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EU Soil Suitability Calculator: conceptual framework and methodological approach for assessing the impact of EU consumption on global soils

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Contents

Abstract

Healthy soils are in good chemical, biological and physical condition so that they can provide ecosystem services. This technical report introduces the "EU Soil Suitability Calculator," a robust methodology designed to quantify soil suitability at a global scale for crops consumed within the European Union. The report elaborates on a two-step approach that evaluates the soil suitability index and assesses the environmental impacts of agricultural practices necessary for optimal nutrition levels. Through this methodology, the intricate relationships between crop production, soil properties, and environmental effects are quantified, highlighting areas where sub-optimal soil conditions hinder productivity and unveiling potential trade-offs between yield optimisation and environmental sustainability. The calculator offers diverse outcomes, such as land use optimisation, enhanced soil organic carbon levels, improved soil pH management, soil compaction assessment, and soil erosion management. These findings have profound implications for policymakers, providing accurate data to support evidence-based decisions, targeted interventions, and evaluations of policy effectiveness. The proposed EU soil suitability calculator is ready to be tested for a given relevant crop consumed in EU.

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1. Introduction

Healthy soils are crucial for providing ecosystem services (Arias-Navarro et al., 2024), but Europe's soils are significantly degraded, with 62% already damaged (Vieira et al., 2024). To address some policy actions including the Soil monitoring and resilience directive - Soil Monitoring Law (EU 2025/2360 - SML) and the "EU Consumption Footprint Platform" have been implemented to provide a harmonised definition of soil health and to monitor the environmental footprint of EU production and consumption (European Commission, 2023) respectively. The platform aims to reduce the EU's global footprint, a key objective of the "A Soil Deal for Europe" mission (Panagos et al., 2024a). To refine the connection between production and consumption systems and soil quality, the Joint Research Centre (JRC) has developed the Land Footprint (LAFO) model, which estimates the EU's yearly land footprint (De Laurentis et al., 2024). Other policy developments including EU Soil Strategy (European Commission. (2021)), EU Soil Observatory – EUSO (Broothaerts et al. 2026), the Common Agricultural Policy – CAP (EU 2021/2115) and Mission Soil are focused in providing a effective framework for sustainable soil management in agricultural areas by aiming specific objectives such as to reduce land degradation, conserving and increasing soil organic carbon stocks, reducing soil pollution, reducing EU global footprint on soils, and reducing soil erosion and compaction. To further develop this approach, a "Soil Suitability Calculator" is created to estimate the potential soil degradation of imported crops, integrating spatial data on land use, soil type, and soil erosion (Panagos et al., 2024b).

The main objective of this work is to develop an EU soil suitability calculator to quantify the impact of EU consumption on soils globally, with two secondary objectives: assessing the share of soil cultivated outside EU borders that is being used at its full potential, and investigating the trade-offs between yield optimization and environmental sustainability in order to support the EU global footprint on soils.

2. Methodology

The methodology for the EU soil suitability calculator is developed by implementing two steps.

Step1: The first step focuses on calculating a soil suitability index for the land (in hectares) needed to produce those crops consumed in EU.

Step 2: evaluating the environmental impacts of the agricultural practices required to achieve optimal nutritional levels on the land and, in parallel, on the estimation of the reduction in cropland needed to meet EU consumption if optimal yields are reached.

Step 1. Soil suitability index

First step aimed to calculate the distribution of the **soil suitability index**, or the actual soil quality status, at pixel level, for the land (in hectares) needed to produce those crops consumed in EU. To evaluate the suitability is necessary to track the land associated to the production of each product imported in the EU back to its country of origin, to measure the corresponding soil quality. For that, a methodological procedure was designed in different steps:

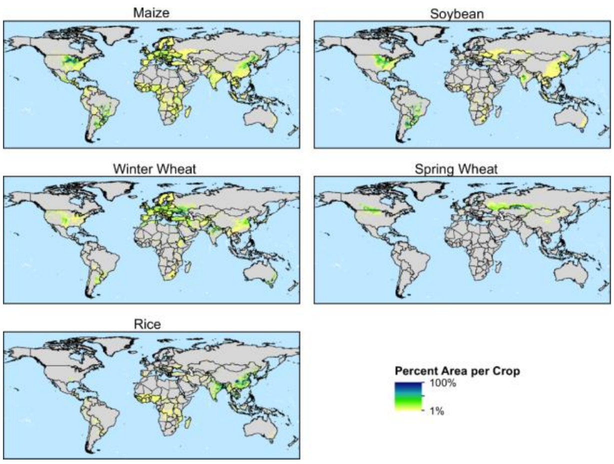
Step 1.1. Crop Selection

Identify the crops that have the largest impact on the EU's annual land footprint (hectares). Data from LAFO model (De Laurentis et al., 2024) can be used to know the total imported areas for selected crops.

Step 1.2. Selection of crop and soil layers at global level

A spatial analysis approach will be employed to quantify the global distribution of key crops. Utilizing geospatial data, the methodology will involve mapping the extent of major crops at a country level, providing insights into the total area allocated to each crop worldwide. As example, raster maps from Becker-Reshef et al. (2023) for five dominant crops (maize, soybeans, rice, winter wheat, and spring wheat) could be used to determine the total area (hectares) being used for each crop per country at global level (Figure 1) and to calculate the soil suitability index at pixel level.

Figure 1. Raster maps showing the percent per pixel at 0.05 degrees of five crops (maize, soybean, winter wheat, spring wheat, and rice). (Becker-Reshef et al. 2023)



Source: Becker-Reshef et al. (2023)

For this specific case, raster maps show the coverage area per crop (in percentage) at pixel level. Each crop's area per pixel must be recalculated factoring in the mean percentage of pixel coverage for each individual crop (Table 1).

