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LUCAS 2018 Soil Module

Presentation of dataset and results

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Best wishes to Oihane in her new career with DG AGRI – a huge thanks for all the support over the past six years.

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Executive Summary

This report summarises the soil dataset collected as part of the 2018 Land Use/Cover Area frame statistical Survey' (generally referred to as LUCAS Soil Module). It presents an overview of the various laboratory analysis and describes the spatial variability of soil properties by land cover (LC) class and a comparative analysis of the soil properties for NUTS 2 regions.

The LUCAS Soil Module is the only mechanism that currently provides a harmonised and regular collection of soil data for the entire territory of the European Union, addressing all major land cover types simultaneously, in a single sampling period (April – October).

At the same time, the LUCAS Soil module can support further policy needs through a flexibility that permits both the collection of new field data, if required, from new sampling sites. In turn, this can be complemented with additional laboratory analysis (e.g. micronutrients, specific pollutants). This capacity addresses the needs of a diverse policy user base and an evolving policy landscape.

Several new developments were put in place for the 2018 LUCAS Soil module. These included:

- Assessment of bulk density for a subset of locations.
- Trial to extend sampling depth to 30 cm (only in Portugal).
- An assessment of different types of soil erosion (sheet, rill, gully, wind).
- Measuring the depth of organic soils.
- The collection of fresh samples in order to extract DNA from the soil fabric to assess soil biodiversity and detect the presence of antibiotic resistance genes.
- Selected measurements of metals, and a pilot to assess residues of plant protection products and veterinary antibiotics in a subset of samples.

Initially, 27,069 locations were identified for soil sampling, incorporating locations visited in 2015. At the close of the survey, a soil related activity (i.e. assessing type of erosion, organic soil check sample collection) was made at 19,345 locations (i.e. LUCAS Grid Points). After the removal of samples that could not be identified or were mislabelled or lost in transit, the LUCAS 2018 Soil Module dataset contains data for 18,984 locations.

As in the previous exercises, a common sampling procedure, single laboratory, standard analytical methods were applied.

Additional soil parameters that were collected from all LUCAS field points primarily to support soil erosion modelling (e.g. signs of ploughing, presence of crop residues, percentage of stones) are not presented here but are included in the LUCAS 2018 microdata, which is made available by EUROSTAT.

A parallel report will present an assessment of changes in soil properties between 2009, 2015 and 2018.

The results of analysis into metals, biodiversity assessment, antimicrobial resistance genes, antibiotics, residues of plant protection products, and microplastics, as well as changes between 2009 and 2018, will be presented as separate reports.

Data can be downloaded from

https://esdac.jrc.ec.europa.eu/content/lucas2018-topsoil-data

Abstract

This report accompanies the release of the soil dataset collected as part of the 2018 Land Use/Cover Area frame statistical Survey' (generally referred to as LUCAS Soil). It presents an overview of the laboratory analysis data and provides a detailed description of the results for the European Union (EU) and the United Kingdom as it was still a Member State at the time of the survey. The report describes the spatial variability of soil properties by land cover (LC) class and a comparative analysis of the soil properties for NUTS 2 regions.

Regular monitoring provides a unique perspective on pressures affecting soils. In this respect, the soil module of LUCAS supports the specific needs of the European Commission by collecting data that characterises soil condition and health, which can be affected in relation to land use practices and other activities that are driven by specific policy instruments.

The LUCAS Soil module is the only mechanism that currently provides a harmonised and regular collection of soil data for the entire territory of the EU, addressing all major land cover types simultaneously, in a single sampling period (April – October).

At the same time, the LUCAS Soil module can support further policy needs through a flexibility that permits both the collection of new field data, if required, from new sampling sites. In turn, this can be complemented with additional laboratory analysis (e.g. micronutrients, specific pollutants). This capacity addresses the needs of a diverse policy user base and an evolving policy landscape.

The drive to collect soil samples under the umbrella of LUCAS was led initially by DG Environment, who provided funding for the 2009 survey to collect a baseline dataset on a range of soil characteristics such as organic matter content, nutrient status, fertility, acidification and soil pollution (metals). At that time, the main LUCAS survey was planned for 23 EU Member States (MS). Bulgaria and Romania were added in 2012 while Croatia, Cyprus and Malta were formally included in 2015. In the 2018 survey, all 28 MS at the time were included.

The initial premise was developed to collect samples from a depth of 20 cm following a common sampling procedure from 10% of the sites where field visits were to be carried out as part of the main LUCAS survey. In 2009, this gave around 235,000 possible locations for a nominal target of 23,500 soil samples. At the end of the survey, about 20,000 had been collected. These samples were analysed according to standard analytical methods in a single laboratory for a range of physical and chemical properties. In addition, visible and near-infrared spectra were acquired for all samples. The process was repeated in 2012 for Bulgaria and Romania, where samples were collected from about 2,000 locations. In total, 22,003 samples were analysed for 2009/2012.

In 2015, 90% of the locations sampled in 2009 and 2012 were maintained with the remaining 10% being substituted by new locations, including points at altitudes above 1,000 m, which were out of scope of the earlier surveys. In total, 21,859 samples were collected, of which 4,246 were at new locations compared with the 2009/2012 campaign. In addition, the soil module was extended by the JRC Enlargement and Integration Programme to Albania, Bosnia and Herzegovina, Croatia, Montenegro, North Macedonia, and Serbia (1,015 samples were eventually collected). Switzerland also participated following standard LUCAS protocols (150 samples were collected by Agroscope).

For 2018, 27,069 locations were identified for soil sampling. A soil related activity (i.e. assessing type of erosion, organic soil check sample collection) was made at 19,345 locations (LUCAS Grid Points). After the removal of samples that could not be identified or were mislabelled or lost in transit, the LUCAS 2018 Soil Module dataset contains data for 18,984 locations.

As in the previous exercises, a common sampling procedure, single laboratory, standard analytical methods were applied.

It is worth noting that several new developments were put in place for the 2018 LUCAS Soil module. These included:

- Assessment of bulk density for a subset of locations.
- Trial to extend sampling depth to 30 cm (only in Portugal).
- An assessment of different types of soil erosion (sheet, rill, gully, wind).
- Measuring the depth of organic soils.
- The collection of fresh samples in order to extract DNA from the soil fabric to assess soil biodiversity and detect the presence of antibiotic resistance genes.
- Selected measurements of metals, and a pilot to assess residues of plant protection products and veterinary antibiotics in a subset of samples.

Additional soil parameters that were collected from all LUCAS field points primarily to support soil erosion modelling (e.g. signs of ploughing, presence of crop residues, percentage of stones) are not presented here but are included in the LUCAS 2018 microdata, which is made available by EUROSTAT.

A comparison exercise between the results of the 2018 LUCAS Soil survey and the national soil monitoring was carried out in Austria by AGES (LUCASA study) – this will be reported separately.

A parallel report will present an assessment of changes in soil properties between 2009, 2015 and 2018.

A set of descriptive environmental data for the soil sampling sites is available to download from ESDAC.

Some take away messages from LUCAS 2018:

- 3rd iteration of LUCAS Soil, covering all EU Member States in a six month window.
- Laboratory analyses were carried out on samples collected from 18,984 locations
- 16,556 sites were repeat visits to those sampled in 2015 while 75% were also sampled in 2009/2012. In total, 13,375 sites have been visited in all three surveys (2009/2012, 2015, 2018).
- Almost 32,000 individual samples were analysed by the laboratory (standard and bulk density).
- Quality control checks indicate that the laboratory analysis was consistent with 2015.
- The 2018 Survey saw the introduction of several new elements:
    - 6,271 samples were collected using metal cores to assess bulk density, nominally for three depths.
    - 885 fresh samples were collected to assess soil biodiversity.
    - Surveyors were only able to ascertain erosion features in 850 points, predominantly correctly identifying gully erosion. The absence of erosion features may be masked by crops at the time of the survey.
    - The depth of the organic horizon was measured in 1,050 points, with 30% recording 40 cm or more. Most of the sites selected for depth assessments appear not to fulfil the depth criteria for Histosols. However, the assessment failed to assess the reason for very shallow organic soils (e.g. such as on bedrock). The implication could be that many of these locations are either

mineral soils with well-developed organic horizons or that peatlands have been eroded back to the underlying mineral base.

- The elaboration of LUCAS field observations on gully erosion channels combined with on-screen interpretation allowed the creation of a first EU-wide gully erosion inventory of 206 gully points (ca. 1% of the total surveyed points).
- Genetic metabarcoding (also known as eDNA) was used to characterise the complex genetic diversity of soil bacteria, fungi and eukaryotes. Work is ongoing to understand the relationships between environmental drivers, land use and the soil microbiome.
- Analysis of antibiotic residues, presence of antimicrobial resistance genes, and residues of active ingredients of plant protection products are ongoing (delayed by COVID) and will be reported separately (2022 Q2).
- Extractable aluminium and iron oxalate were measured for 2,510 cropland locations (linked to the availability of phosphorous in soils).

- The concentration of metals was measured in 997 locations, 90% of which were resampling of sites from 2009/2012.
- 71% of targeted points were sampled compared to 85% and 95% in LUCAS 2015 and LUCAS 2009/12 surveys, respectively. The percentage of points sampled was below 50 % in Germany, Croatia, Ireland, Malta, the Netherlands, Romania and the United Kingdom. The low rates of sampling were attributed to a change in the survey company (Romania), extreme weather and soil conditions, the presence of dangerous animals, poor access, rocky soils and the presence of fences in cropland complicated the access to the points.
- Legal issues related to accessing private land was the main issue in Germany for not taking samples while in the UK, a denial of access by land owners reflecting the Brexit referendum was an issue in many cases.
- As in the previous studies, highest organic carbon levels (EU mean = 318.1 g kg^{-1}) are found in the wetlands of the Boreal and the Atlantic zones (peat). Organic carbon content was also high in woodland points (EU mean = 88.1 g $kg\text{-}^{1}$), especially in north-western climatic zones (boreal, Atlantic, sub-oceanic, and northern sub-continental). The mean organic carbon content of grasslands was 40.2 g kg^{-1} in grassland points, rising slightly to 55.2 g kg^{-1} in shrubland. Organic carbon content was the lowest in croplands (EU mean = 18.3 g kg^{-1}) and unsurprisingly, in bareland locations (EU mean = 17.3 g kg^{-1}).
- Phosphorous levels are higher in soils under cropland and managed grasslands.
- Potassium content tends to be lower in northern than in southern Europe, with lowest contents in boreal and northern sub-continental zones and highest contents in semi-arid Mediterranean and southern sub-continental zones.
- The results of analysis into metals, biodiversity assessment, antimicrobial resistance genes, antibiotics, residues of plant protection products, and microplastics, as well as changes between 2009 and 2018, will be presented as separate reports.

Data can be downloaded from

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1 Introduction

1.1 Background

Soils deliver fundamental ecosystem services with environmental, economic, and social benefits for people. These services can be grouped into provisioning (food, feed, fuel, fibre and genetic resources), regulating (storage, filtration and cycling of nutrients and water), cultural (aesthetic, spiritual and recreational values) and supporting (essential for the provision of all other services). The provision of these ecosystem services depends on a sustainable management of soils aiming at maintaining/improving their health.

Sustainable soil management is a prerequisite to meet many of the objectives of the Green Deal ([1]): preserving and restoring ecosystems and biodiversity, reducing nutrients losses and the use of pesticides and fertilisers, a zero pollution ambition, the mitigation of and adaptation to climate change, and the conservation of the rural landscape. In this context, a pan-European network of land and soil monitoring is fundamental. The soil assessment module of the LUCAS (Land Use and Cover Area Frame Survey) programme is the only mechanism for a harmonised monitoring (common sampling procedure and standard analysis methods) both in space and time of topsoils in the European Union (EU).

The LUCAS Programme is an area frame statistical survey organised and managed by Eurostat (the Statistical Office of the EU) to monitor changes in land use (LU) and land cover (LC) over time across the EU. Since 2006, Eurostat has carried out LUCAS surveys every three years. The surveys are based on the visual assessment of environmental and structural elements of the landscape in georeferenced control points. The points belong to the intersections of a 2 x 2 km regular grid covering the territory of the EU. This results in around 1,000,000 georeferenced points. In every survey, a subsample of these points is selected for the collection of field-based information.

In LUCAS 2009, about 235,000 points were visited across 25 Member States (Bulgaria, Romania, Cyprus and Malta were not included in the formal survey but some limited soil samples were collected from the latter two by the JRC). In ten percent of these points, soil samples were taken from a depth of 20 cm and analysed for the following properties in a single laboratory: coarse fragments, clay, silt and sand, pH (in $CaCl_2$ and H_2O), organic carbon (OC), carbonates ($CaCO_3$), phosphorous (P), total nitrogen (N), extractable potassium (K), cation exchange capacity, multispectral properties, and metals. The details and outcomes of the 2009 soil survey are fully documented in Tóth et al (2013a).

In LUCAS 2012, the soil survey was conducted in Romania and Bulgaria, whose samples were analysed for the same set of physical and chemical properties as in 2009. Altogether, the LUCAS soil dataset from 2009 and 2012 contains data of physical and chemical properties of 22,003 locations.

In 2015, the LUCAS survey was carried out in all EU-28 Member States (MS). In the countries sampled in 2009 and 2012, 90% of the soil sampling locations were maintained while the remaining 10% of points were substituted by new sampling locations, including points above 1,000 m in elevation, which were out of scope of the LUCAS 2009 and LUCAS 2012 surveys. The 2015 survey was also extended through funding provided by the JRC's Enlargement and Integration Programme to Albania, Bosnia and Herzegovina, Montenegro, North Macedonia, and Serbia. Switzerland also participated in the survey. In total, approximately 26,000 locations were targeted in 2015, of which just under 25,000 were in the EU-28. In the end, 21,859 samples were collected in the EU-28. A further 1,015 samples were eventually collected for the Western Balkan countries by the JRC while 150 samples were collected in Switzerland by Agroscope[2].

In 2015, as for LUCAS 2009 and 2012, samples were collected from a depth of 20 cm following a common procedure and were analysed for physical and chemical properties) in a single laboratory using the same analytical methods (metals were not analysed). In

([1]) The European Green Deal: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en
[2] https://www.agroscope.admin.ch/agroscope/en/home.html

addition, electrical conductivity (EC) was included for the first time. The details and outcomes of the 2015 survey are documented in Jones et al. (2020) and Fernandez Ugalde (2020).

1.2 2018 Survey

In LUCAS 2018, soil sampling was carried out in all EU MS using the same set of 25,947 locations that were targeted in 2015. In 65% of these locations, samples were to be taken following the standardised sampling procedure of previous surveys, in which a spade was used to collect a sample from a depth of 20 cm. In the remaining 35% of the locations (approximately 9,000 points), metallic rings were used to collect soil cores to determine bulk density (BD) from a depth of 0-10 and 10-20 cm[3]. The bulk density sample was aggregated for further laboratory analysis. Finally, in a subset of the locations selected for bulk density determination, 1,000 fresh soil samples were also collected to assess biodiversity.

At the conclusion of the survey, **soil samples exist for 18,984 LUCAS points**. In 18,744 locations, samples were taken from 0-20 cm depth. At a further 381 locations, surveyors took samples through the bulk density method only from a single depth (i.e. 0-10 cm, 10-20 cm or 20-30 cm). For soil biodiversity assessment, samples were eventually taken in 885 points by the end of the survey. The number of locations sampled was lower compared to previous surveys due to a range of issues: land ownership, meteorological conditions during the survey and difficulties in reaching the locations.

As for LUCAS 2009/12 and 2015 surveys, all samples were analysed in a **single laboratory** for physical and chemical properties, including metals, using the same analytical methods. In core samples taken from 20 to 30-cm depth in Portugal, only organic carbon (OC) and $CaCO_3$ were analysed. Cation exchange capacity was not analysed in the 2018 survey. In addition, extractable aluminium and iron oxalate were measured for 2,510 cropland locations.

The concentration of a series of **metals** (As, Cd, Co, Cr, Cu, Hg, Ni, Pb, Sb, V and Zn) was analysed in 997 locations, 90% of which were the resampling of sites measured in the 2009/2012 surveys. The scope of this work is to assess whether there has been any significant change in levels. Approximately 300 new sites were randomly chosen.

Since its inception, the LUCAS Soil Module has demonstrated an ability to adapt to changing policy interests (Figure 1). For the first time, soil biodiversity was assessed through **DNA extraction**, amplification and sequencing of 885 samples from a range of land cover types, which were rapidly preserved after sampling through chilling and eventually freezing. The DNA was used to amplify markers (DNA barcodes) of three groups of soil organisms – archaea, bacteria and eukaryotes (fungi and others).

The genetic analysis used to assess soil biodiversity was also used to measure the presence of **antimicrobial resistance (AMR) genes**. AMR refers to the ability of microorganisms to withstand antimicrobial treatments. The over or misuse of antibiotics has been linked to the emergence and spread of microorganisms which are resistant to them, rendering treatment ineffective and posing a serious risk to public health. Within the context of the LUCAS Soil Module, AMR can be introduced to soil through the application of manure from animals that have been treated by veterinary antibiotics. In total, 630 subsamples from the biodiversity samples taken from agricultural land were analysed (predominantly cropland).

A pilot study was developed (with Wageningen Food Safety Research) to assess the presence of the residues of selected **active ingredients of crop protection products** (PPP) in soil. This analysis, of 118 substances and metabolites in approximately 3,000 locations from agricultural land, is currently ongoing. Among pesticides, neonicotinoids, conazoles, organochlorines, and organophosphorus are included. In parallel, the levels of

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[3] In selected locations in Portugal (142 points), soil cores were planned to be taken also at a 20-30-cm depth to study the depth distribution of bulk density as affected by LC.

two targeted **antibiotics** are being measured in approximately 600 arable sites (same as for AMR). The antibiotics analysed belong to the groups of polypeptides and fluoroquinolones. The results of these pilot studies will be aggregated to develop regional statistics.

Finally, a test was carried out with Wageningen University to assess the presence of **microplastics** (only 50 samples).

Please note that results of the metals, biodiversity assessment, AMR, antibiotics and the PPP residues, and microplastics will be presented in separate reports.

The 2018 survey also included **field-based assessments** by the surveyors of various types of **erosion** (sheet, rill, gully, wind, mass movements, and re-deposited soil). This information should help to improve the modelling of soil erosion at EU level. The **depth of organic and organic-rich soils** was assessed to establish a baseline to assess the degradation of these soils and whether they complied with the depth criteria for Histosols.

The following sections of this report:

(1) summarise the sampling protocols,

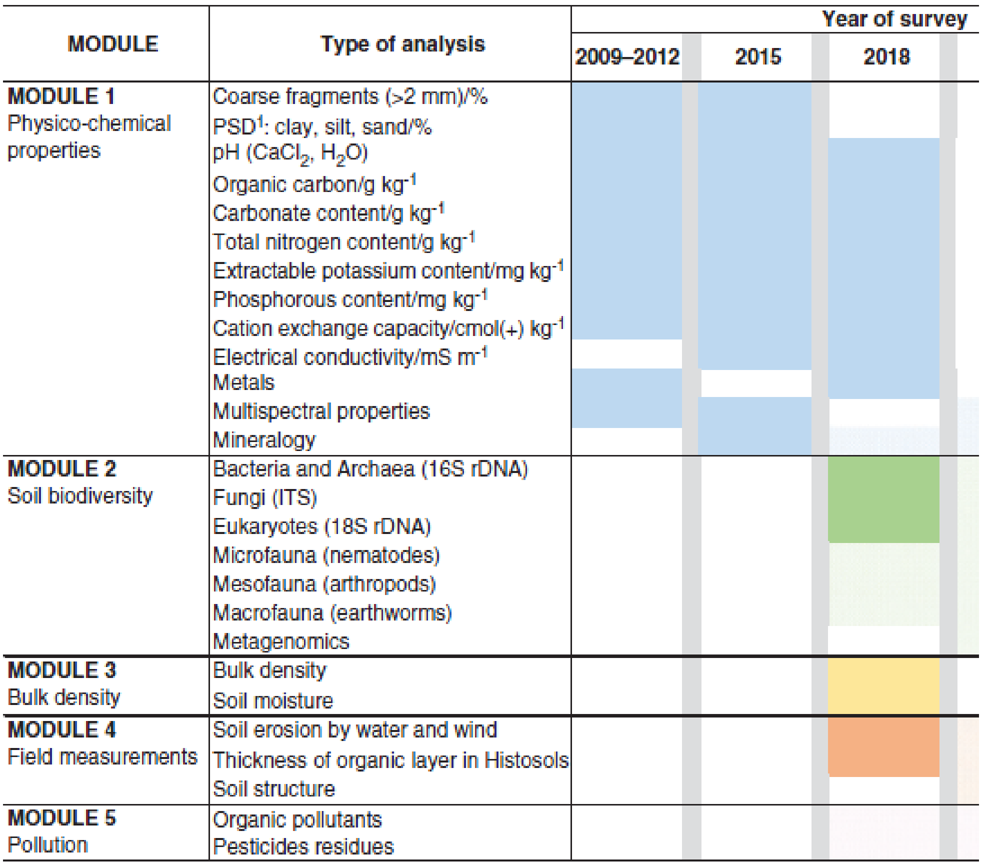
(2) present the dataset of the 2018 LUCAS Soil Module,

(3) provide a detailed description of the results of physical and chemical properties, including metals,

(4) provides an overview of the field-based measurements,

(5) provides a characterisation of the spatial variability of soil properties by land cover class and a comparative analysis of the soil properties by NUTS 2 regions.

Figure 1 Evolution of parameters analysed in LUCAS Soil module

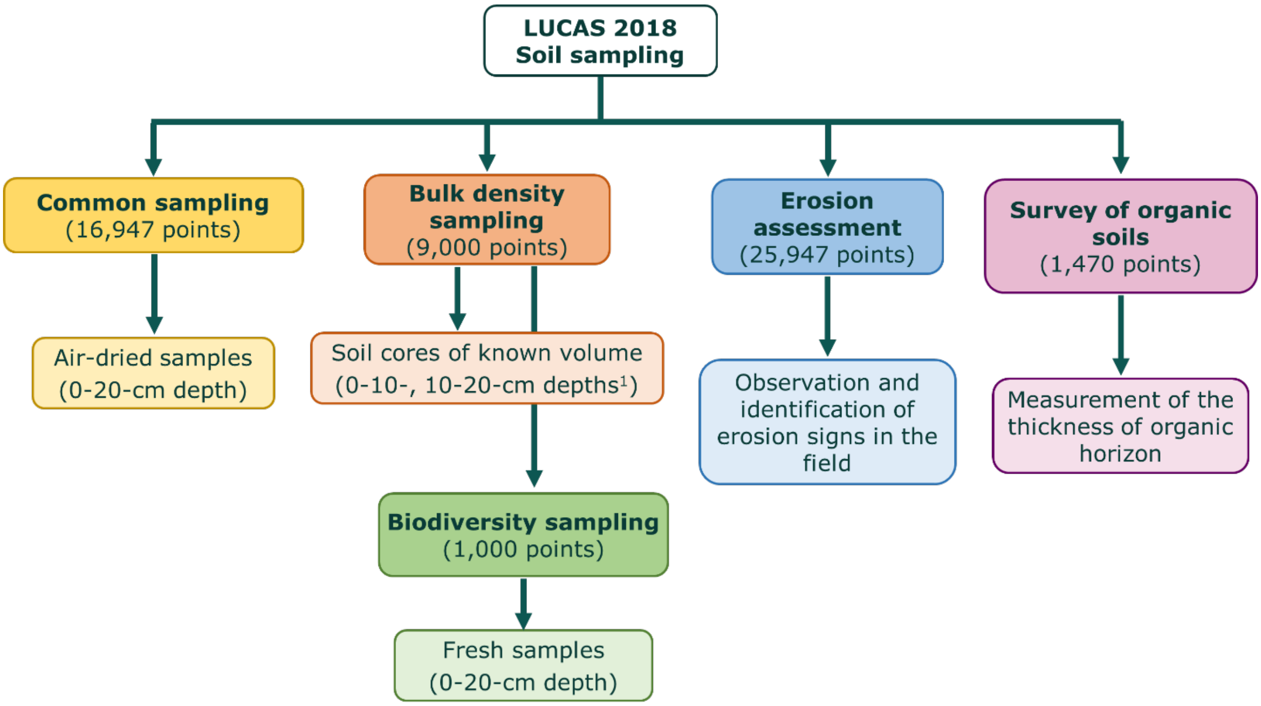


2 LUCAS sampling methodology and laboratory analysis

The LUCAS 2018 soil survey was set for 25,947 points. Soil samples were taken following different types of sampling procedures: the common sampling procedure used in 2009/12 and 2015 surveys, the bulk density sampling (new), and the sampling for biodiversity assessment (also new).

Bulk density sampling was planned for 9,000 points under different LC classes. In 1,000 out of these 9,000 points, samples were to be collected to assess soil biodiversity. In the remainder (16,947 points), the common sampling procedure was to be carried out. It also included the erosion assessment and the survey of organic soils in all points (Figure 2) ([4]).

Figure 2 Sampling schema in the LUCAS 2018 soil survey (numbers indicate initial targets)



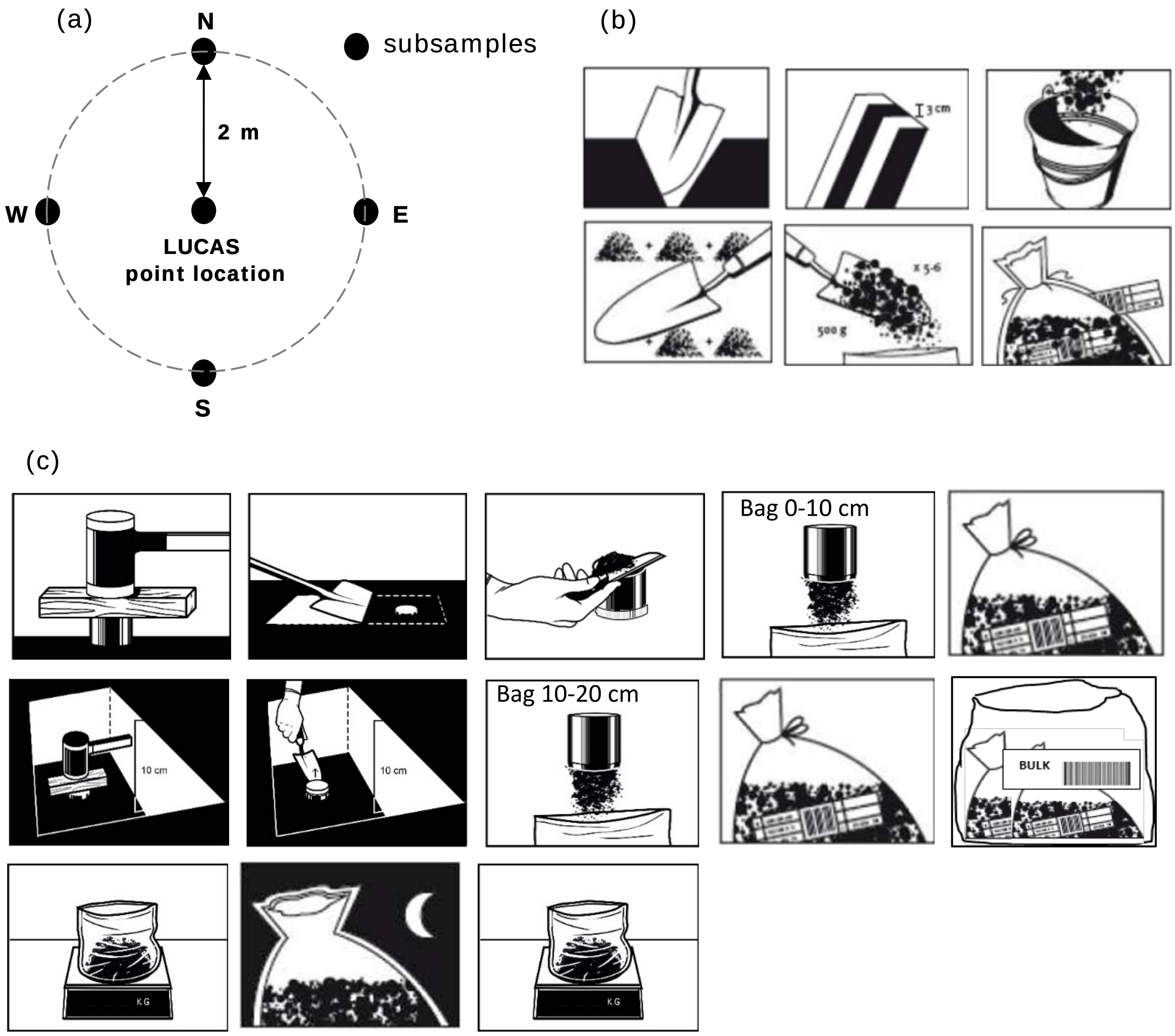
[1] In Portugal, soil cores were also taken from a depth of 20-30 cm.

2.1 Sample collection

With the **common sampling procedure**, a composite sample of approximately 500 g was taken at each LUCAS point. The composite sample consisted of five subsamples taken with the help of a spade. The first subsample was taken at the geo-referenced point location; the other four subsamples were collected at a distance of 2 m following the cardinal directions (North, East, South and West) (Figure 3a). Before taking the subsamples, stones (>6 cm) (FAO, 2006), vegetation residues, grass and litter were removed from soil surface by raking with the spade. As shown by Figure 3b, a V-shaped hole was dug to a depth of 20 cm using the spade and a slice of soil (approximately 3-cm thick) was taken from the side of the hole with the spade. The slice was trimmed at the sides to give a 3-cm wide subsample. The subsample was placed in a bucket. The procedure was repeated at the other four subsample sites. Finally, the five subsamples in the bucket were mixed with a trowel. Vegetation residues and stones were removed. Approximately 500 g of the mixed

([4]) https://ec.europa.eu/eurostat/documents/205002/8072634/LUCAS2018-C1-Instructions.pdf soil was taken with a trowel from the bucket, placed in a plastic bag, and labelled to derive the composite sample. Soil samples were allowed to air dry before the bags were sealed.

Figure 3 (a) LUCAS sampling schema, (b) summary of the common sampling procedure, and (c) summary of the bulk density sampling



For **determining bulk density**, soil cores were collected from 0 to 10 and 10 to 20 cm depths. Soil cores were also taken from 20 to 30 cm depth in Portugal to test the implications of extending the sampling depth in the LUCAS Soil Module. Before taking the soil cores, stones (>6 cm) (FAO, 2006), vegetation residues, grass and litter were removed from soil surface by raking with the spade as in the common sampling procedure. After the cleaning of the soil surface, five soil cores were taken from 0 to 10 cm depth with a metallic ring of 100 cm^3 at each LUCAS point. The first soil core was taken at the geo-referenced point location; the other four soil cores were taken at a distance of 2 m following the cardinal directions (North, East, South and West) (Figure 3a).

As shown in Figure 3c, a metallic ring was gently driven into soil using a wooden block to push the ring with a mallet. This avoided the compaction of soil. The ring was removed from soil with the help of a spade placed underneath the ring. The excess soil around the ring was removed with a knife and the soil core was pushed into a labelled plastic bag. The procedure was repeated in the four cardinal directions and the soil cores collected were placed in the same labelled plastic bag. In the end, five soil cores of known volume were taken at the 0 to 10-cm depth. After sampling the 0-10 cm depth was completed, the sampling of soil cores in the 10 to 20-cm depth was carried out following the same procedure (Figures 3a and 3c).

The soil cores were then allowed to air-dry and their weight was again recoded. The plastic bags were then sealed for their transportation to the laboratory.

In Portugal, due to time restrictions, a minimum of three cores were collected from each depth).

The **assessment of soil biodiversity** was carried out in a subset of locations sampled for bulk density. Field moist samples were taken from a depth of 20 cm using the standard approach. A composite sample of approximately 500 g was taken at each LUCAS point. The composite sample consisted of five subsamples taken with the help of a spade. The first subsample was taken at the geo-referenced LUCAS point location; the other four subsamples were collected at a distance of 2 m following the cardinal directions (North, East, South and West) (Figure 3a). The final sample was placed in a labelled jar and stored in a polystyrene box that had been cooled with freezer packs. Samples were sent by express courier to the JRC to preserve the biological characteristics. Samples were then frozen and stored at -20C at the JRC until their shipment to the laboratory for analysis.

2.2 Sample analysis

2.2.1 Core analysis

Samples were analysed in a single laboratory (SGS Hungary) for each property listed in Table 1 according to standard ISO methods (except for extractable potassium, oxalate extractable Fe and Al, and DNA analysis). Samples taken with the common procedure were analysed for physical and chemical properties (except for bulk density).

