation (q3)		
	Cell	(ha)	(t.ha ⁻¹)	(kt)	(t.ha ⁻¹)	(kt)	% of the maximal reachable stocks	(t.ha ⁻¹)	(kt)	% of the maximal reachable stocks	(t.ha ⁻¹)	(kt)	% of the maximal reachable stocks
Cropland	27390	61628	101,60	6261	8,05	496	7,34	8,05	496	7,34	8,05	496	7,34
Grassland	31622	71150	108,32	7707	8,52	606	7,29	8,52	606	7,29	8,52	606	7,29
Forest	41044	92349	93,74	8657	6,49	599	6,48	6,49	599	6,48	6,49	599	6,48
Wetland	108	243	114,06	28	6,93	2	5,73	6,93	2	5,73	6,93	2	5,73
National level	100164	225369	100,51	22652	7,56	1703	6,99	7,56	1703	6,99	7,56	1703	6,99

Table 15: SOC storage potentials derived from methodology m2 estimated by soilscape and then aggregated by land use at the national scale

Landuse	Surface area		Existing stock		Stock deficit			Stock deficit - low estimation (q1)			Stock deficit - high estimation (q3)		
	Cell	(ha)	(t.ha ⁻¹)	(kt)	(t.ha ⁻¹)	(kt)	% of the maximal reachable stocks	(t.ha ⁻¹)	(kt)	% of the maximal reachable stocks	(t.ha ⁻¹)	(kt)	% of the maximal reachable stocks
Cropland	27390	61628	81,06	4995	9,38	578	10,37	4,37	269	5,12	14,83	914	15,47
Grassland	31622	71150	81,89	5826	11,65	829	12,45	4,99	355	5,75	16,70	1188	16,94
Forest	41044	92349	61,74	5702	16,78	1550	21,37	10,83	1001	14,93	21,96	2028	26,24
Wetland	108	243	85,93	21	5,19	1	5,69	2,16	1	2,46	10,79	3	11,16
National level	100164	225369	73,41	16544	13,12	2958	15,17	7,21	1626	8,95	18,34	4133	19,99

Table 16: SOC storage potentials derived from methodology m3 estimated by soilscape and then aggregated by land use at the national scale

Landuse	Surface area		Existing stock		Stock deficit			Stock deficit - low estimation (q1)			Stock deficit - high estimation (q3)		
	Cell	(ha)	(t.ha ⁻¹)	(kt)	(t.ha ⁻¹)	(kt)	% of the maximal reachable stocks	(t.ha ⁻¹)	(kt)	% of the maximal reachable stocks	(t.ha ⁻¹)	(kt)	% of the maximal reachable stocks
Cropland	27390	61628	101,60	6261	1,42	87	1,38	0,00	0,0	0,00	5,57	343	5,19
Grassland	31622	71150	108,32	7707	2,62	187	2,36	0,00	0,0	0,00	7,25	516	6,27
Forest	41044	92349	93,74	8657	0,06	6	0,07	0,00	0,0	0,00	2,49	230	2,58
Wetland	108	243	114,06	28	0,58	0	0,51	0,49	0,1	0,43	15,17	4	11,74
National level	100164	225369	100,51	22652	1,24	280	1,22	0,00	0,1	0,00	4,85	1092	4,60

Table 17: SOC storage potentials derived from methodology m4 estimated by soilscape and then aggregated by land use at the national scale

Landuse	Surface area		Existing stock		Stock deficit			Stock deficit - low estimation (q1)			Stock deficit - high estimation (q3)		
	Cell	(ha)	(t.ha ⁻¹)	(kt)	(t.ha ⁻¹)	(kt)	% of the maximal reachable stocks	(t.ha ⁻¹)	(kt)	% of the maximal reachable stocks	(t.ha ⁻¹)	(kt)	% of the maximal reachable stocks
Cropland	27390	61628	101,60	6261	11,24	693	9,96	6,74	415	6,22	16,71	1030	14,12
Grassland	31622	71150	108,32	7707	8,04	572	6,91	3,10	221	2,79	13,80	982	11,30
Forest	41044	92349	93,74	8657	11,15	1030	10,63	6,42	593	6,41	17,38	1605	15,64
Wetland	108	243	114,06	28	6,76	2	5,59	1,70	0	1,47	16,13	4	12,39
National level	100164	225369	100,51	22652	10,19	2296	9,20	5,46	1230	5,15	16,06	3620	13,78

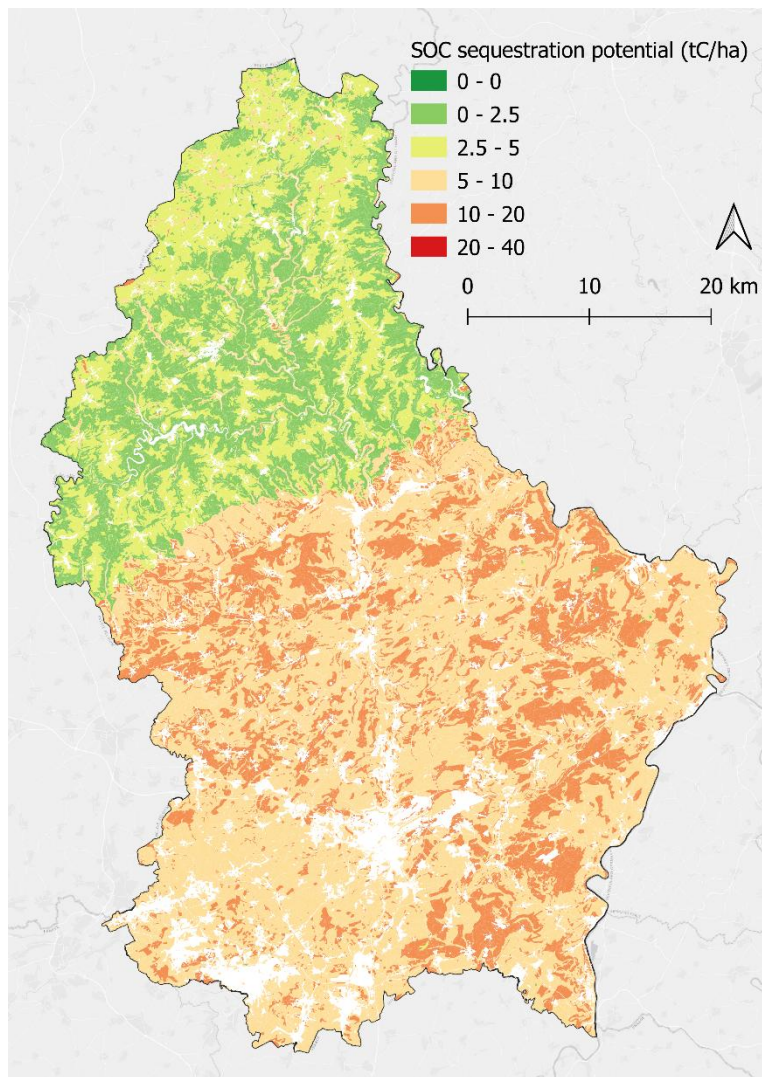


Figure 4: Soilscape-scale map of SOC storage potential based on Methodology m1

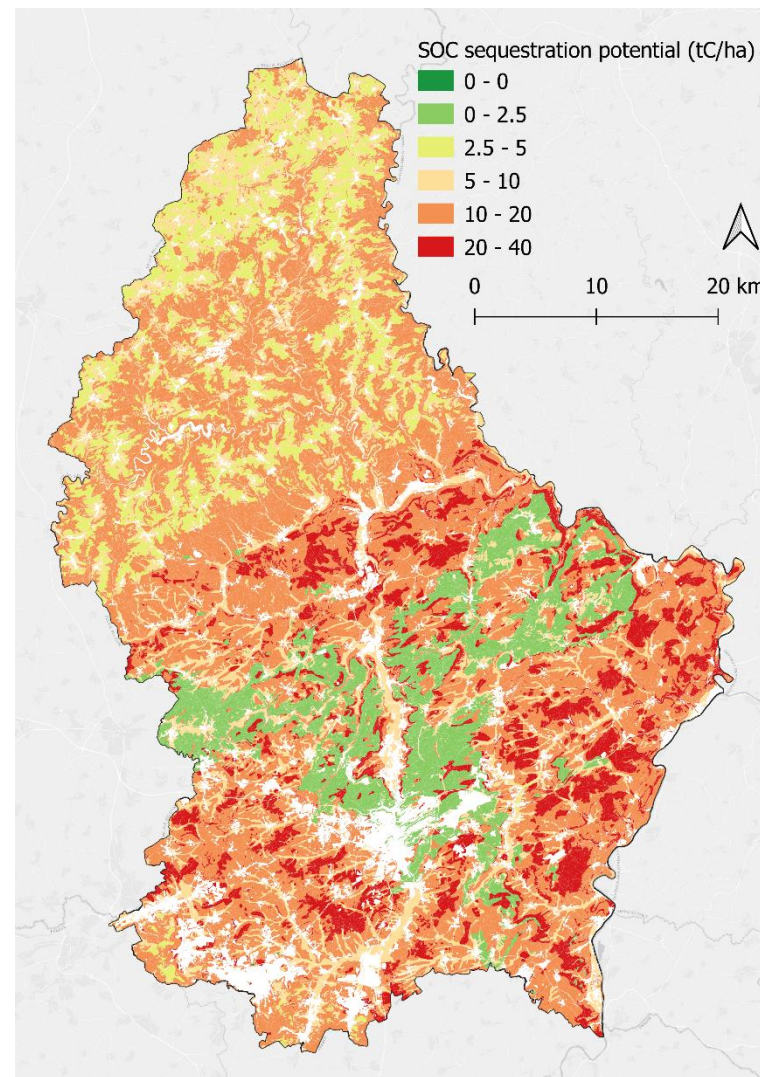


Figure 5: Soilscape-scale map of SOC storage potential based on Methodology m2

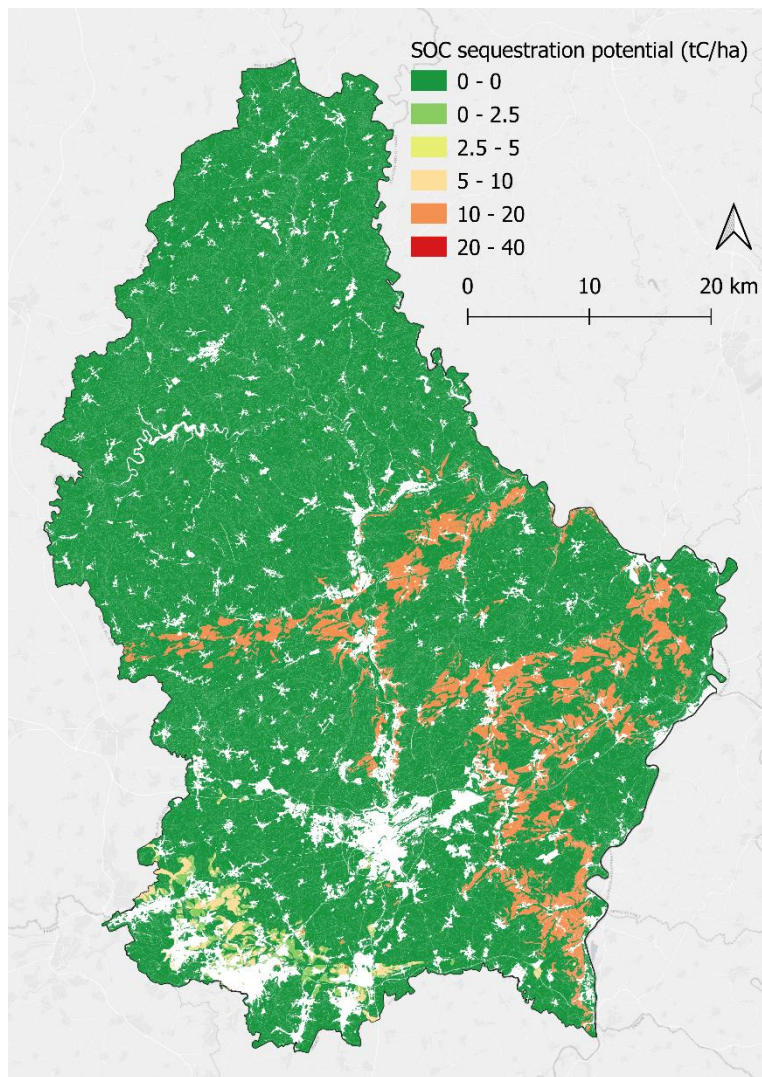


Figure 6: Soilscape-scale map of SOC storage potential based on Methodology m3

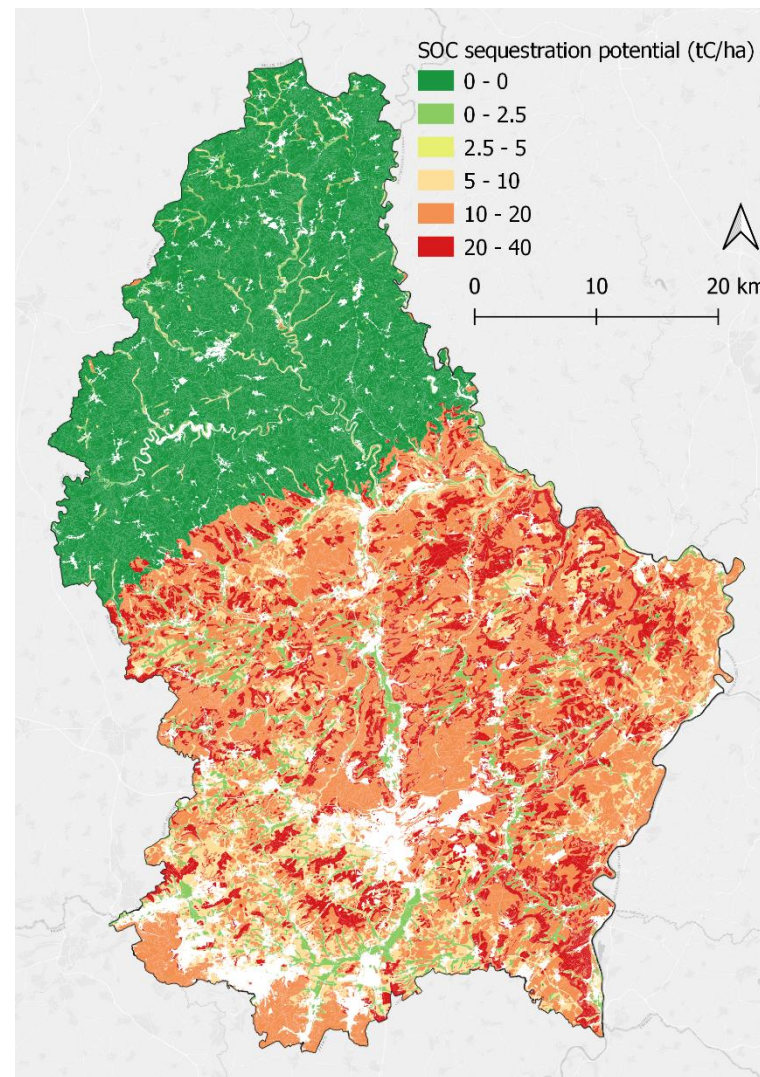


Figure 7: Soilscape-scale map of SOC storage potential based on Methodology m4

5.2 SOC storage potentials estimated at the level of land uses

When SOC storage potentials are estimated directly at the land-use type scale, the results are generally similar to those obtained at the soilscape scale for each methodology. However, it appears that carbon deficits relative to the maximum soil storage capacity are slightly underestimated compared with estimates at the soilscape scale, with deficits ranging from 0% (m3), suggesting that soils are generally saturated, to 13.8% (m2). This underestimation ranges from 0.5 percentage points for m1, representing a difference of only 7 kt at the national scale, to 5.8 percentage points for m4, corresponding to a difference of approximately 1,430 kt nationally. Depending on the methodology employed, the spatial scale used to assess SOC storage potential can have a significant influence and should therefore be taken into account.