Table 1. Recalibration coefficients for crop area calculation by pixel percentage coverage

Percentage area covered per crop at pixel level	Coeff for recalculated area
90-100%	0.95
80-90%	0.85
70-80%	0.75
60-70%	0.65
50-60%	0.55
40-50%	0.45
30-40%	0.35
20-30%	0.25
10-20%	0.15
0-5%	0.05

Source: JRC analysis

Next, investigate and identify global soil property maps that can be used to quantify the level of soil degradation where crops under study are cultivated. Soil degradation processes such as loses of soil organic carbon (De Rosa et al. 2024), soil acidification (Lebron et al. 2025), soil compaction (Panagos et al. 2024c) and soil erosion (Panagos et al. 2024b) were those taken into consideration. Maps of SOC, pH, clay, silt, and sand content as well as bulk density are available (Table 2) from the SoilGrids 2.0 digital soil mapping platform (FAO, 2018 and Poggio et al. 2021). Map for soil erosion at global level is available in the European Soil Data Centre (Borrelli et al. 2020) including the threshold values that could be laid down.

Table 2. Summary of input raster maps used in the analysis, including variable name, description, units, spatial resolution, and source.

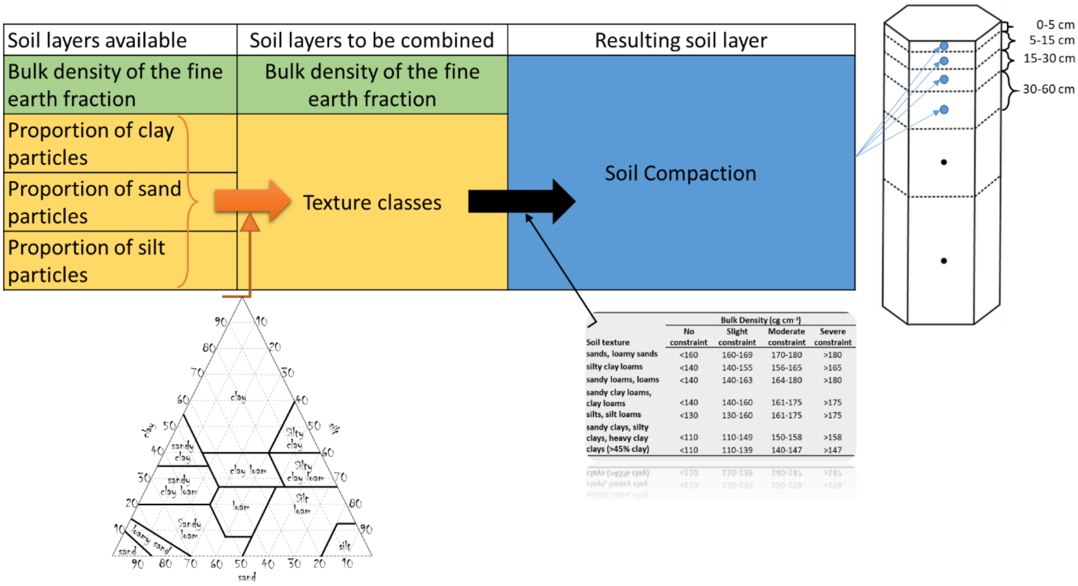
Name	Description	Mapped units	Spatial resolution
Bulk density	Bulk density of the fine earth fraction	cg cm^{-3}	250 m
Clay	Proportion of clay particles (< 0.002 mm) in the fine earth fraction	g kg^{-1}	250 m
Soil pH	Soil pH in water	pHx10	250 m
Sand	Proportion of sand particles (> 0.05/0.063 mm) in the fine earth fraction	g kg^{-1}	250 m
Silt	Proportion of silt particles (≥ 0.002 mm and ≤ 0.05/0.063 mm) in the fine earth fraction	g kg^{-1}	250 m
SOC	SOC content in the fine earth fraction	dg kg^{-1}	250 m
Soil erosion	Soil erosion	Mg ha^{-1} yr^{-1}	250 m
Crops	Percent per pixel of a crop	Area per crop (%)	0.05 degrees

Source: JRC analysis

Six soil depths raster maps are available in SoilGrids database (0-5 cm, 5-15 cm, 15-30 cm, 30-60 cm, 60-100 cm, and 100-200 cm) for bulk density, SOC, Sand, Silt, Clay and soil pH.

Soil compaction layer, as relevant soil degradation process mainly in agricultural soils (Panagos et al. 2024c), was calculated by combining those layers of clay, sand, silt, and bulk density as showed in the workflow described in the Figure 2.

Figure 2. Workflow used to produce the raster map on soil compaction.