Bulk density was determined with soil cores, where the rest of physical and chemical properties were also analysed. In field-moist samples, DNA and antibiotic residues were analysed to assess soil biodiversity. Physical and chemical properties (except for bulk density and oxalate extractable Fe and Al) were also analysed in LUCAS 2009/12 and 2015 following the same laboratory methods. Bulk density, oxalate extractable Fe and Al, and soil biodiversity were determined in the 2018 survey for the first time.

Before the analyses, a subsample of the soil cores taken at each depth was oven-dried and the weight recorded to determine bulk density from 0-10, 10-20 and 20-30 cm depths (the latter only for samples from Portugal). The soil cores from 0-10 cm and 10-20 cm depths were then mixed to derive a composite sample from 0 to 20 cm depth for its analysis. The soil cores collected from 20 to 30 cm depth in Portugal were kept apart and analysed only for organic carbon content.

2.2.2 DNA analysis

DNA extraction, amplification and sequencing of LUCAS Soil samples were carried out by University of Tartu (Estonia). The DNA was used to amplify markers (DNA barcodes) of three groups of soil organisms – archaea, bacteria and eukaryotes (fungi and others). The amplified markers were sequenced using Illumina and PacBio platforms. Most of the 885 samples performed well in sequencing, resulting in thousands of sequences (see below). Only three samples performed poorly, either because of low DNA content or unexpectedly strong inhibition by coextracted soil chemicals. Nonetheless, DNA sequencing was carried out.

DNA extraction

DNA extraction was implemented by use of the Qiagen DNeasy PowerSoil HTP 96 Kit Q12955-4. Three 0.2 g aliquots per sample were extracted. After extraction the three subsamples were pooled. A negative control and positive control were used during extraction to locate any external contamination and cross-contamination.

Quality check and quantification of DNA were performed with Qubit™ 1X dsDNA HS Assay Kit using Qubit 3 fluorometer.

DNA amplification

Polymerase chain reactions (PCRs) were performed in three replicates using 5 x HOT FIREPol® Blend Master Mix (Solis BioDyne, Tartu, Estonia) in 25 µl volume. The optimal number of cycles and optimal annealing temperature were used for each primer pair. In case of PCR failure, the extracted DNA was purified using Favorgen FavorPrep Genomic DNA Clean-up Kit FAGDC001-1 and the PCR repeated. In case of further failure, more cycles were added to the thermocycler program. The PCR conditions were as follows:

- For Archaea, we used the primers: SSU1ArF (TCCGGTTGATCCYGCBRG) + SSU1000ArR (GGCCATGCAMYWCCTCTC). The PCR conditions included annealing temp. 55 °C, number of cycles 35, amount of 1.5 ng/µl DNA template 2 µl. In case of PCR failure even after DNA was purified, 40 cycles were used instead of 35 cycles.
- For Bacteria, we used the primers: 515F (GTGYCAGCMGCCGCGGTAA) + 926R (GGCCGYCAATTYMTTTRAGTTT). The PCR conditions included: annealing temp. 55 °C, number of cycles 26, amount of 1.5 ng/µl DNA template 1 µl. In case of PCR failure even after DNA was purified, 28 cycles were used instead of 26 cycles.
- For eukaryote ITS region, we used the primers: ITS9mun (GTACACACCGCCCGTCG) + ITS4ngsUni (CGCCTSCSCTTANTDATATGC). The PCR conditions included annealing temp. 55 °C, number of cycles 30, amount of 1.5 ng/µl DNA template 1 µl. In case of PCR failure even after DNA was purified, 33 or 35 cycles were used instead of 30 cycles.
- For eukaryote SSU region, we used the primers: Euk575F (ASCYGYGGTAAYWCCAGC) + Euk895R (TCHNHGNATTTCACCNCT). Here, a 4-fold greater amount of the reverse primer was used for optimal performance. The PCR conditions included annealing temp. 55 °C, number of cycles 30, amount of 1.5 ng/µl DNA template 1 µl. In case of PCR failure even after DNA was purified, 33 or 35 cycles were used instead of 30 cycles.

Both the forward and reverse primers were tagged with a 12-base multiplex identifier (MID) tag, except in case of Archaea where only the forward primer was tagged with MID. The three replicates of each reaction were pooled and visualised on TBE 1% agarose gel. PCR products were purified using UltraClean 96 PCR Cleanup Kit (Qiagen). DNA concentrations were measured with Qubit™ 1X dsDNA HS Assay Kit using Qubit 3 fluorometer (Invitrogen).

Metabarcoding library preparation

Illumina amplicon libraries were generated using TruSeq DNA PCR-Free High Throughput Library Prep Kit with TruSeq DNA CD Indexes. For PacBio, SMRTbell library preparation followed precisely the Pacific Biosciences Amplicon library preparation protocol.

Metabarcode sequencing was performed using the Illumina MiSeq platform with 2 x 300 paired-end mode or PacBio Sequel platform. Positive and negative controls of extractions as well as amplifications were used to further infer any contaminations.

Considering the expected richness in samples, the following sequencing strategies and sequencing depth were applied for various groups of organisms:

- Archaea: PacBio Sequel instrument (expected sequencing depth 2000 raw sequences per sample). The samples with less than 1000 reads were subjected to resequencing; for samples with less than 500 reads new tags were selected and then re-sequenced.
- Bacteria: Illumina MiSeq (exp. sequencing depth 120,000 raw sequences per sample). The samples with less than 50,000 reads were subjected to resequencing.
- Eukaryote ITS: PacBio Sequel instrument (exp. sequencing depth 4000 raw sequences per sample). The samples with less than 3000 reads were subjected to resequencing; for samples with less than 1500 reads new tags were selected and then re-sequenced.
- Eukaryote SSU: Illumina MiSeq (exp depth 120,000 raw sequences per sample). The samples with less than 50,000 reads were subjected to resequencing.

Antibiotic resistance genes were sequenced based on shotgun metagenomic analysis of the DNA extracts. Metagenome sequencing was performed by using Illumina HiSeq 2 x 150 in a paired-end mode. Library preparation and indexing for each sample was performed using Nextera XT DNA Library Prep Kit in combination with Nextera XT Index kits v2. Expected sequencing depth was 5,000,000 reads, but was increased to 10,000,000 reads to improve result quality. The samples with less than 5,000,000 reads were subjected to resequencing.

2.2.3 Analysis of plant protection products

A set of multi-residue methods based on Gas Chromatography/Mass Spectrometry (GC-MSMS) and Liquid chromatography–mass spectrometry (LC-MSMS) were developed to analyse the presence and concentrations of 120 molecules of active substances and metabolites of selected plant protection products (PPP). In parallel, a LC-MSMS method was developed to quantify the presence and concentration of antibiotics.

2.3 Field-based assessments

In addition to the sample collection, a range of soil related assessments were carried out in the field by surveyors. These included:

- The presence of rill, gully and wind erosion, mass movements, and re-deposited soil. Surveyors were trained and provided with a photographic guideline ([5]) to identify the various erosion signs. The field form ([6]) included a set of questions to describe and detail the conditions of erosion signs.
- The depth of the organic horizon was measured at each LUCAS point that fulfilled the following conditions in the former LUCAS soil surveys: organic carbon content >200 g kg^{-1} and/or classified as wetland in the LUCAS survey. The measurement was done at the geo-referenced LUCAS point location and at a distance of 2 m following the four cardinal directions (North, East, South and West) giving five measurements of the thickness of organic horizon per LUCAS point.
- The presence of stones and crop residues on the soil surface was assessed.
- The presence of landscape features that could affect soil erosion (walls, hedges, grass margins, etc.).

([5]) https://ec.europa.eu/eurostat/documents/205002/8072634/LUCAS2018-C1-Instructions.pdf
([6]) https://ec.europa.eu/eurostat/documents/205002/8072634/LUCAS2018-C2-FieldForm-GD-Template.pdf

Table 1 Methods used for the analysis of physical and chemical properties in soil samples.

Soil properties	Method	Description
Bulk density	Adapted ISO 11272:2017	Calculated from the mass and the volume of sole cores taken with rings of known volume
Coarse fragments	ISO 11464:2006	Sieving to separate coarse fragments (2-60 mm) from fine earth fraction
Clay, silt and sand	ISO 11277:1998 ISO 13320:2009	Laser diffraction (please note that the sieving and sedimentation method was used in 2009 and 2012)
pH in $CaCl_2$ and in H_2O	ISO 10390:2005	Glass electrode in a 1:5 (V/V) suspension of soil in H_20 and $CaCl_2$
Electrical Conductivity	ISO 11265:1994	Metal electrodes in aqueous extract of soil
Organic carbon	ISO 10694:1995	Dry combustion (elementary analysis)
Carbonates	ISO 10693:1995	Volumetric method
Phosphorus	ISO 11263:1994	Spectrometric determination of P soluble in sodium hydrogen $CaCO_3$ solution
Total nitrogen	ISO 11261:1995	Modified Kjeldahl method
Extractable potassium	USDA–NRCS, 2004	Atomic absorption spectrometry after extraction with NH_4OAc
Oxalate extractable Fe and Al	Ross and Wang, (1993)	Acid ammonium oxalate method
Metals	ISO 11466: 1995	Trace elements are extracted in aqua regia. The resulting solution is analysed by inductively coupled plasma-optical emission spectrometry.
Biodiversity*	DNA analysis Orgiazzi et al (2022)	DNA extraction, amplification and sequencing using Illumina and PacBio platforms
Plant protection products*	Various methodologies	*Sample preparation:* - Multi-residue method QuEChERS - Strong alkaline/acid extractions - McIlvainbuffer/acetonitrile;SPE cleanup - MeOH/0.1 M HCl, 80°C; dilution *Instrumental analysis:* LC-MS/MS and GC-MS/MS

**analysed in different laboratories to physical and chemical parameters*

3 Soil data evaluation

Data validation processes aim to provide certain guarantees of accuracy, completeness and consistency of data. Based on the methodology developed by Hiederer et al. (2018) for other pan-European soil databases, three aspects were assessed for the LUCAS 2018 soil data: compliance, conformity, and uniformity. Compliance concerns the data format, conformity involves the data content, and uniformity is related to the comparability of data between different surveys. The following tests were applied to evaluate compliance and conformity:

— control of the identification and registration of samples during the field survey and in the laboratory (Conformity check, section 3.1),

— agreement of the data format with the specifications indicated in the call for tender of LUCAS 2018 (Compliance check, section 3.2),

— evaluation of soil data produced in the laboratory and application of pedological criteria (Conformity check, section 3.3),

— evaluation of field-based data (Conformity check, section 3.4).

The uniformity of soil data is not addressed by this report. This aspect will be evaluated in the report focused on the comparison of changes in soil data between the various LUCAS soil surveys.

3.1 Identification and registration of samples during the field survey and in the laboratory

Points in the LUCAS grid are identified by unique Point IDs. These Point IDs are used in each survey to record agro-environmental data related to each point in the Data Management Tool (DMT) managed by Eurostat. Furthermore, samples collected in LUCAS points are identified by Soil IDs. The JRC creates these Soil IDs. In each LUCAS survey, surveyors randomly assign these Soil IDs to the samples when collected. Each sample is double-packed with twin labels that have the same Soil ID. At each LUCAS point, surveyors document agro-environmental observations by filling in a field form and by taking photographs. Surveyors have to indicate the Point ID and the Soil ID in the field form. All the data is then stored in the DMT. Thus, each sample has a double identification: the Soil ID and the Point ID. The Soil ID is used to identify the samples in the laboratory and provides the soil data, while the Point ID gives the field data and is used to link information from different LUCAS surveys.

Of the 18,916 samples taken at 0-20 cm depth, 139 did not have any Soil ID assigned, but had a Point ID assigned. This allowed us to identify the samples and link them to LUCAS points in the LUCAS grid. There were also 410 duplications of Soil IDs that affected 821 samples (reasons: transcription errors in the laboratory, identification errors of surveyors in the field). For most of these, we were able to correctly identify them using the analysis groups they belonged to (see Section 3.2), the MS in which they were collected, and their Point ID. However, there were 67 samples with duplicated Soil ID that could not be assigned to unique LUCAS points and agro-environmental information either because they had duplicated Point IDs or they were not recorded in the DMT. As a result, these 67 samples were removed from the dataset. There were also 70 samples with duplicated Point IDs that could be correctly identified using their Soil IDs. Finally, there were 79 samples whose Point IDs were not traceable and had to be removed from the dataset.

While 25,947 LUCAS points were planned for soil sampling, a total of 18,984 LUCAS points were registered with unique records, taken at various depths. These consist of 18,744 unique records with soil data from 0 to 20 cm depth (Table 2). For 141 points (all taken in Portugal), the laboratory also registered samples taken from 20 to 30 cm depth and identified with unique Soil IDs and Point IDs. For these points, only organic carbon and carbonates contents analyses were performed (Table 2). Furthermore, the laboratory registered 232 samples taken from 0-10 cm depth only and 8 samples taken from 10-20-cm depth only (Table 2). These 240 samples were identified with unique Soil IDs and Point IDs, different from the 18,744 points with samples from 0-20 cm depth.

While the determination of bulk density was planned in 9,000 points, the laboratory registered samples taken at different depths in 6,846 LUCAS points. 313 samples had repeated Point IDs (in all, there were 142 repeated Point IDs). We were able to identify 137 out of these points through the groups they belonged to, the MS where they were taken, and the Soil IDs of samples taken in these points. As detailed in section 2, samples were taken at two depths (0-10 and 10-20-cm) in each point. In points from Portugal, extra samples were also taken from 20 to 30-cm depth. All samples collected in a LUCAS point had the same Soil ID. In the end, bulk density data at different depths were available for 6,271 points identified with unique Point IDs (Table 2). Bulk density from 0 to 10 cm depth was determined in 6,246 points and from 10 to 20 cm depth in 5,786 points, and from 20 to 30 cm depth in 140 points. Moreover, bulk density from 0-20 points was calculated in 5,761 points interpolating data from 0-10 and 10-20 cm depths (Table 2).

The soil collected for bulk density was then analysed for physical and chemical properties.

Metals were planned to be analysed in 1,013 points. This was based on locations where one or more metal element(s) showed a high content in the LUCAS 2009/12 survey, together with a randomly selected set of points for assessing changes in locations with low or no concentrations. Overall, the laboratory registered samples taken in 997 LUCAS points: 978 samples from 0 to 20 cm depth, 15 samples from 0 to 10 cm depth only, and 4 samples from 10 to 20 cm depth only (Table 2).

Table 2 Summary of LUCAS points visited and number of samples taken or observations in the LUCAS 2018 soil survey

	LUCAS points		***N* samples**			
	Planned	**Sampled [(1)]**	**0-20 cm**	**0-10 cm**	**10-20 cm**	**20-30 cm[(2)]**
Basic soil properties	25,947	19,125	18,744	232	8	141
Metals	1,013	997	978	15	4	--
Bulk density	9,000	6,271	N/A	6,246	5,786	140
Biodiversity	1,000	885	885	N/A	N/A	N/A
Organic soils	1,470	1,050	N/A	N/A	N/A	N/A
Soil erosion	25,947	24,759	N/A	N/A	N/A	N/A

(1) LUCAS points sampled and identified with unique Point IDs.
(2) These additional samples were taken at a deeper depth on points otherwise also sampled at the standard 0-20cm depth.

3.2 Agreement of the data format with the specifications of the call for tender for laboratory analysis in LUCAS 2015

The technical specifications of the call for tender for the laboratory analysis in the LUCAS 2018 survey ([7]) included the following conditions:

— Data generated in the laboratory for each soil sample shall be appropriately attributed to its Soil ID in the dataset.

— Data of physical and chemical properties shall be delivered in Excel (or 100 % Excel-compatible) workbook.

  o A separate workbook shall be created for each group of samples identified in the technical specifications:

    ▪ *Group 1*: samples taken in organic-rich soils with the common sampling procedure,

    ▪ *Group 2*: samples taken in organic-rich soils with metallic rings for the determination of bulk density,

    ▪ *Group 3*: samples taken in mineral soils with metallic rings for the determination of bulk density,

    ▪ *Group 4*: samples taken in mineral soils with the common sampling procedure.

  o Each workbook shall have two sheets: the first sheet shall contain data of basic physical and chemical properties and the second sheet shall contain data of metals.

— Data in the two sheets of each workbook shall be presented in columns following the order specified in the technical specifications.

— Units and number of decimals for each property shall also follow the technical specifications.

The laboratory delivered an Excel workbook with the data generated for soil samples in each group identified in the technical specifications. As requested, each workbook contained two sheets, one for basic soil properties and other for metals. Data of each soil sample was linked to its identifier, named Soil ID, in the workbooks. The Soil ID permitted to attribute the soil data to a LUCAS point in the LUCAS 2018 database of Eurostat.

Data were ordered in columns as indicated in the technical specifications, except for silt and sand columns that were interchanged in the worksheet of basic soil properties. The laboratory added four extra columns in each of the two sheets of the workbooks with the following information: sample identification (an internal identification of samples in the laboratory), Point ID (unique identifier of the point in the LUCAS Survey grid), group to which each sample belongs, and depth at which the sample was taken. In addition, the laboratory changed the name of the column that contained the identifier of the sample from Soil ID to Client ID in the workbooks.

The technical specifications did not include indications for the coding of missing data nor for data outside detection limits. From the four workbooks it could be concluded that empty fields or fields with 'NA' indicated missing data. This was the case of NAs in Client ID column, which indicated that the sample identifiers (Soil ID) were not found. For physical and chemical properties, the empty fields indicated that these properties were not analysed. Regarding the limits of detection (LOD), the laboratory provided the values for the methods used to analyse the physical and chemical properties (Table 3).

([7]) https://etendering.ted.europa.eu/cft/cft-display.html?cftId=3200

The units and number of decimals reported for each property adjusted to the specifications provided to the laboratory (Table 3).

Table 3 Limits of detection (LOD) of the various physical and chemical properties analysed.

Physical and chemical properties	**Units**	**Decimals**	**LOD**
Basic properties			
Bulk density	g kg^{-1}	2	--
Coarse fragments	%	0	--
Sand	%	0	--
Silt	%	0	--
Clay	%	0	--
pH-$CaCl_2$	--	1	2–10
pH-H_2O	--	2	2–10
Electrical conductivity	mS m^{-1}	2	0.1
Organic carbon	g kg^{-1}	1	2.0
Carbonates	g kg^{-1}	0	1.0
Phosphorous	mg kg^{-1}	1	10.0
Total nitrogen	g kg^{-1}	1	0.2
Extractable potassium	mg kg^{-1}	1	10.0
Oxalate extractable Fe and Al	mg kg^{-1}	1	20 ppm

Physical and chemical properties	**Units**	**Decimals**	**LOD**
Metals			
Arsenic	mg kg^{-1}	1	1.0
Cadmium	mg kg^{-1}	1	0.2
Cobalt	mg kg^{-1}	1	0.5
Chrome	mg kg^{-1}	1	0.5
Copper	mg kg^{-1}	1	2.0
Mercury	mg kg^{-1}	1	0.05
Nickel	mg kg^{-1}	1	1.0
Lead	mg kg^{-1}	1	1.0
Antimony	mg kg^{-1}	1	0.1
Vanadium	mg kg^{-1}	1	0.05
Zinc	mg kg^{-1}	1	2.0

3.3 Evaluation of soil data produced in the laboratory

This section presents an overview of the data of soil properties analysed. For basic physical and chemical properties (except bulk density) and metals, the evaluation focused on the data of samples from 0 to 20 cm depth (i.e. the standard sampling depth on LUCAS 2018). For bulk density, we evaluated data from 0-10, 10-20, 0-20 and 20-30 cm depths.

Table 4 gives an overview of the range of values for each soil property in the 2018 LUCAS Soil Module. The values reported for basic physical and chemical properties by the laboratory were within reasonable limits for soils in Europe. In fact, they were similar to those reported in the LUCAS 2009/12 and 2015 surveys. The range of values for bulk density at different depths were also considered acceptable for soils in Europe, with higher values reported in the 20 to 30 cm depth than in the 0 to 10 and 10 to 20 cm depths. Values of the various metals analysed were similar to those observed in the LUCAS 2009/12 surveys. In addition, all metals showed some high values as in the 2009/12 surveys.

The LOD of the analytical methods were used to highlight the presence of values that were outside the possible ranges (Table 4). For most of the properties, only very few values were recorded below the LOD. Only $CaCO_3$ and P showed a high number of values below their LOD. The high number of outlier values for $CaCO_3$ was due to the use of the value "0" to indicate the absence of $CaCO_3$ in soil samples with low pH (pH<7). The value "0" has later been substituted by "NA" in the dataset. Soil samples with the P content below the LOD were mainly located in woodland and shrubland (altogether 54 %), and grassland and cropland most likely not subject to fertiliser applications (19 % and 23 %, respectively).

Table 4 Range of values and number of samples below the limit of detection (LOD) for soil properties in LUCAS 2018 Soil Module.

Soil parameter	Range actual values	LOD	*N* samples <LOD	% of the data
Basic properties				
Coarse fragments (%)*	0–100	--	--	--
Sand (%)*	2–100	--	--	--
Silt (%)*	0–72	--	--	--
Clay (%)*	0–66	--	--	--
pH-$CaCl_2$	2.6–9.8	2–10	0	0
pH-H_2O	3.34–10.43	2–10	0	0
Electrical conductivity (mS m^{-1})	0.24–1295.6	0.1	0	0
Organic carbon (g kg^{-1})	0–723.9	2.0	31	0.2
Carbonates (g kg^{-1})	0–926	1.0	7652	41
Phosphorous (mg kg^{-1})	0–515	10.0	4918	22
Total nitrogen (g kg^{-1})	0–46.5	0.2	14	0.1
Extractable potassium (mg kg^{-1})	1.4–7578.8	10.0	38	0.2
Oxalate extractable Fe and Al (mg kg^{-1})	Al: 0.1-34.7 Fe: 0.1 – 35.8	20 ppm	2527	13.3
Bulk density, 0-20 cm (g kg^{-1})	0.04–8.66	--	--	--
Bulk density, 0-10 cm (g kg^{-1})	0.03–8.47	--	--	--
Bulk density, 10-20 cm (g kg^{-1})	0.04–8.86	--	--	--
Bulk density, 20-30 cm (g kg^{-1})	0.71–1.72	--	--	--
Soil parameter	**Range accepted values**	**Limit of detection (LOD)**	***N* samples <LOD**	**% of the data**
Metals				
Arsenic (mg kg^{-1})	1.0–939.9	1.0	8	0.8
Cadmium (mg kg^{-1})	0.2–10.4	0.2	58	5.9
Cobalt (mg kg^{-1})	0.5–182.9	0.5	1	0.1
Chrome (mg kg^{-1})	0.5–1203.2	0.5	1	0.1
Copper (mg kg^{-1})	2.0–973.9	2.0	8	0.8
Mercury (mg kg^{-1})	0.05–4	0.05	2	0.2
Nickel (mg kg^{-1})	1.0–3249.3	1.0	11	1.1
Lead (mg kg^{-1})	1.0–294.7	1.0	1	0.1
Antimony (mg kg^{-1})	0.1–35.9	0.1	7	0.7
Vanadium (mg kg^{-1})	1.6–320	0.05	0	-
Zinc (mg kg^{-1})	2.0–2385.6	2.0	2	0.2

*PSD are reported in the 2009 and 2015 datasets

The pedological coherence of the data was assessed with a range of correlations between soil properties. These correlations included:

— *Correlation between OC and N*. A close relationship exists between OC and N levels in soil. The higher the OC concentration, the greater the N concentration (Figure 4). Moreover, the C-to-N ratio is relatively stable across different soil types. Overall, mineral soils generally have a C-to-N ratio close to 12:1 (Table 5), while organic-rich soils shall have a C-to-N ratio close to 30:1 (Table 5). Soil samples with a C-to-N ratio greater than 40:1 need further consideration, since it is not usual for soil organic matter to have values higher than this.

Figure 4 Relation between OC and N in the dataset.

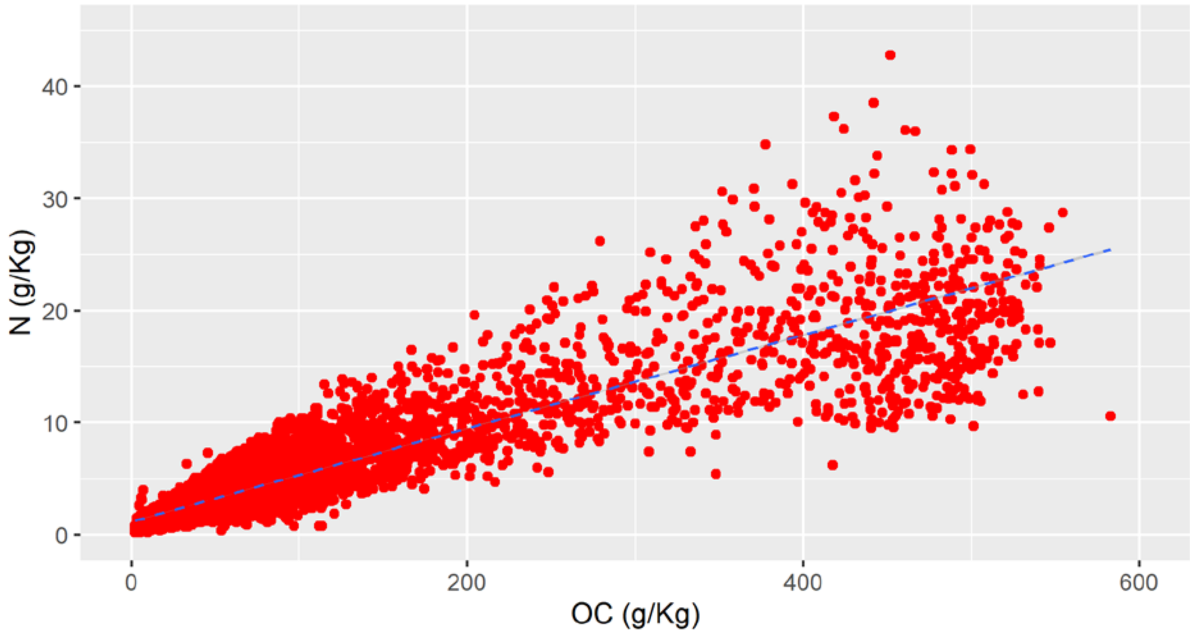


Table 5 Summary statistics of C-N ratio in mineral (<200 g kg-1) and organic (>200 g kg-1) soils

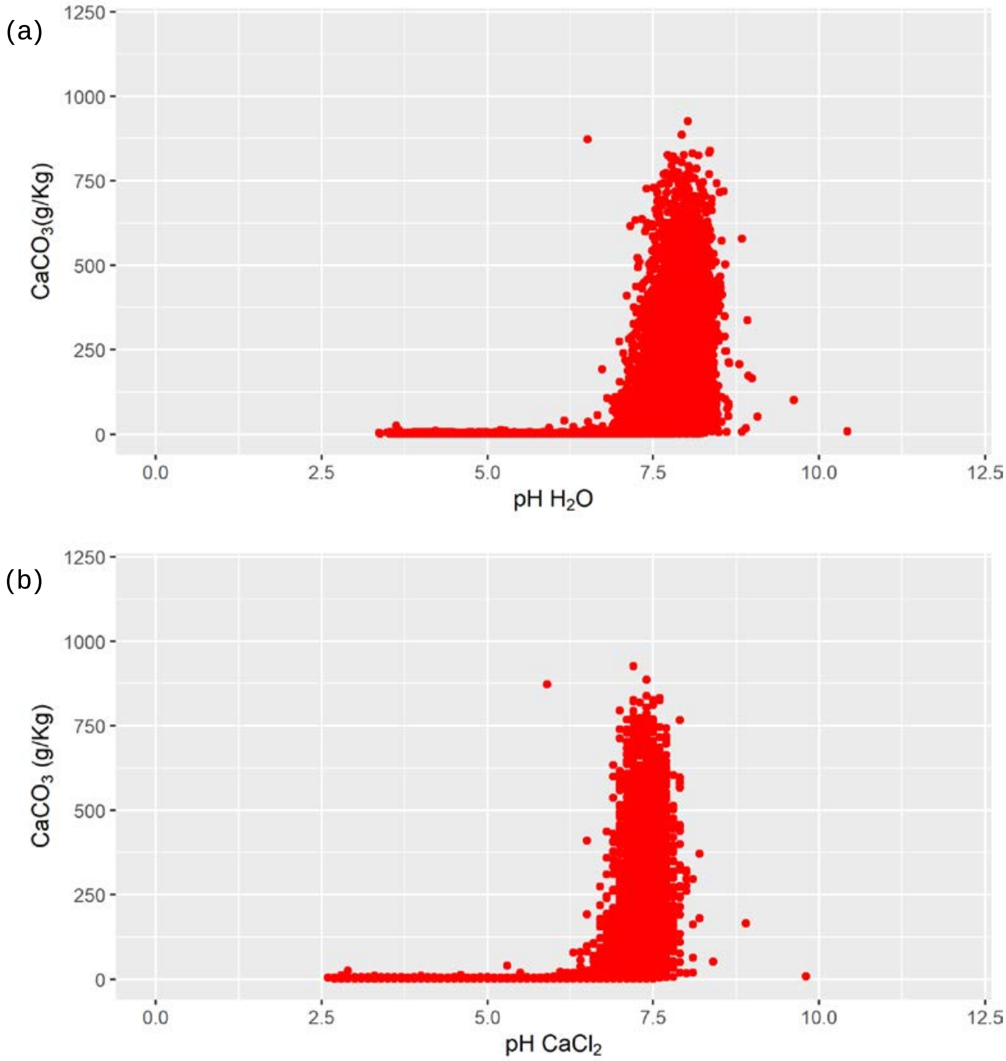
	***N* samples**	**Range values**	**Mean**	**Median**	**Std dev**
Mineral samples	17,847	2:1–142:1	12:1	10:1	6:1
Organic samples	859	10:1–67:1	24:1	23:1	8:1
Samples with C-to-N ratio >40:1	96 (1)	40:1–142:1	51:1	44:1	19:1

(1) Out of the 96 samples, 53 are mineral samples and 43 are organic samples.

— *Correlation between pH and $CaCO_3$.* pH is a measure of the acidity or alkalinity in the soil. Soil pH can be measured in H_2O and in $CaCl_2$. The values of pH in $CaCl_2$ are normally lower than pH in H_2O by 0.5 to 0.9. Soils have commonly pH in H_2O values between 3.5 and 9.0. Calcium carbonate should not be present (or the concentrations should be very low) in soils where pH is below 7, as its solubility is pH-dependent and it does not form under acidic conditions. In accordance with this criterion, Figure 5 shows (i) that pH in H_2O ranges between 3.3 and 10.4 while pH in $CaCl_2$ ranges between

2.6 and 9.8, and (ii) that soil samples with pH around 7.0 – 8.5 have the greatest contents of $CaCO_3$.