Table 18: SOC storage potentials derived from methodology m1 estimated by land use at the national scale

Landuse	Surface area		Existing stock		Stock deficit			Stock deficit - low estimation (q1)			Stock deficit - high estimation (q3)		
	Cell	(ha)	(t.ha ⁻¹)	(kt)	(t.ha ⁻¹)	(kt)	% of the maximal reachable stocks	(t.ha ⁻¹)	(kt)	% of the maximal reachable stocks	(t.ha ⁻¹)	(kt)	% of the maximal reachable stocks
Cropland	27390	61628	109,02	6718	7,21	444	6,20	0,00	0	0,00	9,82	605	8,27
Grassland	31622	71150	112,91	8033	7,67	546	6,36	3,77	268	3,23	11,22	798	9,04
Forest	41044	92349	106,34	9820	7,78	719	6,82	0,00	0	0,00	11,37	1050	9,66
Wetland	108	243	116,56	28	6,95	2	5,62	6,95	2	5,62	6,95	2	5,62
National level	100164	225369	109,155	24600	7,59	1711	6,50	1,20	270	1,09	10,90	2456	9,08

Table 19: SOC storage potentials derived from methodology m2 estimated by land use at the national scale

Landuse	Surface area		Existing stock		Stock deficit			Stock deficit - low estimation (q1)			Stock deficit - high estimation (q3)		
	Cell	(ha)	(t.ha ⁻¹)	(kt)	(t.ha ⁻¹)	(kt)	% of the maximal reachable stocks	(t.ha ⁻¹)	(kt)	% of the maximal reachable stocks	(t.ha ⁻¹)	(kt)	% of the maximal reachable stocks
Cropland	27390	61628	86,64	5339	7,73	476	8,19	0,00	0	0,00	12,87	793	12,93
Grassland	31622	71150	85,21	6062	10,19	725	10,69	2,98	212	3,38	16,65	1185	16,35
Forest	41044	92349	69,76	6442	17,96	1659	20,48	0,10	9	0,15	23,43	2164	25,14
Wetland	108	243	87,77	21	5,83	1	6,23	0,92	0	1,04	11,45	3	11,54
National level	100164	225369	79,2721	17865	12,70	2862	13,81	0,98	221	1,22	18,39	4145	18,83

Table 20: SOC storage potentials derived from methodology m3 estimated by land use at the national scale

Landuse	Surface area		Existing stock		Stock deficit			Stock deficit - low estimation (q1)			Stock deficit - high estimation (q3)		
	Cell	(ha)	(t.ha ⁻¹)	(kt)	(t.ha ⁻¹)	(kt)	% of the maximal reachable stocks	(t.ha ⁻¹)	(kt)	% of the maximal reachable stocks	(t.ha ⁻¹)	(kt)	% of the maximal reachable stocks
Cropland	27390	61628	109,02	6718	0,00	0	0,00	0,00	0	0,00	0,00	0	0,00
Grassland	31622	71150	112,91	8033	0,00	0	0,00	0,00	0	0,00	0,00	0	0,00
Forest	41044	92349	106,34	9820	0,00	0	0,00	0,00	0	0,00	0,00	0	0,00
Wetland	108	243	116,56	28	0,00	0	0,00	0,00	0	0,00	14,92	4	11,34
National level	100164	225369	109,155	24600	0,00	0	0,00	0,00	0	0,00	0,02	4	0,01

Table 21: SOC storage potentials derived from methodology m4 estimated by land use at the national scale

Landuse	Surface area		Existing stock		Stock deficit			Stock deficit - low estimation (q1)			Stock deficit - high estimation (q3)		
	Cell	(ha)	(t.ha ⁻¹)	(kt)	(t.ha ⁻¹)	(kt)	% of the maximal reachable stocks	(t.ha ⁻¹)	(kt)	% of the maximal reachable stocks	(t.ha ⁻¹)	(kt)	% of the maximal reachable stocks
Cropland	27390	61628	109,02	6718	3,99	246	3,53	0,00	0	0,00	9,51	586	8,02
Grassland	31622	71150	112,91	8033	1,21	86	1,06	0,00	0	0,00	11,01	783	8,89
Forest	41044	92349	106,34	9820	5,76	532	5,14	0,00	0	0,00	10,74	992	9,17
Wetland	108	243	116,56	28	4,04	1	3,35	0,00	0	0,00	16,41	4	12,34
National level	100164	225369	109,155	24600	3,84	865	3,40	0,00	0	0,00	10,49	2365	8,77

5.3 Comparison with published estimates

Three scientific publications aimed at assessing the potential SOC storage in soils in Bavaria, Germany (Wiesmeier et al., 2014) and in France (Chen et al., 2019a; Chen et al., 2019b) were identified as relevant for comparing the results obtained in Luxembourg through the application of the four methodologies m1 to m4. These publications quantified the SOC storage potential in cropland, permanent grassland, and forest soils at the regional or national scale (Wiesmeier et al., 2014; Chen et al., 2019a, respectively), or exclusively in cropland soils at the national scale (Chen et al., 2019b). Although French or Bavarian soils may differ in nature from Luxembourg soils, the relative geographical proximity of the studied areas to Luxembourg suggests that at least a significant portion of the soils in these regions are comparable to Luxembourg soils in terms of soil characteristics and pedoclimatic conditions, making comparison of the results possible. Wiesmeier et al. (2014) and Chen et al. (2019a) quantified SOC storage potential using methodology m2 (carbon saturation of the fine soil fraction; Hassink equation (1997)). In contrast, Chen et al. (2019b) used a variant of methodology m1 (reference to a measured stock within an area of interest). They used the same reference as in our study, namely the 80th percentile (p80) of the observed carbon stock distribution, but a different area of interest (carbon-landscape zones), which can be likened to an association of soils under a given climate.

Figure 8 and Figure 9 show that the results obtained in Luxembourg are generally of the same order of magnitude as those obtained in Bavaria or in France. With regard to the results expressed in t/ha (Figure 8), it appears that the average SOC storage potentials of cropland soils estimated in Bavaria (Ba) and in France (FR1) using the carbon saturation of the fine fraction methodology (m2) are approximately 3.2 and 4.3 times higher, respectively, than the potential estimated in Luxembourg using the same m2 method (9.37 t/ha). However, the SOC storage potential estimated in France using the reference-based methodology (FR2) is closer to the estimate obtained in Luxembourg using methodology m1 (FR2: 14.04 t/ha; m1: 8.05 t/ha, i.e. about 1.7 times higher). For forest and permanent grassland soils, the SOC storage potential estimates made in Ba and FR1 are generally similar to those obtained with m2, except for Bavarian forest soils, where the potential is clearly underestimated (about ten times lower) compared to m2.

Regarding the results expressed in kt and scaled down to the surface areas of Luxembourg (Figure 9), the results follow the same patterns as those observed for the results expressed in t/ha.

These comparisons allow three conclusions to be drawn:

- The estimates of SOC storage potential obtained using methodologies m1 to m4 in Luxembourg are generally of the same order of magnitude as those established in Bavaria and France by Wiesmeier et al. (2014), Chen et al. (2019a), and Chen et al. (2019b).
- For arable soils, the SOC storage potentials estimated in Luxembourg are lower than those estimated in Bavaria and France, whereas for forest and permanent grassland soils, the estimates fall within the same range of values.
- Based on the results obtained in Luxembourg, France, and Bavaria, it is clear that estimates of SOC storage potential depend on the methodology used and on land use.

Based on this methodology m2, Wiesmeier et al. (2014) pointed out that 47 % of the cropland soil, 73 % of the grassland soils and 93 % of the forest soils are considered as saturated or oversaturated in Bavaria. These results suggest that a significant SOC storage potential would exist in cropland soils, but it would be limited for grassland soils and almost insignificant for forest soils. Guillaume et al. (2022) found similar results for cropland topsoils of the Fribourg Canton, where $62 \pm 4\%$ of the soils are saturated. In France, nearly 84 % of cropland soils

appeared to be depleted in stable SOC based on this C-saturation concept methodology (Chen et al., 2019), suggesting a significant SOC sequestration potential too. Using the same methodology but a distinct national data set, Angers et al (2011) found that about 70 % of the French agricultural topsoils are unsaturated to some extent. However, this pattern is not observed in Luxembourg according to the results obtained by applying methodology m2, since cropland soils appear to have the lower SOC storage potential (9,37 t/ha) in comparison with forest soils (16,78 t/ha) and grassland soils (11,65 t/ha).

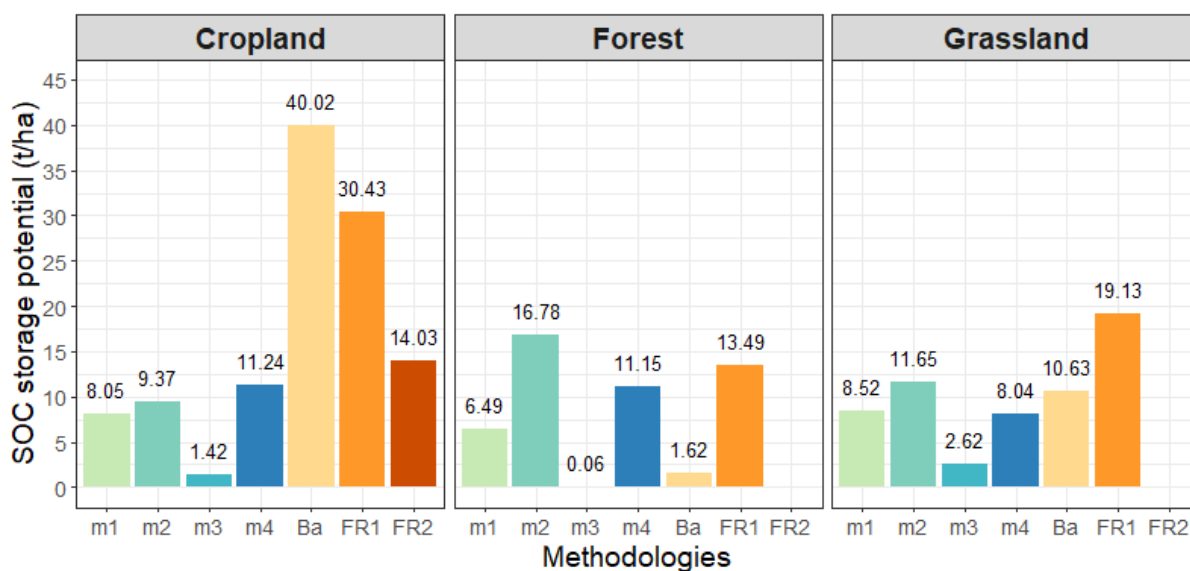


Figure 8: Comparison of the results obtained by applying methodologies m1 to m4 in Luxembourg with the results obtained by Wiesmeier et al. (2014) in Bavaria, Germany (Ba), by Chen et al. (2019a) in France, using methodology m2 (FR1) and by Chen et al. (2019b) in France, using methodology m1 (FR2). Results expressed in t/ha.

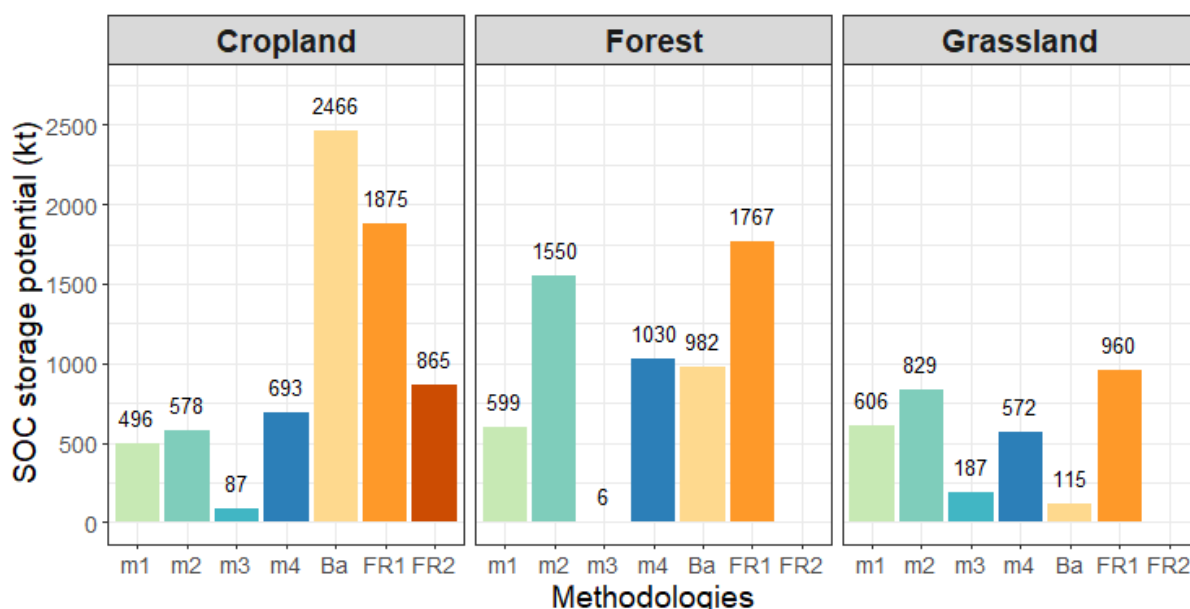


Figure 9: Comparison of the results obtained by applying methodologies m1 to m4 in Luxembourg with the results obtained by Wiesmeier et al. (2014) in Bavaria, Germany (Ba), by Chen et al. (2019a) in France, using methodology m2 (FR1) and by Chen et al. (2019b) in France, using methodology m1 (FR2). Results expressed in kt and related to the Luxembourg area of cropland, forest or grassland.