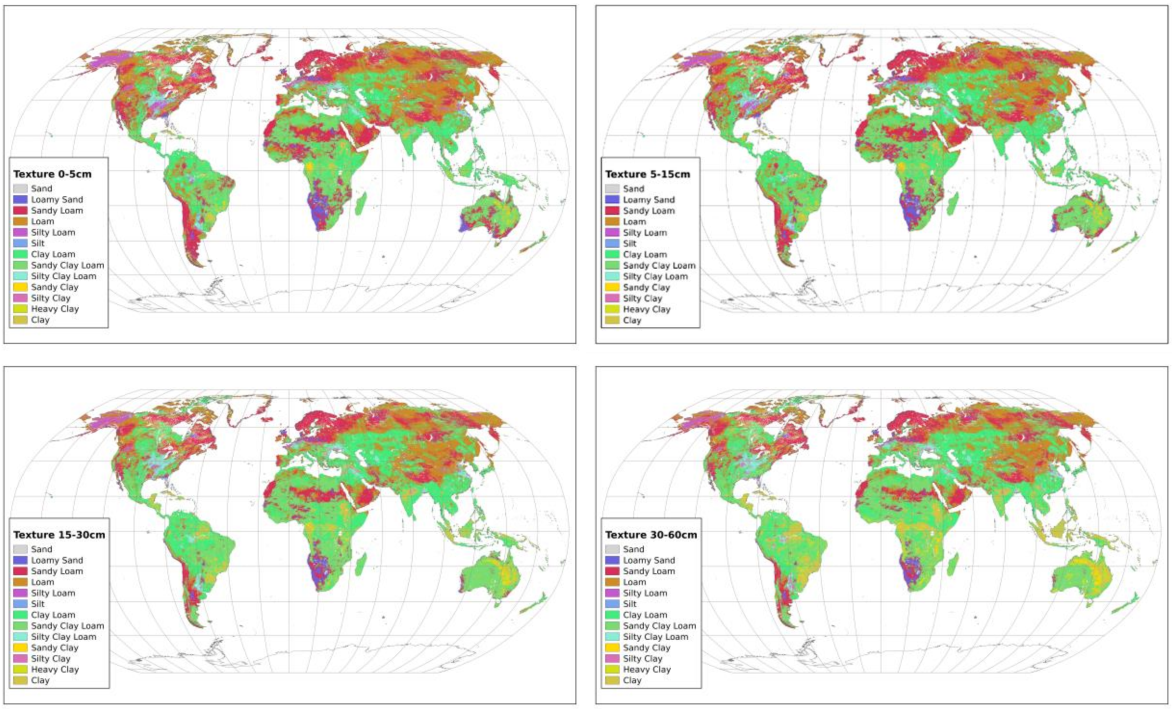


Source: JRC analysis

Detailed process to generate the map of soil compaction, as follows:

- **Data Collection**: Utilize the existing SoilGrid maps (see Table 2) of sand, clay, silt, and bulk density.
- **Textural Class Calculation and mapping:** Calculate the textural classes as laid down in the USDA soil textural triangle (USDA NRCS, 2019) using the SoilGrid maps of clay, silt, and sand. A modified script was used, considering the units of clay, silt, and sand (g kg^{-1}). A new raster map named "Texture Classes (TC) map", based on the calculated textural classes, was generated for the four soil depths (0-5cm, 5-15cm, 15-30cm, and 30-60cm). Texture maps for each of tested soil depths are shown in Figure 3. Soil depths below 60 cm were not taken into consideration for this methodology to manage realistic soil depths for most of the crops. Anyway, other soil depths could be included in the methodology.

Figure 3. Texture classes raster maps for each of soil depths (0-5 cm, 5-15 cm, 15-30 cm, and 30-60 cm)



Source: JRC analysis

- **Soil Compaction Map**: Four soil compaction classes were categorized (Table 3), by considering the relationship between soil bulk density and root growth based on soil texture, as defined by the USDA (USDA NRCS, 2019) and partially included as subsoil compaction criteria in the Soil Monitoring Law (EU 2025/2360).

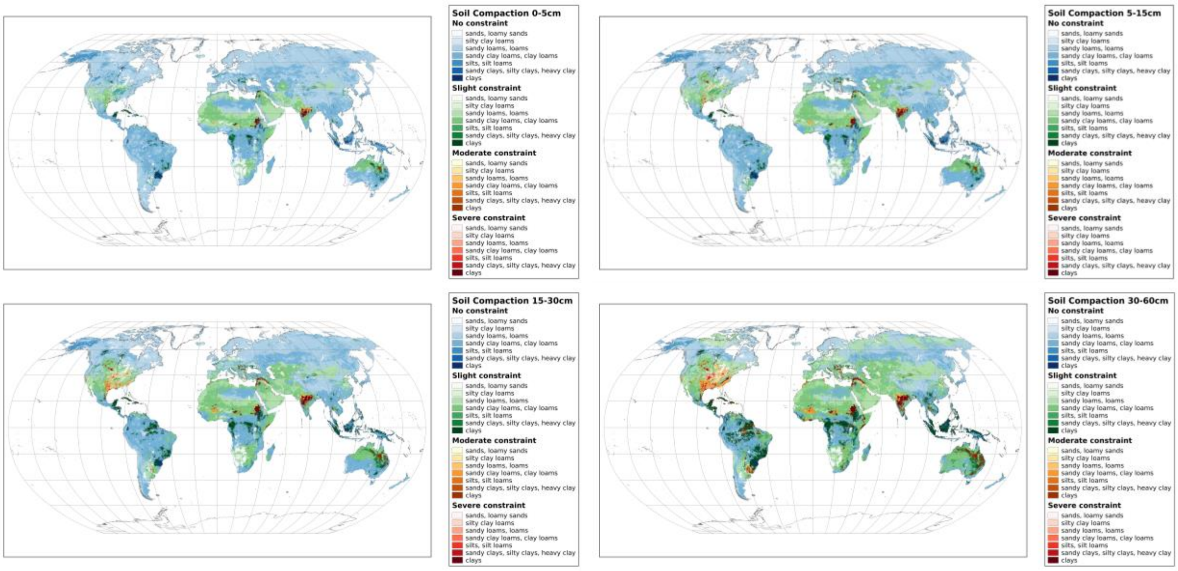
Table 3. Definition of soil compaction classes based on soil texture (USDA NRCS, 2019)

Texture class	No constraint	Slight constraint	Moderate constraint	Severe constraint
	Bulk Density (cg cm^{-3})			
sands, loamy sands	<160	160-169	170-180	>180
silty clay loams	<140	140-155	156-165	>165
sandy loams, loams	<140	140-163	164-180	>180
sandy clay loams, clay loams	<140	140-160	161-175	>175
silts, silt loams	<130	130-160	161-175	>175
sandy clays, silty clays,	<110	110-149	150-158	>158
clays (>45% clay), heavy clay	<110	110-139	140-147	>147

Source: JRC analysis

Both Texture Classes (TC) (Figure 3) and Bulk Density (BD) maps (from SoilGrids) were combined to create the new "Soil Compaction (SC)" raster map (Figure 4) along soil profile.

Figure 4. Soil compaction maps along soil profiles.



Source: JRC analysis

The proposed soil use calculator methodology is used to create detailed maps of soil compaction at various soil depths. These maps provide valuable insights into soil compaction throughout the soil profile, offering a comprehensive understanding of compaction at different depths.

Step 1.3. Selection of soil suitability thresholds to define the soil degradation rate

Available global maps with soil properties will be overlapped to crop maps (see Figure 1) to extract the actual soil suitability status (soil suitability index) when comparing to those optimal soil indicators for each of the selected crops. Six soil suitability classes (SSC) namely, **no constraint (S0), slight constraint (S1), moderate constraint (S2), severe (S3), very severe (S4), and not suitable (S5)** are established for each of soil indicators analysed in this work. Area (in hectares) for each of soil suitability classes (score) will be determined for each crop and each soil indicator (i.e. soil organic carbon, soil acidity, soil compaction, and soil erosion) at pixel level and aggregated per country.