Figure 5 Relation between pH and $CaCO_3$ in the dataset: (a) pH in H_2O, (b) pH in $CaCl_2$



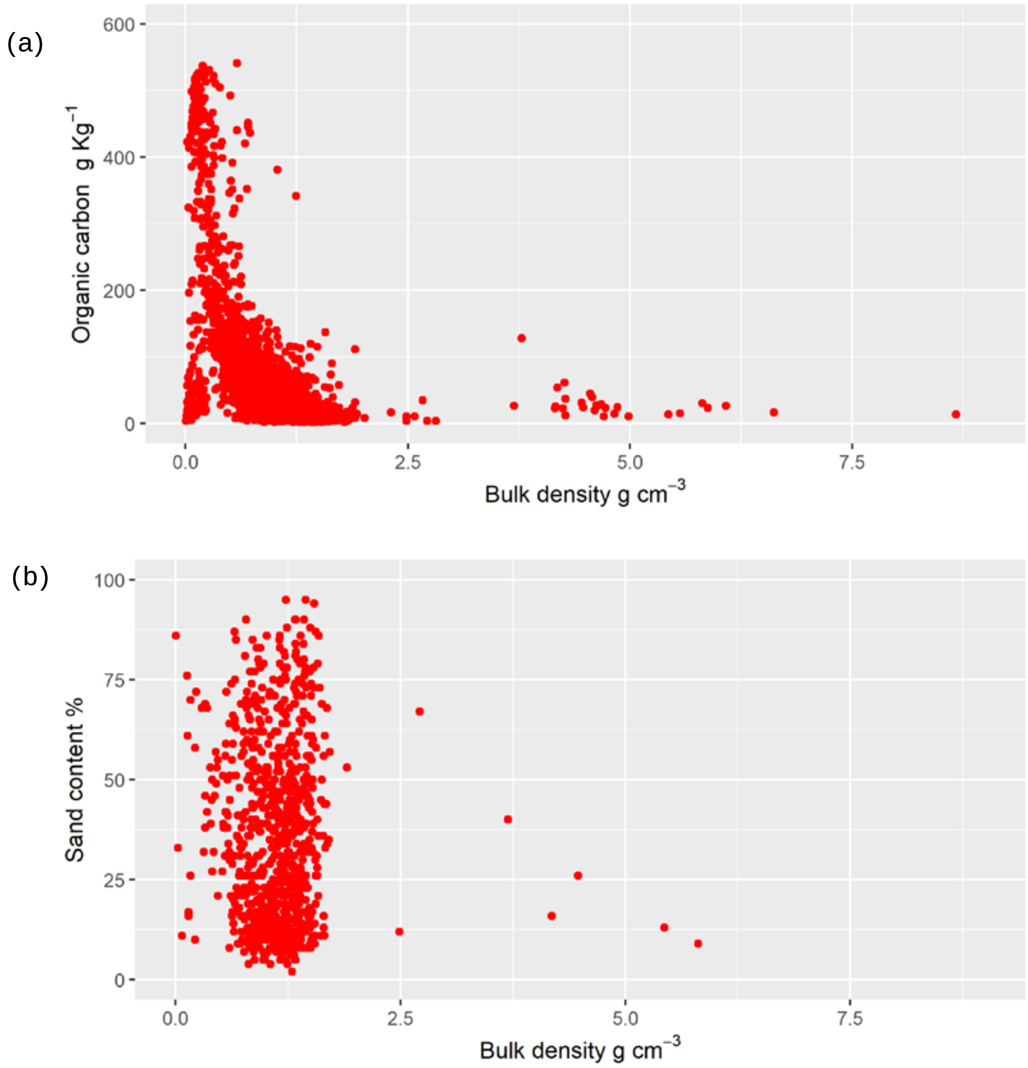
— *Coherence of particle size distribution (PSD) data*. Mineral fraction <2 mm in soil can be split in three size fractions: sand (2-0.063 mm), silt (0.063-0.002 mm) and clay (<0.002 mm). In the LUCAS 2018 survey, these three fractions were measured in 2,505 points, randomly selected, as quality check, for comparison purposes with PSD data from the LUCAS 2009/12 and 2015 surveys ([8]). The random selection considered the variability of sand, silt, and clay contents, and the occurrence of different textural classes in the dataset. In order to check the coherence of the PSD data, we checked that the sum of the mass of the sand, silt and clay fractions was equal to 100 %. The sum of the three fractions ranged between 99 % and 101 % in the dataset because the contents of the three fractions were rounded to the nearest whole number.

— *Correlation between bulk density, sand, and OC contents*. Bulk density depends on OC content, the combination of sand, silt and clay contents (i.e. soil texture), and the structure/porosity of the soil. It was not possible to establish individual correlations

([8]) Comparison of PSD data among surveys will be described in a separate report assessing differences on soil properties among the various soil surveys.

between bulk density and OC or sand content (Figure 6). However, there are some general rules that can be observed. In general, organic-rich soils (>120 g kg^{-1}) tend to have a low bulk density (circa 0.5 g cm^{-3}) (Figure 6a), while sandy soils (sand content > 80 %) have a relatively high bulk density (>1.6 g cm^{-3}) (Figure 6b). Furthermore, compacted soils with low sand content (<20 %) can have very high bulk density values (Figure 6).

Figure 6 Relation between bulk density, OC and sand contents in the dataset: (a) bulk density – OC content, (b) bulk density – sand content



Overall, the actual values of the various physical and chemical properties analysed as part of the 2018 LUCAS Soil Module are considered to be in line with expectations for European soils, and are similar to those reported in the LUCAS 2009/12 and 2015 surveys. In addition, the correlations assessed between soil properties followed the expected trends from a pedological point of view.

3.4 Evaluation of field-based data

Soil erosion and the condition of organic soils were assessed for the first time in the LUCAS 2018 survey. This section presents an overview of the checks carried out on the information collected by surveyors for these two aspects.

a) *Evaluation of soil erosion*

Surveyors were asked to record evidence of soil erosion by water or wind within a distance of 500 m from all the LUCAS points included in the soil module. In case of any evidence, surveyors had to take a picture of the area affected and indicate the type of erosion observed (i.e. rills, gullies, wind erosion, mass movements and/or re-deposited soil), in which cardinal direction signs were observed, and the distance at which signs were observed from the LUCAS point.

The DMT included the following record descriptors regarding soil erosion:

— erosion can do (1 yes / 2 no) [able to assess the presence of erosion],

— signs of erosion (1 yes / 2 no / NR not relevant),

— for each type of erosion observed:

  - o erosion in the LUCAS point, North, East, South, West (1 yes),
  - o distance from LUCAS points for the four cardinal directions (in m).

Empty fields in the responses to 'erosion can do' and 'signs of erosion' were taken as negative responses. Surveyors also used the value "0" or left fields empty to give a negative response or indicate absence of information in the two questions on each erosion type. Zero values were substituted by empty fields to harmonize information in the dataset.

Surveyors were able to assess evidence of erosion in 65% of the assessed points, of which only 850 points showed signs of erosion. Most of the points identified as having erosive features (687 points, 80.8%) showed only one type of erosion. In 126 points (14.8 %), evidence of two types of erosion were observed. The remaining 37 points showed evidence of three or four types of erosion (Figures 7 & 8).

Regarding the distance at which evidence of erosion was observed from the LUCAS point, 642 out of 850 points recorded this information (75.5 %). At four points, no evidence of erosion was recorded, however, information on the observation distance was provided.

Table 6 shows the distribution of points with evidence of erosion according to the various erosion types assessed. In all types of erosion, more than 55 % of the points showed only one type of erosion, followed by those points that showed two types. As expected, the number of points with evidence of three or more types of erosion were negligible.

The photos taken by surveyors showed that sheet, rill and wind erosions, signs of re-deposited soil and mass movements were not correctly identified. Thus, the information of these types of erosion could not be validated and has not been included in this report. On the contrary, surveyors were able to correctly identify evidence of gully erosion. A comparison of field photos with images of remotely sensed data (Google Earth) to validate the data showed a high correspondence to gully erosion. As a result, this report offers a detailed description of gully erosion in the EU during the LUCAS 2018 survey.

Table 6 Distribution of points with evidence of different types of erosion as recorded by surveyors in the LUCAS 2018 survey.

Erosion type	*N* points with evidence of erosion	% of points with only 1 type of erosion	% of points with at least 2 types of erosion
Sheet erosion	192	57.8	31.2
Rill erosion	290	58.9	30.3
Gully erosion	211	69.7	19.4
Mass movement	223	87.4	7.6
Re-deposited soil	96	42.7	37.5
Wind erosion	40	55.0	25.0

Figure 7 Maps showing the locations where signs of deposition by wind (left) and mass movement (right) were recorded by surveyors.

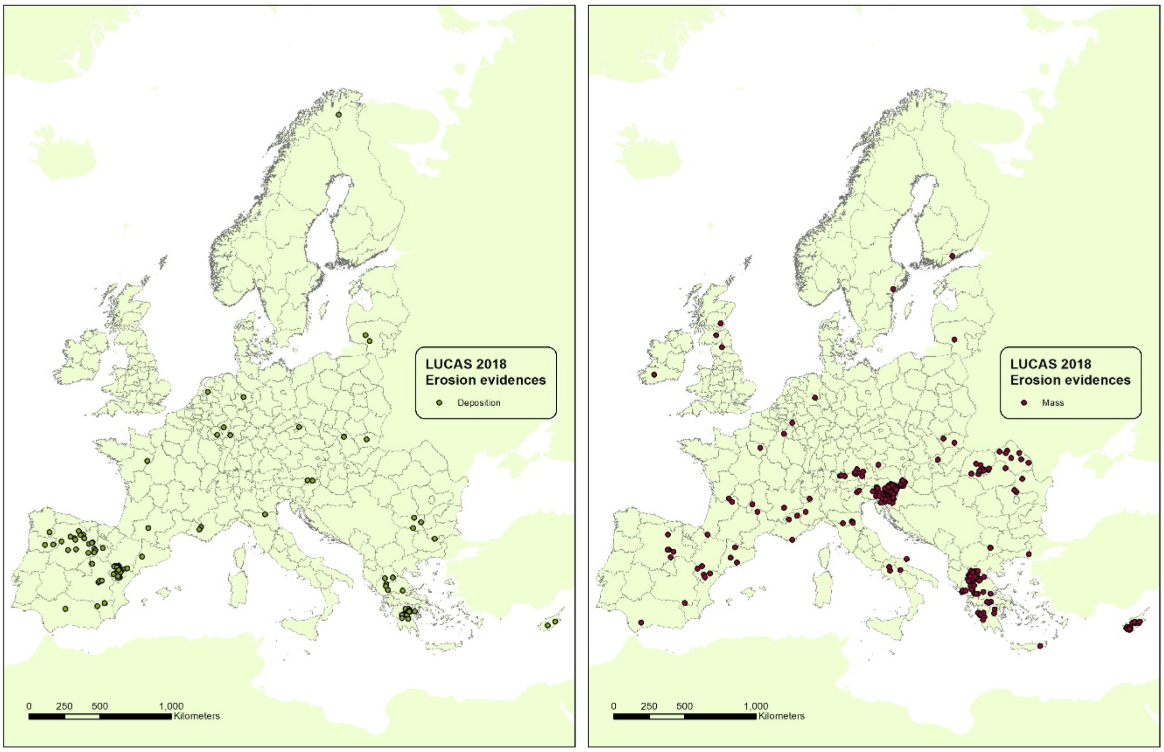
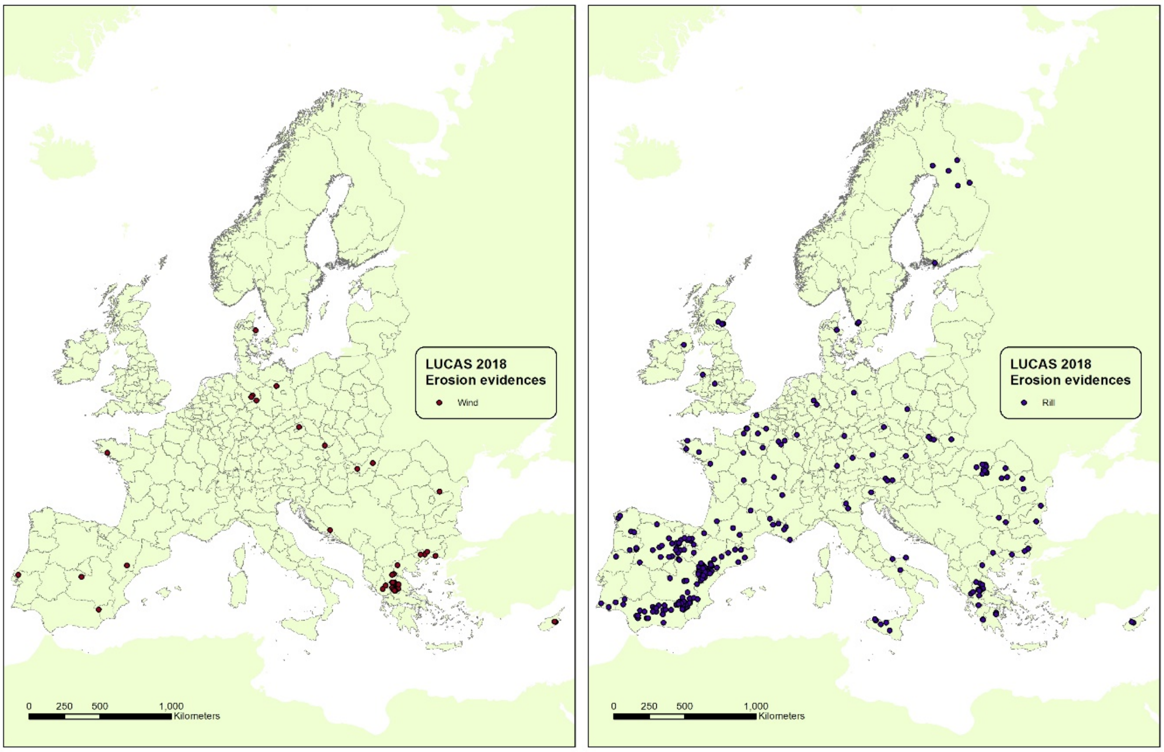


Figure 8 Maps showing the locations where signs of wind erosion (left) and rill erosion (right) were recorded by surveyors.



b) Evaluation of organic soils

The condition of organic soils at specific LUCAS points was assessed by measuring the depth of the organic horizon in five locations (at the LUCAS point and at a distance of 2 m following the four cardinal directions). Surveyors were provided with a list of potential points located in organic soils based on their OC data and LC classification in former LUCAS surveys (OC content >200 g kg^{-1} and/or located in the Wetland LC class). Overall, 1,470 points were identified as potentially being located in organic soils. Surveyors had to indicate whether they could assess the depth of the organic horizon and, if so, record the depth of the organic horizon in the five locations at each LUCAS point. If the depth of the organic horizon was less than 40 cm, surveyors had to indicate the exact depth. If the depth was greater than 40 cm, it was not compulsory to indicate the exact depth (they could record that the depth was >40 cm). In addition, they had to indicate whether the points were in cultivated soils.

The DMT included the following record descriptors regarding the condition of organic soils:

— organic can do (1 yes / 2 no), [able to assess the presence of organic soils]

— organic cultivated (1 yes / 2 no / NR not relevant),

— depth of organic horizon in the LUCAS point, north, east, south, west (in cm),

— depth more than 40 cm (1 yes / 2 no)

The responses to ‘organic can do’ and ‘organic cultivated’ included empty fields that were taken as negative responses. In fact, there was no NR (‘not relevant’) record in the DMT for the question on cultivation of organic soils. In the last two questions, surveyors used the value “0” or left fields empty to give a negative response or indicate absence of information. Zero values were substituted by empty fields to harmonize information in the dataset.

Surveyors were able to measure the depth of organic horizon in 1,050 out of the 1,470 potential points located in organic soils, although depth was finally recorded only in 1,042 points (Figure 9). From these points, the exact depth of the organic horizon was recorded for 731 points (70%) while the depth recorded was >40 cm in the remaining 30% of locations sampled. Where exact depth was recorded, surveyors recorded three measurements of depth in most of the points (in 583 out of the 731 points). Five measurements of depth were recorded only in 77 points (Table 7). Regarding cultivation of organic soils, only 98 points out of 1,042 were located in cultivated fields.

Most of the sites selected for depth assessments appear not to fulfil the depth criteria for Histosols. However, the assessment failed to provide a reason for the very shallow organic soils (e.g. such as on bedrock). The implication is that many of these LUCAS points are on either mineral soils with well-developed organic horizons or that peatlands have been eroded back to the underlying mineral base.

Figure 9 Map showing the locations where the depth of organic soils was measured.

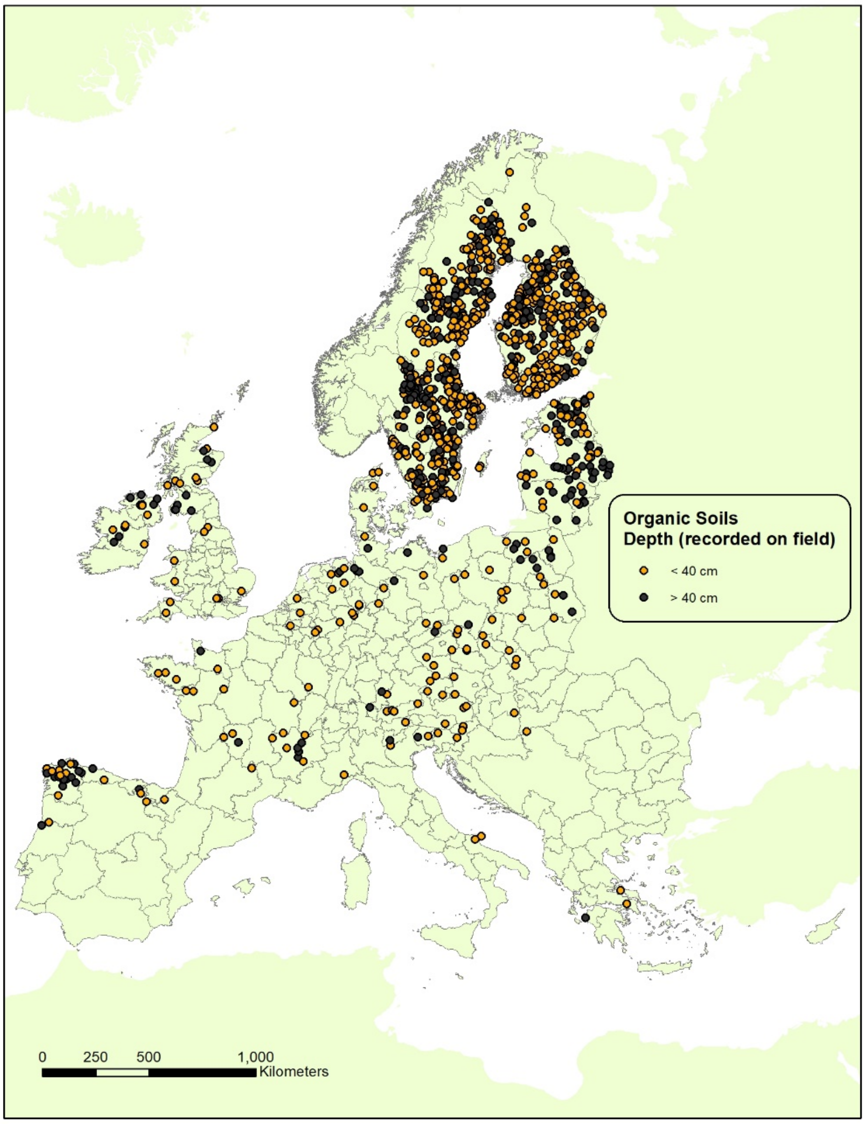


Table 7 Summary of data of organic soils recorded by surveyors in the 2018 LUCAS Soil Module.

Characteristics of organic soils	*N* points			
Depth info recorded	1,042			
Depth > 40 cm recorded	311			N points
Exact depth recorded Range of values (cm)	731 1–55	*N* measurements of depth per point	1	34
			2	21
			3	583
			4	16
			5	77

4 The 2018 LUCAS Soil Module: structure and description

The 2018 LUCAS Soil Module contains various files with different soil data:

- Basic soil properties: data of physical and chemical properties analysed in samples taken at various depths in 18,984 LUCAS points ([9]), as follows:
  - Samples taken from 0-20 cm depth in 18,744 points (in 141 of these points, all taken in Portugal, OC and $CaCO_3$ were also analysed in additional samples taken from 20-30-cm depth)
  - Samples taken from 0-10 cm depth in 232 points,
  - Samples taken from 10-20 cm depth in 8 points,
- Metals: a summary of descriptive statistics of 997 LUCAS points with high and low concentrations of metals,
- Extractable aluminium and iron oxalate for 2,510 cropland locations,
- Erosion assessment: information recorded on erosion evidences for 879 LUCAS points,
- Assessment of organic soils: measurements of depth of organic horizon from 1,050 LUCAS points,
- Biodiversity and plant protection products: summary statistics only,
- Environmental conditions: reference ancillary data describing a range of environmental conditions for all LUCAS points of the soil module.

In the various files, data from each LUCAS point are identified with their Point ID, which serves to link data from the various files of the soil dataset with the field information published in the LUCAS portal of Eurostat ([10]).Table 8 shows the distribution of LUCAS points by MS and LC in the LUCAS 2018 survey. It has to be noted that not all LUCAS points have data for all properties analysed and field-based assessments.

Data of physical and chemical properties in the file of basic soil properties are reported in the fields (columns) as indicated in Table 9a. In addition, a limited number of supplementary data have been extracted from the LUCAS portal of Eurostat to provide a geographical and LC/LU context to users of the soil data (Table 9b).

The file of erosion assessment is arranged in 69 fields that contain information on erosion evidences (Table 10). Similarly, the file of assessment of organic soils contains information of the different measurements of the organic horizon depth made at each LUCAS point. The information is arranged in 14 fields (Table 11).

Supplemental environmental information, such as climate, topographic setting, soil regions, and NATURA 2000 sites, for all soil sampling locations are available from ESDAC.

The 2018 LUCAS Soil dataset is made available in two formats (CSV and SHAPE). Data can be downloaded through the European Soil Data Centre (ESDAC) using the following URL: https://esdac.jrc.ec.europa.eu/resource-type/datasets.

([9]) Note that the dataset contains 88 LUCAS points with bulk density data but no data for the rest of physical and chemical properties.
([10]) https://ec.europa.eu/eurostat/web/lucas/data/primary-data/2015

Table 8 Summary of points by MS and LC in the LUCAS 2018 survey.

NUTS 0	Points	Artificial land	Bareland	Cropland	Grassland	Shrubland	Water	Wetlands	Woodland
AT	449	6	2	90	135	5	0	1	210
BE	130	0	7	81	14	0	0	2	26
BG	574	2	3	274	122	17	0	0	156
CY	69	0	3	30	15	14	0	0	7
CZ	445	1	2	232	104	2	0	1	103
DE	779	5	13	332	213	3	0	1	212
DK	171	1	3	125	24	3	0	0	15
EE	201	2	3	55	37	4	0	0	100
EL	598	1	29	228	127	52	2	0	159
ES	3867	12	338	1870	599	339	0	0	709
FI	1143	2	3	134	50	24	0	1	929
FR	2735	9	84	1383	709	51	2	2	495
HR	106	1	8	9	27	6	0	0	55
HU	354	3	24	198	67	2	0	1	59
IE	143	0	0	17	107	6	0	5	8
IT	1242	1	4	628	297	34	0	0	278
LT	386	0	3	196	98	0	0	0	89
LU	35	1	1	12	12	0	0	0	9
LV	331	0	5	91	88	5	0	0	142
MT	2	0	0	2	0	0	0	0	0
NL	99	2	2	47	33	1	0	1	13
PL	1376	3	18	686	344	6	1	2	316
PT	429	2	6	111	89	50	0	0	171
RO	603	5	23	257	227	19	0	0	72
SE	1906	5	21	120	121	51	0	18	1570
SI	112	1	0	11	27	1	0	0	72
SK	186	3	0	71	49	3	0	1	59
UK	513	3	33	139	254	22	0	4	58
EU+UK	**18984**	**71**	**638**	**7429**	**3989**	**720**	**5**	**40**	**6092**
EU-27	**18471**	**68**	**605**	**7290**	**3735**	**698**	**5**	**36**	**6034**

Table 9a.Table 9 Soil fields in the file of basic soil properties 2018 LUCAS Soil Module.

Field	Description
Depth	Based on sample collected can be 0-10 cm or 0-20 cm
POINTID	LUCAS Point Identifier – link to Eurostat LUCAS Microdata
pH_CaCl2	pH – measured in calcium chloride
pH_H2O	pH – measured in water
EC	Electrical conductivity (milliSiemens per meter – mS m^{-1})
OC	Organic carbon content (g kg^{-1})
CaCO3	Calcium carbonate content (g kg^{-1})
P	Total phosphorus (g kg^{-1})
N	Total nitrogen (g kg^{-1})
K	Extractable potassium (g kg^{-1})
OC (20-30 cm)	Organic carbon content (g kg^{-1}) from different depth
CaCO3 (20-30 cm)	Calcium carbonate content (g kg^{-1}) from different depth
Ox_Al	Oxalate extractable Al (mg kg^{-1})
Ox_Fe	Oxalate extractable Fe (mg kg^{-1})

Table 9b. Non-soil fields in the file of basic soil properties in the 2018 LUCAS Soil Module.

Field	**Description**
NUTS_0	NUTS 0 Code
NUTS_1	NUTS 1 Code
NUTS_2	NUTS 2 Code
NUTS_3	NUTS 3 Code
TH_LAT	LUCAS POINT Theoretical Latitude
TH_LONG	LUCAS POINT Theoretical Longitude
SURVEY_DATE	Date of Survey
Elev	Elevation in meters from surveyor GPS
LC	Primary land cover
LU	Primary land use
LC0_Desc	Description of primary land cover
LC1_Desc	Description of secondary land cover
LU1_Desc	Description of primary land use

Table 10 Fields in the file of soil erosion in the 2018 LUCAS Soil Module

Field	Description
POINTID	LUCAS Point Identifier – link to Eurostat LUCAS Microdata
SURVEY_EROSION_SIGNS	Signs of erosion (1=Yes,2=20)
SURVEY_EROSION_SHEET	Sheet Erosion visible
SURVEY_EROSION_SHEET_P	Sheet erosion in the LUCAS point (Within 500 m if visible)
SURVEY_EROSION_SHEET_N	Sheet erosion in N direction (Within 500 m if visible)
SURVEY_EROSION_SHEET_E	Sheet erosion in E direction (Within 500 m if visible)
SURVEY_EROSION_SHEET_S	Sheet erosion in S direction (Within 500 m if visible)
SURVEY_EROSION_SHEET_W	Sheet erosion in W direction (Within 500 m if visible)
SURVEY_EROSION_SHEET_NR	Always empty/not present in the Manual
SURVEY_EROSION_SHEET_N_DIST_M	Distance from Point Direction N
SURVEY_EROSION_SHEET_E_DIST_M	Distance from Point Direction E
SURVEY_EROSION_SHEET_S_DIST_M	Distance from Point Direction S
SURVEY_EROSION_SHEET_W_DIST_M	Distance from Point Direction W
SURVEY_EROSION_RILL	Presence of Rill erosion
SURVEY_EROSION_RILL_P	Presence of Rill erosion in LUCAS point
SURVEY_EROSION_RILL_N	Rill erosion in N direction (Within 500 m if visible)
SURVEY_EROSION_RILL_E	Rill erosion in E direction (Within 500 m if visible)
SURVEY_EROSION_RILL_W	Rill erosion in S direction (Within 500 m if visible)
SURVEY_EROSION_RILL_S	Rill erosion in W direction (Within 500 m if visible)
SURVEY_EROSION_RILL_NR	Always empty/not present in the Manual
SURVEY_EROSION_RILL_N_DIST_M	Distance from Point Direction N
SURVEY_EROSION_RILL_E_DIST_M	Distance from Point Direction E
SURVEY_EROSION_RILL_S_DIST_M	Distance from Point Direction S

SURVEY_EROSION_RILL_W_DIST_M	Distance from Point Direction W
SURVEY_EROSION_GULLY	Presence of Gully erosion
SURVEY_EROSION_GULLY_P	Presence of Gully erosion in LUCAS point
SURVEY_EROSION_GULLY_N	Gully erosion in N direction (Within 500 m if visible)
SURVEY_EROSION_GULLY_E	Gully erosion in E direction (Within 500 m if visible)
SURVEY_EROSION_GULLY_S	Gully erosion in S direction (Within 500 m if visible)
SURVEY_EROSION_GULLY_W	Gully erosion in W direction (Within 500 m if visible)
SURVEY_EROSION_GULLY_NR	Always empty/not present in the Manual
SURVEY_EROSION_GULLY_N_DIST_M	Distance from Point Direction N
SURVEY_EROSION_GULLY_E_DIST_M	Distance from Point Direction E
SURVEY_EROSION_GULLY_S_DIST_M	Distance from Point Direction S
SURVEY_EROSION_GULLY_W_DIST_M	Distance from Point Direction W
SURVEY_EROSION_MASS	Presence of Mass Movement erosion
SURVEY_EROSION_MASS_P	Presence of Mass Movement erosion in LUCAS point
SURVEY_EROSION_MASS_N	Mass Movement erosion in N direction (Within 500 m if visible)
SURVEY_EROSION_MASS_E	Mass Movement erosion in E direction (Within 500 m if visible)
SURVEY_EROSION_MASS_S	Mass Movement erosion in S direction (Within 500 m if visible)
SURVEY_EROSION_MASS_W	Mass Movement erosion in W direction (Within 500 m if visible)
SURVEY_EROSION_MASS_NR	Always empty/not present in the Manual
SURVEY_EROSION_MASS_N_DIST_M	Distance from Point Direction N
SURVEY_EROSION_MASS_E_DIST_M	Distance from Point Direction E
SURVEY_EROSION_MASS_S_DIST_M	Distance from Point Direction S
SURVEY_EROSION_MASS_W_DIST_M	Distance from Point Direction W
SURVEY_EROSION_DEP	Presence of Re-deposition soil
SURVEY_EROSION_DEP_P	Presence of Re-deposition soil in LUCAS point

SURVEY_EROSION_DEP_N	Re-deposition soil in N direction (Within 500 m if visible)
SURVEY_EROSION_DEP_E	Re-deposition soil in E direction (Within 500 m if visible)
SURVEY_EROSION_DEP_S	Re-deposition soil in S direction (Within 500 m if visible)
SURVEY_EROSION_DEP_W	Re-deposition soil in W direction (Within 500 m if visible)
SURVEY_EROSION_DEP_NR	Always empty/not present in the Manual
SURVEY_EROSION_DEP_N_DIST_M	Distance from Point Direction N
SURVEY_EROSION_DEP_E_DIST_M	Distance from Point Direction E
SURVEY_EROSION_DEP_S_DIST_M	Distance from Point Direction S
SURVEY_EROSION_DEP_W_DIST_M	Distance from Point Direction W
SURVEY_EROSION_WIND	Presence of Wind erosion
SURVEY_EROSION_WIND_P	Presence of Wind erosion in LUCAS point
SURVEY_EROSION_WIND_N	Wind erosion in N direction (Within 500 m if visible)
SURVEY_EROSION_WIND_E	Wind erosion in E direction (Within 500 m if visible)
SURVEY_EROSION_WIND_S	Wind erosion in S direction (Within 500 m if visible)
SURVEY_EROSION_WIND_W	Wind erosion in W direction (Within 500 m if visible)
SURVEY_EROSION_WIND_NR	Always empty/not present in the Manual
SURVEY_EROSION_WIND_N_DIST_M	Distance from Point Direction N
SURVEY_EROSION_WIND_E_DIST_M	Distance from Point Direction E
SURVEY_EROSION_WIND_S_DIST_M	Distance from Point Direction S
SURVEY_EROSION_WIND_W_DIST_M	Distance from Point Direction W
SURVEY_EROSION_RILLGULLY_N	Number of rills or gullies 1-2-3 = <5,5-10,>10)
SURVEY_EROSION_CANDO	Erosion survey can be done? (1=Yes, 2=No)

Table 11 Fields in the file of organic soils in the 2018 LUCAS Soil Module.

Field	Description
POINTID	LUCAS Point Identifier – link to Eurostat LUCAS Microdata
SURVEY_SOIL_ORG_CULTIVATED	Is soil cultivated? (1=Yes,0=N0)
SURVEY_SOIL_ORG_DEPTH_P_CM	Depth of organic horizon at the point (in cm up to 40 cm)
SURVEY_SOIL_ORG_DEPTH_N_CM	Depth of organic horizon at the N hole (in cm up to 40 cm)
SURVEY_SOIL_ORG_DEPTH_E_CM	Depth of organic horizon at the E hole (in cm up to 40 cm)
SURVEY_SOIL_ORG_DEPTH_S_CM	Depth of organic horizon at the S hole (in cm up to 40 cm)
SURVEY_SOIL_ORG_DEPTH_W_CM	Depth of organic horizon at the W hole (in cm up to 40 cm)
SURVEY_SOIL_ORG_DEPTH_P_40_CM	Depth of organic horizon at the point (>40 cm)
SURVEY_SOIL_ORG_DEPTH_N_40_CM	Depth of organic horizon at the N hole (>40 cm)
SURVEY_SOIL_ORG_DEPTH_E_40_CM	Depth of organic horizon at the E hole (>40 cm)
SURVEY_SOIL_ORG_DEPTH_S_40_CM	Depth of organic horizon at the S hole (>40 cm)
SURVEY_SOIL_ORG_DEPTH_W_40_CM	Depth of organic horizon at the W hole (>40 cm)
SURVEY_SOIL_ORG_TAKEN	Soil Organic taken? (1=Yes,0=No)
SURVEY_SOIL_ORG_DEPTH_CANDO	Can you assess the organic layer depth? (1=Yes,0=No)

Table 12 Environmental descriptors at LUCAS sampling points

Field Name	**Description**	**Unit**
Point_ID	Unique ID to be linked to other LUCAS datasets (on ESDAC or EUROSTAT)	-
Clima_COD	Climatic Code based on Köppen-Geiger classification	-
Elevation	Height extracted from EuDEM v1.0	m
Slope	Slope gradient	degree
Aspect	Orientation of slope	Compass degree
BioGeo	Biogeographic Region	-
Natura2000_sitecode 1	Code of Natura2000 site in which the point is located	-
Natura2000_sitecode 2	Code of second Natura2000 site in which the point is located	-
Soil_Group	Estimation of dominant reference soil group	-
Soil_Code	WRB Code of the first dominant soil group	-
BIO1	Annual Mean Temperature	ºC
BIO2	Mean Diurnal Range	ºC
BIO3	Isothermality (BIO2/BIO7) (×100)	ºC
BIO4	Temperature Seasonality (standard deviation ×100)	ºC
BIO5	Max Temperature of Warmest Month	ºC
BIO6	Min Temperature of Coldest Month	ºC
BIO7	Temperature Annual Range (BIO5-BIO6)	ºC
BIO8	Mean Temperature of Wettest Quarter	ºC
BIO9	Mean Temperature of Driest Quarter	ºC
BIO10	Mean Temperature of Warmest Quarter	ºC
BIO11	Mean Temperature of Coldest Quarter	ºC
BIO12	Annual Precipitation	mm
BIO13	Precipitation of Wettest Month	mm
BIO14	Precipitation of Driest Month	mm
BIO15	Precipitation Seasonality (Coefficient of Variation)	mm

4.1 Reflections on 2018 dataset

The number of points actually sampled as part of the 2018 LUCAS survey was less than initially planned. In total, 71 % of points were sampled compared to 85 % and 95 % in LUCAS 2015 and LUCAS 2009/12 surveys, respectively. The percentage of points sampled was especially low (below 50 %) in Germany, Croatia, Ireland, Malta, the Netherlands, Romania and the United Kingdom. Romania, Malta and Germany had the lowest percentages of samples taken with 17 %, 33 % and 37 %, respectively. Different reasons were provided by surveyors to explain the difficulties in taking soil samples:

— In Romania, most of the sampling was carried out between September and October 2018 due to a change in the organisation coordinating the survey. Extreme weather and soil conditions, especially rainfalls, floods and frost, complicated the sampling collection during these months. In addition, surveyors found physical difficulties to reach points on several occasions due to the presence of dangerous animals, together with limited and poor road infrastructure for points in the rest of LC classes. As a result, alternative LUCAS points for soil sampling were selected.