5.4 Limitations of the estimates

The estimates carried out in this study suffer multiple limitations and are therefore unsuitable for any use, particularly by policymakers and land managers. These estimates were performed only to test the applicability of the identified methodologies and to compile all the elements (data, approaches, assumptions, etc.) necessary for their correct application. To obtain reliable results, these estimates must be repeated, correcting the following limitations:

Available data used

The lack of locally measured point data led to the default use of the only available data, namely spatial (raster) datasets derived from national extrapolations (SOC content, clay content, sand content, bulk density) or even European extrapolations (coarse fragment content) (part 4.1). The use of such data had a threefold detrimental effect on the quality of the results obtained.

First, data derived from extrapolation inherently have higher uncertainty than locally measured point data, and this uncertainty propagated and was amplified throughout the estimation of SOC storage potentials, leading to a likely high uncertainty associated with the results obtained (the uncertainty itself could not be quantified).

Second, the combination during calculations of several estimated (extrapolated) parameters at a given geographic location (raster cell) skews the results, as it combines parameters that do not belong to one real soil. Thus, the calculated parameters (such as fine fraction contents, SOC:clay ratios, or stocks) are fictitious estimates not linked to an actual soil. This led to the estimation of outlier values that are not representative of true Luxembourg soils. For example, when evaluating stocks, the combination of extrapolated parameters resulted in particularly high SOC stock values (between 200 and 300 t/ha), values that have not been estimated based on real point measurements in Luxembourg (Chartin et al., 2022).

Finally, and third, these outlier values prevented the use of mean SOC storage potential values established within the geographic units of interest (soilscape, land use, national scale), since the particularly high estimated stock values artificially pulled the means upward, biasing and distorting the calculated averages. To address this issue, it was decided to use only median values of stock estimates and SOC storage potentials. However, this solution is not satisfactory and does not allow for a precise estimation of SOC storage potentials. The results presented in this report are therefore indicative, and it is essential to redo all calculations using the most reliable real point data available in Luxembourg.

Area of interest

The implementation of all the methodologies identified in this study requires the definition of zones serving as spatial units that are considered homogeneous with respect to the factors influencing OC dynamics, and for which pedological information (e.g. SOC content or stocks, texture) can be used either as a reference (m1) or as subsets of data on which statistical procedures are applied to estimate S_{\max} (m2, m3, and m4). In this study, the zones of interest (national territory, six main land-use classes, and soilscapes) defined to test the methodologies were chosen for their ease of implementation, but they present major limitations that reduce the quality of the estimates of SOC storage potentials.

The main problem with these zones of interest is that they group together soils with diverse intrinsic properties that do not necessarily exhibit similar behavior with respect to OC dynamics, in terms of processes related to OC inputs, OC accumulation, and/or OC losses. Moreover, although it has the advantage of facilitating the interpretation of the resulting estimates, the use of the six land-use classes is too coarse to capture the processes involved in OC dynamics because, once again, these classes group soils that are subject to potentially very different management practices. Finally, at the scale of the territory, the influence of climatic variability is relatively poorly accounted by the tested zones of interest.

To improve the homogeneity of the zones of interest, Chen et al. (2019b) and Breure et al. (2025) defined geographic units considered homogeneous with respect to OC dynamics, based on environmental covariates selected for their relevance and roles in this dynamic (Doetterl et al., 2015; Wiesmeier et al., 2019). Chen et al. (2019) refer to these zones as carbon-landscape zones. In detail, Breure et al. (2025) used the following covariates: cumulative net primary productivity, aridity index, soil pH (water), and landform classes derived from digital elevation data.

Chen et al. (2019b), for their part, selected the following covariates: the climatic decomposition index, net primary productivity, and clay content, used as proxies for, respectively, C losses and C inputs that control the SOC balance, and for a controlling factor of SOC persistence.

After applying different geostatistical treatments, namely a Gaussian mixture model and the k-means method, respectively, Chen et al. (2019b) and Breure et al. (2025) defined clusters considered to be homogeneous (10 for metropolitan France and 16 at the scale of the European Union + the UK, respectively), on which they applied methodologies to estimate S_{\max} (respectively, a variant of methodology m1 and a variant of methodology m2).

Defining such clusters, optimized to capture the factors involved in OC dynamics in Luxembourg, appears essential to refine estimates of SOC storage potential. However, these clusters, which are based solely on environmental covariates, do not allow the production of results that are easily and directly usable by stakeholders, as practical management aspects are not included at all. The integration of additional covariates related to land use and management practices into these clusters therefore needs to be investigated. This is supported by Guillaume et al. (2021) who highlighted the importance of the proportion of temporary grasslands within the crop rotation, which has been identified as the main factor affecting the level of mineral-associated OC saturation in croplands, explaining 55% of the variation, even after the inclusion of all other tested environmental factors.

Limitations specific to each methodology

Methodology m1

This methodology is particularly sensitive to the definition of the zones of interest, as it uses a descriptive statistical value of the SOC stock or SOC content distribution within the zones as a reference. Although this methodology is simple to implement and the results obtained are theoretically achievable, since they have actually been measured in some soils, the lack of technical arguments to justify the selection of the descriptive statistical value used as a reference among the many options reported in the literature (p75, p80, p90, p95, maximum value, or the value of a reference land use such as grassland or forest), together with its inherent bias related to uncertainty about the existence of SOC-undepleted soils within the zones of interest, makes this methodology subjective. To reduce this subjectivity, an in-depth analysis of the key parameters should be conducted to define an approach that is relevant to our objective and to the Luxembourg context.

Methodology m2

This methodology is particularly sensitive to the use of extrapolated data rather than point measurements, as it requires the combination of different pedological parameters (fine fraction texture, SOC content). Its main drawback lies in the fact that it considers only the OC contained in the fine soil fraction and ignores OC in the coarse fraction and in particulate organic matter. It is therefore intrinsically prone to underestimating SOC storage potential. However, according to some authors, this drawback is only partial, since SOC in the fine fraction is considered the most stable form of carbon and therefore reflects a long-term storage capacity that is more relevant for mitigating climate change. Although Hassink's (1997) equation has still been used in some recent studies, it appears that the method used to derive it (i.e. least-squares linear regression) is not well suited for estimating maximum soil carbon storage potentials. Other statistical

methods have been proposed and tested, namely the boundary line (BL), piece-wise boundary line (PBL), and non-linear boundary line (NBL) methods (Feng et al., 2013; Breure et al., 2025), with very promising results.

Finally, an additional limitation of this methodology is the need for accurate data on the fine fraction content (clay + silt) as well as on the SOC content of this fine fraction. Initially, Hassink (1997) used the fine silt fraction (<20 µm), but in the absence of data on this fraction, other authors have used variants (<50 µm in Guillaume et al., 2022; <53 µm in Breure et al., 2025). For an application consistent with the original concept established by Hassink (1997), and with the differences in behavior of fine fractions observed by Six et al. (2002) between fine silt (2–20 µm) and coarse silt (20–50 µm), it appears appropriate to investigate the possibility of integrating a systematic soil texture characterization into five classes (including fine silt) in future soil monitoring campaigns in Luxembourg. Finally, according to several authors, the equations describing carbon saturation of the fine fraction could be optimized by including additional parameters, such as clay mineralogy (Feng et al., 2013), soil management practices (Guillaume et al., 2022), or the role of geogenic and sedimentary carbon (Fluvisols) and stabilization processes under reducing conditions (Stagnosols) (Breure et al., 2025).

Methodology m3

This methodology is particularly sensitive to the use of extrapolated data rather than point measurements, as it requires the combination of different pedological parameters (clay content, SOC content). Its main drawback lies in its underlying assumption that a soil with an SOC:clay ratio greater than 1:8, and therefore having a good structure (Johannes et al., 2017), would also have an optimal OC content that could be used to assess soil carbon deficit (Prout et al., 2021), and would thus be comparable to the maximum level (S_{max}) in our study.

Although this hypothesis could not be technically confirmed or invalidated by the study conducted, the estimates of SOC storage potentials obtained in this study show that the results derived from methodology m3 are systematically lower by a factor of 6 to 10 compared with those obtained using the other methodologies (at the national scale). This strong underestimation of SOC storage potentials suggests that this methodology is not suitable for estimating the maximum soil carbon storage potential and therefore implies that the underlying hypothesis is invalid. However, this methodology could prove useful for determining a lower bound of SOC storage potential, corresponding to optimal soil physical properties.

Technically, this methodology has not been validated for soils with coarse textures (clay content < 16%) or very fine textures (clay content > 52%) (Johannes et al., 2023). It would therefore be necessary to adapt it to these extreme textures, either by applying correction coefficients or by using a nonlinear statistical approach, at least across these texture ranges. It would also be relevant to adapt this methodology by accounting for the effects of clay mineralogy, which can influence OC dynamics, similarly to methodology m2 (Feng et al., 2013), and which could therefore modify the optimal threshold of 1:8 established by Johannes et al. (2017) on the basis of Swiss soils and validated by Prout et al. (2021) for soils of England and Wales.

Methodology m4

This methodology is particularly sensitive to the definition of the zones of interest, as it uses a descriptive statistical value of the SOC content distribution within the zones as a reference. It is also highly sensitive to the use of extrapolated data rather than point measurements, as it requires the combination of different pedological parameters (clay content, SOC content). Its main drawback lies in its relative subjectivity due to the lack of technical arguments to justify the use of the p75 of the distribution of the $SOC_{exp}:SOC_{obs}$ ratio within the area of interest as a reference. Moreover, like methodology m1, the use of such a reference exposes the results to a systematic underestimation bias of SOC storage potential due to the underlying assumption that at least part of the soils in the area of interest are not SOC-undepleted.

More broadly, methodology m4 has both the advantages and the limitations of methodologies m1 and m3, as it can be seen as a combination of these two approaches. Indeed, it relies on the determination of the expected SOC content (SOC_{exp}), which is based on the relationship between OC and clay content and can be interpreted as a variant of the SOC saturation content (not based on the fine fraction). In addition, it uses a reference derived from a descriptive statistical value of the SOC content distribution of soils within an area of interest to determine whether a soil has reached its SOC storage capacity or exhibits an SOC deficit.

Choice of the most appropriate method

One of the main findings of this study is the absence of a scientific consensus on the method used to estimate S_{max} . Although the four methods employed make it possible to estimate relatively similar SOC storage potentials, policymakers who will use the results want to be able to rely on the most robust results possible. To this end, it is necessary to select the best methodology, that is, the methodology that yields the most reliable results.

The term “best” is subjective and depends on the objectives to be achieved. From a scientific perspective, the best methodology would be the one that estimates results with the least possible uncertainty, regardless of the resources required (data needs, time, budget). By contrast, for decision-makers, such as the MECB, which would use these results to develop a national CCUS strategy, the term “best” refers to a methodology that is:

- Conservative (absolutely avoid overselling);
- Pragmatic and easy to implement in terms of required resources (ideally, applicable using available data);
- Associated with the lowest possible uncertainty.

In our case, the choice of the best methodology will have to be made on the basis of the criteria set by the decision-maker (i.e. MECB), and it may take three distinct forms:

- Either a single methodology is selected from among the four tested (or the six identified);
- Or several methodologies are selected, and the differences between their respective estimates are used to define a range of values rather than a single value;
- Or a combination of several of the tested methodologies may be developed.

It should be noted that methodology m1, based on the use of references, and methodology m2, which uses the concept of carbon saturation of the fine fraction, appear to be the most commonly used methodologies in the literature.

Assess and locate uncertainty

Like any estimation, the estimation of SOC storage potentials is associated with a certain level of uncertainty. In this study, the uncertainty associated with the results was not estimated, notably due to the use of spatial data (rasters) whose own uncertainty was unknown. However, it is essential to estimate the uncertainties associated with these results. At least four sources of uncertainty need to be taken into account:

- Uncertainty inherent to the assumptions used in applying a given methodology (e.g. for m1, the assumption that at least part of the soils within an area of interest are not SOC-depleted; for m2, the assumption that Hassink’s (1997) equation is applicable to Luxembourg soils);
- Uncertainty related to the variability of the data used, arising from the natural variability of soils and from sampling and analytical uncertainties (e.g. measured variability of a parameter within an area of interest);
- Uncertainty related to the calculation of the parameters used in estimating C_{max} or S_{max} , as well as uncertainty arising from the estimation of carbon stocks;

- Uncertainty related to the national-scale extrapolation of point-based results, either through simple linear extrapolation by area of interest or through geospatial extrapolation involving explanatory covariates.

To address these uncertainties, several approaches are possible, such as introducing a range of values (low and high assumptions), using confidence intervals (e.g. 95%), or applying uncertainty propagation through successive calculations. The application of these approaches may lead to very high levels of uncertainty, which could hinder the practical use of the results, for example, in the development of a CCUS strategy. It should also be noted that the estimation of SOC storage potentials is intrinsically associated with high uncertainty that cannot be fully quantified due to the impossibility of directly measuring this parameter (e.g. cross-validation is not possible).

Including excluded aspects

The identified, and a fortiori tested, methodologies explicitly or implicitly take into account the main factors involved in SOC dynamics. However, these methodologies exclude certain aspects that could significantly improve the results obtained.

For the sake of simplification and due to a lack of data, urban soils were excluded from the national estimates. However, urban soils in green spaces can store sometimes substantial amounts of SOC and including them in the calculations would improve national results, especially since these are managed soils for which technical levers of action are available. The specific characteristics of urban soils nevertheless make it difficult to apply methodologies m2 and m3, which were explicitly developed for agricultural soils.

Breure et al. (2025) estimate that the results of the variant of methodology m2 they implemented could be improved by accounting for the pedological particularities of soils whose carbon dynamics are strongly influenced by factors not explicitly considered. These include, for example, SOC dynamics in reduced or redox-affected soils that are permanently or temporarily waterlogged (Stagnosols), as well as the inclusion of geogenic carbon, such as in soils developed on sedimentary deposits (e.g., Fluvisols).

Another example of a potential avenue for improvement is proposed by Feng et al. (2013), who suggest that the equations used in methodology m2 could be more effective if they accounted for clay mineralogy (2:1 clays versus 1:1 clays).