Soil suitability index (SSI) is scored by calculating the variations between the actual and the optimal soil conditions for a given crop. Crop nutritional soil requirements for 55 crops are defined in the Global agro-ecological zones model (Fischer et al. 2021). Each soil suitability class is defined by an optimal value for each soil indicator, and it is directly related to crop yield (Table 4 shows data for soybean production as example).

Table 4. Definition of soil suitability classes in relation to soybean yield and soil indicators such as Soil Organic Carbon (SOC), Soil acidity and Soil erosion.

Soil suitability classes	Yield (%)	SOC (g kg^{-1})	Soil acidity (pH values)	Soil Erosion (t ha^{-1})
No constraint (S0)	100	20	6.0 – 7.5	< 2
Slight constraint (S1)	90	12	5.5-6.0 // 7.5-7.8	2-5
Moderate constraint (S2)	70	8	5.4-5.5 // 7.8-8.2	5-10
Severe constraint (S3)	50	0.0	5.2-5.4 // 8.2-8.3	>10
Very severe constraint (S4)	30	0.0	4.7-5.2	

Not suitable (S5)	10	0.0	<4.2 // > 8.3

Source: JRC analysis

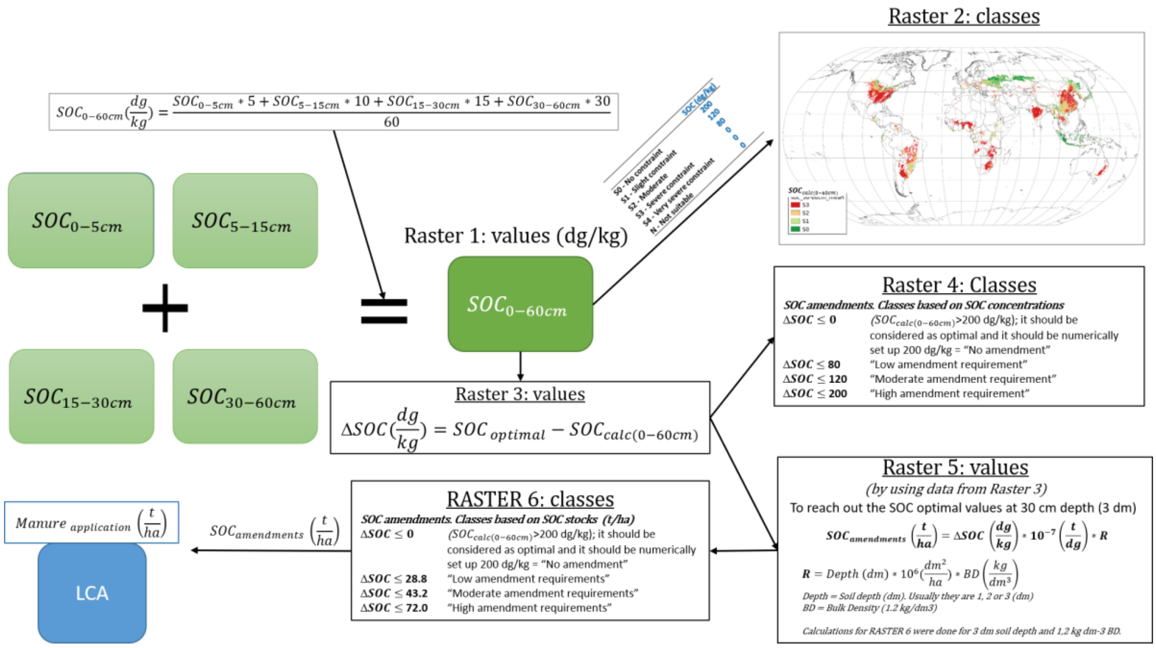
Each of soil suitability classes provide detailed information how far is each pixel from the optimal value for each soil indicator (SOC, pH, soil compaction and soil erosion) and, therefore, further actions to achieve the optimal value for each of four soil depths could be applied. The current methodology has been described to provide an example of how SOC and pH requirements are calculated, when applying manure and lime as soil amendments, respectively.

Soil organic carbon requirements.

Requirements for soil organic carbon will be determining by using the workflow shown in Figure 5.

Firstly, a new raster of SOC 0-60 cm will be created by merging the raster maps for the different soil depths to calculate the SOC requirements per soil sample.

Figure 5. Workflow for determination of SOC requirements. Optimal values for soybean were used as example



Source. JRC analysis

Then, the methodology for calculating and classifying Soil Organic Carbon (SOC) amendments can be extracted as follows:

— Step 1: Calculate the SOC concentration at the 0-60 cm soil depth compiling the raster maps for SOC at different soil depths by using the weighing factor as shown in Equation 1

Equation 1

$$SOC_{0-60cm}\left(\frac{dg}{kg}\right) = \frac{SOC_{0-5cm}*5+SOC_{5-15cm}*10+SOC_{15-30cm}*15+SOC_{30-60cm}*30}{60}$$

Calculations can be adapted taken into consideration the local factors including soil type, crop type, agricultural practices, etc. It will be affecting not only on the SOC concentration but also on the SOC requirements as well as the final quantities of SOC improvers to be applied.

— Step 2: Categorize the step 1 by using the same soil suitability classes as those already described in the Table 4. A raster map will be created

— Step 3: Calculations of SOC requirements: Calculate the SOC amendment required using the Equation 2**.**

Equation 2

$$\Delta SOC\left(\frac{dg}{kg}\right) = SOC_{optimal} - SOC_{calc(0-60cm)}$$

where: $SOC_{optimal}$ value is optimal SOC content (Fisher et al. 2021) and SOC_{calc} is given from the resulting 0-60cm SOC raster map as produced in step 2.

— Step 4: Classify the SOC amendment requirements into different categories based on the delta (ΔSOC) values as calculated in step 3.