— In Malta and Croatia, compaction and rocky soils under cropland and shrubland complicated the sampling. Presence of fences in cropland complicated the access to the points.

— Legal issues related to accessing private land was the main issue in Germany for not taking samples, and this affected all LC classes.

— In Ireland, water saturation in wetland and woodland points due to bad weather complicated the sampling. In addition, the distance of the points from the roads and technical problems with the transmission of point IDs affected the sampling for other LC classes.

— In the United Kingdom, denial of access by land owners reflecting the upcoming Brexit referendum was the main difficulty for the sampling.

4.2 Spatial representation of soil properties in the EU-28

Point data of each physical and chemical soil property is presented on four maps: one for the whole dataset and three for cropland, grassland and woodland points separately. The same ranges of values, based on pedological and agrochemical criteria, were used as in the maps presented in the reports of LUCAS 2009 (Tóth et al., 2013a) and LUCAS 2015 (Jones et al., 2020) to characterise and describe these properties.

Maps of aggregated data at NUTS 2 level are also presented for all points and for the three main LC classes separately (cropland, woodland, and grassland). Maps of bareland, shrubland and wetland are not shown due to the low number of points at each NUTS 2 region. The NUTS classification of 2016[11] was used for this exercise, which has 281 regions for the EU-28 MS[12] at NUTS level 2. The 2018 LUCAS Soil Module was carried out in 254 of these regions, although the number of regions sampled is lower when considering each LC class separately (Table 13). Wetland points, for example, are principally present in northern regions from Sweden, followed by Ireland and the United Kingdom. On the contrary, bareland points are mainly present in southern regions from Spain and France. Cropland, grassland, and woodland points are present in almost all regions (Table 8). For data aggregation, we only considered NUTS 2 regions in which at least 3 samples were taken. This resulted in 242 (out of 253) regions when considering the whole dataset, 206 regions for cropland, 204 regions for grassland, 181 regions for woodland, 48 regions for bareland, 57 regions for shrubland and 3 regions for wetland (Table 13).

As shown in Table 13, the median values of the sampling density in NUTS 2 regions were below 300 km^2 per sample, except for woodland and wetland. The point density in woodland was only slightly above 300 km^2 per sample. These values of sampling density can be considered acceptable, at least for the assessment of soil organic carbon content, as proposed by Jandl et al. (2011). These authors suggested that a minimum sampling density of one sample for every 300 km^2 could be enough to assess changes on topsoil organic carbon content over a 10-year time lapse at European level. Similarly, Panagos et al. (2013) considered that a sampling density of approximately 200 km^2 could be reasonable for the LUCAS Soil survey to measure soil organic carbon. Based on these studies, we considered a minimum density of 250 km^2 per sample as being a reasonable preliminary indicator for the confidence level of the LUCAS 2018 Soil survey to measure chemical soil properties. According to this criterion, the sampling density was below or equal to 250 km^2 per sample in at least 50% of the NUTS 2 regions in cropland, grassland, bareland and shrubland (Table 13, Figure 10). When considering the whole dataset (all LC together), the percentage of NUTS 2 regions with an acceptable point density was slightly lower, at 49% (Table 13). However, the number of regions with a minimum sampling density of 250 km^2 per sample was significantly low in woodland and wetland (Table 13).

([11]) Regional data of LUCAS 2018 is presented based on NUTS 2016 classification at the Eurostat webpage. Thus, we decided to use the same classification to describe LUCAS 2018 soil data in this report.

[12] i.e. the EU-27 Member States and the UK, then also an EU Member State.

Table 13 Summary statistics of the sampling density in NUTS 2 regions of the 2018 LUCAS Soil Module.

	NUTS 2 regions sampled	**NUTS 2 regions with ≥3 samples**	**Sampling density (km^2 per sample)**		**% of NUTS 2 regions with density <250 km^2 per sample**
			Mean of NUTS 2 regions	**Median** of NUTS 2 regions	
Whole dataset	253	242	353.6	253.1	49
Cropland	238	206	915.4	652.3	8
Grassland	238	204	1013.7	1480.3	1
Woodland	218	181	919.2	1353.4	2
Bareland	124	48	5281	3357	0
Shrubland	109	57	3771.6	5054.6	0
Wetland	22	3	14405	12024	0

Both point data and aggregated data are described following the climatic zones for soil quality assessment identified in Tóth et al. (2013b) (Figure 11), to match the reports of LUCAS 2009 and LUCAS 2015 Surveys (Tóth et al., 2013a and Jones at al., 2020, respectively).

Figure 10 (a) Sampling density in NUTS 2 regions for the complete dataset of the 2018 LUCAS Soil Module; number of points in each NUTS2 region for (b) cropland, (c) grassland, (d) woodland

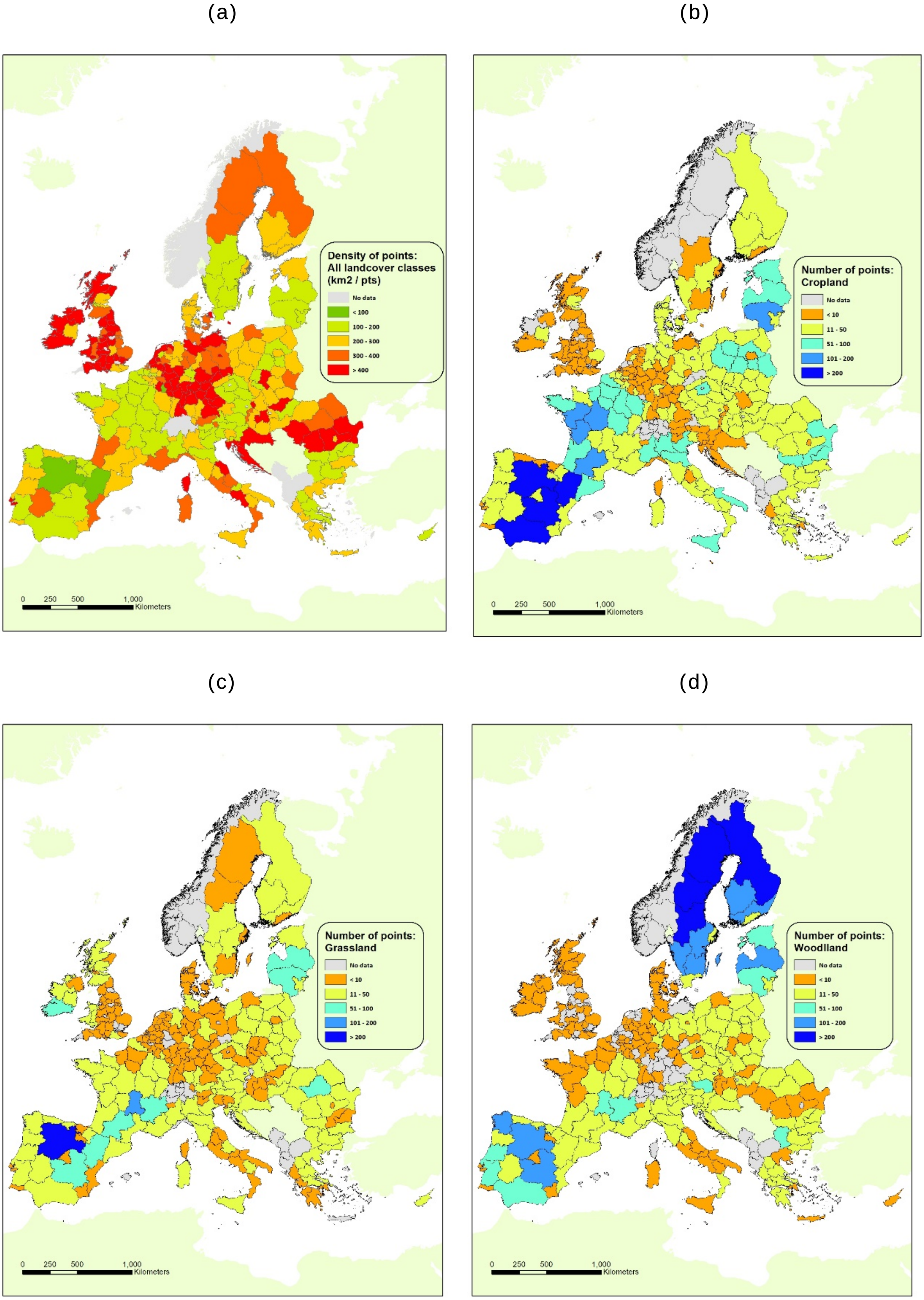
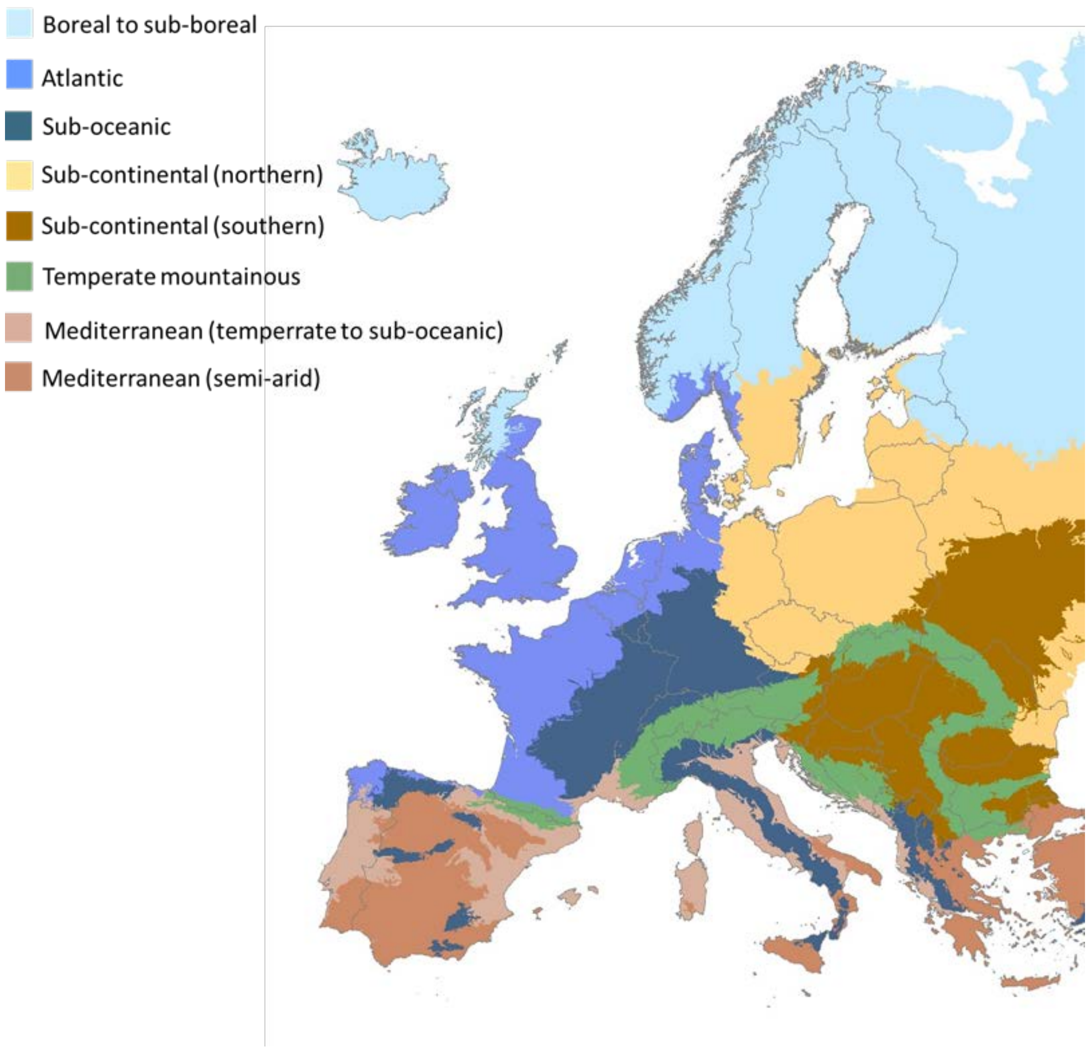


Figure 11 Climatic zones identified in Tóth et al. (2013b)



4.3 Assessment of gully erosion

Sheet and rill erosion (Panagos et al., 2020), wind erosion (Borrelli et al., 2017) and soil loss due to harvesting crops (Panagos et al., 2019) can be assessed at a pan-European scale. However, gully erosion susceptibility assessments are currently limited to local and regional scale applications due to the lack of large-scale inventory data for calibration/validation purposes. Accordingly, we lack harmonized national and continental scale gully erosion monitoring and assessments to better understand the geographical distribution of gully erosion processes and to evaluate the threats to soil and the environment.

We integrated a soil erosion component into the 2018 LUCAS Soil Module to support actions to prevent soil degradation. We will discuss and explore opportunities to further improve this method. Erosion observations were conducted in around 10% (n = 24,759) of the 238,077 LUCAS 2018 in-field survey sites. Gully erosion channels were detected for ca. 1% (211 sites) of the visited sites (Borrelli et al., 2022). Overall, the findings indicate that the approach tested in the survey is effective for detecting the incidence of gully erosion. The morphogenesis of the mapped gullies suggests that the approach is an effective tool to map permanent gullies, whereas it appears less effective in detecting short-lived ephemeral gullies. Spatial patterns emerging from the field observations provide new insights on typical gully formation sites across the EU and UK. This can help design further targeted research activities. An extension of this approach to all LUCAS sites in the next LUCAS Survey would significantly enhance our understanding of the geographical distribution of gully erosion processes across the EU.

If repeated every three years, LUCAS soil erosion surveys could provide a unique temporal dimension. It will enable the monitoring of, and eventually predict, the dynamics of gully erosion. Data collected are publicly available by downloading the LUCAS Gully Erosion Visual Assessment inventory (GE-LUCAS v1.0).

https://esdac.jrc.ec.europa.eu/content/gully-erosion-based-lucas

Out of 24,759 locations visited, the surveyors recorded a total of 211 sites with gully erosion channels (equal to ca. 1% of total) (Figure 12). The surveyors also registered the number of gullies observable from the visited sites (ranging in length 1–420 m from the LUCAS sampling point, with a median distance of 50 m) and classified them into three different categories based on the number of gullies present: i) < 5 gullies, ii) 5–10 gullies, and iii) > 10 gullies. The majority of the sites have less than 5 gullies (159 sites) while 28 sites have 5–10 gullies and 19 sites have more than 10 gullies. 5 points could not be verified as being gully erosion (i.e. false positives).

The gully erosion observations have been validated using Google Earth imagery (Figure 13). The procedure of post-survey validation showed that the majority of the field observations could be confirmed through on-screen visual interpretation and included in the GE-LUCAS inventory. Only five sites (2% of total) reported that gullies could not be validated and were classified as possible false positives. The remaining 206 field observations were verified as follows: i) 50 sites (24% of total) based on the most recent Google Earth images, ii) 117 sites (56% of total) with an in-depth procedure including interpretation of historical high-resolution satellite and aerial GE images and Street View terrestrial images, and iii) 30 sites (14% of total) with LUCAS 2018 terrestrial photos. The remaining 9 (4% of total) sites were validated using other high-resolution satellite images. Concerning the presence of possible false negatives, the onscreen visual assessment of the 250 randomly selected LUCAS Topsoil sites confirmed the presence of at least one gully erosion channel in 14 of the observed sites (equal to 5.6% of the total).

Figure 12 Spatial distribution of the sites for which potential gully erosion channels were observed during the 2018 LUCAS Topsoil field survey. The light blue dots indicate the sites validated through expert-based on-screen visual interpretation, while the red ones could not be observed during this phase

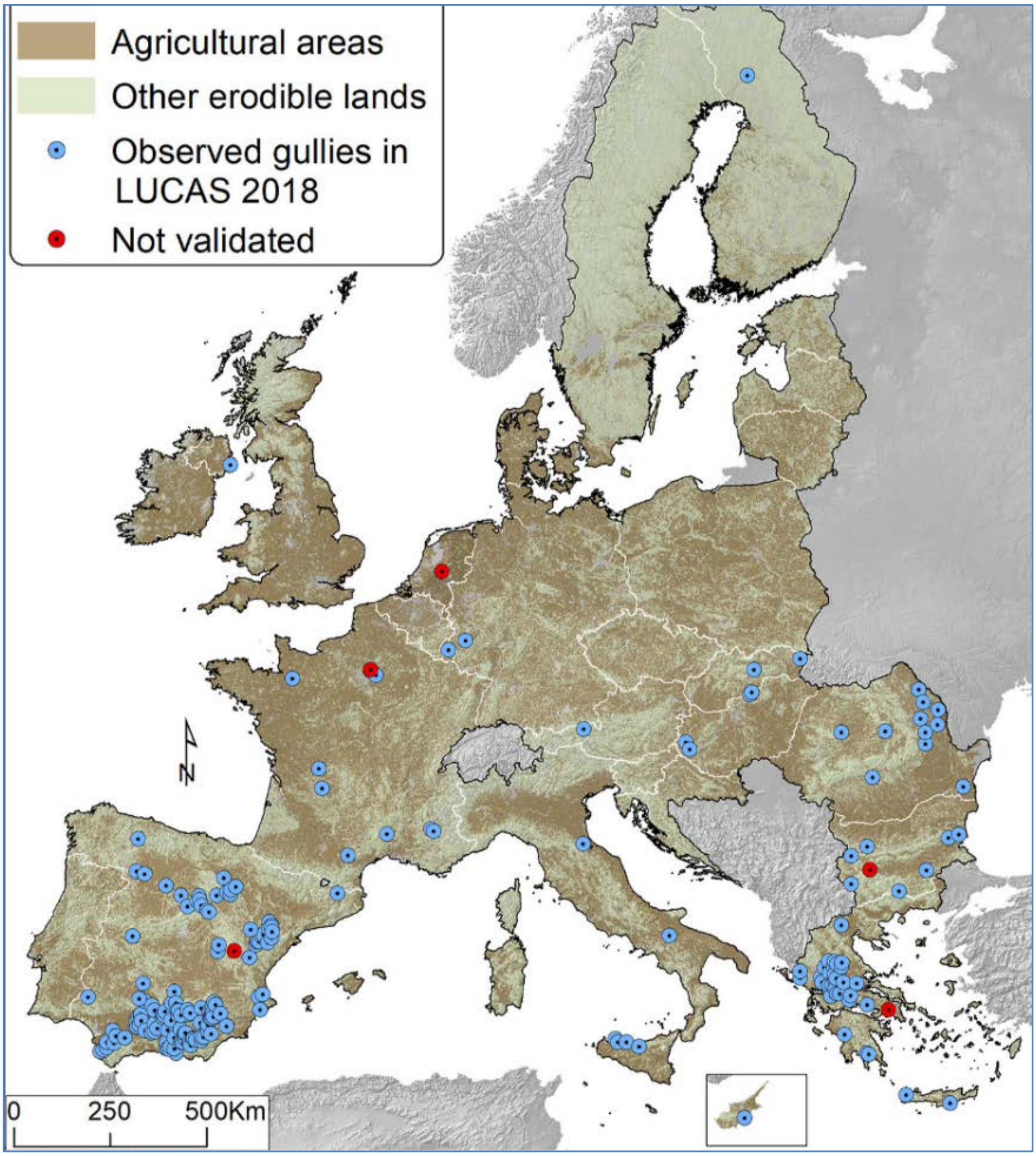
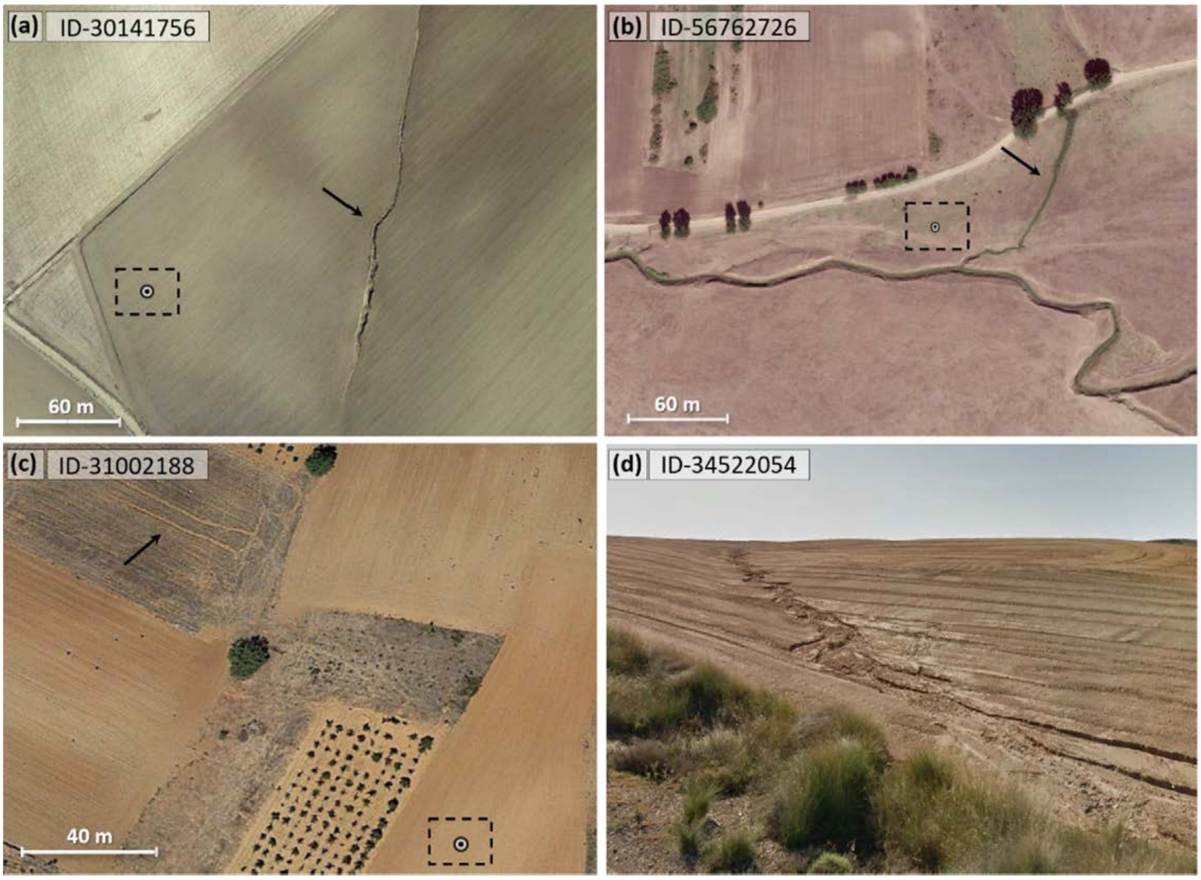


Figure 13 Examples of gully erosion channels validated by reviewing Google Earth Images (Credit Google Earth).



Panel (a): Spain, Andalusia, 37.73N, 4.82W, image date: October 2019; Panel (b): Romania, Barlad, 46.18N, 27.72E, image date: August 2012; Panel (c): Spain, Castile and Leon, 41.71N, 4.72W, image date: September 2017; Panel (d): Spain, Zaragoza, 41.05N, 0.32W, image date: October 2018.

The circle within the black dotted rectangle indicates the location of a LUCAS point (from Borrelli et al., 2022).

4.4 Condition of organic soils

A novel aspect of the 2018 survey was to ascertain the depth of the organic horizon in locations where it was determined from previous LUCAS surveys that the land cover was wetland or that the soil organic matter content was greater than 200 g mg^{-1}. The depth (up to 40 cm) was measured in 1,050 points (measurement locations were concurrent with the subsampling sites of the Soil Module – Figure 3a).

Most of the sites selected for depth assessments appear not to fulfil the depth criteria for Histosols (i.e. >40 cm or 10 cm above a hard contact). Approximately 30% of sites recorded organic horizons with a depth of 40 cm or more, which would seem to indicate the presence of Histosols.

However, the assessment failed to record the reason for very shallow organic soils (e.g. such as the presence of bedrock close to the surface). The implication could be that many of these locations are either mineral soils with well-developed organic horizons or that peatlands have been eroded back to the underlying mineral base.

4.5 Bulk density and particle size distribution

Bulk density is expressed as the dry weight of soil divided by its volume, which includes the volume of soil particles and the volume of pores among soil particles. Bulk density is typically expressed in g cm^{-3}. Bulk densities in undisturbed soils tend to range from about 1.0-1.4 g/cm^3 with higher values typical for sandy soils and with increasing depth.

An increasing bulk density implies a decrease of large pores and a corresponding increase in micropores. A reduction in pore space affects the flow of oxygen into the soil and carbon dioxide out of the soil. Soil compaction is often associated with development of crusts on the surface of soils, which in turn, reduces infiltration and thus an increase in surface runoff. In addition, the growth of plants in compacted soil is greatly reduced.

It is an important parameter since it can measure whether soils are compacted in response to land use and soil management practices. Bulk density determines infiltration capacity of the soil, available water capacity, soil porosity, rooting depth restrictions, soil microorganism activity, root proliferation and nutrient availability. Bulk density is a critical parameter in the calculation of soil organic carbon stocks.

4.6 Organic carbon

The climate, vegetation type and land use determine the spatial variability of organic carbon (OC) content across the EU. Based on the 2018 OC measurements, OC content increases from south-eastern to north-western climatic zones (Table 14, Figure 14). This trend confirms that the cooler and more humid conditions in north-western climatic zones prevent decomposition of organic residues and promote accumulation of OC in soil. On the contrary, the drier and warmer conditions in south-eastern climatic zones accelerate organic matter decomposition which explains the lower OC content. In addition, OC content was higher in wetland, woodland, shrubland and grassland compared to cropland and bareland in most of the countries (Table 14, Figure 15). In line with these trends, OC content was the highest in wetland points in the boreal zone (mean = 345.1 g kg^{-1}, median = 436.6 g kg^{-1} in SE) and the Atlantic zone (mean = 380.2 g kg^{-1}, median = 455.6 g kg^{-1} in IE) and the lowest in bareland points in the Mediterranean climatic zones (EL, IT, ES). However, difference in OC content among LC classes differed from the general trend in some countries due to specific combinations of pedoclimatic conditions and type of vegetation. In Cyprus, for instance, woodland points were located in pine forests with shallow and coarse textured soils, while cropland, grassland and shrubland points were located in soils with medium to fine textures. As a result, OC content in woodland points was lower than in the rest of LC classes. Organic carbon content in bareland was similar to that in woodland, shrubland and grassland in Portugal and Sweden (Figure 15). The land use recorded for most of the bareland points in the two countries can explain this condition: mainly forestry and (semi-)natural areas not in use. Lastly, cropland points in Finland had a similar OC content to those in woodland, shrubland and grassland (Figure 15). This observation can be related to (1) the presence of organic farming in Finland (13.5% against 7.9% in the EU - Eurostat, 2019), (2) the association of cropland with natural vegetation in the landscape (present in approximately 56% of cropland in 2015, IIASA & SDSN 2020), and (3) the cultivation of organic soils, including peats, which accounted for 11% of the cropland of Finland (Myllys et al., 2019; MTK, 2020).

Altogether, 40 points were sampled in **wetlands** in 22 (out of 281) NUTS 2 regions. These points recorded the highest levels of OC (mean = 318.1 g kg^{-1}, Table 14, Figure 16) and were located mainly in the boreal and the Atlantic zones (Table 15); although a few points were also identified in the sub-oceanic (1 point), sub-continental (5 points), temperate mountainous (1 point), and temperate to sub-oceanic Mediterranean (1 point) zones. According to their OC content, the soil was organic (OC >200 g kg^{-1}) in 27 points (69 %), and it was mineral with high OC content (>30 g kg^{-1}) in eight points. Organic carbon content was <30 g/kg in five points, which is considered common in mineral soils. A similar situation was also observed in the LUCAS 2009 Soil survey (de Brogniez et al., 2015).

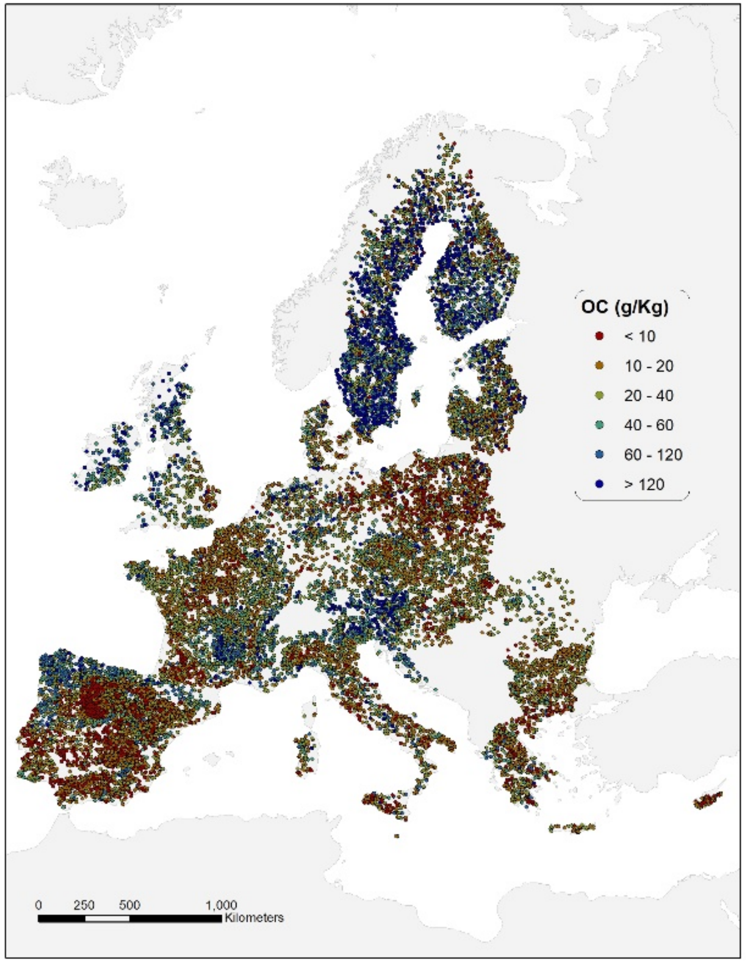
These data suggest a large variability of OC content in wetland points both among climatic zones and within each climatic zones (among NUTS 2 regions), most likely due to differences in management practices and local climatic conditions. The NUTS 2 region with the highest content of OC in wetland was IE04 (mean = 517.8 g kg^{-1}, median = 527.2 g kg^{-1}), followed by SE31 (mean = 482.1 g kg^{-1}, median = 487.9 g kg^{-1}) and SE33 (mean = 309.3 g kg^{-1}, median = 407.9 g kg^{-1}) (Table 15). The remaining 18 regions with wetland points had less than three samples or low sampling densities for this LC class.