6 Conclusion and prospects

This study made it possible to identify six different methodologies for estimating the soil SOC (Soil Organic Carbon) storage potential. Each of these methodologies uses a different concept:

- Modelling of the SOC dynamics,
- References from soils in good condition,
- SOC storage rates of management practices,
- Carbon saturation of the fine fraction,
- SOC to clay ratio,
- Expected SOC content.

Among these methodologies, only four appear to be applicable in the short and medium term, given the information currently available at the national level. Indeed, implementing the methodology based on carbon dynamics modeling, as well as the one based on storage rates, would require models calibrated to Luxembourg's conditions, comprehensive knowledge of the storage rates associated with soil management practices applied in the country, and the definition of exhaustive national scenarios optimized for carbon storage. At present, none of these elements are available, and obtaining them would require a significant investment of time and resources.

The other four methodologies, based respectively on the use of reference values, on the concept of carbon saturation of the fine fraction, on the SOC:clay ratio, and on the concept of expected SOC content, are applicable in the short term based on the information currently available in the country. The implementation of these four methodologies showed that all four are interesting and produce promising results, broadly consistent (in terms of order of magnitude) with results found in the international scientific literature (Bavaria–Germany, France).

However, the results produced are only provisional and must under no circumstances be reused, particularly by policymakers or land managers. Indeed, they are subject to numerous technical limitations that make them unreliable. Moreover, the SOC storage potential values obtained are theoretical values and should not, by default, be considered as targets to be achieved without taking into account other operational aspects. These include constraints related to agricultural or forestry production, spatial planning, the protection of biodiversity, water resources and soil quality, as well as other relevant socio-economic factors (housing, industry, etc.).

In order to obtain reliable estimates of SOC storage potential at the national scale, it is necessary to redo the calculations while addressing the limitations identified in this study.

In the short term, it would therefore be worthwhile to reassess the estimates using the four methodologies tested, relying on the best available data and resolving the highlighted limitations. To do so, one or more of the identified methodologies could be applied, or some of them could even be combined to develop a new hybrid methodology that may prove more effective.

In the long term, it would be worthwhile to develop and calibrate models that would enable the implementation of the methodology based on SOC dynamics modeling. Indeed, although this methodology is demanding, data-intensive, and complex to implement, it appears capable of offering numerous advantages that the other methodologies cannot provide. Among these advantages is the ability to predict the dynamics of carbon stocks as a function of parameters external to the soil system, such as the effects of climate change or those of public strategies or policies. The results obtained through this methodology would therefore constitute a powerful decision-support tool for public decision-makers working in the fields of the environment (climate, soil protection) and agriculture.

7 References

- Akpa, S.I.C., Odeh, I.O.A., Bishop, T.F.A., Hartemink, A.E., and Amapu, I.Y., 2016. Total soil organic carbon and carbon sequestration potential in Nigeria. *Geoderma*, 271, 202–215
- Andriulo A, Mary B, Guerif J (1999) Modelling soil carbon dynamics with various cropping sequences on the rolling pampas. *Agron Sustain Dev* 19:365–377. <https://doi.org/10.1051/agro:19990504>
- Angers, D.A., Arrouays, D., Saby, N.P.A., Walter, C., 2011. Estimating and mapping the carbon saturation deficit in French agricultural topsoils. *Soil Use Manage.* 27, 448–452.
- ASTA, 2016. Carte des associations de sols au 1/100 000 – version simplifiée. Administration des services techniques de l’agriculture. Data.public.lu, <https://data.public.lu/fr/datasets/carte-des-associations-de-sols/>
- Balesdent, J., 1996. The significance of organic separates to carbon dynamics and its modelling in some cultivated soils. *Eur. J. Soil Sci.* 47, 485–493.
- Balesdent, J., Besnard, E., Arrouays, D., and Chenu, C., 1998. The dynamics of carbon in particle-size fractions of soil in a forest cultivation sequence. *Plant and Soil*, 201, 49-57
- Barré, P., Angers, D.A., Basile-Doelsch, I., Bispo, A., Cécillon, L., Chenu, C., Chevallier, T., Derrien, D., Eglin, T.K., Pellerin, S., 2017. Ideas and perspectives: Can we use the soil carbon saturation deficit to quantitatively assess the soil carbon storage potential, or should we explore other strategies? *Biogeosci. Discuss.* 2017. <https://doi.org/10.5194/bg-2017-395>
- Batjes, N.H., 2011. Soil organic carbon stocks under native vegetation - Revised estimates for use with the simple assessment option of the Carbon Benefits Project system. *Agriculture Ecosystems and Environment*, 142, 365-373
- Besnard, E., Chenu, C., Robert, M., 2001. Influence of organic amendments on copper distribution among particle size and density fractions in Champagne vineyard soils. *Environmental Pollution*, 112, 329-337
- Boon, W., 1984. Onderzoek naar het verband tussen het koolstofpercentage en de volumedichtheid van de grond. Intern Rapport Bodemkundige Dienst België, Heverlee (in Dutch).
- Brisson, N.; Gary, C.; Justes, E.; Roche, R.; Mary, B.; Ripoche, D.; Zimmer, D.; Sierra, J.; Bertuzzi, P.; Burger, P.; Bussiere, F.; Cabidoche, Y.M.; Cellier, P.; Debaeke, P.; Gaudillere, J.P.; Henault, C.; Maraux, F.; Seguin, B.; Sinoquet, H., 2003. An overview of the crop model STICS. *European Journal of Agronomy*, 18 (3-4): 309-332. [http://dx.doi.org/10.1016/s1161-0301\(02\)00110-7](http://dx.doi.org/10.1016/s1161-0301(02)00110-7)
- Brisson, N.; Mary, B.; Ripoche, D.; Jeuffroy, M.H.; Ruget, F.; Nicoullaud, B.; Gate, P.; Devienne Barret, F.; Antonioletti, R.; Durr, C.; 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 balances. I. Theory and parameterization applied to wheat and corn. *Agronomie*, 18 (5-6): 311-346. <http://dx.doi.org/10.1051/agro:19980501>
- Calanca, P.; Vuichard, N.; Campbell, C.; Viovy, N.; Cozic, A.; Fuhrer, J.; Soussana, J.F., 2007. Simulating the fluxes of CO₂ and N₂O in European grasslands with the Pasture Simulation Model (PaSim). *Agriculture Ecosystems & Environment*, 121 (1-2): 164-174. <http://dx.doi.org/10.1016/j.agee.2006.12.010>
- Campbell, E.E.; Paustian, K., 2015. Current developments in soil organic matter modeling and the expansion of model applications: a review. *Environmental Research Letters*, 10 (12). <http://dx.doi.org/10.1088/1748-9326/10/12/123004>
- Cardinael, R., Chevallier, T., Barthes, B.G., Saby, N.P.A., et al., 2015. Impact of alley cropping agroforestry on stocks, forms and spatial distribution of soil organic carbon – A case study in a Mediterranean context. *Geoderma*, 259, 288-299
- Chartin C., van Weselman B., Marx S., Steffen S., Leydet L., 2022. Organic carbon in soils of the Grand-Duchy of Luxembourg: Past, Present and Future. April 2022. UCLouvain, ASTA. 110p

- Chartin C., van Wesemael B., Marx S., Steffen M., Leydet L., 2022. Organic carbon in soils of the Grand Duchy of Luxembourg: past, present and future. Earth and life institute, Université Catholique de Louvain - ministry of agriculture, viticulture and rural development, Luxembourg. 110p.
- Chen S., Arrouays D., Angers D.A., Chenu C., Barré P., Martin M.P., Saby N.P.A., Walter C., 2019b. National estimation of soil organic carbon storage potential for arable soils: a data-driven approach coupled with carbon-landscape zones. *Science of the Total Environment* 666, 355–367
- Chen, S., Arrouays, D., Angers, D. A., Martin, M. P., & Walter, C. (2019a). Soil carbon stocks under different land uses and the applicability of the soil carbon saturation concept. *Soil and Tillage Research*, 188, 53–58. <https://doi.org/10.1016/j.still.2018.11.001>
- Chen, S., Martin, M.P., Saby, N.P.A., Walter, C., Angers, D.A., Arrouays, D., 2018. Fine resolution map of top- and subsoil carbon sequestration potential in France. *Sci. Total Environ.* 630, 389–400.
- Chimento, C., Almagro, M., and Amaducci, S., 2016. Carbon sequestration potential in perennial bioenergy crops: the importance of organic matter inputs and its physical protection. *Global Change Biology Bioenergy*, 8, 111-121
- Coleman, K.; Jenkinson, D.S., 1996. RothC-26.3 - a model for the turnover of carbon in soil. In: Powlson, D.S.; Smith, J.U.; Smith, P., eds. *Evaluation of soil organic matter models using existing long term data-sets*. Heidelberg: Springer-Verlag (NATO ASI Series I), 237-246.
- Conant, R.T., Paustian, K., Elliott, E.T., 2001. Grassland management and conversion into grassland: effects on soil carbon. *Ecol. Appl.* 11, 343–355.
- DATer, 2025. LIS-L Land Use 2007, 2015, 2018, 2021. Département de l'aménagement du territoire. Data.public.lu, <https://data.public.lu/fr/datasets/lis-l-land-use-2007-2015-2018-2021/>
- De Vos B., Van Meirvenne M., Quataert P., Deckers J., Muys B., 2005. Predictive quality of pedotransfer functions for estimating bulk density of forest soils. *Soil Science Society of America Journal*, 69(2):500_510
- Dignac, M.F., Derrien, D., Barré, P., Barot, S., Cécillon, L., Chenu, C., Chevallier, T., Freschet, G.T., Garnier, P., Guenet, B., Hedde, M., 2017. Increasing soil carbon storage: mechanisms, effects of agricultural practices and proxies. A review. *Agron. Sustain. Dev.* 37, 14.
- Doetterl, S. et al., 2015. Soil carbon storage controlled by interactions between geochemistry and climate. *Nat.Geosci.* 8, 780–783
- Dûfrene, E.; Davi, H.; Francois, C.; le Maire, G.; Le Dantec, V.; Granier, A., 2005. Modelling carbon and water cycles in a beech forest Part I: Model description and uncertainty analysis on modelled NEE. *Ecological Modelling*, 185 (2-4): 407-436. <http://dx.doi.org/10.1016/j.ecolmodel.2005.01.004>
- Dupla X., Gondret K., Sauzet O., Verrecchia E., Boivin P., 2021. Changes in topsoil organic carbon content in the Swiss leman region cropland from 1993 to present. Insights from large scale on-farm study. *Geoderma* 400:115125
- Feng, W., Plante, A.F., Six, J., 2013. Improving estimates of maximal organic carbon stabilization by fine soil particles. *Biogeochemistry* 112 (1-3), 81–93. <https://doi.org/10.1007/s10533-011-9679-7>.
- Feng, W., Xu, M., Fan, M., Mahli, S.S., Schoenau, J.J., Six, J., and Plante, A.F., 2014. Testing for soil carbon saturation behavior in agricultural soils receiving long-term manure amendments. *Canadian Journal of Soil Science*, 94, 281-294
- Guillaume T., Makowski D., Libohova Z., Bragazza L., Sallak F., Sinaj S., 2022. Soil organic carbon saturation in cropland-grassland systems : storage potential and soil quality. *Geoderma* 406 115529, <https://doi.org/10.1016/j.geoderma.2021.115529>
- Guo, L.B., Gifford, R., 2002. Soil carbon stocks and land use change: a meta-analysis. *Glob. Change Biol. Bioenergy* 8, 345–360.
- Guzman, J., and M. Al-Kaisi. 2010. Soil carbon dynamics and soil carbon budget of newly reconstructed tall-grass prairies in south central Iowa. *J. Environ. Qual.* 39:136–146. doi:10.2134/jeq2009.0063

- Hassink, J., 1997. The capacity of soils to preserve organic C and N by their association with clay and silt particles. *Plant Soil* 191, 77–87.
- IPCC, 2006. IPCC guidelines for national greenhouse gas inventories. Volume 4: Agriculture, Forestry and other Land use. Chapter 2: Generic Methodologies applicable to multiple land-use categories, 59 pp
- IPCC, 2019. Refinement to the 2006 IPCC guidelines for national greenhouse gas inventories, chapter 3. Key Concepts Unchanged From the 2006 IPCC Guidelines.
- IPCC, 2019. Refinement to the 2006 IPCC guidelines for national greenhouse gas inventories. Volume 4: Agriculture, Forestry and other Land use. Chapter 2: Generic Methodologies applicable to multiple land-use categories, 96 pp
- Jensen, J.L., Schjønning, P., Watts, C.W., Christensen, B.T., Peltre, C., Munkholm, L.J., 2019. Relating soil C and organic matter fractions to soil structural stability. *Geoderma* 337, 834–843. <https://doi.org/10.1016/j.geoderma.2018.10.034>.
- Johannes A, Matter A, Schulin R, Weisskopf P, Baveye PC, Boivin P, 2017. Optimal organic carbon values for soil structure quality of arable soils. Does clay content matter? *Geoderma* 302, pp 14-21
- Johannes A., Sauzet O., Matter A., Boivin P., 2023. Soil organic carbon content and soil structure quality of clayey cropland soils: A large-scale study in the Swiss Jura region. *Soil Use Manage.* 2023;00:1–10.
- Johannes, A., Weisskopf, P., Schulin, R., Boivin, P., 2016. To what extent do physical measurements match with visual evaluation of soil structure? *Soil Tillage Res.* <http://dx.doi.org/10.1016/j.still.2016.06.001>.
- Jolivet, C., Arrouays, D., Leveque, J., Andreux, F., Chenu, C., 2003. Organic carbon dynamics in soil particle-size separates of sandy Spodosols when forest is cleared for maize cropping. *Eur. J. Soil Sci.* 54, 257–268.
- Kaiser K, Eusterhues K, Rumpel C, Guggenberger G, Kögel-Knabner I, 2002. Stabilization of organic matter by soil minerals - investigations of density and particlesize fractions from two acid forest soils. *Journal of Plant Nutrition and Soil Science*, 165, 451–459.
- Kleber M, Mikutta R, Torn MS, Jahn R, 2005. Poorly crystalline mineral phases protect organic matter in acid subsoil horizons. *European Journal of Soil Science*, 56, 717–725.
- Kleber, M., Eusterhues, K., Keiluweit, M., Mikutta, C., Mikutta, R., and Nico, P.S., 2015. Mineral-Organic Associations: Formation, Properties, and Relevance in Soil Environments. *Advances in Agronomy*, 130, 1-140
- Letten, S.; Van Orshoven, J.; van Wesemael, B.; De Vos, B.; Muys, B., 2005. Stocks and fluxes of soil organic carbon for landscape units in Belgium derived from heterogeneous data sets for 1990 and 2000. *Geoderma*, 127 (1-2): 11-23. <http://dx.doi.org/10.1016/j.geoderma.2004.11.001>
- Lugato, E., Bampa F., Panagos P., Montanarella L., Jones A., 2014. Potential carbon sequestration of European arable soils estimated by modelling a comprehensive set of management practices. *Global Change Biology* 20 (11), pp. 3557-3567
- Manzoni, S.; Porporato, A., 2009. Soil carbon and nitrogen mineralization: Theory and models across scales. *Soil Biology & Biochemistry*, 41 (7): 1355-1379. <http://dx.doi.org/10.1016/j.soilbio.2009.02.031>
- Martin M:P., Arrouays D., Barré P., Boulonne L., Cécillon L., Chen S., Chenu C., Eglin T., Guenet B., Meersmans J., Mulder V. L., Saby N.P.A., 2022. Le réseau de Mesure de la qualité des sols pour l'étude du carbone organique des sols en France métropolitaine – Avancées scientifiques et applications. *Le RMQS pour l'étude du carbone organique des sols. Étude et Gestion des Sols*, 29, 239-351
- Matamala, R., J.D. Jastrow, R.M. Miller, and C.T. Garten. 2008. Temporal changes in C and N stocks of restored prairie: Implications for C sequestration strategies. *Soil Sci. Soc. Am. J.* 18:1470–1488.
- McBratney A.B., Mendonça-Santos, M.L., and Minasny, B., 2003. On digital soil mapping. *Geoderma* 117:3–52.
- McLauchlan, K.K., S.E. Hobbie, and W.M. Post. 2006. Conversion from agriculture to grassland builds soil organic matter on decadal timescales. *Ecol. Appl.* 16:143–153.