— Step 5: SOC Amendment Calculation: Calculate the SOC amendment (stocks) required using the Equation 3

Equation 3

$$SOC_{amendments}\left(\frac{t}{ha}\right) = DSOC\left(\frac{dg}{kg}\right) * 10^{-7}\left(\frac{t}{dg}\right) * R$$

Where R is defined in terms of soil depth (Depth) and Bulk density (BD) Equation 4

Equation 4

$$\mathrm{R} = \mathrm{Depth\ (dm)}*10^{6}(\frac{\mathrm{dm}^{2}}{\mathrm{ha}})*\mathrm{BD}\left(\frac{\mathrm{kg}}{\mathrm{dm}^{3}}\right)$$

Depth = Soil depth (dm). Usually they are 1, 2 or 3 (dm)

BD =Soil Bulk Density. A 1.2 kg/dm^3 BD could be used as a mean value from LUCAS survey for croplands (Panagos et al. 2024c) but any other *ad hoc* BD values can be used as well.

— Step 6: SOC Amendment Classification: Classify the SOC amendment requirement into different categories based on the SOC amendments (t/ha) stocks:

This workflow enables us to precisely quantify the Soil Organic Carbon (SOC) requirements, both in terms of concentration and total stock, at a highly detailed pixel level. The resulting data will then be used to determine the optimal amount of soil organic improvers needed for application in soils, as outlined in step 2.1, and to assess the potential environmental impact of applying these improvers.

Liming requirements

Liming and gypsum requirements will be calculated to manage two main objectives: to raise the optimal pH values of acidic soils for a given crop and to reduce the alkalinity of highly alkaline soils (pH > 8.5), respectively. To achieve these goals, recommendations will be provided on the necessary amounts of lime (to increase pH) and gypsum (to decrease alkalinity), as these are common and effective agricultural practices.

They will be determined by taking into consideration the soil pH values where crops to be consumed in Europe are cultivated (see Table 4 for soybean). Soil suitability classes were classified into 10 categories to be directly related to liming and gypsum requirements as well as to analyse the environmental impact including CO_2 emissions (Table 5).

Table 5. Categorization of soil suitability classes based on pH levels, required amendments, and estimated CO_2 emissions for soybean crop production.

Soil suitability classes	pH classes	Categories	Amendments	Requirements (t ha^{-1})	CO_2 emissions (t C t^{-1}lime)
Not Suitable	pH > 8.3	Extremely alkaline	Gypsum	3.1	No emissions
Severe	8.2 < pH < 8.3	High alkalinity	-	-	
Moderate	7.8 < pH < 8.2	Moderate alkalinity	-	-	
Slight constraint	7.5 < pH < 7.8	Slight alkalinity	-	-	
No constraint	6.0 < pH < 7.5	No constraint	No amendments	-	
Slight constraint	5.5 < pH < 6.0	Slight acidity	Lime	1.5	0.1416
Moderate	5.4 < pH < 5.5	Moderate acidity	Lime	3.0	0.1770
Severe	5.2 < pH < 5.4	High acidity	Lime	3.6	0.2124
Very severe	4.7 < pH < 5.2	Very high acidity	Lime	4.5	0.2655
Not suitable	pH < 4.7	Extremely acidity	Lime	6.0	0.3540

Source. JRC analysis

First, a suitable soil depth for calculating liming requirements must be defined by, for instance, analysing the soil acidity categories by depth.

If no significant variations in pH values are found along soil depths, the pH value at a selected soil depth will be used as a representative value for calculating liming requirements

In case that criteria for selecting a representative soil depth based on soil acidity categories by depth does not work, other methodological approaches could be used, as follows:

Use a weighted average approach: An alternative approach is to calculate a weighted average pH value, considering the distribution of soil acidity categories across various depths, as that used to determine the 0-60 cm SOC raster map.

CAUTION: it is crucial to exercise caution when applying this methodological approach, as the weighting factor must be carefully determined to account for the logarithmic scale of pH values, ensuring that the calculation accurately reflects the underlying soil chemistry.

Select a depth based on root zone distribution: Choose a soil depth that corresponds to most of the root zone of the tested crop. This could be a more relevant indicator of the soil pH that the crop is experiencing.

Use a fixed depth as a proxy: Select a fixed depth (e.g. 20 cm or 60 cm) as a proxy for the representative soil depth, based on general knowledge of soil profile characteristics and crop root distribution. Identification of diagnosis soil horizon (or the genetic ones) would be a must for this approach. A sensitivity analysis to evaluate how different soil depths and pH values affect the calculation of liming requirements could be performed as well. This could help identify the most critical soil depth and pH range for the calculation.

Use expert judgment and local knowledge: Consult with local experts, farmers, and soil scientists to gather knowledge on the typical soil profile characteristics and crop management practices in the region. This could provide valuable insights for selecting a representative soil depth.

These alternative strategies could be used alone or in combination to develop a more robust and effective approach for selecting a representative soil depth for calculating liming requirements.

A resulting global map showing the different categories of acidity by using the mask of tested crop will be generated.

Next, liming requirements will be determined by taking into consideration current pH, target pH and soil texture as defined in the Equation 5 (Government of South Australia (https://cdn.environment.sa.gov.au/landscape/docs/hf/soil-lime-notepad.pdf)

Equation 5

$$Lime\ requirement\ (t\ ha^{-1}) = \left(pH_{target} - pH_{observed}\right) * Factor_{soil\ texture}$$

Where $pH_{observed}$ show the values obtained directly from the soil pH map, pH_{target} is the optimal pH value for maximum crop yield (no constraint soil suitability class in Table 5). $Factor_{soil\ texture}$ was stablished to be; 4 for loam and clay loam soils; 3 for sandy loam soils, and 2 for sandy soils). In this study soil pH map (soilgrids) and soil texture map (Figure 3) were used as masks to identify the factor soil texture to be used in the Equation 5.

Liming requirements map will be used to calculate CO_2 emissions at pixel level and then they will be aggregated by country.