Table 14 Summary of organic carbon content in the 2018 LUCAS Soil Module, by climatic zone and by land cover class

	Organic carbon (g kg^{-1})		
Climatic zones	**Mean**	**Median**	**Std Dev**
Boreal to sub-boreal	114.8	44.2	147.3
Atlantic	41.5	22.6	66.5
Sub-continental (northern)	49.6	19.5	88.5
Sub-oceanic	41.3	30.3	39.6
Sub-continental (southern)	23.7	19.1	20.1
Temperate mountainous	58.5	37.1	70.1
Mediterranean (semi-arid)	16.8	12.7	15.4
Mediterranean (temperate to sub-oceanic)	27.4	18.2	26.1
Mediterranean zones	19.9	13.9	19.7
Land cover classes			
Wetland	318.1	418.2	200.9
Woodland	88.1	42.7	118.3
Shrubland	55.2	32.6	77.3
Grassland	40.2	27.7	51.6
Cropland	18.3	14.7	20.6
Bareland	17.3	12.6	25.6

Figure 14 Organic carbon content (all 2018 LUCAS Soil Module points) presented (a) as point data and (b) average aggregated at NUTS 2 level

(a)



(b)

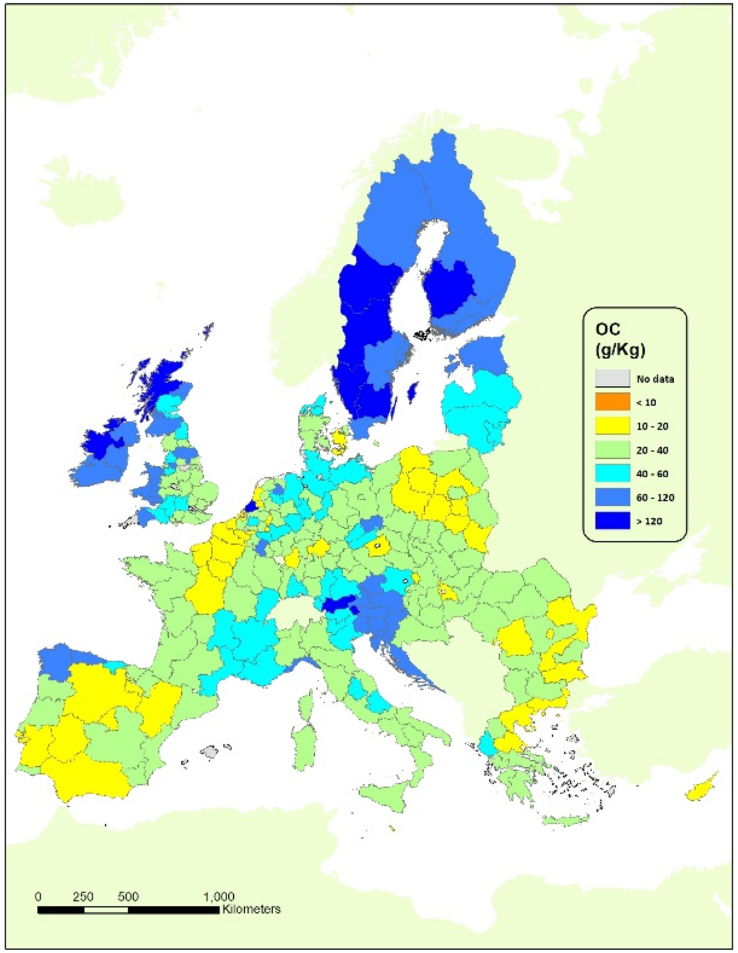
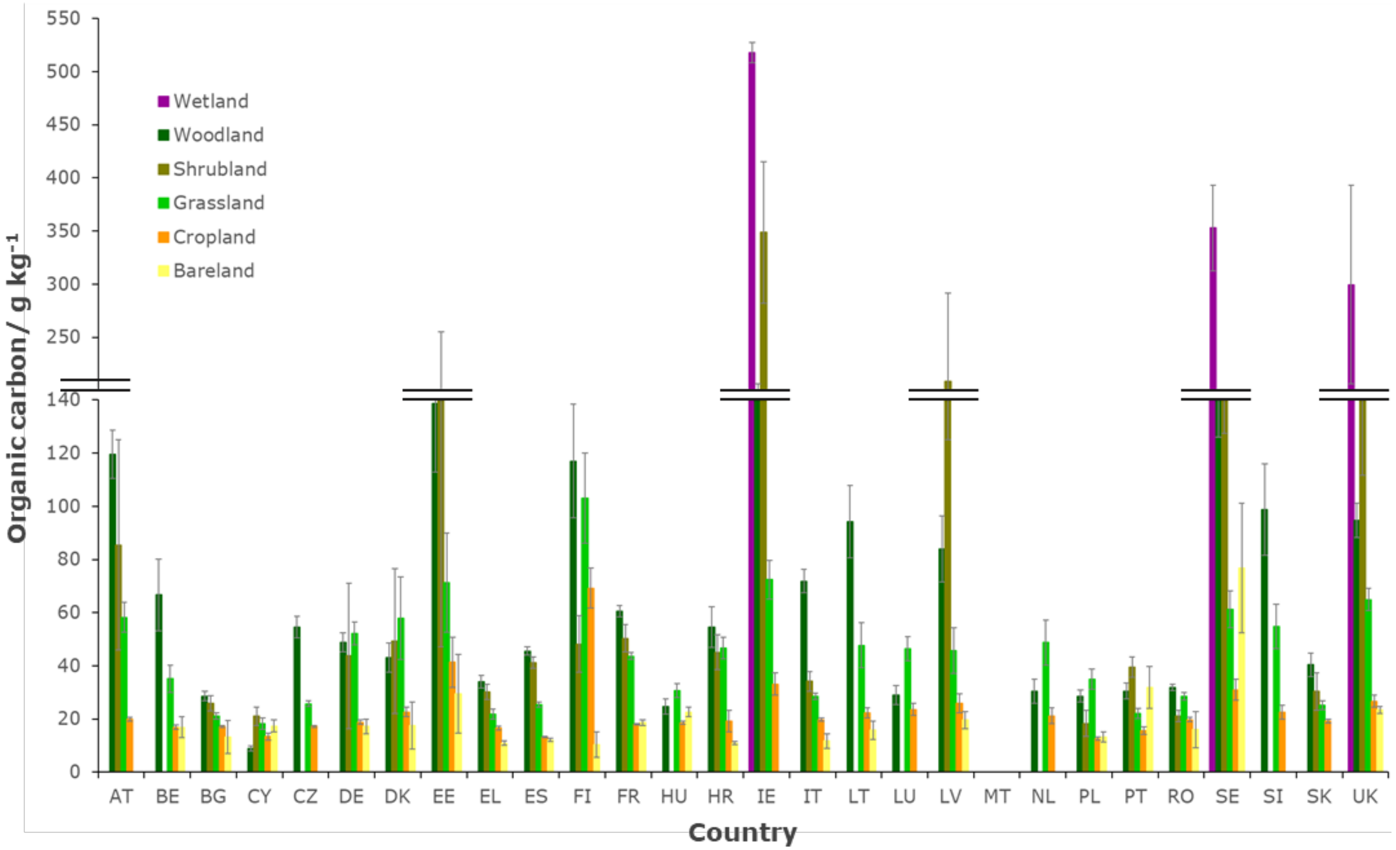


*Figure 15 Organic carbon content in the 2018 LUCAS Soil Module (mean and standard error) by land cover class in the 27 Member States and the UK **



*the horizontal lines indicate breaks in y-axis to facilitate the viewing of the data.

Table 15 Summary of organic carbon in wetland points in the 2018 LUCAS Topsoil survey.

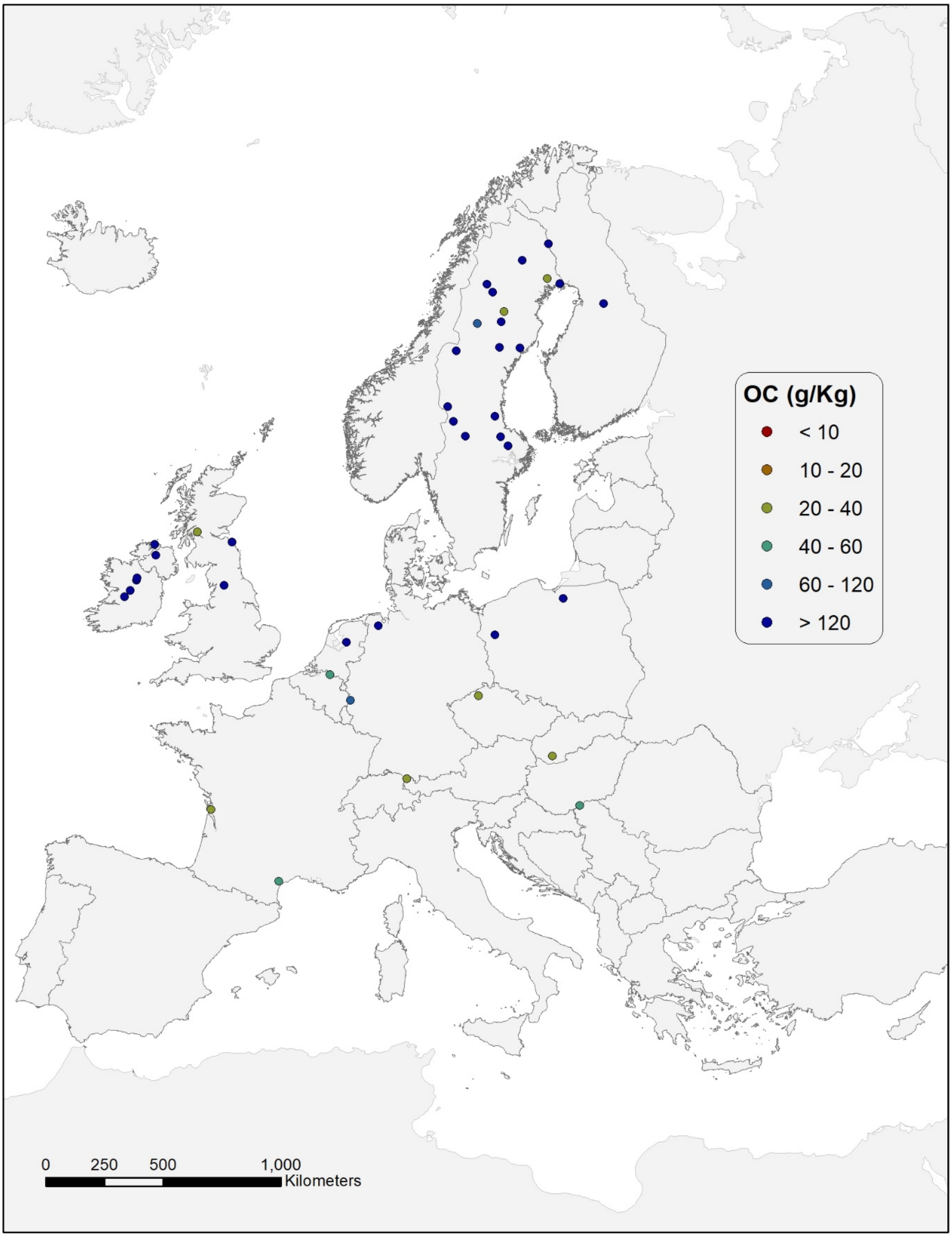
<table>
<tr><th>Climatic zone</th><th>N points</th><th>Mean
(g kg^{-1})</th><th>Median
(g kg^{-1})</th><th>Std dev
(g kg^{-1})</th><th>NUTS 2 with highest OC content in wetland (g kg^{-1}) (1)</th><th>NUTS 2 with lowest OC content in wetland (g kg^{-1}) (1)</th></tr>
<tr><td>Boreal to sub-boreal</td><td>20</td><td>345.1</td><td>436.6</td><td>182.6</td><td>SE31
N points = 5
mean = 482.1
median = 487.9</td><td>SE33
N points = 10
mean = 309.3
median = 407.9</td></tr>
<tr><td>Atlantic</td><td>12</td><td>380.2</td><td>455.6</td><td>189.2</td><td colspan="2">IE04
N points = 5
mean = 517.8
median = 527.2</td></tr>
<tr><td>Sub-continental (northern)</td><td>3</td><td>330.2</td><td>444.2</td><td>256.8</td><td colspan="2">None of the regions had at least 3 points</td></tr>
</table>

(1) only NUTS 2 regions with three or more points were considered.

Table 16 Summary of organic carbon in woodland points in the 2018 LUCAS Topsoil survey.

Climatic zone	***N* points**	**Mean (g kg-1)**	**Median (g kg-1)**	**Std dev (g kg-1)**	**NUTS 2 with highest OC content in woodland (g kg^{-1})** (1)	**NUTS 2 with lowest OC content in woodland (g kg^{-1})** (1)
Boreal to sub-boreal	2095	122.1	50.1	152.0	SE31 *N* points = 296 mean = 160.6 median = 78.5	LV00 *N* points = 81 mean = 87.3 median = 41.7
Atlantic	374	86.9	50.6	106.4	IE05 *N* points = 4 mean = 295.2 median = 283.0	FRB0 *N* points = 17 mean = 22.9 median = 20.0
Sub-oceanic	693	61.2	45.7	53.1	ITF1 *N* points = 14 mean = 184.7 median = 179.0	EL63 *N* points = 3 mean = 11.7 median = 9.3
Sub-continental (northern)	1145	94.6	45.1	123.9	FI1B *N* points = 4 mean = 294.2 median = 319.9	PL72 *N* points = 6 mean = 9.8 median = 10.2
Sub-continental (southern)	275	36.2	26.6	34.1	SI04 *N* points = 11 mean = 111.8 median = 113.4	HU12 *N* points = 11 mean = 12.2 median = 10.2
Temperate mountainous	665	78.5	51.1	85.9	AT12 *N* points = 17 mean = 172.9 median = 147.3	BG32 *N* points = 5 mean = 19.0 median = 16.6
Mediterranean (semi-arid)	425	30.0	22.6	25.6	ITG1 *N* points = 3 mean = 83.9 median = 71.6	CY00 *N* points = 7 mean = 9.0 median = 7.8
Mediterranean (temperate to sub-oceanic)	323	43.7	35.5	37	ES22 *N* points = 11 mean = 84.2 median = 54.3	PT18 *N* points = 23 mean = 16.6 median = 9.9

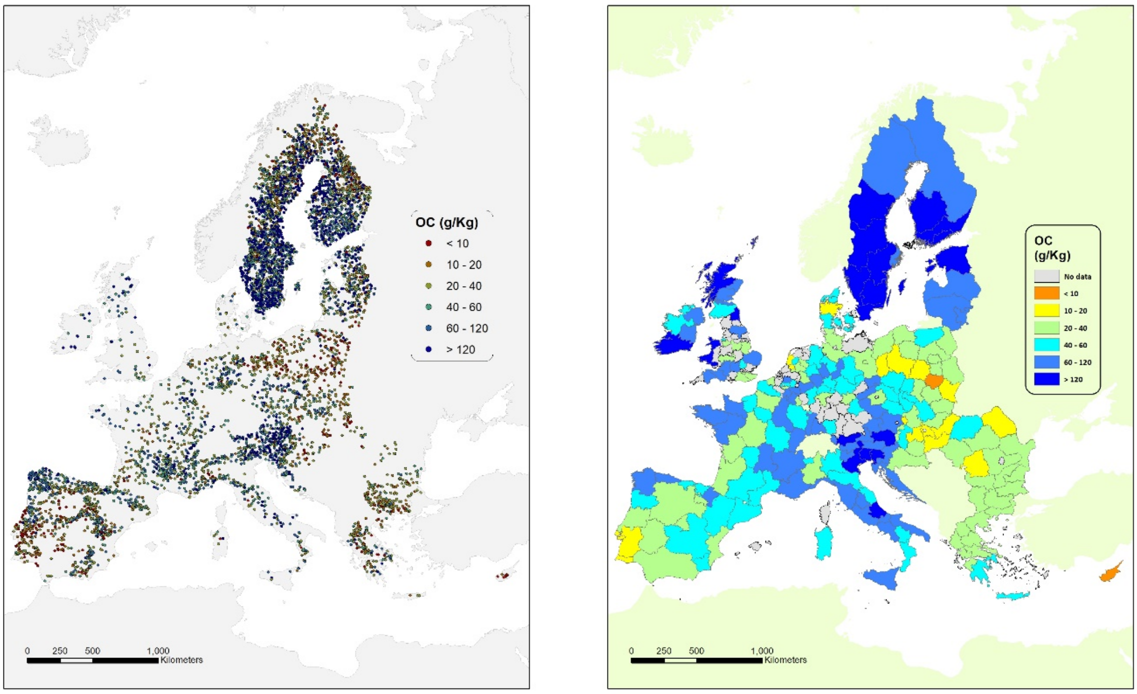
Figure 16 Organic carbon content in wetland presented as point data



Organic carbon content in **woodland** points was also high (mean = 88.1 g kg^{-1},Table 14). It was higher in north-western climatic zones (boreal, Atlantic, sub-oceanic, and northern sub-continental) than in the south-eastern climatic zones (Mediterranean and southern sub-continental) (Table 16, Figure 17). In the north-western climatic zones, the mean OC content ranged from 122.1 g kg^{-1} (median = 50.1 g kg^{-1}) in the boreal to sub-boreal zone to 61.2 g kg^{-1} (median = 45.7 g kg^{-1}) in the sub-oceanic zone (Table 16). The highest content of OC was observed in the NUTS 2 region SE31 (mean OC = 160.6 g kg^{-1}, median OC = 78.5 g kg^{-1}) and the lowest in EL63 (mean = 11.7 g kg^{-1}, median = 9.3 g kg^{-1}) (Table 16). In the south-eastern zones, mean OC content ranged from 43.7 g kg^{-1} (median = 35.5 g kg^{-1}) in the temperate to sub-oceanic Mediterranean zone to 30.0 g kg^{-1} (median = 22.6 g kg^{-1}) in the semi-arid Mediterranean zone (Table 16). The highest content of OC in woodland was observed in the NUTS 2 region SI04 (mean OC = 111.8 g kg^{-1}, median OC = 113.4 g kg^{-1}) and the lowest in CY00 (mean = 9.0 g kg^{-1}, median = 7.8 g kg^{-1}) (Table 16). The temperate mountainous zone had woodland OC levels similar to these in the north-western zones (Table 16, Figure 17). This variability of OC content in woodland could be due to differences in climatic conditions (temperature and precipitation) and to quality and quantity of litter that regulate, at least partially, organic matter decomposition in soil (Hanewinkel et al., 2013).

Figure 17 Organic carbon content in woodland: (a) point data and (b) average aggregated at NUTS 2 level

(a) (b)



The mean OC content was 40.2 g kg^{-1} in **grassland** points and 55.2 g kg^{-1} in **shrubland** points (Table 14). In both LC classes, OC content increased from south-eastern to north-western climatic zones (Figures 18 and 19), as also observed for woodland points. Organic carbon content was the highest in the boreal to sub-boreal zone, followed by the Atlantic zone both in grassland and shrubland (Tables 17 and 18). In these zones, OC content in grassland ranged from 154.5 g kg^{-1} (median = 78.7 g kg^{-1}) in the NUTS 2 region UKM6 in the boreal to sub-boreal zone, to 18.2 g kg^{-1} (median = 19.0 g kg^{-1}) in FR10 region in the Atlantic zone (Table 17). In shrubland, OC content ranged from 279.6 g kg^{-1} (median = 281.3 g kg^{-1}) in the IE06 region in the Atlantic zone to 27.2 g kg^{-1} (median = 22.2 g kg^{-1}) in FI1D region in the boreal to sub-boreal zone (Table 18). Organic carbon content was intermediate in the sub-oceanic, northern sub-continental and temperate mountainous zones in both LC classes. The temperate to sub-oceanic Mediterranean zone showed also intermediate values of OC content in shrubland. It ranged from 53.4 g kg^{-1} (median = 42.3 g kg^{-1}) in ES22 region in the temperate mountainous zone to 32.2 g kg^{-1} (median = 33.4 g kg^{-1}) in ES23 region in the sub-oceanic zone (Table 17). In shrubland, OC content ranged from 127.5 g kg^{-1} (median = 87.8 g kg^{-1}) in the SE12 region in the northern sub-continental zone to 18.7 g kg^{-1} (median = 16.9 g kg^{-1}) in ES43 region in the temperate to sub-oceanic Mediterranean zone (Table 18). Lastly, OC content was the lowest in the southern sub-continental and semi-arid Mediterranean zones in both grassland and shrubland (Tables 17 and 18). It ranged from 67.0 g kg^{-1} (median = 68.0 g kg^{-1}) in HU21 region in the southern sub-continental zone to 9.1 g kg^{-1} (median = 7.1 g kg^{-1}) in ES51 region in the semi-arid Mediterranean zone (Table 17). In shrubland, OC content ranged from 43.7 g kg^{-1} (median = 33.8 g kg^{-1}) in the ITG1 region to 15.1 g kg^{-1} (median = 18.9 g kg^{-1}) in ES22 region, both in the semi-arid Mediterranean zone (Table 18). The spatial variability of OC in grassland and shrubland reflects the distribution of various types of grassland and climatic conditions in the EU, ranging from permanent grassland and moorlands that dominate the north and north-western cool and humid regions to dry, and desert-like grassland and Mediterranean *maquis* that predominate in the southern and south-eastern.

Table 17 Summary of organic carbon in grassland points of the 2018 LUCAS Topsoil survey.

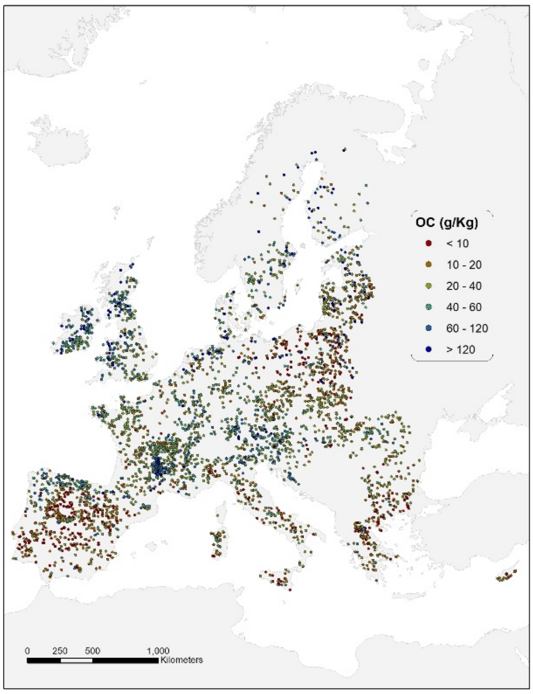
Climatic zone	***N* points**	**Mean (g kg-1)**	**Median (g kg-1)**	**Std dev (g kg-1)**	**NUTS 2 with highest OC content in grassland (g kg^{-1})** (1)	**NUTS 2 with lowest OC content in grassland (g kg^{-1})** (1)
Boreal to sub-boreal	167	75.0	31	103.6	UKM6 *N* points = 6 mean = 154.5 median = 78.7	FI1C *N* points = 10 mean = 48.3 median = 32.9
Atlantic	715	54.7	38.6	60.4	DK05 *N* points = 5 mean = 134.7 median = 55	FR10 *N* points = 4 mean = 18.2 median = 19
Sub-oceanic	789	43.6	35.9	32.9	AT31 *N* points = 4 mean = 109.3 median = 41.4	ITF2 *N* points = 5 mean = 12 median = 12.9
Sub-continental (northern)	703	40.7	21.1	69.1	DE80 *N* points = 5 mean = 106.8 median = 18.8	PL21 *N* points = 16 mean = 18.4 median = 14.9
Sub-continental (southern)	355	26.6	22	20.0	HU21 *N* points = 5 mean = 67.0 median = 68	RO41 *N* points = 13 mean = 13.3 median = 9.8
Temperate mountainous	413	43.6	34.9	43.5	AT31 *N* points = 5 mean = 123.7 median = 38.6	BG34 *N* points = 5 mean = 18.9 median = 13.9
Mediterranean (semi-arid)	537	17.4	13.4	14.7	EL65 *N* points = 8 mean = 30.6 median = 22.5	ES51 *N* points = 3 mean = 9.1 median = 7.1
Mediterranean (temperate to sub-oceanic)	261	25.9	20.7	18.9	ITH3 *N* points = 6 mean = 45.1 median = 43.1	PT17 *N* points = 4 mean = 11.3 median = 10.1

Table 18 Summary of organic carbon in shrubland points of the 2018 LUCAS Topsoil survey.

Climatic zone	***N* points**	**Mean (g kg-1)**	**Median (g kg-1)**	**Std dev (g kg-1)**	**NUTS 2 with highest OC content in shrubland (g kg^{-1})** (1)	**NUTS 2 with lowest OC content in shrubland (g kg^{-1})** (1)
Boreal to sub-boreal	76	126.7	56.3	148.7	SE31 *N* points = 15 mean = 231.4 median = 161.3	FI1D *N* points = 15 mean = 27.2 median = 22.2
Atlantic	56	117.1	68.4	137.7	IE06 *N* points = 3 mean = 279.6 median = 281.3	UKL1 *N* points = 4 mean = 59.5 median = 48.0
Sub-oceanic	126	51.9	37.8	49.6	ES12 *N* points = 3 mean = 109.3 median = 105.2	ES23 *N* points = 4 mean = 32.3 median = 33.4
Sub-continental (northern)	18	57.5	37.1	67.1	SE12 *N* points = 4 mean = 127.5 median = 87.8	SE21 *N* points = 4 mean = 62.1 median = 54.7
Sub-continental (southern)	30	28.63	25.6	15.4	RO31 *N* points = 4 mean = 29.5 median = 21.5	RO11 *N* points = 6 mean = 23.6 median = 24.2
Temperate mountainous	33	51.0	36.2	41.6	ES22 *N* points = 3 mean = 53.4 median = 42.3	BG41 *N* points = 5 mean = 30.3 median = 31.3
Mediterranean (semi-arid)	223	29.7	24.5	23.8	ITG1 *N* points = 5 mean = 43.7 median = 33.8	ES22 *N* points = 3 mean = 15.1 median = 18.9
Mediterranean (temperate to sub-oceanic)	136	41.4	34.1	26.8	ES11 *N* points = 3 mean = 53 median = 52.1	ES43 *N* points = 4 mean = 18.8 median = 16.9

Figure 18 Organic carbon content in grassland: (a) point data and (b) average aggregated at NUTS 2 level

(a)



(b)

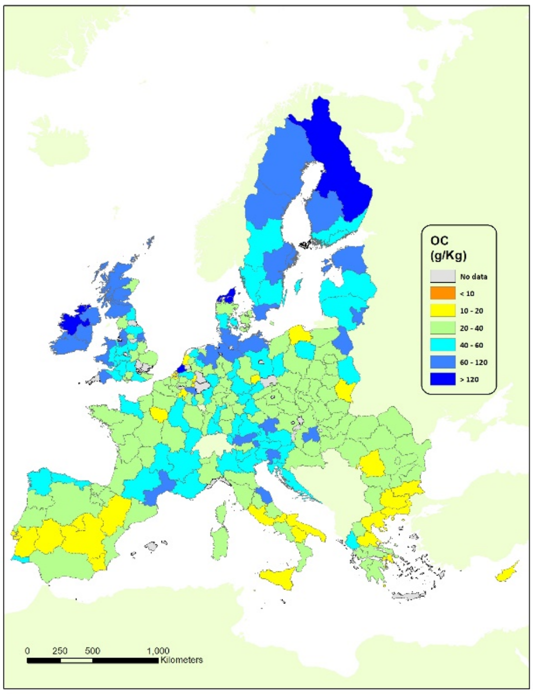
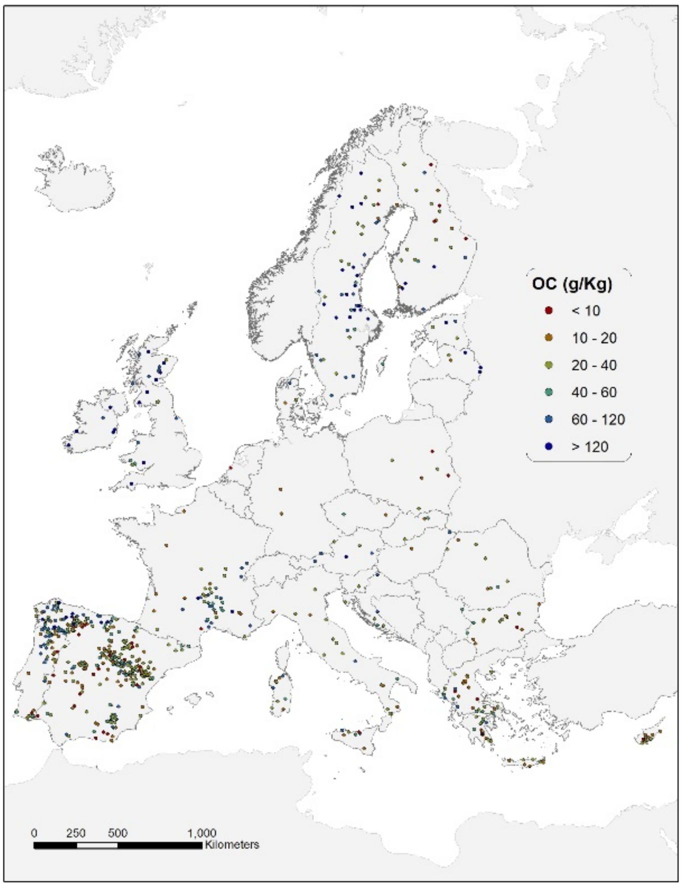


Figure 19 Organic carbon content in shrubland presented as point data



Organic carbon content was on average 18.3 g kg^{-1} in **cropland** points and 17.3 g kg^{-1} in **bareland** points (Table 14), showing an increasing trend from south-eastern to north-western climatic zones (Figures 20 and 21). The lowest contents of OC in cropland were measured in points from the semi-arid Mediterranean, ranging from 9.0 g kg^{-1} in ES30 region to 33.7 g kg^{-1} in PT15 region (Table 19, Figure 20).

Surprisingly, the lowest mean OC content in bareland was observed in the temperate mountainous zone (8.6 g kg^{-1}, Table 20); although care must be taken in interpreting this result since the number of bareland samples for this climatic zone is low (8 points sampled). If this climatic zone is not considered, the lowest OC contents in bareland are found in the semi-arid Mediterranean zone, ranging from 17.4 g kg^{-1} in CY00 region to 11.2 g kg^{-1} in ES41 region (Table 20, Figure 21). Dry and warm climatic conditions, and low agricultural potential of many soils (e.g. Calcisols, Leptosols, Arenosols) characteristic of the semi-arid Mediterranean zone hinder OC accumulation in this climatic zone. On the contrary, OC content was the highest in the boreal to sub-boreal zone both in cropland (55.1 g kg^{-1}) and bareland (56 g kg^{-1}), followed by the temperate mountainous and the sub-oceanic zones in cropland (21.8 g kg^{-1} and 21.4 g kg^{-1}, respectively) (Table 19, Figure 20) and by the sub-oceanic zone in bareland (22.4 g kg^{-1}) (Table 20, Figure 21). The cooler and more humid conditions can explain the larger accumulation of OC in soil in these zones, in which characteristic soils such as Luvisols, Phaeozems and Cambisols are found, which are particularly suited to agricultural production.

Table 19 Summary of organic carbon in cropland points of the 2018 LUCAS Topsoil survey.

Climatic zone	***N* points**	**Mean (g kg-1)**	**Median (g kg-1)**	**Std dev (g kg-1)**	**NUTS 2 with highest OC content in cropland (g kg^{-1})** (1)	**NUTS 2 with lowest OC content in cropland (g kg^{-1})** (1)
Boreal to sub-boreal	210	55.1	26.7	80.2	FI1D *N* points = 37 mean = 123.9 median = 60.2	LV00 *N* points = 25 mean = 17.5 median = 16.1
Atlantic	1438	19.0	15.6	14.8	NL13 *N* points = 4 mean = 71.3 median = 69.9	FRJ1 *N* points = 3 mean = 9.5 median = 10.1
Sub-oceanic	814	21.4	18.4	12.3	ITH4 *N* points = 19 mean = 49.9 median = 49.7	EL53 *N* points = 3 mean = 9.3 median = 8.7
Sub-continental (northern)	1429	17.6	13.9	21.7	EE00 *N* points = 7 mean = 45.0 median = 38.4	PL43 *N* points = 19 mean = 10.1 median = 9.1
Sub-continental (southern)	754	17.9	16.7	8.2	RO12 *N* points = 11 mean = 23.2 median = 21.9	PL81 *N* points = 27 mean = 11.4 median = 9.8
Temperate mountainous	170	21.8	18.7	12.2	ITH2 *N* points = 10 mean = 36.9 median = 35.7	EL51 *N* points = 10 mean = 10.8 median = 10.1
Mediterranean (semi-arid)	1905	13.0	11.4	8.1	PT15 *N* points = 7 mean = 33.7 median = 23.6	ES30 *N* points = 18 mean = 9.0 median = 8.1
Mediterranean (temperate to sub-oceanic)	615	17.2	14	13.4	ES11 *N* points = 6 mean = 54.4 median = 46.7	PT18 *N* points = 11 mean = 7.8 median = 8.2

Table 20 Summary of organic carbon in bareland points of the 2018 LUCAS Topsoil survey.