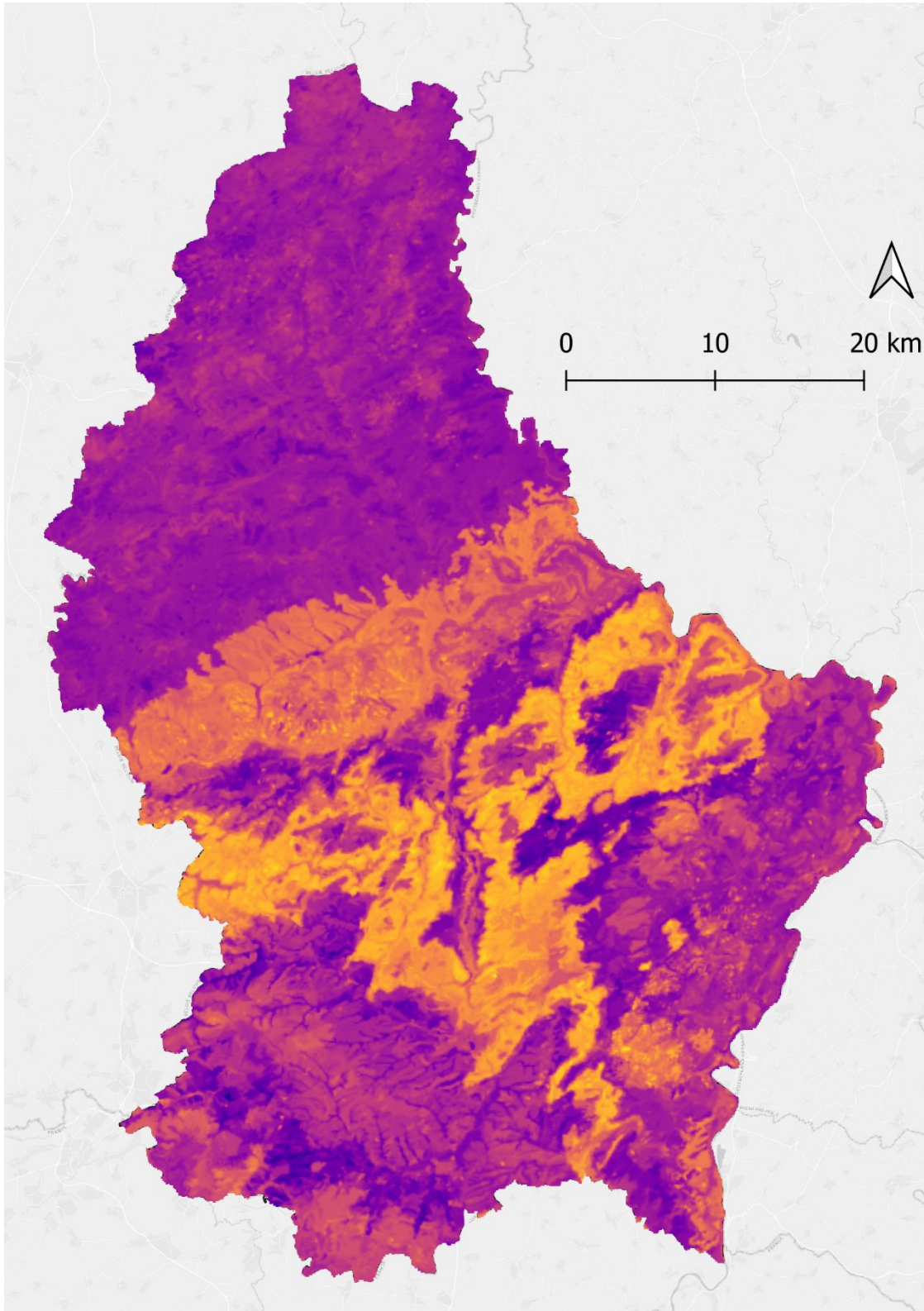
- OJEU, 2018. Regulation (EU) 2018/841 of the European Parliament and of the Council of 30 May 2018 on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry in the 2030 climate and energy framework, and amending Regulation (EU) No 525/2013 and Decision No 529/2013/EU. Official Journal of the European Union
- Olson K.R., Al-Kaisi M.M., Lal R., Lowery B., 2014. Experimental consideration, treatments, and methods in determining soil organic carbon sequestration rates. *Soil sciences society of America journal*, 78:348-360
- Parton, W.J.; Schimel, D.S.; Cole, C.V.; Ojima, D.S., 1987. Analysis of Factors Controlling Soil Organic Matter Levels in Great Plains Grasslands. *Soil Science Society of America Journal*, 51 (5): 1173-1779. <http://dx.doi.org/10.2136/sssaj1987.03615995005100050015x>
- Pellerin Sylvain et Laure Bamière (pilotes scientifiques), Camille Launay, Raphaël Martin, Michele Schiavo, Denis Angers, Laurent Augusto, Jérôme Balesdent, Isabelle Basile-Doelsch, Valentin Bellassen, Rémi Cardinael, Lauric Cécillon, Eric Ceschia, Claire Chenu, Julie Constantin, Joël Darroussin, Philippe Delacote, Nathalie Delame, François Gastal, Daniel Gilbert, Anne-Isabelle Graux, Bertrand Guenet, Sabine Houot, Katja Klumpp, Elodie Letort, Isabelle Litrico, Manuel Martin, Safya Menasseri, Delphine Mézière, Thierry Morvan, Claire Mosnier, Jean Roger-Estrade, Laurent Saint-André, Jorge Sierra, Olivier Théron, Valérie Viaud, Régis Grateau, Sophie Le Perchec, Olivier Réchauchère, 2020. *Stocker du carbone dans les sols français, Quel potentiel au regard de l'objectif 4 pour 1000 et à quel coût ?* Rapport scientifique de l'étude, INRA (France), 540 p.
- Poeplau C., Don A., 2023. A simple soil organic carbon level metric beyond the organic carbon-to-clay ratio. *Soil use and management* 39:1057-1067
- Prout J.M., Shepherd K.D., McGrath S.P., Krik G.J.D, Haefele S.M., 2021. What is a good level of soil organic matter? An index based on organic carbon to clay ratio. *European Journal of Soil Science* 2021;72:2493–2503. DOI: 10.1111/ejss.13012
- Rawls W.J., 1983. Estimating soil bulk density from particle size analysis and organic matter content. *Soil Science*, 135(2):123_125
- Six, J., Conant, R., Paul, E.A., Paustian, K., 2002. Stabilization mechanisms of soil organic matter: implications for c-saturation of soils. *Plant Soil* 241, 155–176.
- Sparling, G., Parfitt, R.L., Hewitt, A.E., and Schipper, L.A., 2003 Three approaches to define desired soil organic matter content. *Journal of Environmental Quality*, 32, 760-766.
- Stevens A., van Wesemael B., Marx S., Leydet L., 2014. Mapping topsoil organic carbon stocks in Grand-Duchy of Luxembourg. UCLouvain, ASTA. 16p
- Stewart, C.E., Paustian, K., Conant, R.T., Plante, A.F., Six, J., 2007. Soil carbon saturation: concept, evidence and evaluation. *Biogeochemistry* 86, 19–31.
- Todd-Brown, K.E.O.; Randerson, J.T.; Post, W.M.; Hoffman, F.M.; Tarnocai, C.; Schuur, E.A.G.; Allison, S.D., 2013. Causes of variation in soil carbon simulations from CMIP5 Earth system models and comparison with observations. *Biogeosciences*, 10 (3): 1717-1736. <http://dx.doi.org/10.5194/bg-10-1717-2013>
- Vereecken, H.; Schnepf, A.; Hopmans, J.W.; Javaux, M.; Or, D.; Roose, D.O.T.; Vanderborght, J.; Young, M.H.; Amelung, W.; Aitkenhead, M.; Allison, S.D.; Assouline, S.; Baveye, P.; Berli, M.; Bruggemann, N.; Finke, P.; Flury, M.; Gaiser, T.; Govers, G.; Ghezzehei, T.; Hallett, P.; Franssen, H.J.H.; Heppell, J.; Horn, R.; Huisman, J.A.; Jacques, D.; Jonard, F.; Kollet, S.; Lafolie, F.; Lamorski, K.; Leitner, D.; McBratney, A.; Minasny, B.; Montzka, C.; Nowak, W.; Pachepsky, Y.; Padarian, J.; Romano, N.; Roth, K.; Rothfuss, Y.; Rowe, E.C.; Schwen, A.; Simunek, J.; Tiktak, A.; Van Dam, J.; van der Zee, S.; Vogel, H.J.; Vrugt, J.A.; Wohling, T.; Young, I.M., 2016. Modeling Soil Processes: Review, Key Challenges, and New Perspectives. *Vadose Zone Journal*, 15 (5). <http://dx.doi.org/10.2136/vzj2015.09.0131>
- Vogel, L.E.; Makowski, D.; Garnier, P.; Vieublé-Gonod, L.; Coquet, Y.; Raynaud, X.; Nunan, N.; Chenu, C.; Falconer, R.; Pot, V., 2015. Modeling the effect of soil meso- and macropores topology on the biodegradation of a soluble carbon substrate. *Advances in Water Resources*, 83: 123-136. <http://dx.doi.org/10.1016/j.advwatres.2015.05.020>

- Wiesmeier M., Mayer S., Burmeister J., Hübner R., Kögel-Knabner I., 2020. Feasibility of the 4 per 1000 initiative in Bavaria: A reality check of agricultural soil management and carbon sequestration scenarios. *Geoderma* 369, 114333, 11p
- Wiesmeier, M., Hübner, R., Spörlein, P., Geuss, U., Hangen, E., Reischl, A., Schilling, B., von Lütow, M., and Kögel-Knabner, I., 2014. Carbon sequestration potential of soils in southeast Germany derived from stable soil organic carbon saturation. *Global Change Biology*, 20, 653-665
- Wiesmeier, M., Munro, S., Barthold, F., Steffens, M., Schad, P., and Kögel-Knabner, I., 2015. Carbon storage capacity of semiarid grassland soils and sequestration potentials in northern China. *Global Change Biology*, 5 21, 3836-3845
- Wiesmeier, M. et al., 2019. Soil organic carbon storage as a key function of soils—a review of drivers and indicators at various scales. *Geoderma* 333, 149–162
- Wutzler, T.; Reichstein, M., 2007. Soils apart from equilibrium - consequences for soil carbon balance modelling. *Biogeosciences*, 4 (1): 125- 136. <http://dx.doi.org/10.5194/bg-4-125-2007>

8 Appendix

Appendix 1: SOC content raster (resolution = 100m) (ASTA)