Gypsum amendment

The quantity of an amendment necessary to reclaim sodic soil depends on the total quantity of sodium that must be replaced. This, in turn, depends on such factors as the soil texture and mineralogical makeup of the clay, extent of soil deterioration as measured by exchangeable sodium percentage (ESP) and the crops intended to be grown. If a quantitative exchange of applied soluble calcium for adsorbed sodium is assumed, replacement of each mole of adsorbed sodium per 100 g soil will require half a mole of soluble calcium (Equation 6).

Equation 6

$$Soil - Na + Ca^{2+} \leftrightarrow Soil - Ca + 2Na^{+}$$

The quantity of pure gypsum required to supply half a cmol of calcium per kg soil for the upper 30 cm soil depth will be as shown in Equation 7.

Equation 7

$$Gypsum\left(\frac{t}{ha}\right) = \frac{MW_{Gypsum}}{200} * \frac{3.6 \cdot 10^3\ t\ soil}{1\ ha} * \frac{1\ t}{1000\ kg} = \mathbf{3.1}\frac{t}{ha}$$

Step 1.4. Soil Suitability Analysis for EU Crop Consumption

After determining the soil suitability classes for each soil indicator across all areas where a specific crop is cultivated, the classes should be re-calculated for each given area using the data from the LAFO model per each country.

The proportions of each soil suitability class, as defined in Table 4, for each country, will be used to recalculate the soil suitability categories for the agricultural land (in hectares) dedicated to growing crops consumed in the European Union. This step will ensure consistency with the LAFO model data, allowing for an accurate assessment of the soil suitability for crops consumed in the EU. The two-steps methodological approach is shown in Figure 6.

Figure 6. Methodological procedure for determining the land area (in hectares) associated with each soil suitability class that is consumed in the European Union, utilizing data from LAFO model.

Country X	Land (Ha)
No constraint	1000
Slight constraint	500
Moderate constraint	250
Severe constraint	200
Very severe	50
Not suitable	0
Total	**2000**

Coeff factor
0.500
0.250
0.125
0.100
0.025
0.000
1.000

Country X	LAFO
Imported land (ha)	100

Country X	Recalculated Land (ha)
No constraint	50
Slight constraint	25
Moderate constraint	12.5
Severe constraint	10
Very severe	2.5
Not suitable	0
Total	**100**

Source. JRC analysis

Step 1.4.1: Determine the Coefficient Factors for Each Soil Suitability class

— Calculate the total land area (in hectares) for each country producing a specific crop (e.g. 2000 ha producing a certain crop in the country X)

— Determine the proportion of land area in each soil suitability for each country (grey table in Figure 6)

— Calculate the coefficient factor for each soil suitability class (black table in Figure 6) by dividing the proportion of land area in each soil suitability class by the total land area for each country (grey table in Figure *6*)

Step 1.4.2: Recalculate the Land Area for each Soil Suitability class

— Multiply the coefficient factor for each soil suitability class (black table in Figure 6) by the total land area imported from the LAFO data for each country (e.g. 100 ha out of 2000 ha of a certain crop are consumed in Europe)

— Calculate the land area (in hectares) for each soil suitability class by summing the products of the coefficient factors and the total land area imported (blue table in Figure 6)

Coefficient factors for each soil suitability class will be determined per each country and per each soil depth. It will be carried out for each soil indicator.

By following previous steps, we can calculate the land area for each soil suitability class consumed in Europe by using the data from LAFO, considering the total land area for each country producing the specific crop and the proportion of land area in each soil suitability class.

By analysing the land outside the EU that is cultivated to produce key crops for EU consumption, we can determine the proportion of land in exporting countries that is being used to its full potential in terms of yield, compared to the maximum achievable yield based on soil indicators. Furthermore, we can identify the areas where land is being underutilized and assess the potential benefits of optimizing its use (step 1). We can evaluate the environmental impact of implementing agricultural practices that improve soil quality to achieve maximum yields for each crop, as well as estimate the amount of land that could be saved by increasing yields, thereby reducing the pressure on additional land resources (step 2).

Step 2. Environmental impact and land savings assessment

The second step focuses on assessing the environmental impact of agricultural practices used to achieve optimal nutritional status on the land used to grow crops consumed in the EU. In addition, it will assess the potential reduction in required cropland to meet EU consumption in case optimum yield is reached in all locations.

At this point, the EU soil use calculator will focus on evaluating the environmental impact associated with optimizing two critical soil parameters: Soil Organic Carbon (SOC) and pH. To reach optimal levels of SOC and pH, which are crucial for maximizing crop yields, we will calculate the amounts of manure and liming materials needed to be applied. Our assessment will then examine the potential environmental consequences of using these soil amendments to achieve optimal SOC and pH values, with the goal of determining the maximum achievable crop yields

Step 2.1. Manure applications as soil organic amendments

In this work application of manure was considered as the only soil organic improver to achieve the optimal soil organic content for a certain crop. Soil use calculator approach could be used for other soil organic improvers including biochar, compost, and sewage sludge.

To achieve optimal crop production as defined, for example by Fischer et al. (2021), the environmental impact of using manure as an organic soil amendment will be assessed, drawing on existing manure datasets (Bohl et al. 2024). The manure database is composed by 477 952 manure formulations collected from 1998 to 2023. The manures entries are classified taking into consideration, among others; the animal type, manure type, manure treatment, physical properties (moisture, total suspended solids, total dissolved solids), chemical properties (pH, electrical conductivity, total carbon, total nitrogen, and total phosphorus), alkaline metals (calcium (Ca), sodium (Na), potassium (K), magnesium (Mg)), and metal(loids) (aluminium (Al), arsenic (As), boron (B), cadmium (Cd), cobalt (Co), total chromium (Cr), copper (Cu), Iron (Fe), lead (Pb), molybdenum (Mo), nickel (Ni), selenium (Se), and zinc (Zn)). All manure parameters were recorded as received (wet) basis. This study focused on data from solid manures (>20% total solids), excluding other liquid manures to minimize potential uncertainties for larger water content and ensure more reliable results. First, content of all the chemical manure parameters (apart pH and electrical conductivity) was transformed into dry matter by using the moisture content. Six different manure types (beef, dairy, poultry, swine, other animals, and other organic amendments) were analysed, and a representative manure composition was designed as well by calculating the arithmetic mean values for each manure parameter above mentioned ("Mean" column in the Table 6).