Climatic zone	***N* points**	**Mean (g kg-1)**	**Median (g kg-1)**	**Std dev (g kg-1)**	**NUTS 2 with highest OC content in bareland (g kg^{-1})** (1)	**NUTS 2 with lowest OC content in bareland (g kg^{-1})** (1)
Boreal to sub-boreal	18	56	20.1	83	SE12 *N* points = 3 mean = 130.7 median = 25.4	LV00 *N* points = 4 mean = 16.8 median = 18.2
Atlantic	95	18.8	17.4	8.1	UKF2 *N* points = 10 mean = 28.2 median = 29	FRC1 *N* points = 5 mean = 12.4 median = 11.4
Sub-oceanic	48	22.4	19.2	17.7	FRK1 *N* points = 6 mean = 30.2 median = 27	DE73 *N* points = 4 mean = 14.9 median = 12.9
Sub-continental (northern)	41	34.7	18.5	67.7	LT02 *N* points = 3 mean = 15.8 median = 15.9	PL42 *N* points = 3 mean = 10.25 median = 10.35
Sub-continental (southern)	55	19.1	18.7	8.2	HU31 *N* points = 3 mean = 34.6 median = 24.3	RO41 *N* points = 3 mean = 14.4 median = 17.2
Temperate mountainous	8	8.6	8.5	3.4	EL52 *N* points = 4 mean = 9.5 median = 9.1	
Mediterranean (semi-arid)	309	11.5	10.1	7.3	PT11 *N* points = 3 mean = 39.6 median = 40.7	CY00 *N* points = 3 mean = 17.4 median = 15.4
Mediterranean (temperate to sub-oceanic)	54	17.3	11.6	18.7	ES41 *N* points = 3 mean = 11.2 median = 10.8	PT18 *N* points = 3 mean = 39.6 median = 40.7

Figure 20 Organic carbon content in cropland: (a) point data and (b) average aggregated at NUTS 2 level

(a) (b)

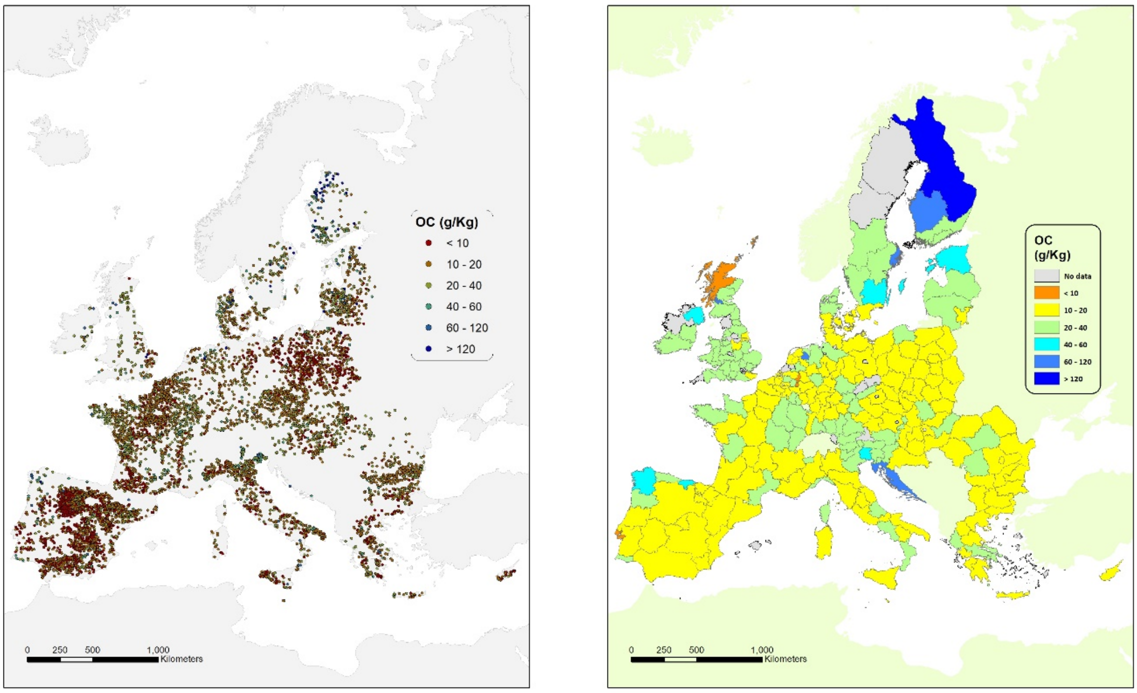
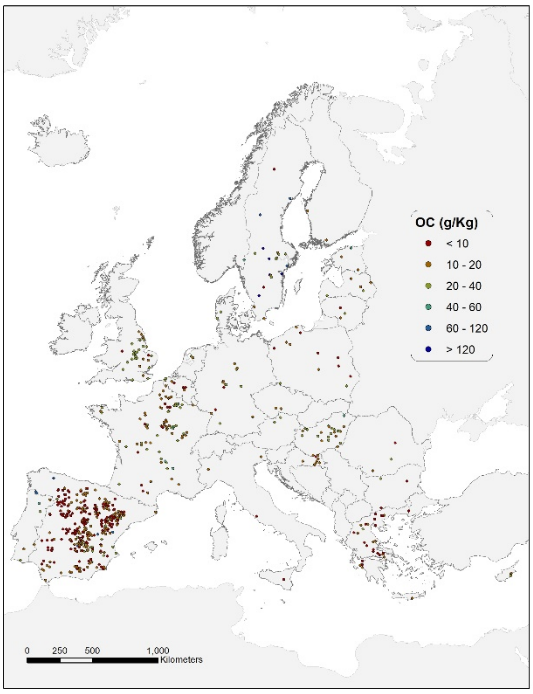


Figure 21 Organic carbon content in bareland presented as point data



4.7 Nitrogen, phosphorus, and potassium

4.7.1 Nitrogen content

The spatial distribution of nitrogen (N) was highly correlated with that of OC, given that N is a main component of soil organic matter: (i) N content increased from south-eastern to north-western regions (Table 21, Figure 22), and (ii) it was greater in wetland, woodland, grassland and shrubland than in cropland and bareland (Table 21, Figure 23). Thus, as for OC, the main drivers of N content in soil were climate and the type of vegetation.

Table 21 Summary of nitrogen content in the 2018 LUCAS Topsoil survey, by climatic zone and by land cover class

	Nitrogen (g kg^{-1})		
Climatic zones	**Mean**	**Median**	**Std Dev**
Boreal to sub-boreal	5.2	2.4	6.3
Atlantic	3.3	2.3	3.3
Sub-continental (northern)	3.2	1.9	4.2
Sub-oceanic	3.5	2.8	2.5
Sub-continental (southern)	2.2	1.9	1.4
Temperate mountainous	4.2	3.4	3.5
Mediterranean (semi-arid)	1.6	1.3	1.0
Mediterranean (temperate to sub-oceanic)	2.2	1.7	1.6
Mediterranean zones	1.8	1.4	1.3
Land cover classes			
Wetland	13.8	15.2	8.1
Woodland	4.5	2.7	5.0
Shrubland	3.7	2.7	3.6
Grassland	3.6	2.8	3.5
Cropland	1.8	1.6	1.3
Bareland	1.6	1.4	1.1

Overall, **wetland**, **woodland**, **grassland** and **shrubland** showed a relatively large proportion of points with high content of N (>3 g kg^{-1}) in the boreal to sub-boreal, Atlantic, temperate mountainous and sub-oceanic zones (Figures 24 to 27). The average nitrogen content was >3 g kg^{-1} for these LC in the climatic zones mentioned, except for wetland in the temperate mountainous zone that had a slightly lower content (2.6 g kg^{-1}) (Table 21). In addition, the median was >3 g kg^{-1} in woodland, grassland and shrubland in the Atlantic, temperate mountainous and sub-oceanic zones, which indicates that N content was >3 g kg^{-1} in more than50 % of the points in these zones (Table 21). Similarly, the median of N content was >3 g kg^{-1} in the boreal to sub-boreal, Atlantic, and sub-oceanic zones (Table 21). However, as shown in Tables 22 to 25, the N content varied largely in woodland, grassland and shrubland within each climatic zone mentioned. The largest variations in N content in woodland, grassland and shrubland were observed in the Atlantic zone: the average N content ranged from 1.5 g kg^{-1} in the NUTS 2 region FRB0 to 14.7 g kg^{-1} in IE05 region in woodland, from 1.9 g kg^{-1} in FR10 region to 10.3 g kg^{-1} in DK05 region in grassland, and from 4.8 g kg^{-1} in ES11 region to 13.5 g kg^{-1} in IE06 region in shrubland (Table 23 to 25). In wetland, the N content ranged from 13.6 g kg^{-1} in SE33 region to 17.4 g kg^{-1} in SE31 region (Table 22). None of the NUTS 2 regions in the other climatic zones had enough points (>3 points) to be included in the statistics. On the contrary, the average N content in woodland, grassland and shrubland in the sub-continental and Mediterranean zones was <3 g kg^{-1}, except for woodland (4.6 g kg^{-1}) and grassland (3.5 g kg^{-1}) in the northern sub-continental zone (Table 21). In all climatic zones, the median N content was <3 g kg^{-1}, which means that less than50 % of the points had N contents >3 g kg^{-1}.

Figure 22 Nitrogen content (all 2018 LUCAS Soil Module points) presented (a) as point data and (b) average aggregated at NUTS 2 level

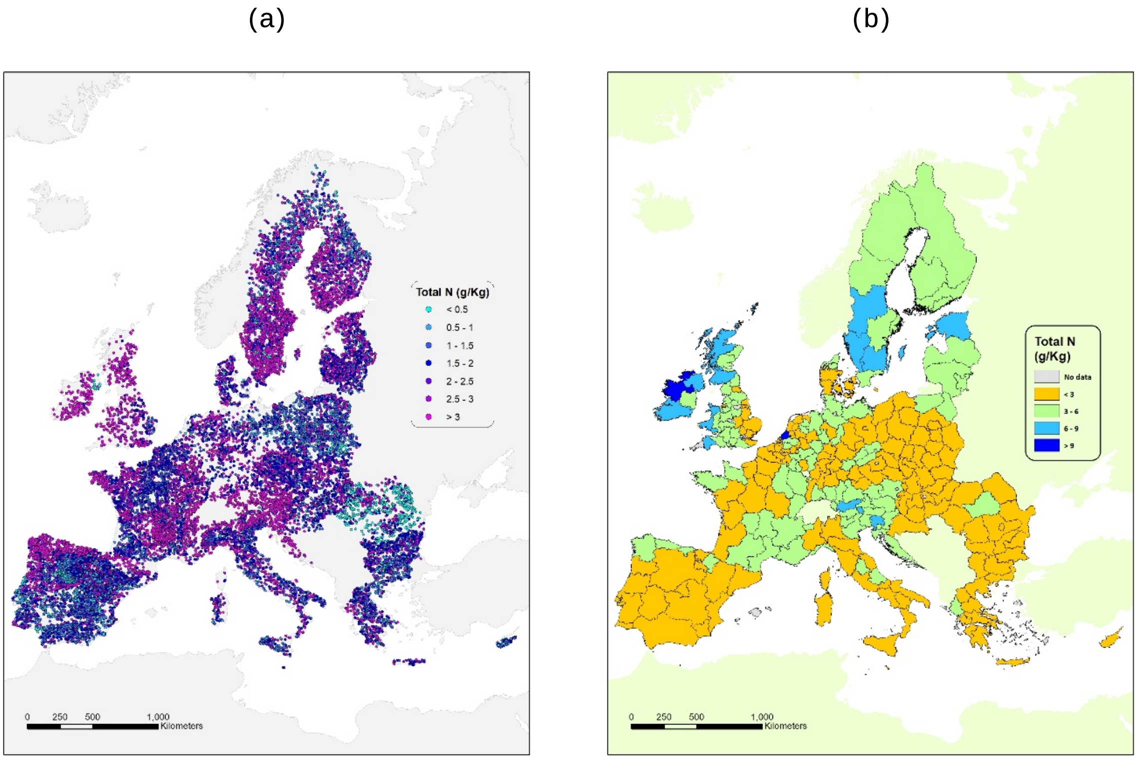
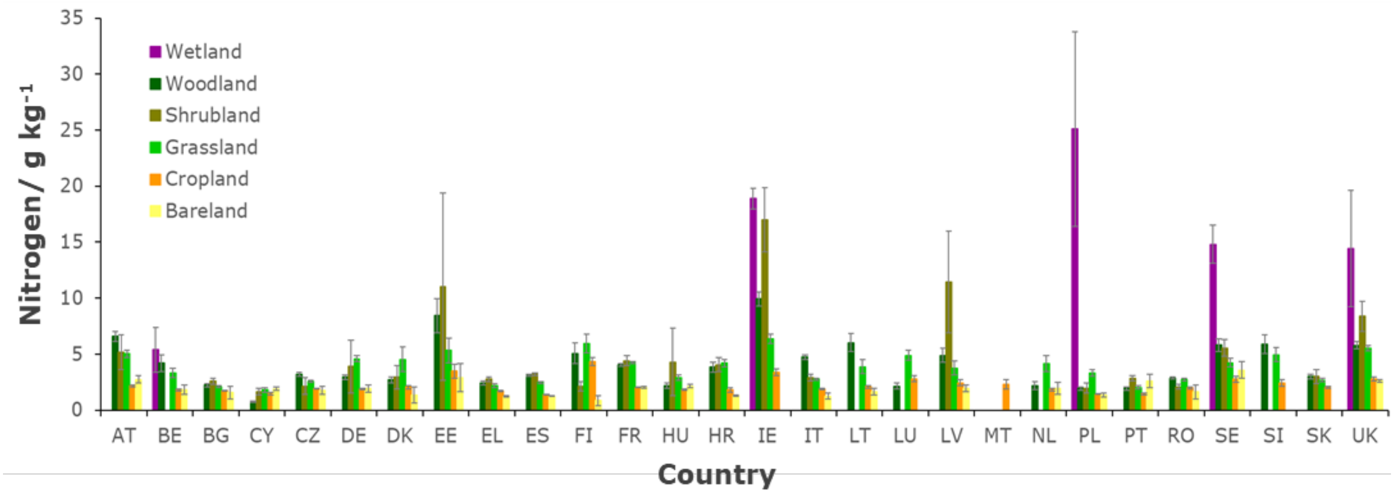


Figure 23 Nitrogen content (mean and standard error) by land cover class in the 27 Member States and the UK



Nitrogen content was lower in **cropland** and **bareland** compared to wetland, woodland, grassland and shrubland (Table 21). Nitrogen content in these two LC classes was especially low in the sub-continental and Mediterranean zones (Figures 27-29). Both the mean and median contents of N were >2 g kg^{-1} in cropland and bareland in the climatic zones mentioned (Table 21). In cropland, the mean N content ranged from 0.8 g kg^{-1} in ES62 region in the temperate to sub-oceanic Mediterranean zone to 4.2 g kg^{-1} in EE00 region in the northern sub-continental zone (Table 26). In bareland, mean N content ranged from 1 g kg^{-1} in ES43 region in the semi-arid Mediterranean zone to 3.6 g kg^{-1} in SE12 region in the northern-sub-continental zone (Table 27).

The N contents observed in LUCAS 2018 are consistent with the estimations produced by Ballabio et al. (2019) based on the LUCAS 2009/2012 data. In the N map produced by these authors, woodland and grassland in boreal-to sub-boreal, Atlantic and temperate mountainous zones clearly stand out for their high N contents. The cool and humid conditions in these climatic zones favour organic matter accumulation, which results in high contents of OC and N in topsoil. The N map shows also low N contents in the Mediterranean and sub-continental zones. The warm and/or dry conditions accelerate organic matter decomposition in the Mediterranean zones, which can explain the lower N content in cropland in these zones compared to cropland in other climatic zones. Soil texture also plays a role in preserving organic matter and, thus, OC and N. For instance, N content tends to be lower in the coarse textured soils found in the northern sub-continental zones even if other factors, such as climate, are favourable. In addition, it must be noted that different fertilization practices at regional and national scales can influence the spatial distribution of N in soils under cropland.

Figure 24 Nitrogen content in wetland presented as point data

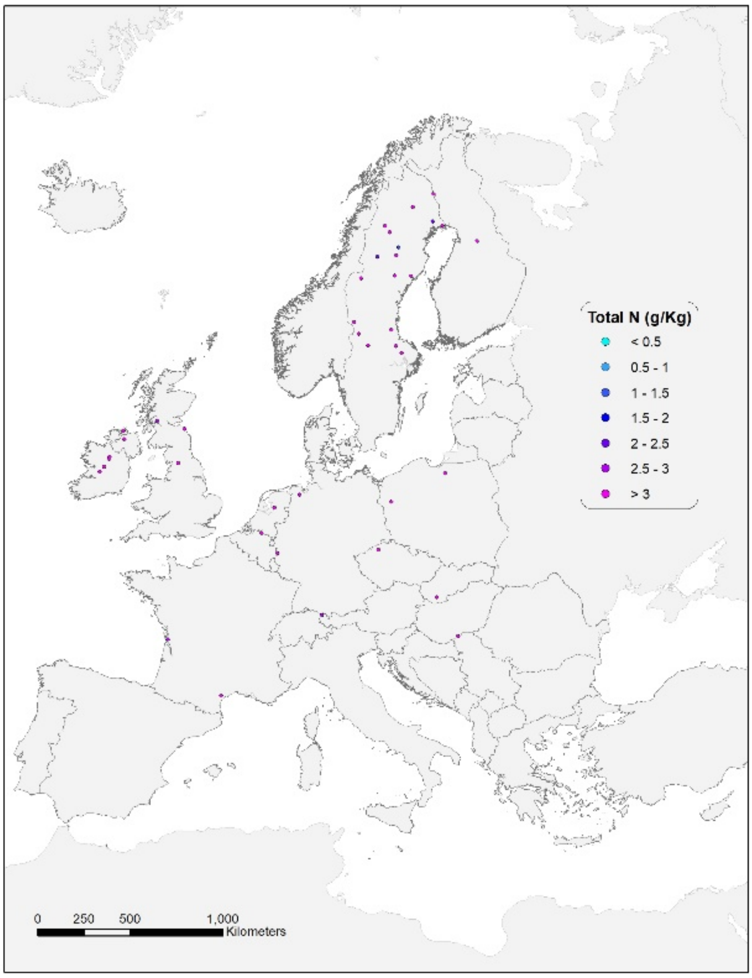


Figure 25 Nitrogen content in woodland presented (a) as point data and (b) average aggregated at NUTS 2 level

(a) (b)

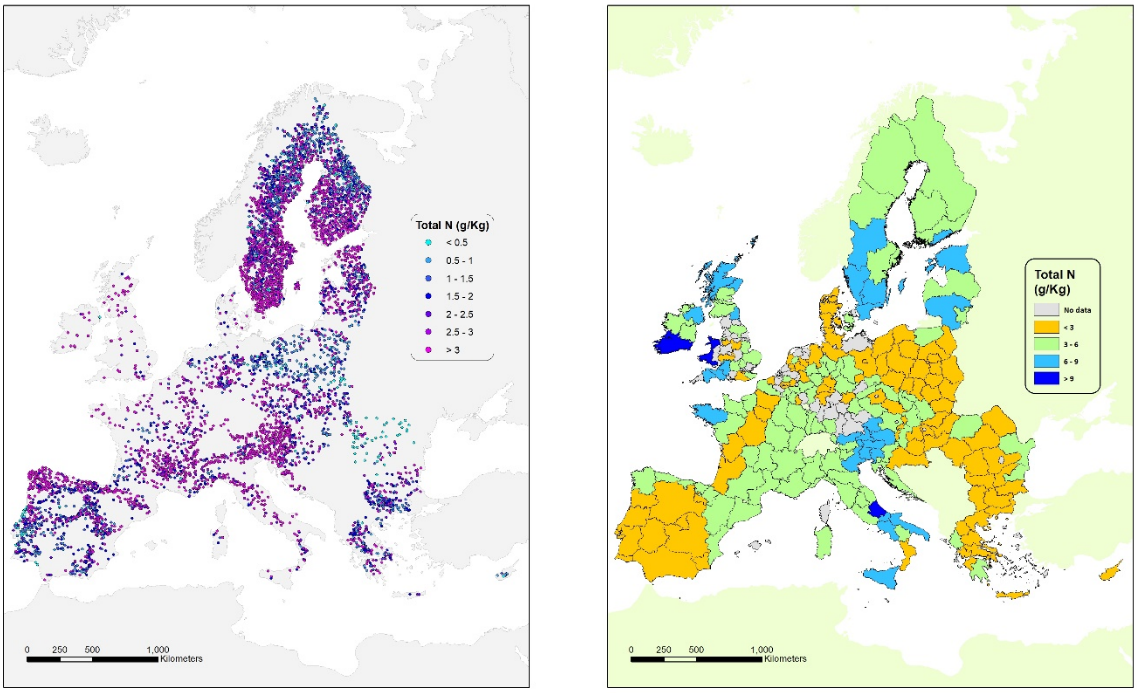


Figure 26 Nitrogen content in grassland presented (a) as point data and (b) average aggregated at NUTS 2 level

(a) (b)

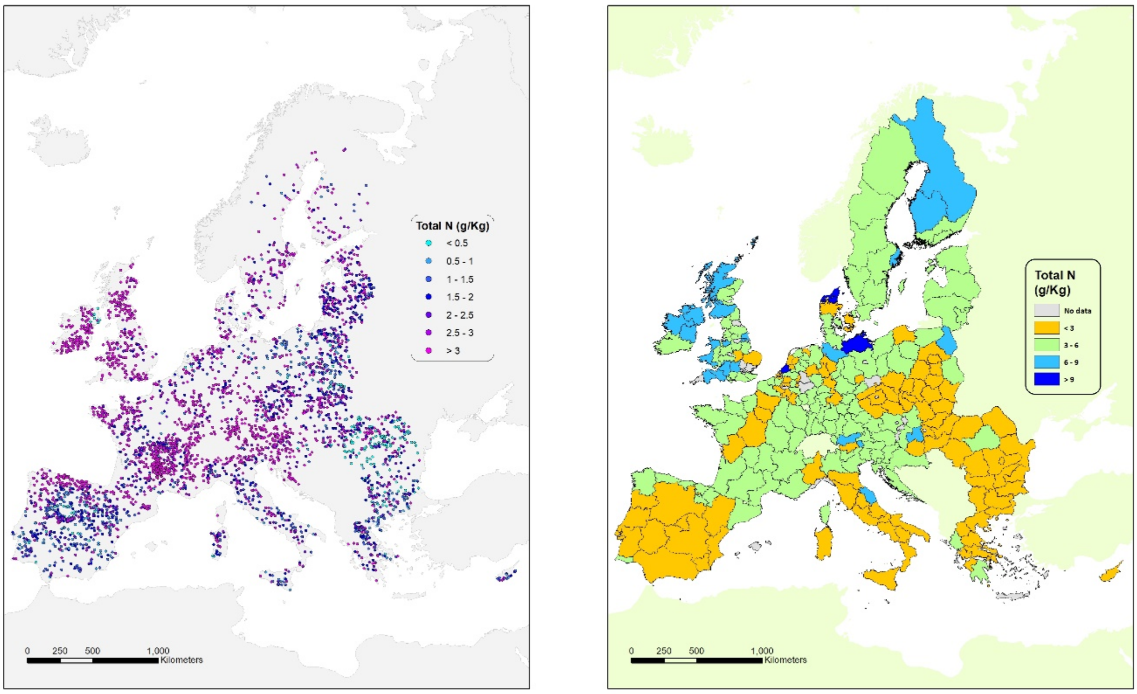


Figure 27 Nitrogen content in cropland presented (a) as point data and (b) average aggregated at NUTS 2 level

(a) (b)

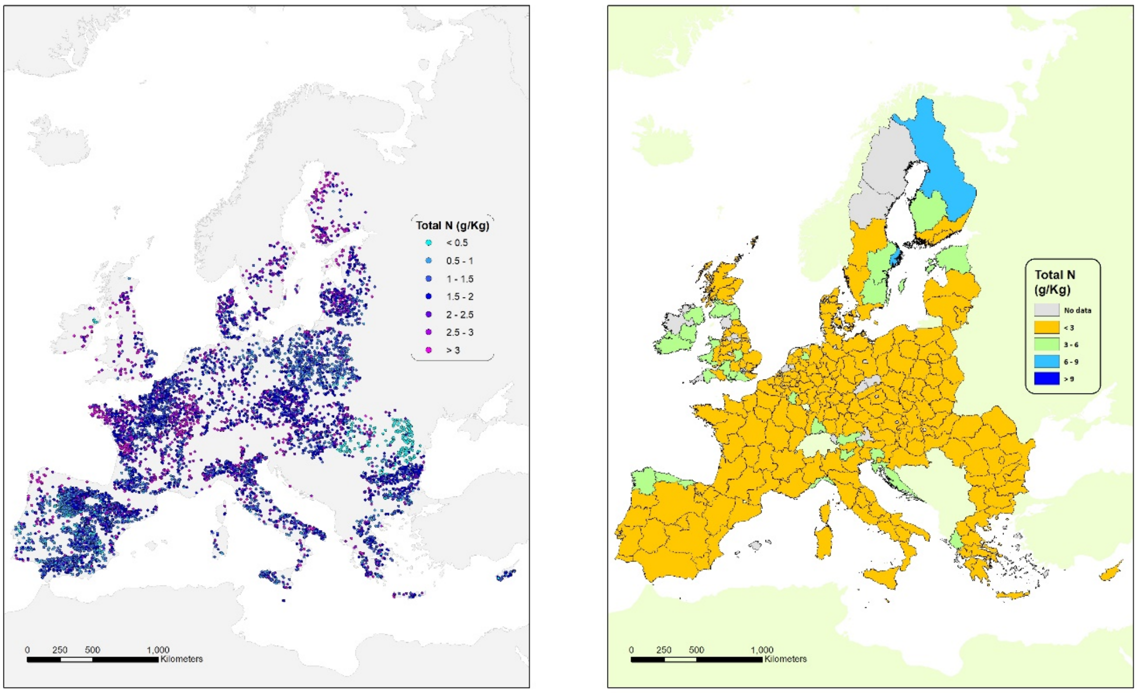


Figure 28 Nitrogen content in bareland presented as point data

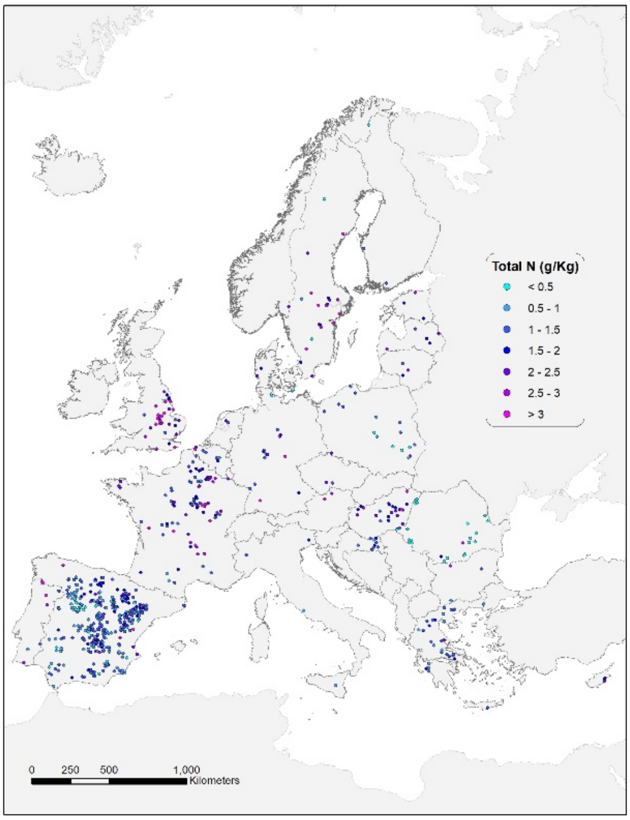


Figure 29 Nitrogen content in shrubland presented as point data

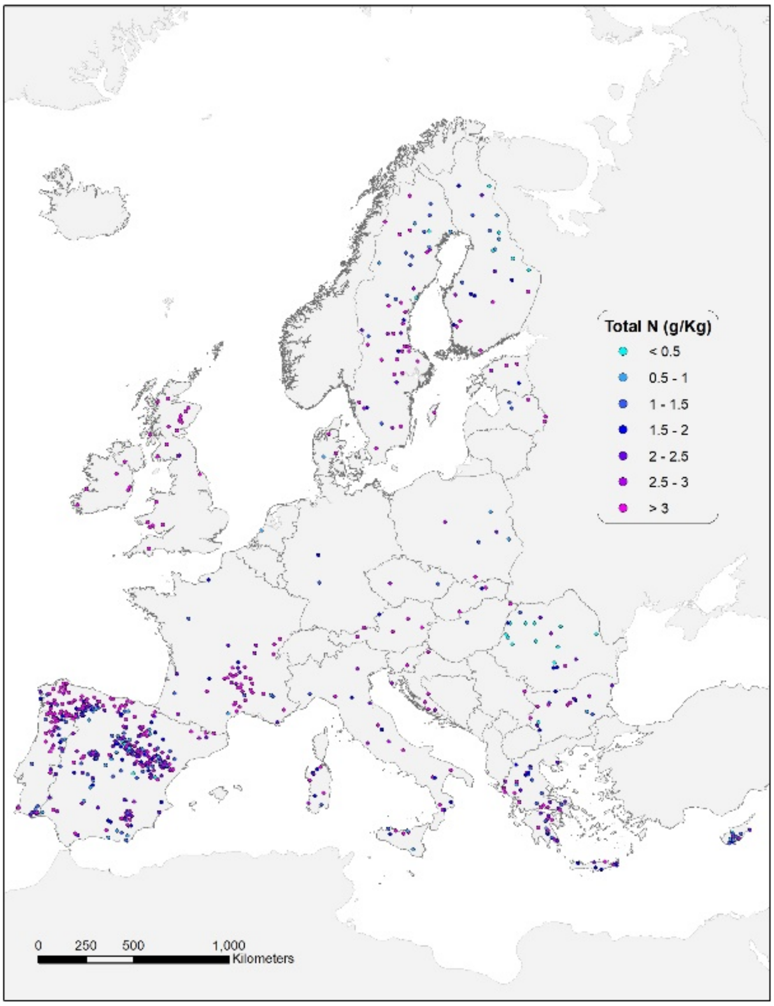


Table 22 Summary of nitrogen content in wetland in the 2018 LUCAS Topsoil survey

Climatic zone	***N* points**	**Mean (g kg-1)**	**Median (g kg-1)**	**Std dev (g kg-1)**	**NUTS 2 with highest N content in wetland (g kg^{-1})** (1)	**NUTS 2 with lowest N content in wetland (g kg^{-1})** (1)
Boreal to sub-boreal	20	14.5	15.9	7.5	SE31 *N* points =5 mean = 17.4 median = 15.2	SE33 *N* points =10 mean = 13.58 median = 15.4
Atlantic	12	15.2	16.5	7.1	IE04 *N* points = 5 mean = 18.9 median = 19.4	
Sub-oceanic	1	7.4	7.4	NA	None of the regions had at least 3 points	
Sub-continental (northern)	3	18.0	16.4	15.0	None of the regions had at least 3 points	
Sub-continental (southern)	2	4.4	4.4	1.2	None of the regions had at least 3 points	
Temperate mountainous	1	2.6	2.6	NA	None of the regions had at least 3 points	
Mediterranean (temperate to sub-oceanic)	1	5.1	5.1	NA	None of the regions had at least 3 points	

Table 23 Summary of nitrogen content in woodland in the 2018 LUCAS Topsoil survey