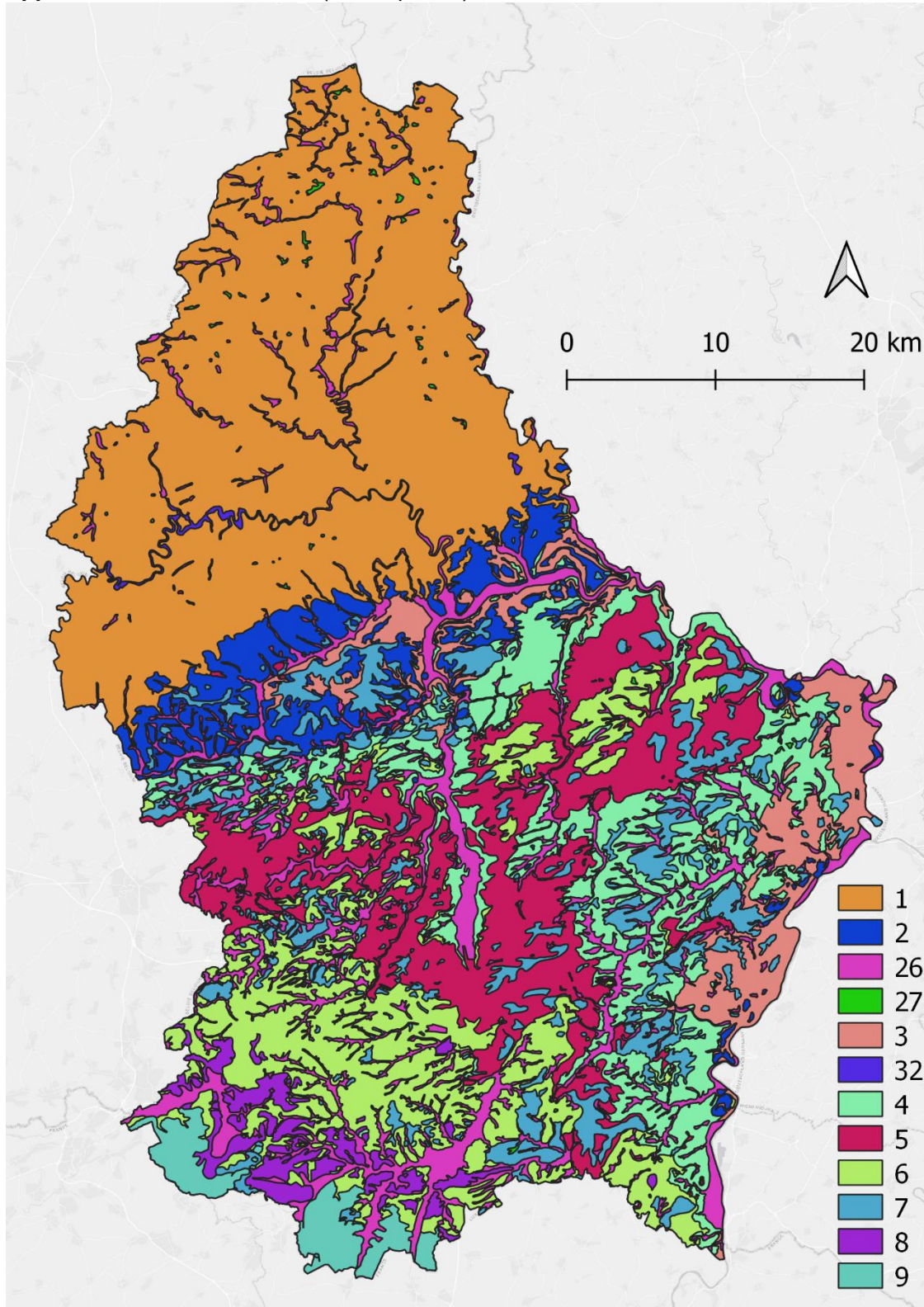
Value range : from 1.27% to 5.16%



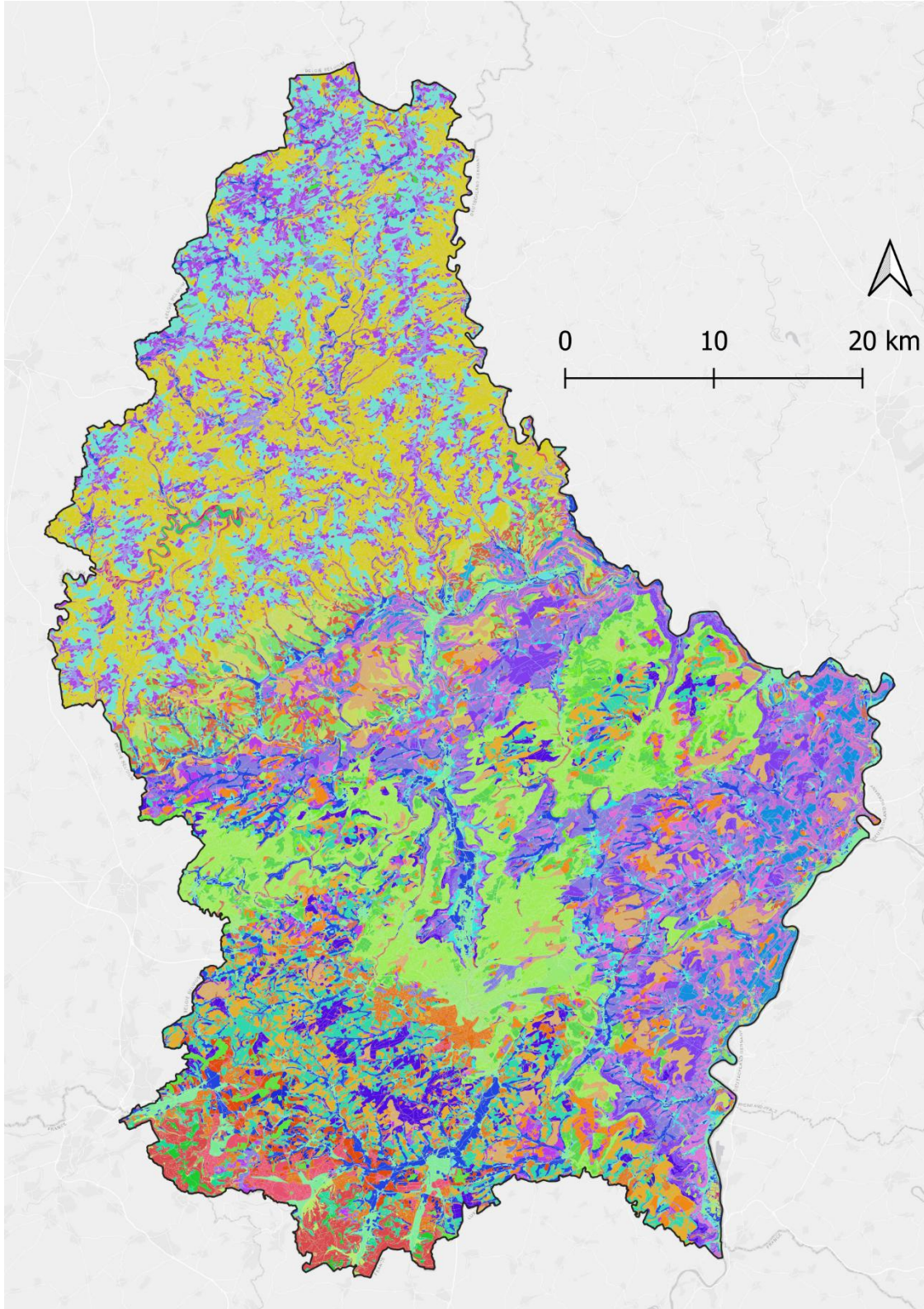
Appendix 2: Data from the EcoDataCube project (<https://ecodatacube.eu>) (EDC) which was tested and finally rejected:

- **Soil organic carbon content** (SOC_{content}_EDC) [g.kg⁻¹]: this data was published by EDC (EcoDataCube), in the form of a raster characterized by:
 - Projection: EPSG = 3035
 - Resolution: 30m x 30m
 - Dimensions: 151552 x 216700 = 32841318400 cells
 - Extent: Europe⁶
- **Clay content** (clay_EDC) [g.kg⁻¹]: (clay = < 2µm) this data was published by EDC (EcoDataCube), in the form of a raster characterized by:
 - Projection: EPSG = 3035
 - Resolution: 30m x 30m
 - Dimensions: 151552 x 216700 = 32841318400 cells
 - Extent: Europe⁶
- **Silt content** (silt_EDC) [g.kg⁻¹]: (2 µm < silt < 63 µm) this data was published by EDC (EcoDataCube), in the form of a raster characterized by:
 - Projection: EPSG = 3035
 - Resolution: 30m x 30m
 - Dimensions: 151552 x 216700 = 32841318400 cells
 - Extent: Europe⁶
- **Sand content** (sand_EDC) [g.kg⁻¹]: (63 µm < silt < 2000 µm) this data was published by EDC (EcoDataCube), in the form of a raster characterized by:
 - Projection: EPSG = 3035
 - Resolution: 30m x 30m
 - Dimensions: 151552 x 216700 = 32841318400 cells
 - Extent: Europe⁶

⁶ 9e+05, 7401000, 899000, 5445560 (xmin, xmax, ymin, ymax)

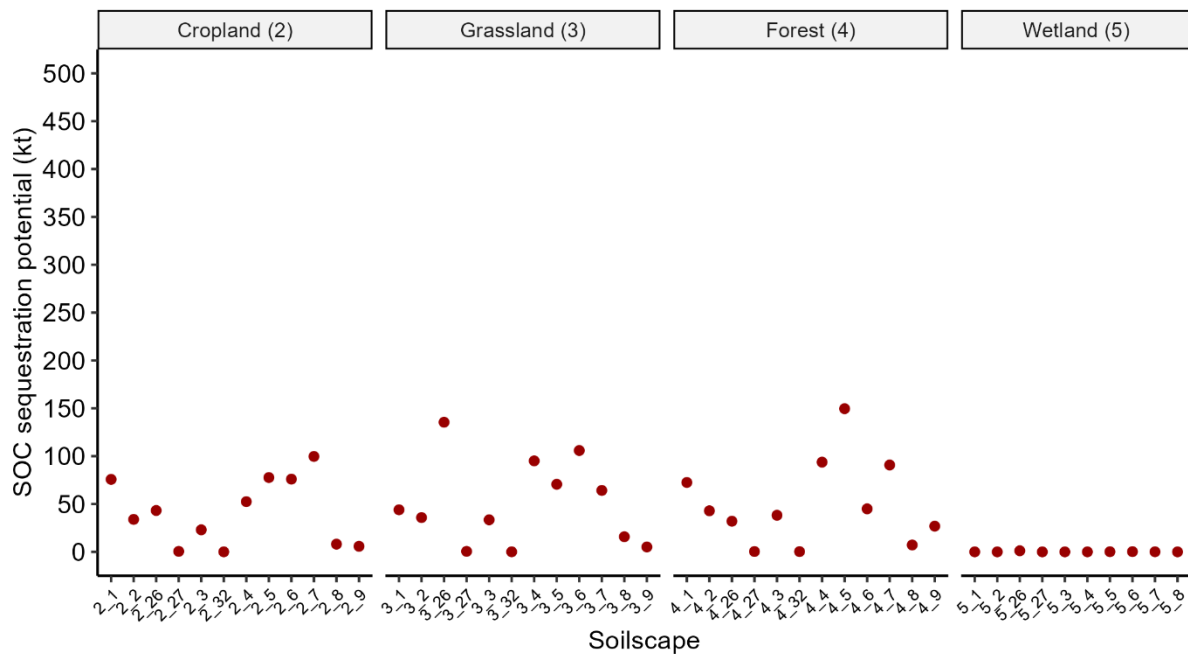
Appendix 3: Soil associations (12 simplified)

Appendix 4: Soilscares (72 classes)



Appendix 5: SOC storage potential aggregated at soilscape level

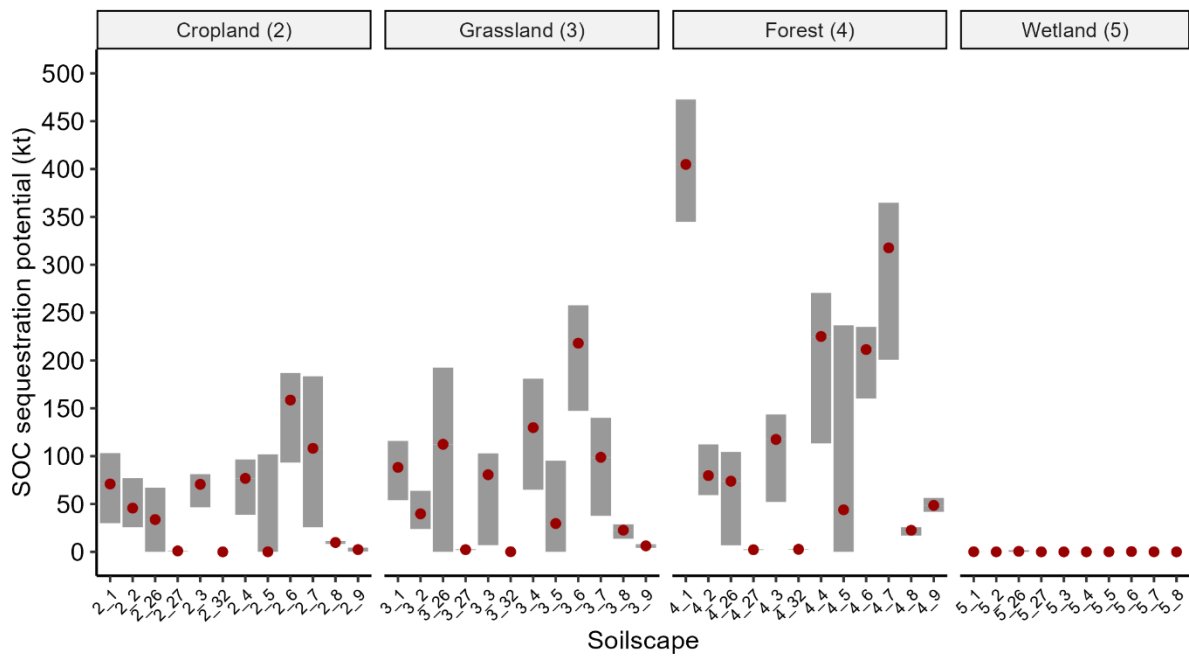
Methodology m1: (reference = p80)



SOC storage potential (kt) per soilscape, estimated according to the [methodology m1](#). Red dots are the median value of the SOC storage potential for each soilscape.