Table 6. Mean values for physical and chemical characterization of 37 061 solid manures from a different manure types (Bohl et al. 2024). Concentrations of manure parameters were recalculated to be as dry matter (DM) as the original data from the database are presented as received (wet).

Manure parameters	Beef	Dairy	Other animal	Poultry	Swine	Other amendment	Mean
N	*3595*	*13214*	*3801*	*15657*	*595*	*199*	*37061*
Moisture (g kg^{-1})	635	594	570	507	506	455	545
pH	8.28	8.35	7.91	7.76	7.09	6.83	7.71
EC (dS m^{-1})	4.77	22.9	84.8	283	261	2.22	110
SOM (g kg^{-1})	335	458	456	802	336	430	469
Total C (g kg^{-1})	299	305	419	504	449	264	373
Total N (g kg^{-1})	22.5	14.5	14.4	52.9	18.0	19.5	23.6
C:N ratio	13.3	21.1	29.1	9.5	25.0	13.5	15.8
Ca (g kg^{-1})	24.9	27.7	31.3	71.7	38.3	41.7	39.3
K (g kg^{-1})	9.79	5.83	6.36	17.27	5.49	6.00	8.46
Mg (g kg^{-1})	7.97	9.71	7.66	9.38	8.95	10.6	9.05
Na (g kg^{-1})	2.88	2.30	3.15	9.05	3.09	3.17	3.94
As (mg kg^{-1})	1.59	1.09	9.36	2.89	1.73	20.1	6.13
B (mg kg^{-1})	21.5	24.5	37.6	85.6	23.7	38.0	38.5
Cd (mg kg^{-1})	1.49	2.89	1.90	0.94	2.52	1.99	1.96
Cr (mg kg^{-1})	15.5	14.1	11.2	20.3	17.2	48.1	21.1
Mo (mg kg^{-1})	5.40	5.79	3.16	12.28	7.41	17.7	8.62
Co (mg kg^{-1})	1.78	3.16	2.66	0.88	0.54	4.55	2.26
Cu (mg kg^{-1})	68.3	84.7	111	449	224	73.0	168
Pb (mg kg^{-1})	5.58	12.1	6.04	5.04	2.54	46.9	13.0
Fe (g kg^{-1})	3.58	3.86	5.55	1.82	6.33	4.83	4.32
Mn (mg kg^{-1})	307	202	375	762	414	222	380
Ni (mg kg^{-1})	7.41	21.7	38.9	47.1	38.6	27.0	30.1
Al (g kg^{-1})	3.79	2.84	4.54	1.95	5.88	2.54	3.59
Se (mg kg^{-1})	1.09	3.00	0.663	0.434	4.81	6.15	2.69
Zn (mg kg^{-1})	190	149	252	750	1018	278	439
Total P (g kg^{-1})	6.32	3.79	4.53	21.2	17.6	4.68	9.69
N_2O factor (g kg^{-1} wet)[1]	22.4	22.4	22.4	22.4	22.4	22.4	22.4
N_2O emissions g_kg $^{-1}$ (dry)	0.503	0.324	0.323	1.184	0.403	0.438	0.529
N_2O emissions g_kg^{-1} (wet)[2]	0.184	0.132	0.139	0.585	0.219	0.216	0.241

[1] N_2O emission factor as defined in FAOSTAT

[2] N_2O emission factor by taking into consideration the water content for each manure types.

Source. JRC analysis

Manure application rates (t) were calculated by considering both Soil Organic Carbon (SOC) requirements, as above calculated, and carbon content of the manure. Manure content (nitrogen content) was calculated as well to be used for calculations of N_2O emissions taking into consideration the nitrogen content for each manure type.

Nitrous oxide (N_2O) emission factor was calculated by following the FAO procedure (FAO, 2024) by dividing manure applied (N content) to soils (in kg) by the emissions (N_2O) from manure applied (in kt) for all the countries with data from 2012 to 2022. The FAOSTAT data were estimated at Tier 1 following the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). The N_2O emission factor was calculated for each of the countries and also for each of the manure types included in the FAO dataset and for both wet and dry manure by taking into consideration the manure moisture (Table *6*). In this study, a default N_2O emission factor of 22.393 g N_2O per kilogram of wet manure (based on nitrogen content) was used. Alternative emission factors can be employed using Tier 2 or Tier 3 approaches, depending on availability and specific requirements.

The impact of manure application on soil fertility and soil contamination will be assessed by calculating the amounts of nutrients (N, P, K, Na, Ca, Mg, B, and Mo) and metal(loids) (As, Cd, Cu, Cr, Pb, Ni, Fe, Mn, Al, Se, and Zn) put into soils for each crop-producing country that exports to Europe, considering the manure application rates required to achieve optimal levels of SOC. The calculations will be expressed in total quantities (in tonnes or kg), soil stocks (t ha^{-1} or kg ha^{-1}), and concentrations (g kg^{-1} or mg kg^{-1}) for each element and for each manure type as presented in Table *6*.

Step 2.2. Liming and Gypsum amendments

Emissions from liming amendments

Net CO_2 emissions for applications of liming amendments to reach out the optimal pH values were calculated by using the factor of 0.059 Mg C per Mg_limestone (West & McBride, 2005). It is indicating that 49% of total applied lime is transformed to CO_2 taking into consideration the slow solubilization rate of lime. This contrasts with IPCC estimates of 0.12 and 0.13 Mg C per Mg limestone and dolomite, respectively as they are supposing a 100% of applied lime is transformed into CO_2 (IPCC, 2006).

Step 2.3. Reduction in cultivated area attributable to improved crop yields

The use of manure and lime as organic and liming amendments to optimize soil nutrition and maximize crop yields has a direct and positive effect on yields. Furthermore, this approach can also help reduce the amount of land needed to produce crops consumed in Europe, thereby freeing up land for alternative uses such as cultivating other crops or restoring natural habitats. Therefore, the benefits of land savings should be quantified to fully understand the potential advantages of this approach. For that the relation between soil suitability classes and yield was used and corresponding coefficient factors were given per each of soil suitability classes (see Table *7* by using nutritional optimal values for soybean crop as example).