Climatic zone	***N* points**	**Mean (g kg-1)**	**Median (g kg-1)**	**Std dev (g kg-1)**	**NUTS 2 with highest N content in woodland (g kg^{-1})** (1)	**NUTS 2 with lowest N content in woodland (g kg^{-1})** (1)
Boreal to sub-boreal	2095	5.3	2.4	6.5	EE00 *N* points = 87 mean = 8.5 median = 4.4	SE33 *N* points = 462 mean = 4.3 median = 1.5
Atlantic	374	4.9	3.6	4.4	IE05 *N* points = 4 mean = 14.7 median = 13.5	FRB0 *N* points = 17 mean = 1.5 median = 1.4
Sub-oceanic	693	4.1	3.3	2.8	ITF1 *N* points = 4 mean = 11.8 median = 11.5	EL63 *N* points = 3 mean = 1 median =0.9
Sub-continental (northern)	1145	4.6	2.7	5.2	FI1B *N* points = 4 mean = 9.1 median = 10.3	PL72 *N* points = 6 mean = 0.9 median = 0.9
Sub-continental (southern)	275	2.8	2.3	2.1	SI04 *N* points = 11 mean = 7.2 median = 6.8	HU12 *N* points = 11 mean = 1.2 median = 1
Temperate mountainous	665	4.8	3.6	4.1	AT12 *N* points = 17 mean = 8.7 median = 6.3	EL51 *N* points = 15 mean = 1.7 median = 1.1
Mediterranean (semi-arid)	427	2.1	1.7	1.4	ITG1 *N* points = 3 mean = 5.3 median = 6.8	CY00 *N* points = 7 mean = 0.7 median = 0.7
Mediterranean (temperate to sub-oceanic)	321	2.9	2.4	2.3	ES22 *N* points = 11 mean = 5.9 median = 4.3	PT18 *N* points = 23 mean = 1.1 median = 0.7

Table 24 Summary of nitrogen content in grassland in the 2018 LUCAS Topsoil survey

Climatic zone	***N* points**	**Mean (g kg-1)**	**Median (g kg-1)**	**Std dev (g kg-1)**	**NUTS 2 with highest N content in grassland (g kg^{-1})** (1)	**NUTS 2 with lowest N content in grassland (g kg^{-1})** (1)
Boreal to sub-boreal	167	4.9	2.7	5.9	UKM6 *N* points = 6 mean = 11 median = 5.7	FI1C *N* points = 10 mean = 3.2 median = 2.4
Atlantic	716	4.8	3.8	3.7	DK05 *N* points = 5 mean = 10.3 median = 5.3	FR10 *N* points = 4 mean = 1.9 median = 2
Sub-oceanic	789	4.3	3.7	2.7	AT31 *N* points = 4 mean = 8.7 median = 4.6	ITF2 *N* points = 5 mean = 1.3 median = 1.2
Sub-continental (northern)	704	3.5	2.1	5.1	DE80 *N* points = 5 mean = 9.1 median = 2	PL82 *N* points = 11 mean = 1.9 median = 1.7
Sub-continental (southern)	355	2.6	2.3	1.7	HU21 *N* points = 5 mean = 6.1 median = 4.5	RO41 *N* points = 13 mean = 1.3 median = 1
Temperate mountainous	413	4.1	3.5	3.0	AT33 *N* points = 15 mean = 7.9 median = 5.9	EL52 *N* points = 4 mean = 1.4 median = 1.3
Mediterranean (semi-arid)	538	1.8	1.5	1.3	EL65 *N* points = 8 mean = 3.0 median = 2.4	EL52 *N* points = 17 mean = 1.1 median = 1.1
Mediterranean (temperate to sub-oceanic)	261	2.3	1.9	1.3	ES21 *N* points = 3 mean = 3.7 median = 4	PT17 *N* points = 4 mean = 1.1 median = 1.0

Table 25 Summary of nitrogen content in shrubland in the 2018 LUCAS Topsoil survey

Climatic zone	***N* points**	**Mean (g kg-1)**	**Median (g kg-1)**	**Std dev (g kg-1)**	**NUTS 2 with highest N content in shrubland (g kg^{-1})** (1)	**NUTS 2 with lowest N content in shrubland (g kg^{-1})** (1)
Boreal to sub-boreal	76	5.5	2.4	6.6	LV00 *N* points = 5 mean = 11.4 median = 12	FI1D *N* points = 15 mean = 1.3 median = 1
Atlantic	56	7.0	4.8	6.3	IE06 *N* points = 3 mean = 13.5 median = 11.1	ES11 *N* points = 19 mean = 4.8 median = 3.6
Sub-oceanic	126	4.0	3.2	2.5	FRC2 *N* points = 3 mean = 7 median =6	EL54 *N* points = 3 mean = 2.8 median = 2.3
Sub-continental (northern)	18	3.1	2.55	2.4	SE12 *N* points =4 mean = 5.6 median = 4.5	SE21 *N* points = 4 mean = 3.1 median = 3.3
Sub-continental (southern)	30	2.7	2.55	1.4	RO31 *N* points =4 mean = 2.7 median = 2.1	BG31 *N* points = 3 mean = 2.2 median = 1.8
Temperate mountainous	33	4.4	3.6	3.0	ES22 *N* points = 3 mean = 4.2 median = 3.8	BG41 *N* points = 5 mean = 3.1 median = 3
Mediterranean (semi-arid)	226	2.4	2.1	1.7	ITG1 *N* points = 5 mean = 2.9 median = 1.6	ES22 *N* points = 3 mean = 1.5 median = 1.6
Mediterranean (temperate to sub-oceanic)	136	3.2	2.85	1.8	EL54 *N* points = 5 mean = 4.3 median = 3.8	ES43 *N* points = 4 mean = 2.3 median = 2

Table 26 Summary of nitrogen content in cropland in the 2018 LUCAS Topsoil survey

Climatic zone	***N* points**	**Mean (g kg-1)**	**Median (g kg-1)**	**Std dev (g kg-1)**	**NUTS 2 with highest N content in cropland (g kg^{-1})** (1)	**NUTS 2 with lowest N content in cropland (g kg^{-1})** (1)
Boreal to sub-boreal	210	3.7	2.3	4.1	FI1D *N* points = 37 mean = 6.5 median = 3.9	LV00 *N* points = 25 mean = 1.7 median = 1.7
Atlantic	1438	2.0	1.8	1.2	UKN0 *N* points = 7 mean = 4.4 median = 3.9	FRJ1 *N* points = 3 mean = 1.1 median = 1.2
Sub-oceanic	814	2.2	2	1.0	BE34 *N* points = 3 mean = 4.3 median = 4.3	EL53 *N* points = 3 mean = 1 median =1
Sub-continental (northern)	1428	1.8	1.5	1.6	EE00 *N* points = 7 mean = 4.2 median = 3.6	PL91 *N* points =8 mean = 1.1 median = 1.05
Sub-continental (southern)	754	1.8	1.7	0.6	SK04 *N* points = 5 mean = 2.7 median = 2.7	PL81 *N* points = 27 mean = 1.3 median = 1.2
Temperate mountainous	170	2.3	1.9	1.1	AT22 *N* points = 3 mean = 3.4 median = 3.5	EL51 *N* points = 10 mean = 1.4 median = 1.2
Mediterranean (semi-arid)	1916	1.4	1.3	0.7	PT15 *N* points = 7 mean = 2.4 median = 2.3	PT16 *N* points = 4 mean = 0.9 median = 0.9
Mediterranean (temperate to sub-oceanic)	615	1.7	1.5	1.0	ES11 *N* points = 6 mean = 4.2 median = 3.5	ES62 *N* points = 6 mean = 0.8 median = 0.8

Table 27 Summary of nitrogen content in bareland in the 2018 LUCAS Topsoil survey

Climatic zone	***N* points**	**Mean (g kg-1)**	**Median (g kg-1)**	**Std dev (g kg-1)**	**NUTS 2 with highest N content in bareland (g kg^{-1})** (1)	**NUTS 2 with lowest N content in bareland (g kg^{-1})** (1)
Boreal to sub-boreal	18	2.8	1.8	2.7	SE12 *N* points = 3 mean = 5.6 median = 2.9	LV00 *N* points = 4 mean = 1.7 median = 1.7
Atlantic	95	2.1	1.9	0.8	UKF3 *N* points = 3 mean = 3.1 median = 3.4	FRC1 *N* points = 5 mean = 1.4 median = 1.4
Sub-oceanic	48	2.3	2.0	1.2	FRF2 *N* points = 4 mean = 3.2 median = 2.8	DE73 *N* points =4 mean = 1.8 median = 1.6
Sub-continental (northern)	41	2.4	2	2.2	SE12 *N* points = 8 mean = 3.6 median = 2.6	PL42 *N* points = 3 mean = 1.2 median = 1.2
Sub-continental (southern)	55	1.9	1.9	0.7	HU31 *N* points = 3 mean = 3.2 median = 2.1	HR04 *N* points = 8 mean = 1.4 median = 1.3
Temperate mountainous	8	1.1	1.1	0.3	EL52 *N* points = 4 mean = 1.1 median = 1.2	EL52 *N* points = 4 mean = 1.1 median = 1.2
Mediterranean (semi-arid)	312	1.2	1.2	0.5	CY00 *N* points = 3 mean = 1.9 median = 1.8	ES43 *N* points = 11 mean = 1 median =1
Mediterranean (temperate to sub-oceanic)	54	1.5	1.2	1.2	PT11 *N* points = 3 mean = 3.1 median = 3.1	ES24 *N* points =22 mean = 1.3 median = 1.1

4.7.2 Phosphorus content

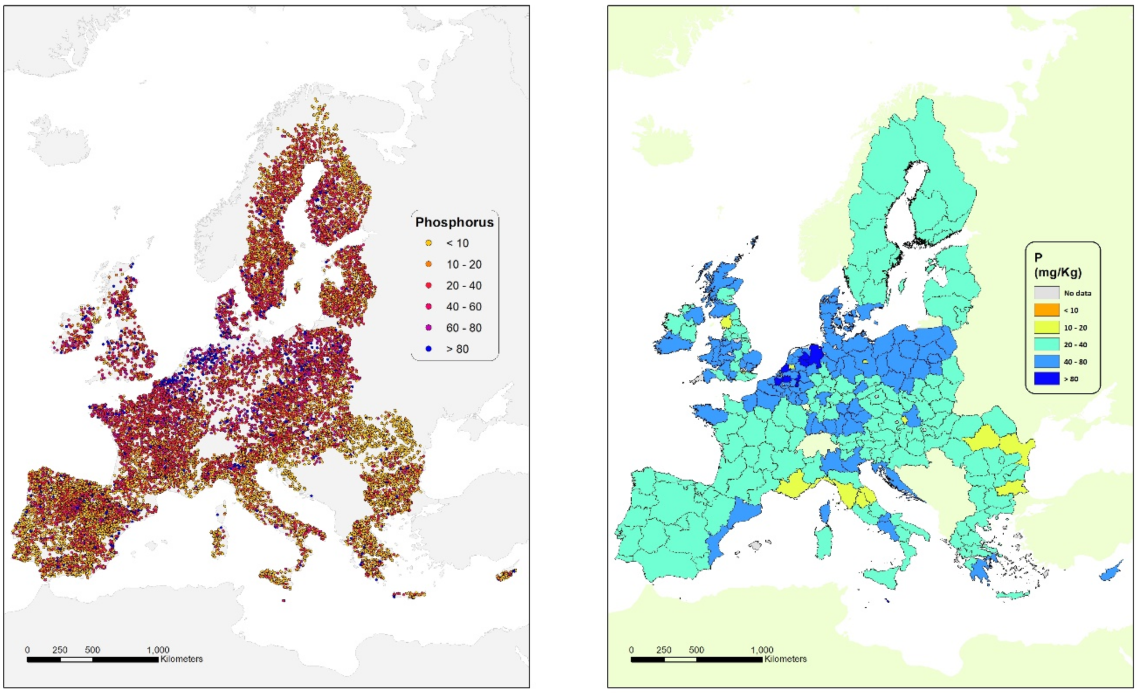
Phosphorus (P) content in soil across the various climatic zones appears to reflect land cover type. The highest contents were measured in cropland, followed by grassland and bareland in the Atlantic, sub-oceanic and northern sub-continental zones, while the lowest contents were observed in woodland and shrubland in the Mediterranean and sub-continental zones (Table 28, Figure 30). This reflects the application of phosphorous fertilzers on croplands and managed grasslands.

Table 28 Summary of phosphorus content by climatic zone and by land cover class

	Phosphorus (mg kg^{-1})		
Climatic zones	**Mean**	**Median**	**Std Dev**
Boreal to sub-boreal	30.3	24.3	20.7
Atlantic	44.9	37.2	30.6
Sub-continental (northern)	34.2	26.2	24.9
Sub-oceanic	37.3	30.2	26.3
Sub-continental (southern)	27.4	19.3	25.4
Temperate mountainous	27.0	19.7	23.6
Mediterranean (semi-arid)	30.9	22.0	31.2
Mediterranean (temperate to sub-oceanic)	32.3	22.2	28.6
Mediterranean zones	31.3	22	30.5
Land cover classes			
Wetland	25.4	20.1	16.2
Woodland	28.2	21.8	21.0
Shrubland	28.8	20.2	24.3
Grassland	34.5	24.8	30.2
Cropland	39.1	31.2	29.2
Bareland	34.3	25.9	25.2

Figure 30 Phosphorus content (all 2018 LUCAS Soil Module points) presented (a) as point data (mg/kg) and (b) average aggregated at NUTS 2 level

(a) (b)



Average P content in **woodland** ranged from 23.6 mg kg^{-1} (median = 18.7 mg kg^{-1}) in the temperate mountainous region to 34.2 mg kg^{-1} (median = 23.3 mg kg^{-1}) in the Atlantic regions (Table 29, Figure 31). A similar range of values was observed in **shrubland**, varying from 19.8 mg kg^{-1} (median = 14.1 mg kg^{-1}) in the semi-arid Mediterranean zone to 42.1 mg kg^{-1} (median = 29.9 mg kg^{-1}) in the Atlantic zones (Table 30, Figure 32). These values indicate that P content was low (<40 mg kg^{-1}) in most of the woodland and shrubland points. In woodland, 89% of the points had <40 mg kg^{-1}. In shrubland, P content was <40 mg kg^{-1} in 91 % of the points.

Grassland and **bareland** had higher P contents than woodland and shrubland. Average P content in grassland ranged from 23.8 mg kg^{-1} (median = 17.4 mg kg^{-1}) in the southern sub-continental zone to 44.2 mg kg^{-1} (median = 36.1 mg kg^{-1}) in the Atlantic zone (Table 31, Figures 33 & 34). Average P content in bareland ranged from 14.4 mg kg^{-1} (median = 13 mg kg^{-1}) in the temperate mountainous zone to 45.3 mg kg^{-1} (median = 38.9 mg kg^{-1}) in the sub continental (northern) zone (Table 32). Thus, the percentage of points with low P content was lower than in woodland and shrubland. Both in grassland and bareland, 78% of the points had <40 mg kg^{-1} of P.

Cropland showed the highest contents of P, ranging from 28.9 mg kg^{-1} (median = 21.7 mg kg^{-1}) in the southern sub-continental zone to 47.3 mg kg^{-1} (median = 40.5 mg kg^{-1}) in the Atlantic zone (Table 33, Figure 35). Sixty-eight percent of cropland points had P contents <40 mg kg^{-1}.

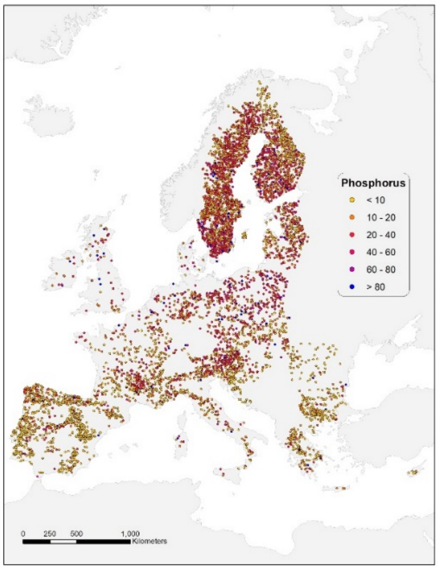
This trend among land cover classes reflects the effect of fertilization in soil. Woodland and shrubland are normally not subjected to fertilization practices, which explains the low content of P in these LC classes. Grassland and bareland classes include managed soils, that most likely are fertilized, and (semi-)natural soils.

Table 29 Summary of phosphorus content in woodland in the 2018 LUCAS Topsoil survey

Climatic zone	***N* points**	**Mean (mg kg-1)**	**Median (mg kg-1)**	**Std dev (mg kg-1)**	**NUTS 2 with highest P content in woodland (mg kg^{-1})** (1)	**NUTS 2 with lowest P content in woodland (mg kg^{-1})** (1)
Boreal to sub-boreal	1471	27.8	22.9	17.9	UKM6 *N* points = 3 mean = 42.0 median = 18.5	SE12 *N* points = 20 mean = 20.9 median = 18.4
Atlantic	252	34.2	23.3	31.7	BE21 *N* points = 4 mean = 108.4 median = 90.2	FRC1 *N* points = 3 mean = 11.2 median = 10.6
Sub-oceanic	392	25.8	19.4	18.3	DE14 *N* points = 4 mean = 57.5 median = 30.3	FRI1 *N* points = 6 mean = 13.1 median = 12.3
Sub-continental (northern)	925	30.8	25.3	20.7	AT31 *N* points = 5 mean = 64.8 median = 33.2	CZ02 *N* points = 7 mean = 15.8 median = 14.9
Sub-continental (southern)	140	24.9	16.1	25.4	RO41 *N* points = 6 mean = 48.4 median = 18.7	RO42 *N* points = 5 mean = 10.3 median = 8.2
Temperate mountainous	350	23.6	18.7	15.5	AT32 *N* points = 13 mean = 34.8 median = 27.3	RO12 *N* points = 3 mean = 11.4 median = 12.4
Mediterranean (semi-arid)	107	25.6	17.0	36.7	EL65 *N* points = 8 mean = 66.3 median = 24.1	EL53 *N* points = 8 mean = 15.6 median = 15.7
Mediterranean (temperate to sub-oceanic)	82	25.8	16.2	25.4	ES11 *N* points = 2 mean = 55.7 median = 15.2	ITI1 *N* points = 3 mean = 11.4 median = 11.4

Figure 31 Phosphorous content in woodland presented (a) as point data (mg/kg) and (b) average aggregated at NUTS 2 level

(a)



(b)

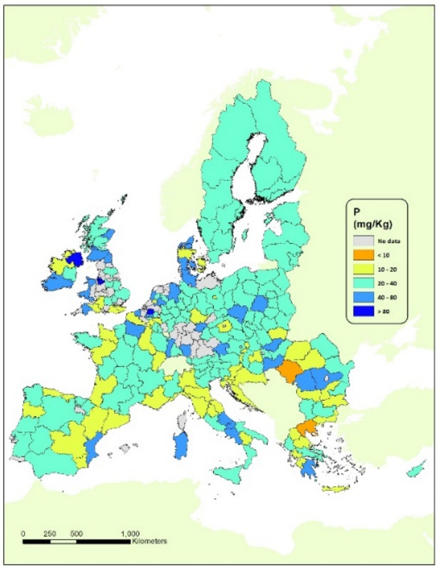


Figure 32 Phosphorous content in shrubland presented as point data (mg/kg)

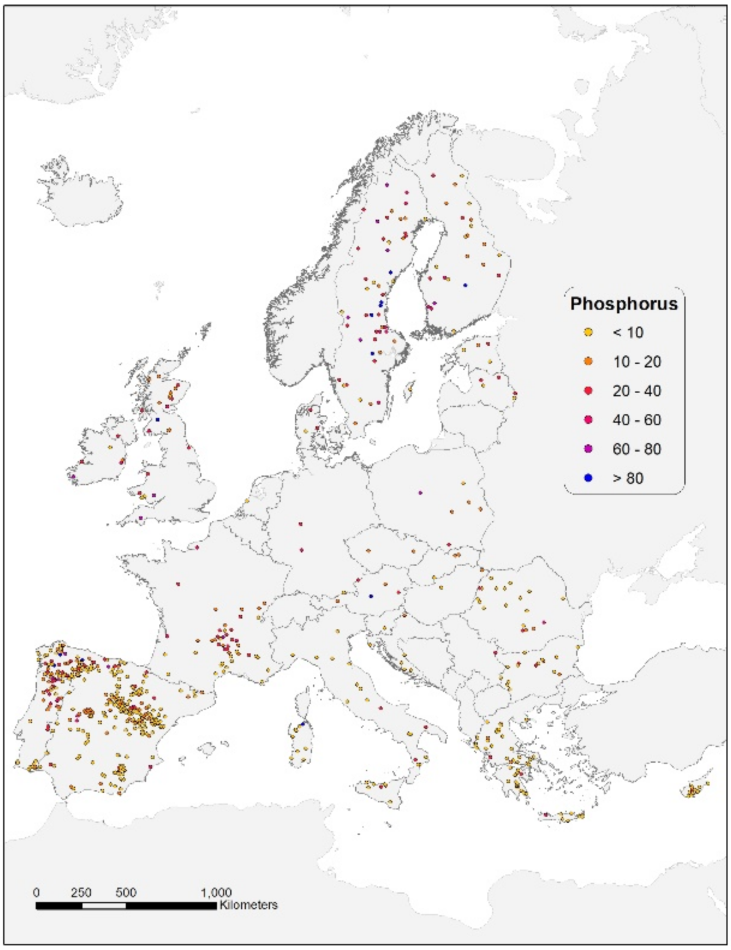


Table 30 Summary of phosphorus content in shrubland in the 2018 LUCAS Topsoil survey

Climatic zone	***N* points**	**Mean (mg kg-1)**	**Median (mg kg-1)**	**Std dev (mg kg-1)**	**NUTS 2 with highest P content in shrubland (mg kg^{-1})** (1)	**NUTS 2 with lowest P content in shrubland (mg kg^{-1})** (1)
Boreal to sub-boreal	59	36.4	26.9	24.2	FI19 *N* points = 6 mean = 61.4 median =59.5	UKM6 *N* points = 3 mean = 17.4 median = 18.3
Atlantic	35	42.1	29.9	34.5	UKM9 *N* points = 3 mean = 86.7 median =59.1	UKM5 *N* points = 3 mean = 16.8 median = 17.8
Sub-oceanic	67	24.5	20.0	16.7	FRK1 *N* points = 11 mean = 28.4 median =22	ES11 *N* points = 6 mean = 16.7 median = 14.4
Sub-continental (northern)	14	27.9	14.5	24.1	SE12 *N* points = 4 mean = 37.9 median =24.2	
Sub-continental (southern)	20	24.3	16.6	18.0	RO31 *N* points = 4 mean = 24.0 median =14.7	RO11 *N* points = 5 mean = 20.2 median = 11.8
Temperate mountainous	14	27.0	19.2	29.7	NA	NA
Mediterranean (semi-arid)	49	19.8	14.1	12.9	ES61 *N* points = 4 mean = 17.2 median =15.4	ES42 *N* points = 6 mean = 14.2 median = 12.55
Mediterranean (temperate to sub-oceanic)	47	27.4	15.8	28.7	PT11 *N* points = 17 mean = 34.8 median =21.4	ES24 *N* points = 10 mean = 13.1 median = 12.15

Table 31 Summary of phosphorus content in grassland in the 2018 LUCAS Topsoil survey

Climatic zone	*N* points	Mean (mg kg-1)	Median (mg kg-1)	Std dev (mg kg-1)	NUTS 2 with highest P content in grassland (mg kg^{-1}) (1)	NUTS 2 with lowest P content in grassland (mg kg^{-1}) (1)
Boreal to sub-boreal	142	35.6	28.3	30.5	UKM6 *N* points =6 mean = 52.5 median = 36.8	FI1B *N* points =3 mean = 25.5 median = 19
Atlantic	670	44.2	36.1	32.7	UKF1 *N* points = 6 mean = 106.5 median = 84.1	FRI2 *N* points = 3 mean = 15.8 median = 16.9
Sub-oceanic	644	31.4	23.7	22.4	DE22 *N* points = 3 mean = 76 median = 86.7	ITI1 *N* points = 3 mean = 15 median = 13
Sub-continental (northern)	595	36.2	27.4	29.2	PL91 *N* points = 8 mean = 72.4 median = 29.0	RO22 *N* points = 3 mean = 18.2 median = 19.5
Sub-continental (southern)	210	23.8	17.4	22.1	BG32 *N* points = 3 mean = 59.8 median = 44.4	RO22 *N* points = 8 mean = 13.0 median = 6.5
Temperate mountainous	281	27.3	19.1	25.0	ITH3 *N* points = 4 mean = 65.6 median = 37.7	RO42 *N* points = 3 mean = 9.5 median = 9
Mediterranean (semi-arid)	299	31.8	19.8	43.3	EL64 *N* points = 6 mean = 109 median = 27.3	ITG2 *N* points =4 mean = 16.8 median = 14
Mediterranean (temperate to sub-oceanic)	140	30.5	21.1	24.3	PT11 *N* points = 15 mean = 54.8 median = 62	FRJ1 *N* points = 6 mean = 15.3 median = 13.9

Figure 33 Phosphorous content in grassland presented (a) as point data (mg/kg) and (b) average aggregated at NUTS 2 level

(a) (b)

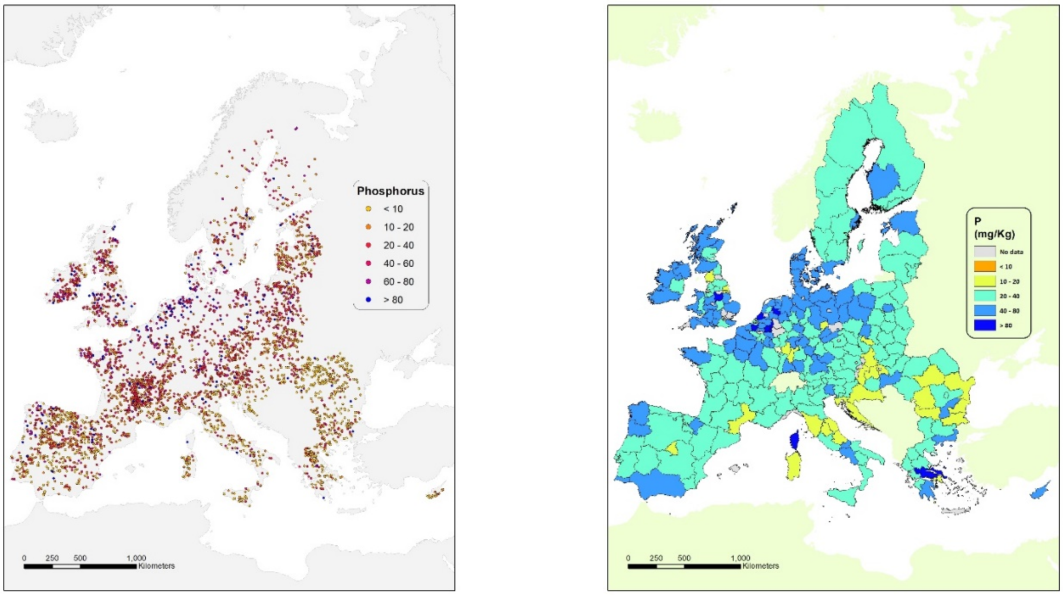


Figure 34 Phosphorous content in bareland presented as point data (mg/kg)

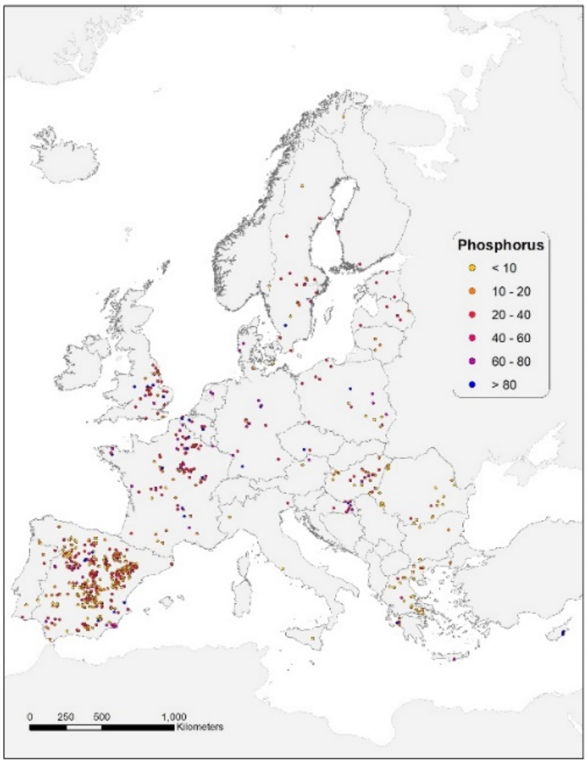


Table 32 Summary of phosphorus content in bareland in the 2018 LUCAS Topsoil survey

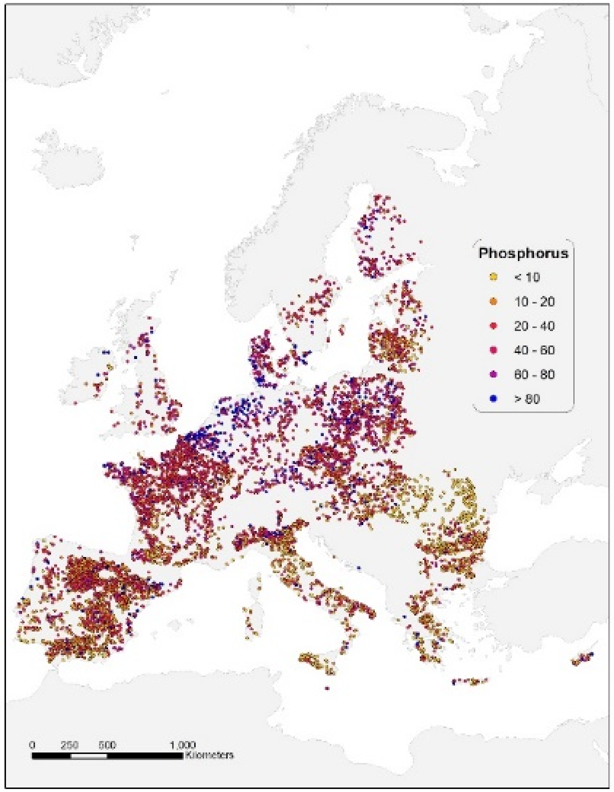
Climatic zone	***N* points**	**Mean (mg kg-1)**	**Median (mg kg-1)**	**Std dev (mg kg-1)**	**NUTS 2 with highest P content in bareland (mg kg^{-1})** (1)	**NUTS 2 with lowest P content in bareland (mg kg^{-1})** (1)
Boreal to sub-boreal	16	34.8	28.6	14.6	EE00 *N* points = 3 mean = 41.7 median = 51.2	SE12 *N* points = 3 mean = 22.8 median = 21.5
Atlantic	93	44.5	35.6	27.1	FRH0 *N* points = 3 mean = 67.8 median = 78.1	UKE1 *N* points = 6 mean = 23.9 median = 23.3
Sub-oceanic	43	38.8	29.4	27.2	FRK1 *N* points = 6 mean = 56.9 median = 46.4	FRC1 *N* points = 14 mean = 31.5 median = 26.5
Sub-continental (northern)	37	45.3	38.9	26.8	PL42 *N* points = 3 mean = 41 median = 38.9	SE12 *N* points =7 mean = 34.3 median = 23.2
Sub-continental (southern)	48	33..8	26.1	23.1	HR04 *N* points = 8 mean = 54.3 median = 54.7	RO41 *N* points = 3 mean = 19.2 median = 5.1
Temperate mountainous	3	14.4	13.0	7.0	*NA*	NA
Mediterranean (semi-arid)	221	28.5	20.2	23.1	CY00 *N* points = 3 mean = 89.2 median = 101.5	ES43 *N* points = 8 mean = 16.7 median = 17.0
Mediterranean (temperate to sub-oceanic)	38	29.7	21.4	23.7	ES52 *N* points = 4 mean = 47.8 median = 37	PT11 *N* points = 3 mean = 18.5 median = 17.5

Table 33 Summary of phosphorus content in cropland in the 2018 LUCAS Topsoil survey

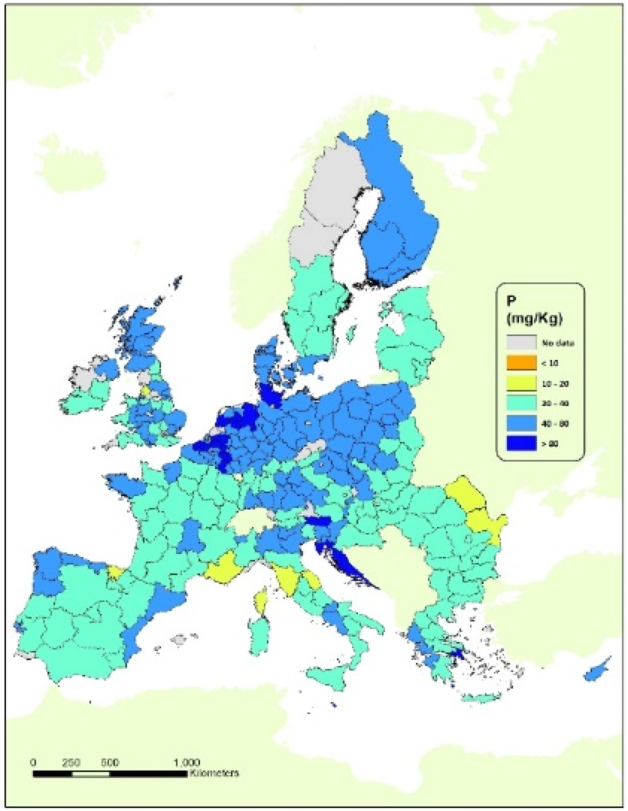
Climatic zone	***N* points**	**Mean (mg kg-1)**	**Median (mg kg-1)**	**Std dev (mg kg-1)**	**NUTS 2 with highest P content in cropland (mg kg^{-1})** (1)	**NUTS 2 with lowest P content in cropland (mg kg^{-1})** (1)
Boreal to sub-boreal	203	43.6	40.7	25.3	FI19 *N* points = 46 mean = 56.4 median = 47.6	SE31 *N* points = 7 mean = 22.4 median = 19.4
Atlantic	1385	47.3	40.5	29.0	NL21 *N* points = 4 mean = 113.4 median = 77.1	SE23 *N* points = 3 mean = 23.5 median = 23
Sub-oceanic	707	42.0	35.5	28.2	BE34 *N* points = 3 mean = 84.0 median = 83.5	ITI1 *N* points = 7 mean = 14.4 median = 13.3
Sub-continental (northern)	1360	42.1	36.0	27.5	DE23 *N* points = 5 mean = 105.7 median = 100.8	RO22 *N* points = 24 mean = 12.8 median = 9.7
Sub-continental (southern)	587	28.9	21.7	26.8	SI03 *N* points = 6 mean = 52.1 median = 46.1	RO22 *N* points = 21 mean = 14.7 median = 9.6
Temperate mountainous	129	35.6	28.4	34.1	SK02 *N* points = 8 mean = 58.3 median = 59.1	FRK2 *N* points = 3 mean = 12.8 median = 13.7
Mediterranean (semi-arid)	1379	32.0	23.9	29.1	EL30 *N* points = 3 mean = 83.8 median = 38.1	PT18 *N* points = 20 mean = 22.4 median = 17.1
Mediterranean (temperate to sub-oceanic)	460	34.8	24.8	30.5	ES11 *N* points = 6 mean = 61.2 median = 52.7	ITI2 *N* points = 3 mean = 14.3 median = 15.2

Figure 35 Phosphorous content in cropland presented (a) as point data (mg/kg) and (b) average aggregated at NUTS 2 level

(a)



(b)



4.7.3 Potassium content

Potassium (K) content in soil across the various climatic zones appears to reflect the influence of land cover. Highest levels were observed in croplands of the Mediterranean Region while the lowest levels were observed in woodlands of the Boreal Zones (Table 34, Figure 36).