Soilscape	Landuse	Surface area		Existing stock		Stock deficit (median)			Stock deficit - low estimation (q1)			Stock deficit - high estimation (q3)		
		Cell	(ha)	(t.ha ⁻¹)	(kt)	(t.ha ⁻¹)	(kt)	% of the maximal reachable stocks	(t.ha ⁻¹)	(kt)	% of the maximal reachable stocks	(t.ha ⁻¹)	(kt)	% of the maximal reachable stocks
2_1	Cropland	10206	22964	103,06	2366,63	3,30	75,74	3,10	3,30	75,74	3,10	3,30	75,74	3,10
2_2	Cropland	2015	4534	84,31	382,24	7,48	33,92	8,15	7,48	33,92	8,15	7,48	33,92	8,15
2_26	Cropland	1739	3913	112,00	438,24	11,05	43,23	8,98	11,05	43,23	8,98	11,05	43,23	8,98
2_27	Cropland	54	122	100,99	12,27	4,24	0,52	4,03	4,24	0,52	4,03	4,24	0,52	4,03
2_3	Cropland	1778	4001	106,57	426,34	5,76	23,04	5,13	5,76	23,04	5,13	5,76	23,04	5,13
2_32	Cropland	6	14	96,66	1,30	2,17	0,03	2,19	2,17	0,03	2,19	2,17	0,03	2,19
2_4	Cropland	2436	5481	114,39	626,95	9,57	52,48	7,72	9,57	52,48	7,72	9,57	52,48	7,72
2_5	Cropland	2498	5621	71,52	401,97	13,81	77,64	16,19	13,81	77,64	16,19	13,81	77,64	16,19
2_6	Cropland	3576	8046	113,71	914,93	9,45	76,01	7,67	9,45	76,01	7,67	9,45	76,01	7,67
2_7	Cropland	2528	5688	97,07	552,11	17,53	99,70	15,30	17,53	99,70	15,30	17,53	99,70	15,30
2_8	Cropland	305	686	119,85	82,25	11,77	8,07	8,94	11,77	8,07	8,94	11,77	8,07	8,94
2_9	Cropland	249	560	99,71	55,86	10,38	5,82	9,43	10,38	5,82	9,43	10,38	5,82	9,43
3_1	Grassland	6704	15084	101,35	1528,69	2,91	43,95	2,79	2,91	43,95	2,79	2,91	43,95	2,79
3_2	Grassland	1534	3452	86,78	299,52	10,38	35,83	10,68	10,38	35,83	10,68	10,38	35,83	10,68
3_26	Grassland	6088	13698	116,89	1601,17	9,89	135,46	7,80	9,89	135,46	7,80	9,89	135,46	7,80
3_27	Grassland	106	239	101,36	24,17	2,23	0,53	2,15	2,23	0,53	2,15	2,23	0,53	2,15
3_3	Grassland	2047	4606	106,77	491,74	7,27	33,49	6,38	7,27	33,49	6,38	7,27	33,49	6,38
3_32	Grassland	10	23	95,51	2,15	2,57	0,06	2,63	2,57	0,06	2,63	2,57	0,06	2,63
3_4	Grassland	5132	11547	117,69	1358,91	8,23	95,08	6,54	8,23	95,08	6,54	8,23	95,08	6,54
3_5	Grassland	1686	3794	80,78	306,45	18,62	70,62	18,73	18,62	70,62	18,73	18,62	70,62	18,73
3_6	Grassland	4906	11039	114,64	1265,40	9,59	105,90	7,72	9,59	105,90	7,72	9,59	105,90	7,72
3_7	Grassland	2224	5004	104,97	525,26	12,83	64,19	10,89	12,83	64,19	10,89	12,83	64,19	10,89
3_8	Grassland	874	1967	121,40	238,74	8,05	15,82	6,22	8,05	15,82	6,22	8,05	15,82	6,22
3_9	Grassland	311	700	92,48	64,71	7,32	5,12	7,33	7,32	5,12	7,33	7,32	5,12	7,33
4_1	Forest	15438	34736	95,93	3332,07	2,09	72,51	2,13	2,09	72,51	2,13	2,09	72,51	2,13
4_2	Forest	1965	4421	83,16	367,69	9,71	42,93	10,46	9,71	42,93	10,46	9,71	42,93	10,46
4_26	Forest	1806	4064	109,96	446,82	7,88	32,03	6,69	7,88	32,03	6,69	7,88	32,03	6,69
4_27	Forest	56	126	97,01	12,22	2,91	0,37	2,92	2,91	0,37	2,92	2,91	0,37	2,92
4_3	Forest	1790	4028	103,55	417,04	9,50	38,25	8,40	9,50	38,25	8,40	9,50	38,25	8,40
4_32	Forest	93	209	92,82	19,42	1,36	0,28	1,44	1,36	0,28	1,44	1,36	0,28	1,44
4_4	Forest	3382	7610	107,71	819,62	12,32	93,75	10,26	12,32	93,75	10,26	12,32	93,75	10,26
4_5	Forest	8467	19051	71,07	1353,86	7,85	149,60	9,95	7,85	149,60	9,95	7,85	149,60	9,95
4_6	Forest	2529	5690	110,71	629,95	7,90	44,96	6,66	7,90	44,96	6,66	7,90	44,96	6,66
4_7	Forest	3768	8478	101,49	860,42	10,71	90,77	9,54	10,71	90,77	9,54	10,71	90,77	9,54
4_8	Forest	389	875	119,07	104,22	8,21	7,19	6,45	8,21	7,19	6,45	8,21	7,19	6,45
4_9	Forest	1361	3062	95,77	293,27	8,77	26,86	8,39	8,77	26,86	8,39	8,77	26,86	8,39
5_1	Wetland	9	20	95,23	1,93	0,76	0,02	0,79	0,76	0,02	0,79	0,76	0,02	0,79
5_2	Wetland	1	2	104,52	0,24	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
5_26	Wetland	73	164	116,67	19,16	6,97	1,15	5,64	6,97	1,15	5,64	6,97	1,15	5,64
5_27	Wetland	1	2	96,33	0,22	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
5_3	Wetland	1	2	119,22	0,27	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
5_4	Wetland	5	11	124,67	1,40	1,55	0,02	1,23	1,55	0,02	1,23	1,55	0,02	1,23
5_5	Wetland	4	9	96,58	0,87	17,85	0,16	15,60	17,85	0,16	15,60	17,85	0,16	15,60
5_6	Wetland	9	20	116,39	2,36	12,52	0,25	9,71	12,52	0,25	9,71	12,52	0,25	9,71
5_7	Wetland	3	7	95,56	0,65	12,80	0,09	11,81	12,80	0,09	11,81	12,80	0,09	11,81
5_8	Wetland	2	5	140,46	0,63	1,05	0,00	0,74	1,05	0,00	0,74	1,05	0,00	0,74
National level		100164	225369	100,5122	22652,33	7,56	1703,41	6,99	7,56	1703,41	6,99	7,56	1703,41	6,99

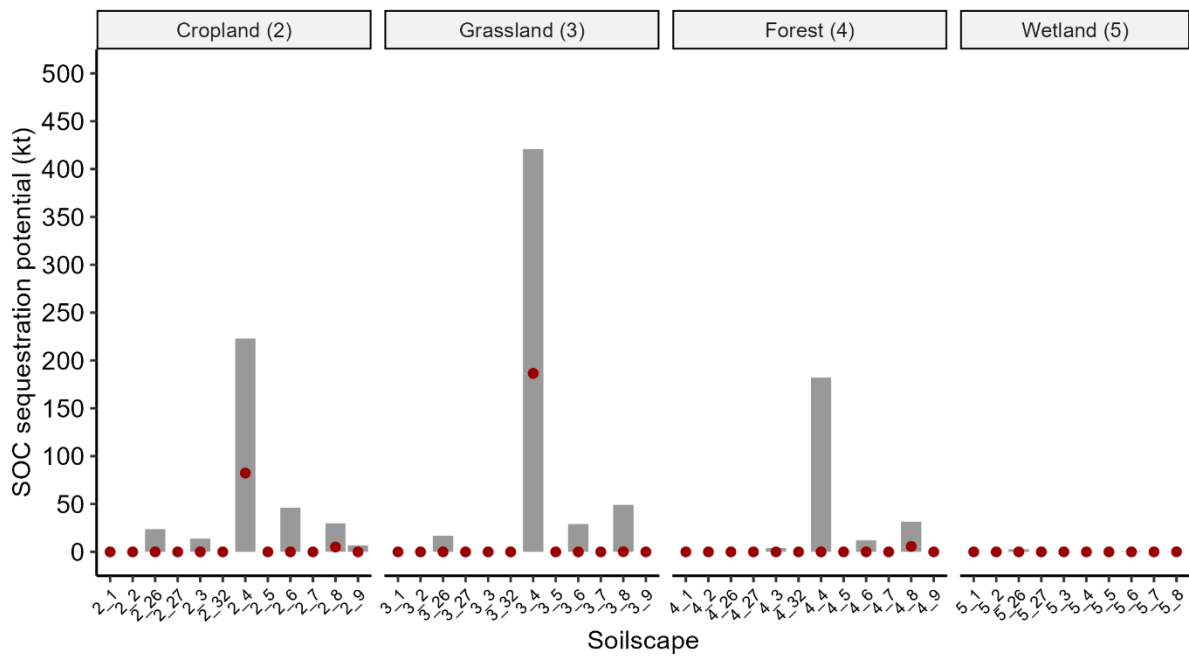
Methodology m2:



SOC storage potential (kt) per soilscape, estimated according to the [methodology m2](#). Red dots are the median value of the SOC storage potential for each soilscape. Gray intervals represent the interquartile interval (between q1 and q3) of the SOC storage potential for each soilscape.

Soilscape	Landuse	Surface area		Existing stock		Stock deficit			Stock deficit - low estimation (q1)			Stock deficit - high estimation (q3)		
		Cell	(ha)	(t.ha ⁻¹)	(kt)	(t.ha ⁻¹)	(kt)	% of the maximal reachable stocks	(t.ha ⁻¹)	(kt)	% of the maximal reachable stocks	(t.ha ⁻¹)	(kt)	% of the maximal reachable stocks
2_1	Cropland	10206	22964	81,50	1871,50	3,09	70,93	3,65	1,30	29,96	1,58	4,49	103,15	5,22
2_2	Cropland	2015	4534	68,57	310,88	10,08	45,72	12,82	5,70	25,84	7,67	16,99	77,03	19,86
2_26	Cropland	1739	3913	89,25	349,20	8,62	33,75	8,81	0,00	0,00	0,00	17,13	67,01	16,10
2_27	Cropland	54	122	80,10	9,73	8,18	0,99	9,27	5,48	0,67	6,40	10,01	1,22	11,11
2_3	Cropland	1778	4001	84,90	339,65	17,64	70,58	17,20	11,64	46,59	12,06	20,29	81,16	19,29
2_32	Cropland	6	14	76,69	1,04	0,46	0,01	0,60	0,13	0,00	0,16	0,76	0,01	0,98
2_4	Cropland	2436	5481	90,81	497,74	14,01	76,78	13,36	7,04	38,60	7,20	17,61	96,54	16,24
2_5	Cropland	2498	5621	58,97	331,42	0,01	0,07	0,02	0,00	0,00	0,00	18,15	102,00	23,53
2_6	Cropland	3576	8046	90,54	728,47	19,71	158,60	17,88	11,61	93,38	11,36	23,22	186,86	20,41
2_7	Cropland	2528	5688	78,38	445,81	19,02	108,18	19,53	4,54	25,81	5,47	32,25	183,42	29,15
2_8	Cropland	305	686	94,74	65,02	14,27	9,79	13,09	12,02	8,25	11,26	16,50	11,32	14,83
2_9	Cropland	249	560	79,93	44,78	4,28	2,40	5,09	0,65	0,36	0,81	7,95	4,45	9,05
3_1	Grassland	6704	15084	76,29	1150,81	5,85	88,27	7,12	3,58	53,93	4,48	7,68	115,91	9,15
3_2	Grassland	1534	3452	66,96	231,10	11,52	39,75	14,67	6,92	23,90	9,37	18,47	63,76	21,62
3_26	Grassland	6088	13698	88,11	1206,94	8,21	112,40	8,52	0,00	0,00	0,00	14,05	192,43	13,75
3_27	Grassland	106	239	76,42	18,23	9,76	2,33	11,32	8,48	2,02	9,98	11,74	2,80	13,31
3_3	Grassland	2047	4606	80,90	372,61	17,50	80,60	17,78	1,52	7,02	1,85	22,32	102,81	21,63
3_32	Grassland	10	23	72,13	1,62	5,95	0,13	7,62	3,98	0,09	5,23	6,81	0,15	8,63
3_4	Grassland	5132	11547	88,52	1022,20	11,24	129,80	11,27	5,63	64,98	5,98	15,67	181,00	15,04
3_5	Grassland	1686	3794	62,76	238,10	7,80	29,60	11,06	0,00	0,00	0,00	25,13	95,34	28,59
3_6	Grassland	4906	11039	86,62	956,13	19,75	218,02	18,57	13,36	147,44	13,36	23,34	257,61	21,22
3_7	Grassland	2224	5004	79,99	400,25	19,74	98,80	19,80	7,55	37,76	8,62	27,97	139,96	25,91
3_8	Grassland	874	1967	90,97	178,89	11,52	22,66	11,24	6,97	13,71	7,12	14,56	28,63	13,80
3_9	Grassland	311	700	70,73	49,50	9,01	6,30	11,30	6,17	4,32	8,03	11,38	7,97	13,86
4_1	Forest	15438	34736	62,58	2173,71	11,65	404,82	15,70	9,93	344,98	13,70	13,61	472,67	17,86
4_2	Forest	1965	4421	55,40	244,95	18,03	79,71	24,55	13,41	59,30	19,49	25,40	112,31	31,44
4_26	Forest	1806	4064	72,11	293,04	18,17	73,83	20,13	1,67	6,80	2,27	25,67	104,29	26,25
4_27	Forest	56	126	63,40	7,99	17,96	2,26	22,08	15,42	1,94	19,57	21,54	2,71	25,36
4_3	Forest	1790	4028	68,12	274,35	29,17	117,49	29,98	12,93	52,09	15,96	35,63	143,52	34,35
4_32	Forest	93	209	60,71	12,70	12,82	2,68	17,43	11,88	2,49	16,37	14,16	2,96	18,91
4_4	Forest	3382	7610	70,84	539,03	29,58	225,07	29,46	14,90	113,40	17,38	35,56	270,63	33,43
4_5	Forest	8467	19051	47,89	912,30	2,31	43,94	4,60	0,00	0,00	0,00	12,43	236,75	20,60
4_6	Forest	2529	5690	72,74	413,89	37,15	211,40	33,81	28,14	160,10	27,89	41,32	235,14	36,23
4_7	Forest	3768	8478	67,01	568,15	37,47	317,64	35,86	23,67	200,67	26,10	43,03	364,83	39,10
4_8	Forest	389	875	77,73	68,04	25,78	22,56	24,90	19,34	16,93	19,92	29,54	25,86	27,54
4_9	Forest	1361	3062	63,20	193,53	15,85	48,55	20,05	13,66	41,82	17,77	18,43	56,44	22,58
5_1	Wetland	9	20	71,67	1,45	6,44	0,13	8,24	5,83	0,12	7,52	8,41	0,17	10,50
5_2	Wetland	1	2	79,67	0,18	12,89	0,03	13,93	12,89	0,03	13,93	12,89	0,03	13,93
5_26	Wetland	73	164	87,86	14,43	3,48	0,57	3,81	0,00	0,00	0,00	10,12	1,66	10,33
5_27	Wetland	1	2	72,55	0,16	10,89	0,02	13,05	10,89	0,02	13,05	10,89	0,02	13,05
5_3	Wetland	1	2	89,36	0,20	9,24	0,02	9,37	9,24	0,02	9,37	9,24	0,02	9,37
5_4	Wetland	5	11	93,19	1,05	0,74	0,01	0,79	0,40	0,00	0,42	9,77	0,11	9,49
5_5	Wetland	4	9	74,32	0,67	11,47	0,10	13,37	2,35	0,02	3,06	14,44	0,13	16,27
5_6	Wetland	9	20	87,78	1,78	15,70	0,32	15,17	13,23	0,27	13,10	17,71	0,36	16,79
5_7	Wetland	3	7	73,25	0,49	8,06	0,05	9,92	5,96	0,04	7,52	17,51	0,12	19,29
5_8	Wetland	2	5	103,70	0,47	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
National level		100164	225369	73,409216	16544,16	13,12	2957,66	15,17	7,21	1625,67	8,95	18,34	4133,28	19,99