Table 7. Relationship between coefficient factors and crop productivity (for soybean) for each of soil suitability classes defined for SOC and soil pH different soil pH. Fischer et al. (2021)

Soil suitability classes	pH classes	Categories	SOC (g kg^{-1})	Yield (%)	Coeff. factor
No constraint	6.0 < pH < 7.5	Optimal	≥ 20	100	1.0
Slight constraint	5.5 < pH < 6.0 7.5 < pH < 7.8	Slight acidity Slight alkalinity	12	90	0.9
Moderate	5.4 < pH < 5.5 7.8 < pH < 8.2	Moderate acidity Moderate alkalinity	8	70	0.7
Severe	5.2 < pH < 5.4 8.2 < pH < 8.3	High acidity High alkalinity	0.0	50	0.5
Very severe	4.7 < pH < 5.2	Very high acidity	0.0	30	0.3
Not suitable	4.7 > pH pH > 8.3	Extremely acidity Extremely alkaline	0.0	10	0.1

Source. JRC analysis

Corrected area (ha) of each soil suitability class (as calculated in step 1.3) is multiplied by the corresponding coefficient factor (Table 7). Next, saved area is calculated as difference between total area (from LAFO model) and the corrected area previously calculated. Saved area is the area that is not used whether selected crop was growth at maximum yield by reaching out the optimal soil parameters.

The detailed methodology involves two-step calculations to determine the 'Saved Area' for a given crop.

Step 2.3.1: Calculation of corrected area

Firstly, the corrected area (in hectares) for each soil suitability class is obtained by multiplying the area of each class by the corresponding coefficient factor (as shown in Table 7).

Corrected Area (ha) = Σ (Area of each soil suitability class x Coefficient Factor)

Where:

- Area of each soil suitability class = [insert value from step 1.3]
- Coefficient Factor = [insert value from Table 7]

This coefficient factor represents the yield percentage of the crop under different soil pH and SOC conditions, allowing for the adjustment of the area based on its suitability for the crop.

Step 2.3.2: Calculation of saved area

Secondly, the 'Saved Area' is calculated as the difference between the total area (as estimated by the LAFO model) and the corrected area, as follows:

Saved Area (ha) = Total Area (ha) - Corrected Area (ha)

The 'Saved Area' represents the area that can be spared or not utilized if the selected crop is grown at its maximum yield potential, assuming optimal soil parameters are achieved once soil amendments added. This approach enables the identification of areas that can be potentially saved or allocated for alternative uses, thereby optimizing land use planning and crop production.

3. Conclusions

This technical report has developed a comprehensive methodology, known as the "EU Soil suitability Calculator", to quantify the suitability of soils used for EU consumption at global level. By implementing a two-step approach, this methodology can be used to assess the soil suitability index for land used to produce crops consumed in the EU and to evaluate the environmental effects of agricultural practices required to achieve optimal nutritional levels.

The results of this methodology may quantify the relationships between crop production, soil properties, and environmental impacts, highlighting areas where sub-optimal soil conditions limit crop productivity and identifying potential trade-offs between yield optimization and environmental sustainability. The estimation of saved area, through the application of soil organic carbon improvers and liming materials, has shown that significant land savings can be achieved by optimizing soil parameters to their ideal levels.

The application of the proposed EU soil use calculator can yield a range of outcomes, including:

1. **Optimization of land use**: By identifying areas where soil health can be improved, the calculator can help reduce the amount of land required for crop production.
2. **Enhanced soil organic carbon**: The calculator can determine the amount of organic carbon needed to achieve optimal one, which can lead to improved soil fertility and structure. However, this agricultural practice may also result in negative impact including increased greenhouse gas emissions, such as N_2O and accumulation of metal(loid)s in soil but also in a positive impact increasing the content of nutrients in soils. Other SOC improvers including compost, sludge, and biochar could be assessed by using the proposed methodology.
3. **Improved soil pH management**: The calculator can identify areas where soil pH needs to be adjusted and determine the amount of lime required to achieve optimal pH levels. This can lead to improved crop yields and reduced land use but may also result in increased CO_2 emissions.
4. **Soil compaction assessment**: The calculator can evaluate the extent of soil compaction, identifying areas with no, slight, moderate, or severe constraints. This information can inform strategies to mitigate soil compaction and improve soil health.
5. **Soil erosion management**: The calculator can assess the risk of soil erosion, identifying areas with no, slight, moderate, or severe constraints. This information can be used to develop targeted strategies to reduce soil erosion and protect soil health.

The proposed methodology has significant implications for policy makers, as it can inform and support the development of evidence-based policies and strategies for sustainable agriculture and soil management. Specifically:

1. **Informed decision-making:** The calculator can provide policy makers with accurate and reliable data on soil health, land use, and environmental impact, enabling them to make informed decisions about agricultural policies and practices.
2. **Targeted interventions:** By identifying areas with specific soil health constraints, policy makers can develop targeted interventions and strategies to address these issues, such as soil conservation programs or incentives for sustainable agriculture practices.

3. **Evaluation of policy effectiveness**: The calculator can be used to evaluate the effectiveness of existing policies and programs aimed at improving soil health and reducing environmental impact, allowing policy makers to refine and improve their approaches.
4. **Support for climate change mitigation and adaptation:** By promoting sustainable agriculture practices and reducing greenhouse gas emissions, the calculator can support policy makers in their efforts to mitigate and adapt to climate change.

As a next step, the proposed EU soil use calculator methodology will be tested and applied to a range of crops that are highly relevant to EU consumption but are primarily produced in countries outside of the EU.

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List of abbreviations and definitions

Abbreviations	Definitions
SML	Soil Monitoring Law
JRC	Joint Research Centre
LAFO	Land Footprint
CAP	Common Agricultural Policy
EUSO	EU Soil Observatory
SOC	Soil Organic Carbon
BD	Bulk Density

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