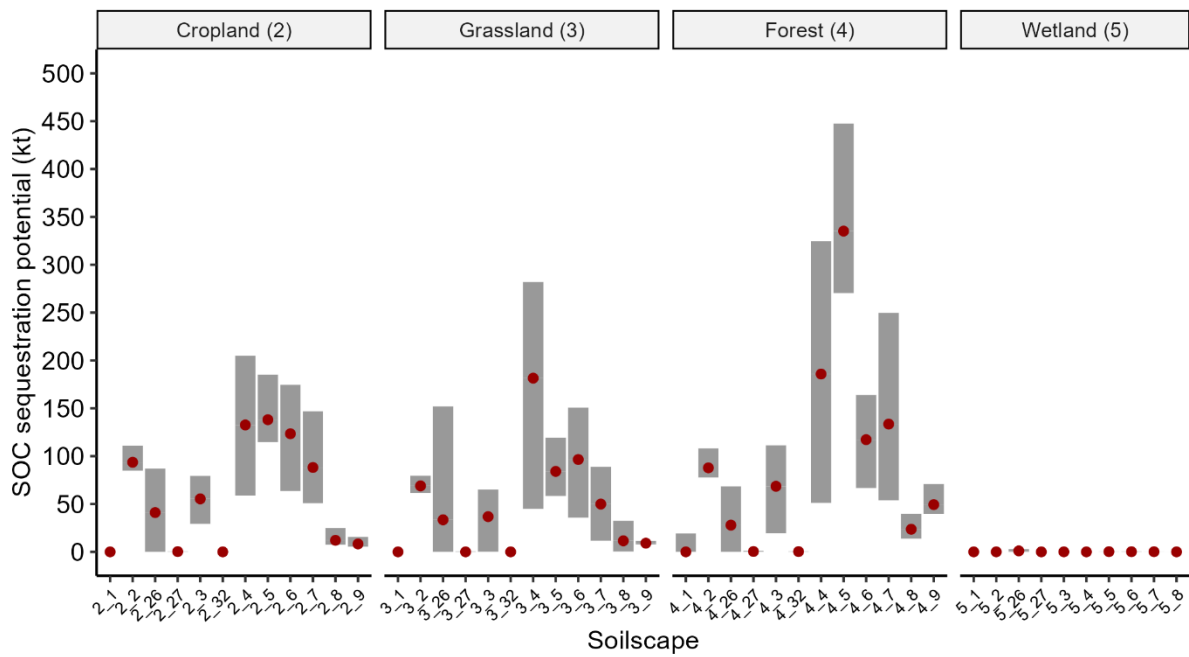
Methodology m3:



SOC storage potential (kt) per soilscape, estimated according to the [methodology m3](#). Red dots are the median value of the SOC storage potential for each soilscape. Gray intervals represent the interquartile interval (between q1 and q3) of the SOC storage potential for each soilscape.

Soilscape	Landuse	Surface area		Existing stock		Stock deficit			Stock deficit - low estimation (q1)			Stock deficit - high estimation (q3)		
		Cell	(ha)	(t.ha ⁻¹)	(kt)	(t.ha ⁻¹)	(kt)	% of the maximal reachable stocks	(t.ha ⁻¹)	(kt)	% of the maximal reachable stocks	(t.ha ⁻¹)	(kt)	% of the maximal reachable stocks
2_1	Cropland	10206	22964	103,06	2366,63	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
2_2	Cropland	2015	4534	84,31	382,24	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
2_26	Cropland	1739	3913	112,00	438,24	0,00	0,00	0,00	0,00	0,00	0,00	6,06	23,72	5,14
2_27	Cropland	54	122	100,99	12,27	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
2_3	Cropland	1778	4001	106,57	426,34	0,00	0,00	0,00	0,00	0,00	0,00	3,46	13,85	3,15
2_32	Cropland	6	14	96,66	1,30	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
2_4	Cropland	2436	5481	114,39	626,95	15,03	82,36	11,61	0,00	0,00	0,00	40,66	222,84	26,22
2_5	Cropland	2498	5621	71,52	401,97	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
2_6	Cropland	3576	8046	113,71	914,93	0,00	0,00	0,00	0,00	0,00	0,00	5,75	46,24	4,81
2_7	Cropland	2528	5688	97,07	552,11	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
2_8	Cropland	305	686	119,85	82,25	7,37	5,06	5,80	0,00	0,00	0,00	43,49	29,85	26,63
2_9	Cropland	249	560	99,71	55,86	0,00	0,00	0,00	0,00	0,00	0,00	11,67	6,54	10,47
3_1	Grassland	6704	15084	101,35	1528,69	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
3_2	Grassland	1534	3452	86,78	299,52	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
3_26	Grassland	6088	13698	116,89	1601,17	0,00	0,00	0,00	0,00	0,00	0,00	1,22	16,73	1,03
3_27	Grassland	106	239	101,36	24,17	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
3_3	Grassland	2047	4606	106,77	491,74	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
3_32	Grassland	10	23	95,51	2,15	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
3_4	Grassland	5132	11547	117,69	1358,91	16,15	186,49	12,07	0,00	0,00	0,00	36,45	420,94	23,65
3_5	Grassland	1686	3794	80,78	306,45	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
3_6	Grassland	4906	11039	114,64	1265,40	0,00	0,00	0,00	0,00	0,00	0,00	2,63	29,07	2,25
3_7	Grassland	2224	5004	104,97	525,26	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
3_8	Grassland	874	1967	121,40	238,74	0,08	0,16	0,07	0,00	0,00	0,00	24,93	49,03	17,04
3_9	Grassland	311	700	92,48	64,71	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
4_1	Forest	15438	34736	95,93	3332,07	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
4_2	Forest	1965	4421	83,16	367,69	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
4_26	Forest	1806	4064	109,96	446,82	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
4_27	Forest	56	126	97,01	12,22	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
4_3	Forest	1790	4028	103,55	417,04	0,00	0,00	0,00	0,00	0,00	0,00	1,03	4,14	0,98
4_32	Forest	93	209	92,82	19,42	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
4_4	Forest	3382	7610	107,71	819,62	0,00	0,00	0,00	0,00	0,00	0,00	23,91	181,96	18,17
4_5	Forest	8467	19051	71,07	1353,86	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
4_6	Forest	2529	5690	110,71	629,95	0,00	0,00	0,00	0,00	0,00	0,00	2,12	12,04	1,88
4_7	Forest	3768	8478	101,49	860,42	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
4_8	Forest	389	875	119,07	104,22	6,45	5,65	5,14	0,00	0,00	0,00	36,06	31,56	23,24
4_9	Forest	1361	3062	95,77	293,27	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
5_1	Wetland	9	20	95,23	1,93	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
5_2	Wetland	1	2	104,52	0,24	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
5_26	Wetland	73	164	116,67	19,16	0,00	0,00	0,00	0,00	0,00	0,00	16,60	2,73	12,46
5_27	Wetland	1	2	96,33	0,22	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
5_3	Wetland	1	2	119,22	0,27	24,17	0,05	16,86	24,17	0,05	16,86	24,17	0,05	16,86
5_4	Wetland	5	11	124,67	1,40	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
5_5	Wetland	4	9	96,58	0,87	0,00	0,00	0,00	0,00	0,00	0,00	12,66	0,11	11,59
5_6	Wetland	9	20	116,39	2,36	0,00	0,00	0,00	0,00	0,00	0,00	33,53	0,68	22,37
5_7	Wetland	3	7	95,56	0,65	0,00	0,00	0,00	0,00	0,00	0,00	0,54	0,00	0,57
5_8	Wetland	2	5	140,46	0,63	19,28	0,09	12,07	14,32	0,06	9,25	24,23	0,11	14,71
National level		100164	225369	100,5122	22652,33	1,24	279,87	1,22	0,00	0,12	0,00	4,85	1092,20	4,60

Methodology m4:



SOC storage potential (kt) per soilscape, estimated according to the [methodology m4](#). Red dots are the median value of the SOC storage potential for each soilscape. Gray intervals represent the interquartile interval (between q1 and q3) of the SOC storage potential for each soilscape.

Soilscape	Landuse	Surface area		Existing stock		Stock deficit			Stock deficit - low estimation (q1)			Stock deficit - high estimation (q3)		
		Cell	(ha)	(t.ha ⁻¹)	(kt)	(t.ha ⁻¹)	(kt)	% of the maximal reachable stocks	(t.ha ⁻¹)	(kt)	% of the maximal reachable stocks	(t.ha ⁻¹)	(kt)	% of the maximal reachable stocks
2_1	Cropland	10206	22964	103,06	2366,63	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
2_2	Cropland	2015	4534	84,31	382,24	20,65	93,61	19,67	18,73	84,91	18,18	24,46	110,89	22,49
2_26	Cropland	1739	3913	112,00	438,24	10,50	41,07	8,57	0,00	0,00	0,00	22,24	87,02	16,57
2_27	Cropland	54	122	100,99	12,27	2,24	0,27	2,17	0,56	0,07	0,55	4,98	0,60	4,70
2_3	Cropland	1778	4001	106,57	426,34	13,84	55,36	11,49	7,34	29,34	6,44	19,83	79,32	15,69
2_32	Cropland	6	14	96,66	1,30	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
2_4	Cropland	2436	5481	114,39	626,95	24,20	132,61	17,46	10,71	58,72	8,56	37,40	204,99	24,64
2_5	Cropland	2498	5621	71,52	401,97	24,57	138,08	25,57	20,39	114,61	22,19	32,93	185,11	31,53
2_6	Cropland	3576	8046	113,71	914,93	15,34	123,41	11,89	7,91	63,62	6,50	21,70	174,57	16,02
2_7	Cropland	2528	5688	97,07	552,11	15,50	88,19	13,77	8,94	50,87	8,44	25,81	146,79	21,00
2_8	Cropland	305	686	119,85	82,25	17,57	12,06	12,79	11,07	7,60	8,46	36,18	24,83	23,19
2_9	Cropland	249	560	99,71	55,86	14,77	8,28	12,91	9,80	5,49	8,95	27,98	15,67	21,91
3_1	Grassland	6704	15084	101,35	1528,69	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
3_2	Grassland	1534	3452	86,78	299,52	19,97	68,94	18,71	17,86	61,63	17,06	23,03	79,50	20,98
3_26	Grassland	6088	13698	116,89	1601,17	2,44	33,49	2,05	0,00	0,00	0,00	11,09	151,87	8,66
3_27	Grassland	106	239	101,36	24,17	0,00	0,00	0,00	0,00	0,00	0,00	2,22	0,53	2,14
3_3	Grassland	2047	4606	106,77	491,74	7,99	36,81	6,96	0,03	0,13	0,03	14,14	65,13	11,70
3_32	Grassland	10	23	95,51	2,15	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
3_4	Grassland	5132	11547	117,69	1358,91	15,72	181,51	11,78	3,89	44,95	3,20	24,41	281,90	17,18
3_5	Grassland	1686	3794	80,78	306,45	22,16	84,06	21,53	15,40	58,43	16,01	31,44	119,27	28,02
3_6	Grassland	4906	11039	114,64	1265,40	8,74	96,52	7,09	3,25	35,82	2,75	13,65	150,72	10,64
3_7	Grassland	2224	5004	104,97	525,26	9,98	49,93	8,68	2,32	11,62	2,16	17,75	88,84	14,47
3_8	Grassland	874	1967	121,40	238,74	5,87	11,55	4,61	0,22	0,43	0,18	16,51	32,47	11,97
3_9	Grassland	311	700	92,48	64,71	13,00	9,10	12,33	11,24	7,87	10,84	16,32	11,42	15,00
4_1	Forest	15438	34736	95,93	3332,07	0,00	0,00	0,00	0,00	0,00	0,00	0,56	19,29	0,58
4_2	Forest	1965	4421	83,16	367,69	19,85	87,78	19,27	17,58	77,72	17,45	24,42	107,99	22,70
4_26	Forest	1806	4064	109,96	446,82	6,87	27,93	5,88	0,00	0,00	0,00	16,84	68,44	13,28
4_27	Forest	56	126	97,01	12,22	3,12	0,39	3,12	0,27	0,03	0,28	8,39	1,06	7,96
4_3	Forest	1790	4028	103,55	417,04	17,02	68,54	14,11	4,85	19,53	4,47	27,62	111,24	21,06
4_32	Forest	93	209	92,82	19,42	1,41	0,29	1,49	0,68	0,14	0,72	3,06	0,64	3,20
4_4	Forest	3382	7610	107,71	819,62	24,42	185,82	18,48	6,73	51,23	5,88	42,67	324,68	28,37
4_5	Forest	8467	19051	71,07	1353,86	17,59	335,14	19,84	14,20	270,45	16,65	23,49	447,52	24,84
4_6	Forest	2529	5690	110,71	629,95	20,61	117,25	15,69	11,73	66,74	9,58	28,80	163,89	20,65
4_7	Forest	3768	8478	101,49	860,42	15,75	133,52	13,43	6,35	53,84	5,89	29,44	249,61	22,49
4_8	Forest	389	875	119,07	104,22	26,99	23,62	18,48	15,83	13,86	11,73	45,47	39,80	27,63
4_9	Forest	1361	3062	95,77	293,27	16,12	49,36	14,41	12,98	39,75	11,94	23,11	70,76	19,44
5_1	Wetland	9	20	95,23	1,93	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
5_2	Wetland	1	2	104,52	0,24	14,00	0,03	11,81	14,00	0,03	11,81	14,00	0,03	11,81
5_26	Wetland	73	164	116,67	19,16	6,21	1,02	5,06	0,00	0,00	0,00	17,14	2,82	12,81
5_27	Wetland	1	2	96,33	0,22	1,67	0,00	1,70	1,67	0,00	1,70	1,67	0,00	1,70
5_3	Wetland	1	2	119,22	0,27	16,53	0,04	12,17	16,53	0,04	12,17	16,53	0,04	12,17
5_4	Wetland	5	11	124,67	1,40	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
5_5	Wetland	4	9	96,58	0,87	23,82	0,21	19,79	12,29	0,11	11,29	35,46	0,32	26,86
5_6	Wetland	9	20	116,39	2,36	7,85	0,16	6,32	6,10	0,12	4,98	25,60	0,52	18,03
5_7	Wetland	3	7	95,56	0,65	23,87	0,16	19,99	14,93	0,10	13,51	25,01	0,17	20,74
5_8	Wetland	2	5	140,46	0,63	3,21	0,01	2,24	1,13	0,01	0,80	5,29	0,02	3,63
National level		100164	225369	100,5122	22652,33	10,19	2296,13	9,20	5,46	1229,82	5,15	16,06	3620,28	13,78