Overall, woodland points tend to display low-middle levels of K. Around half of the points show K content <100 mg kg-1 while about three-quarters of points had K levels <150 mg kg-1.

Potassium levels in cropland and grassland points were both higher than in woodland points (Table 36. Figures 37-40). In croplands, mean K content ranged from around 163 mg kg-1 in both the Boreal and the Northern subcontinental zones to around 315 mg kg-1 in the temperate Mediterranean zone (Table 29). In grassland, mean K content ranged from 121.3 mg kg-1 (median = 88.8 mg kg-1) in the boreal zone to 275.9 mg kg-1 (median = 161.0 mg kg-1) in both of the Mediterranean zones (Table 35). Higher K contents in these zones and land cover classes are linked to the application of mineral fertiliser. In addition, texture also played a key role in the distribution of K with lower contents in the northern sub-continental and boreal zones, where soils with sandy textures are more prone to leaching and thus the removal of K. Soils with higher clay and silt contents, such as found in the Atlantic, oceanic and Mediterranean zones, manifest themselves with higher K levels. K levels in grasslands tend to be lower than croplands.

Potassium content was lowest in the woodlands of the boreal zone (mean = 100.6 mg kg-1, median = 61.3 mg kg-1) where soils are where relatively young, coarse textured and highly leached soils (Figure 39 and Table 37). Woodland points in Portugal had also quite low contents of K, probably reflecting their relatively high proportion of sand particles. Finally, points in the Atlantic and sub-oceanic zones in northern Spain had also low to middle K contents most likely due to the leaching (Figure 39).

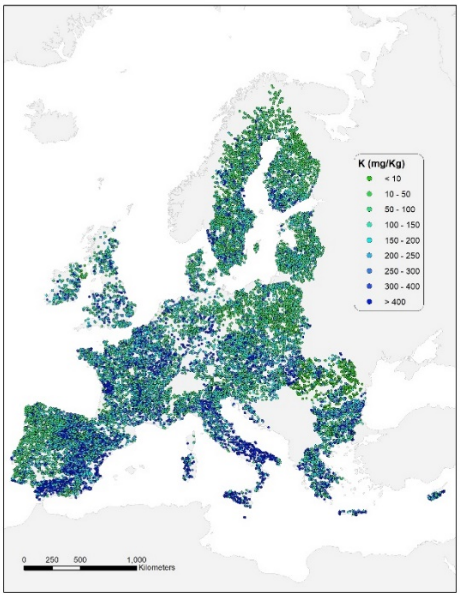
Potassium contents in shrubland were also relatively low, with more than half of the points analysed recording <150 mg kg-1. Lowest values were observed in the Boreal Zones, as was the case for other land cover classes (mean = 125.9 mg kg-1). In the southern sub-continental zones, in Bulgaria and Romania, K contents in shrubland were relatively high (mean= 276.5 mg kg-1) (Table 38, Figure 40).

Table 34 Summary of potassium content by climatic zone and by land cover class

	Potassium (mg kg^{-1})		
Climatic zones	**Mean**	**Median**	**Std Dev**
Boreal to sub-boreal	109.0	70.2	113.2
Atlantic	206.9	167.5	166.4
Sub-continental (northern)	228.4	177.3	177.8
Sub-oceanic	135.1	103.8	121.7
Sub-continental (southern)	238.9	197.6	217.4
Temperate mountainous	182.8	144.5	151.1
Mediterranean (semi-arid)	283.3	220.2	229.9
Mediterranean (temperate to sub-oceanic)	282.7	206.7	391.1
Mediterranean zones	283.1	215.4	285.9
Land cover classes			
Wetland	206.9	141.2	256.8
Woodland	138.7	93.3	152.0
Shrubland	218.6	165.3	178.4
Grassland	206.9	146.7	257.2
Cropland	250.9	200.8	207.2
Bareland	242.6	204.6	176.1

Figure 36 Potassium content (all 2018 LUCAS Soil Module points) presented (a) as point data and (b) average aggregated at NUTS 2 level

(a)



(b)

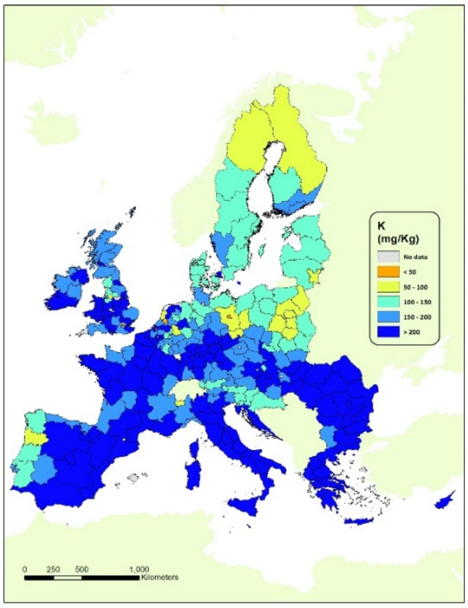
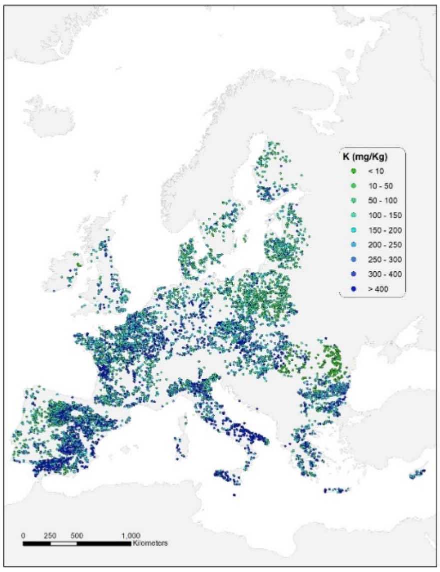


Figure 37 Potassium content in cropland presented (a) as point data and (b) average aggregated at NUTS 2 level

(a)



(b)

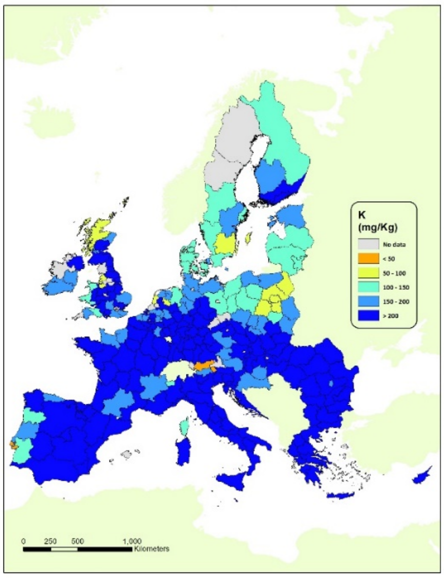


Table 35 Summary of potassium content in cropland in the 2018 LUCAS Topsoil survey

Climatic zone	***N* points**	**Mean (g kg-1)**	**Median (g kg-1)**	**Std dev (g kg-1)**	**NUTS 2 with highest K content in cropland (g kg^{-1})** (1)	**NUTS 2 with lowest K content in cropland (g kg^{-1})** (1)
Boreal to sub-boreal	210	163.2	131.5	109.9	FI19 *N* points = 46 mean = 56.4 median = 47.6	SE31 *N* points = 7 mean = 22.4 median = 19.4
Atlantic	1438	223.2	188.1	156.0	NL21 *N* points = 4 mean = 113.4 median = 77.1	SE23 *N* points = 3 mean = 23.5 median = 23
Sub-oceanic	814	276.7	228.6	190.4	BE34 *N* points = 3 mean = 84.0 median = 83.5	ITI1 *N* points = 7 mean = 14.4 median = 13.3
Sub-continental (northern)	1428	164.2	133.0	134.2	DE23 *N* points = 5 mean = 105.7 median = 100.8	RO22 *N* points = 24 mean = 12.8 median = 9.7
Sub-continental (southern)	754	251.2	217.8	147.8	SI03 *N* points = 6 mean = 52.0 median = 46.1	RO22 *N* points = 3 mean = 12.8 median = 13.7
Temperate mountainous	170	223.9	188.7	122.7	SK02 *N* points = 8 mean = 58.5 median = 59.1	FRK2 *N* points = 3 mean = 12.8 median = 13.7
Mediterranean (semi-arid)	1916	316.4	254.9	237.8	EL30 *N* points = 3 mean = 83.8 median = 38.1	PT18 *N* points = 20 mean = 22.4 median = 17.1
Mediterranean (temperate to sub-oceanic)	615	315.5	243.2	338.9	ES11 *N* points = 6 mean = 61.2 median = 52.7	ITI2 *N* points = 3 mean = 14.3 median = 15.2

Table 36 Summary of potassium content in grassland in the 2018 LUCAS Topsoil survey

Climatic zone	***N* points**	**Mean (g kg-1)**	**Median (g kg-1)**	**Std dev (g kg-1)**	**NUTS 2 with highest K content in grassland (g kg^{-1})** (1)	**NUTS 2 with lowest K content in grassland (g kg^{-1})** (1)
Boreal to sub-boreal	167	133.1	102.0	111.3	UKM6 *N* points = 6 mean = 52.5 median = 36.8	FI1B *N* points = 3 mean = 25.5 median = 19
Atlantic	716	200.2	153.5	175.2	UKF1 *N* points = 6 mean = 106.5 median = 84.1	FRI2 *N* points = 3 mean = 15.8 median = 16.9
Sub-oceanic	789	217.6	166.7	181.5	DE22 *N* points = 3 mean = 76 median = 86.7	ITI1 *N* points = 3 mean = 15 median = 13
Sub-continental (northern)	700	126.2	91.5	109.7	PL91 *N* points = 8 mean = 72.4 median = 29.0	RO22 *N* points = 3 mean = 18.1 median = 19.5
Sub-continental (southern)	355	244.4	181.3	239.4	BG32 *N* points = 3 mean = 59.8 median = 44.4	RO22 *N* points = 8 mean = 13.0 median = 6.5
Temperate mountainous	413	188.5	139.0	200.6	ITH3 *N* points = 4 mean = 65.6 median = 37.7	RO42 *N* points = 3 mean = 9.5 median = 9
Mediterranean (semi-arid)	539	259.0	177.6	252.2	EL64 *N* points = 6 mean = 109 median = 27.3	ITG2 *N* points = 4 mean = 16.8 median = 14
Mediterranean (temperate to sub-oceanic)	261	326.9	195.2	678.2	PT11 *N* points = 15 mean = 54.7 median = 62	FRJ1 *N* points = 6 mean = 15.3 median = 13.9

Figure 38 Potassium content in grassland presented (a) as point data and (b) average aggregated at NUTS 2 level

(a) (b)

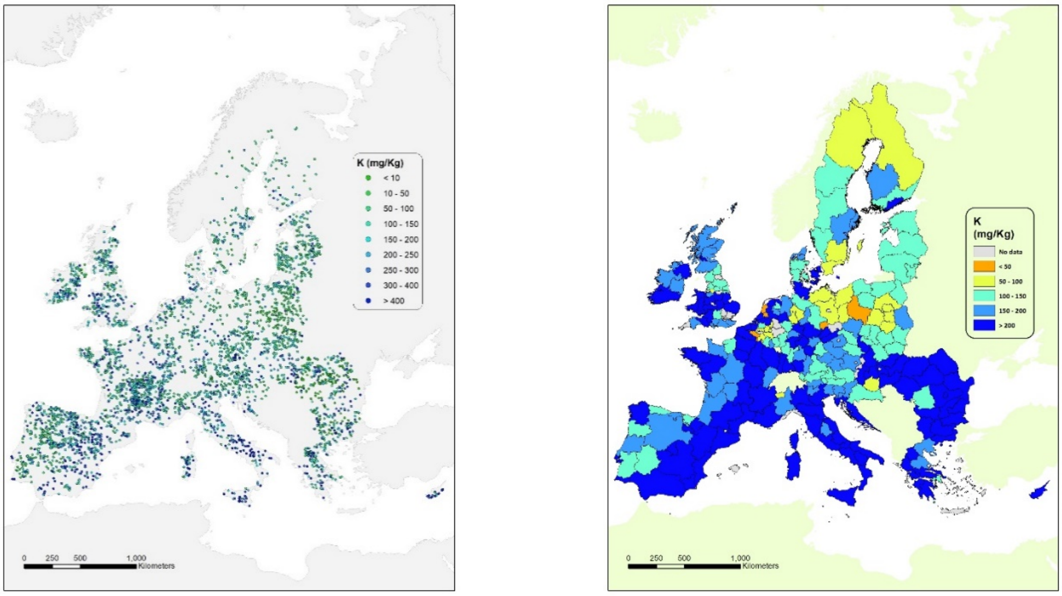


Figure 39 Potassium content in woodland presented (a) as point data and (b) average aggregated at NUTS 2 level

(a) (b)

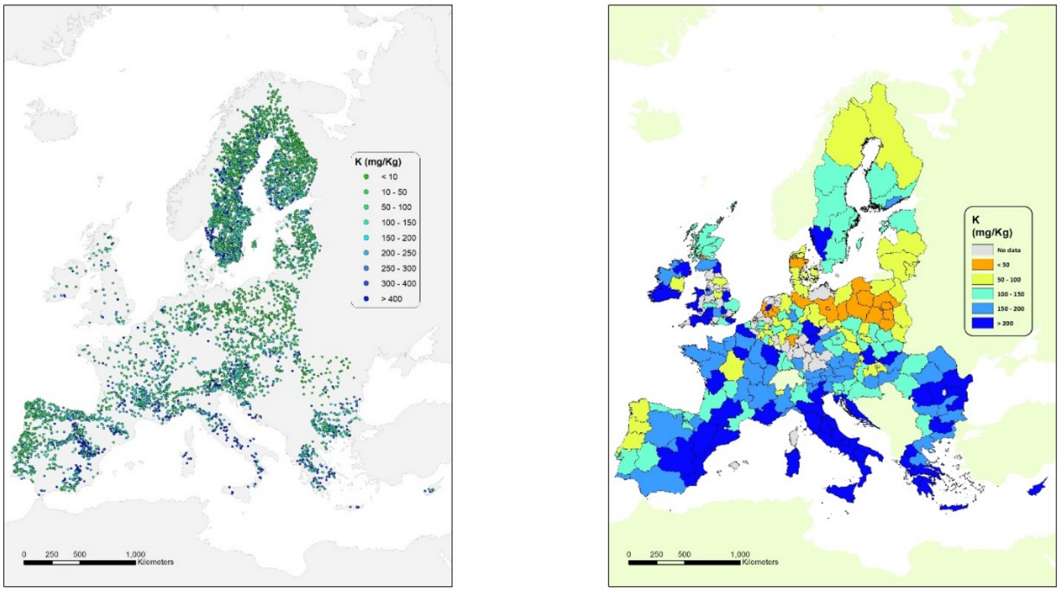


Table 37 Summary of potassium content in woodland in the 2018 LUCAS Topsoil survey

Climatic zone	***N* points**	**Mean (g kg-1)**	**Median (g kg-1)**	**Std dev (g kg-1)**	**NUTS 2 with highest K content in woodland (g kg^{-1})** (1)	**NUTS 2 with lowest K content in woodland (g kg^{-1})** (1)
Boreal to sub-boreal	2076	100.6	61.3	111.8	UKM6 *N* points = 3 mean = 42.0 median = 18.5	SE12 *N* points =20 mean = 20.9 median = 18.4
Atlantic	374	153.1	93.9	174.2	BE21 *N* points = 4 mean = 108.4 median = 90.2	FRC1 *N* points = 3 mean = 11.2 median = 10.6
Sub-oceanic	693	183.8	147.8	136.4	DE14 *N* points = 4 mean = 57.5 median = 30.3	FRI1 *N* points =6 mean = 13.1 median = 12.3
Sub-continental (northern)	1137	101.8	72.1	100.2	AT31 *N* points = 5 mean = 64.8 median = 33.2	CZ02 *N* points = 7 mean = 15.8 median = 14.9
Sub-continental (southern)	275	186.7	130.4	328.4	RO41 *N* points = 6 mean = 48.4 median = 18.7	RO42 *N* points = 5 mean = 10.3 median = 9.2
Temperate mountainous	664	167.9	136.0	116.4	AT32 *N* points = 13 mean = 34.8 median = 27.3	RO12 *N* points = 3 mean = 11.4 median = 12.4
Mediterranean (semi-arid)	427	206.3	144.6	179.4	EL65 *N* points = 8 mean = 66.3 median = 24.1	EL53 *N* points = 8 mean = 15.6 median = 15.7
Mediterranean (temperate to sub-oceanic)	322	209.1	139.6	202.9	ES11 *N* points = 3 mean = 55.7 median = 15.2	ITI1 *N* points = 3 mean = 11.4 median = 11.4

Table 38 Summary of potassium content in shrubland in the 2018 LUCAS Topsoil survey

Climatic zone	***N* points**	**Mean (g kg-1)**	**Median (g kg-1)**	**Std dev (g kg-1)**	**NUTS 2 with highest K content in shrubland (g kg^{-1})** (1)	**NUTS 2 with lowest K content in shrubland (g kg^{-1})** (1)
Boreal to sub-boreal	76	125.9	82.2	126.4	FI19 *N* points =6 mean = 61.4 median = 59.6	UKM6 *N* points =3 mean = 17.4 median = 18.3
Atlantic	56	162.7	114.2	120.0	UKM9 *N* points = 3 mean = 86.7 median = 59.1	UKM53 *N* points = 3 mean = 16.8 median = 17.8
Sub-oceanic	126	207.6	150.3	170.6	FRK1 *N* points = 11 mean = 28.4 median = 22	ES11 *N* points = 6 mean = 16.7 median = 14.4
Sub-continental (northern)	18	139.1	115.9	120.5	SE12 *N* points = 4 mean = 37.9 median = 24.2	SE12 *N* points = 4 mean = 38 median = 24.2
Sub-continental (southern)	30	276.5	256.4	204.0	RO31 *N* points = 4 mean = 24.0 median = 14.7	RO11 *N* points = 5 mean = 20.2 median = 11.8
Temperate mountainous	33	222.4	180.1	157.9	NA	NA
Mediterranean (semi-arid)	227	248.7	195.4	187.4	ES61 *N* points = 4 mean = 17.2 median = 15.4	ES42 *N* points = 6 mean = 14.2 median = 12.5
Mediterranean (temperate to sub-oceanic)	136	250.3	205.8	194.2	PT11 *N* points = 17 mean = 34.8 median = 21.4	ES24 *N* points = 10 mean = 13.1 median = 12.1

Figure 40 Potassium content in shrubland presented as point data

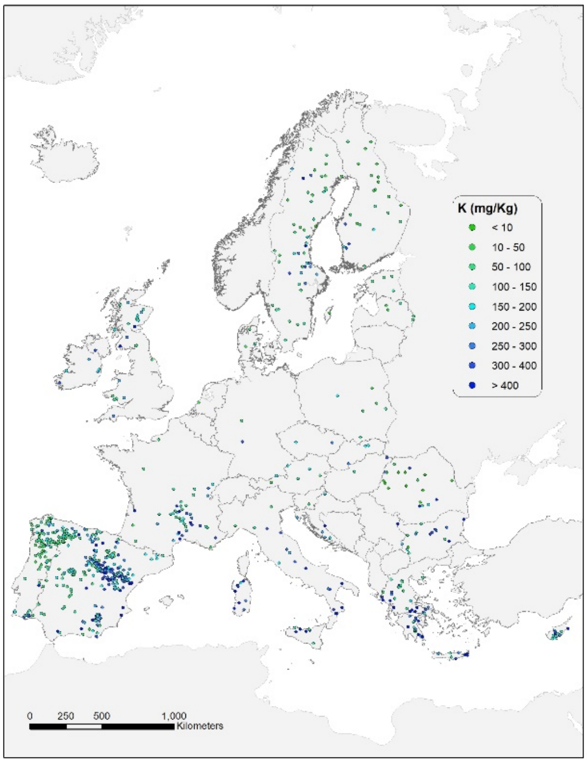


Table 39 Summary of potassium content in wetland in the 2018 LUCAS Topsoil survey

Climatic zone	***N* points**	**Mean (g kg-1)**	**Median (g kg-1)**	**Std dev (g kg-1)**	**NUTS 2 with highest K content in wetland (g kg^{-1})** (1)	**NUTS 2 with lowest K content in wetland (g kg^{-1})** (1)
Boreal to sub-boreal	20	136.6	100.6	109.1	SE31 *N* points =5 mean = 19.7 median = 7.7	SE33 *N* points =9 mean = 16.8 median = 12.6
Atlantic	12	305.7	213.1	424.9	IE04 *N* points =4 mean = 19.5 median = 18.6	
Sub-oceanic	1	82.1	82.1	NA	None of the regions had at least 3 points	
Sub-continental (northern)	3	225.5	281.2	100.2	None of the regions had at least 3 points	
Sub-continental (southern)	2	294.1	294.1	136.3	None of the regions had at least 3 points	
Temperate mountainous	1	81.9	81.9	NA	None of the regions had at least 3 points	
Mediterranean (temperate to sub-oceanic)	1	447.3	447.3	NA	None of the regions had at least 3 points	

Figure 41 Potassium content in wetland presented as point data

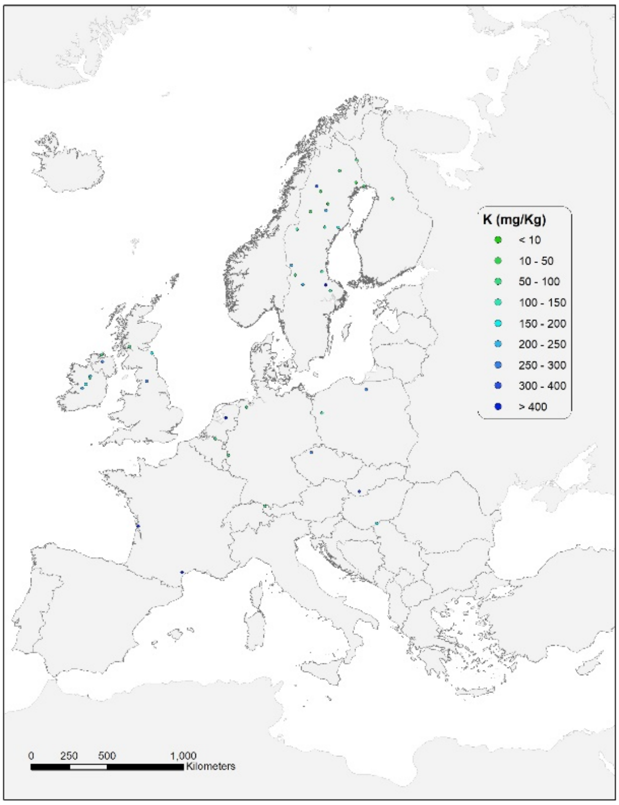


Figure 42 Potassium content in bareland presented as point data

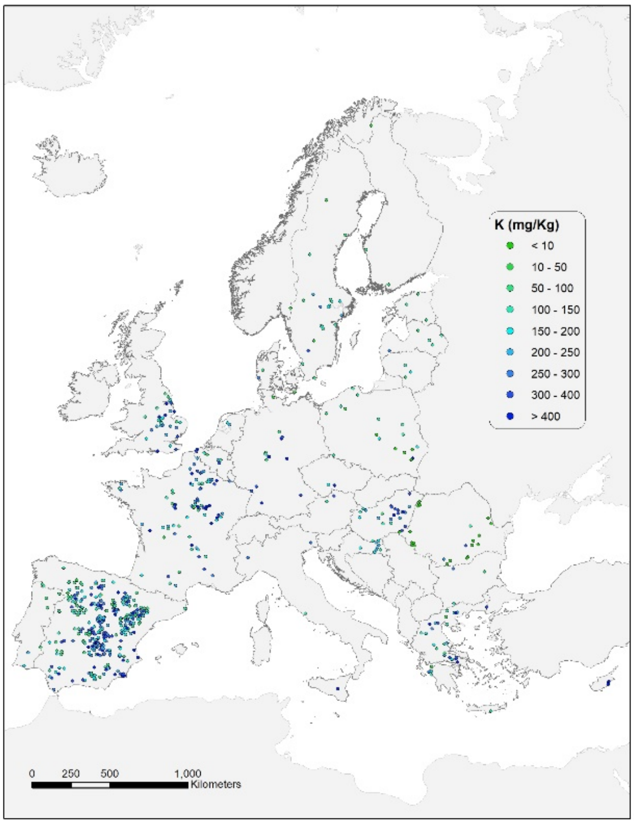


Table 40 Summary of potassium content in bareland in the 2018 LUCAS Topsoil survey

Climatic zone	*N* points	Mean (g kg-1)	Median (g kg-1)	Std dev (g kg-1)	NUTS 2 with highest K content in bareland (g kg^{-1}) (1)	NUTS 2 with lowest K content in bareland (g kg^{-1}) (1)
Boreal to sub-boreal	19	114.1	91.0	64.2	EE00 *N* points =3 mean = 41.6 median = 51.2	SE12 *N* points =3 mean = 22.8 median = 21.5
Atlantic	96	235.7	205.8	134.3	FRH0 *N* points = 3 mean = 67.7 median =	UKE1 *N* points = 6 mean = 23.9 median = 23.3
Sub-oceanic	48	288.9	231.4	233.5	FRK1 *N* points = 6 mean = 56.9 median = 46.4	FRC1 *N* points = 14 mean = 31.5 median = 26.5
Sub-continental (northern)	42	186.3	129.8	148.5	PL42 *N* points = 3 mean = 41 median = 38.9	SE12 *N* points = 7 mean = 34.4 median = 23.2
Sub-continental (southern)	55	265.0	242.2	147.4	HR04 *N* points = 8 mean = 54.3 median = 54.7	RO41 *N* points = 3 mean = 19.2 median = 5.1
Temperate mountainous	8	229.1	203.1	131.4	None of the regions had at least 3 points	
Mediterranean (semi-arid)	313	253.9	212.2	190.6	CY00 *N* points = 3 mean = 89.2 median = 101.5	ES43 *N* points = 8 mean = 16.7 median = 17.0
Mediterranean (temperate to sub-oceanic)	54	216.9	168.6	145.9	ES52 *N* points = 4 mean = 47.85 median = 37	PT11 *N* points = 3 mean = 18.5 median = 17.5

4.8 pH and carbonates

4.8.1 pH

Soil pH (also known as the soil reaction) is an indication of the acidity or alkalinity of the soil and is measured in pH units. Soil pH is defined as the negative logarithm of the hydrogen ion concentration. The pH scale goes from 0 to 14 with pH 7 as the neutral point. A very acid soil will exhibit a lower pH as hydrogen ion concentrations are higher. Conversely, alkaline soils, with low hydrogen ion concentrations, will display higher pH values. As for most soil characteristics, the natural pH of the soil generally depends on its parent materials, the climate, vegetation, topography and time. Most soils have pH values between 3.5 and 10. Where rainfall is higher, the natural pH of most soils typically ranges from 5 to 7 as primary carbonates are leached from the soil while temperatures are too low for secondary carbonates to develop. In drier climates, the range tends to be 6.5 to 9. Soils with pH values of 6.5 to 7.5 are broadly considered as neutral.

pH affects the solubility of nutrients and chemicals and therefore their availability to plants. Some nutrients are more available under low pH conditions while others are more available under more alkaline conditions. However, most nutrients are readily available to plants when soil pH is near neutral. Increasing acidity can result in poor plant growth due to either aluminium or manganese toxicity or a deficiency in calcium or magnesium. Increased alkalinity may result in deficiencies of nutrients such as zinc, copper, boron and manganese. Soils with a very high pH (>8.5) are likely to contain high levels of sodium. Soil pH can be changed through the application of lime (i.e. calcium carbonate raises pH) or fertilisers (those containing sulphur or are ammonium-based can lower pH).

The LUCAS data on pH (Tables 41-46; Figures 43-46) clearly show a trend of increasing pH from northern to southern regions. Lowest values are recorded for woodlands in the Boreal zone, corresponding to the large expanses of podzolic soils that are characteristics of this region. Most landcover types display higher pH levels in the Mediterranean region.

Cropland points have generally neutral pH in almost all climatic zones. Slightly lower and higher values were recorded by pH in H2O the Boreal zone (6.2) and Semi-arid Mediterranean zone (7.7), respectively (Tables 41 and 42, Figure 44).

A slightly higher pH is generally observed in cropland (mean and median pH in H2O were 6.2 to 7.7) compared to grassland (mean and median pH in H2O were 5.8 to 7.0; Tables 43 and 44, Figure 45). Woodland points in the Boreal and Atlantic Zones had very acid pH (< 5) (Figure 46, Tables 45 and 46). The iron-humus accumulation on the topsoil of podzols, predominant soil type in the boreal zone, can explain these very low values. Woodland points in the Mediterranean zones had close to neutral pH (>6.5). This slightly lower than expected value is most likely due to the averaging of points under Mediterranean conifers (mostly pines) with acidic soils with those with soils derived from calcareous parent materials or with the presence of secondary carbonates in the soil.

4.8.2 Carbonates

Carbonates are minerals containing the carbonate ion, CO^{2-}_3. The most common carbonate mineral in soils is calcium carbonate (CaCO3). Carbonates in soil solution are highly soluble, especially at lower pH values, and are often leached from the soil where precipitation is high. In contrast, soils where evaporation rates exceed precipitation can often see the formation of secondary carbonates, especially if irrigated with water with high mineral content. Free calcium carbonates typically do not occur in soils with pH values below 5.0. As shown by the data (Tables 47-49; Figure 47), the presence and concentrations of carbonates reflect the main environmental and climatic controls described above. Levels are highest in the Mediterranean region and lowest in the more acidic conditions of Scandinavia (especially under conifer forests). Trends for individual land cover classes mirror those described for pH, with lowest values in the Boreal Zone and highest in the Semi-arid Zone with croplands ranging from 9.7 to 227 g kg-1, grasslands 13 to 179 g kg-1 and woodlands from 2 to 97 g kg-1, respectively.

Figure 43 pH in H_2O (all 2018 LUCAS Soil Module points) presented (a) as point data and (b) average aggregated at NUTS 2 level

(a) (b)

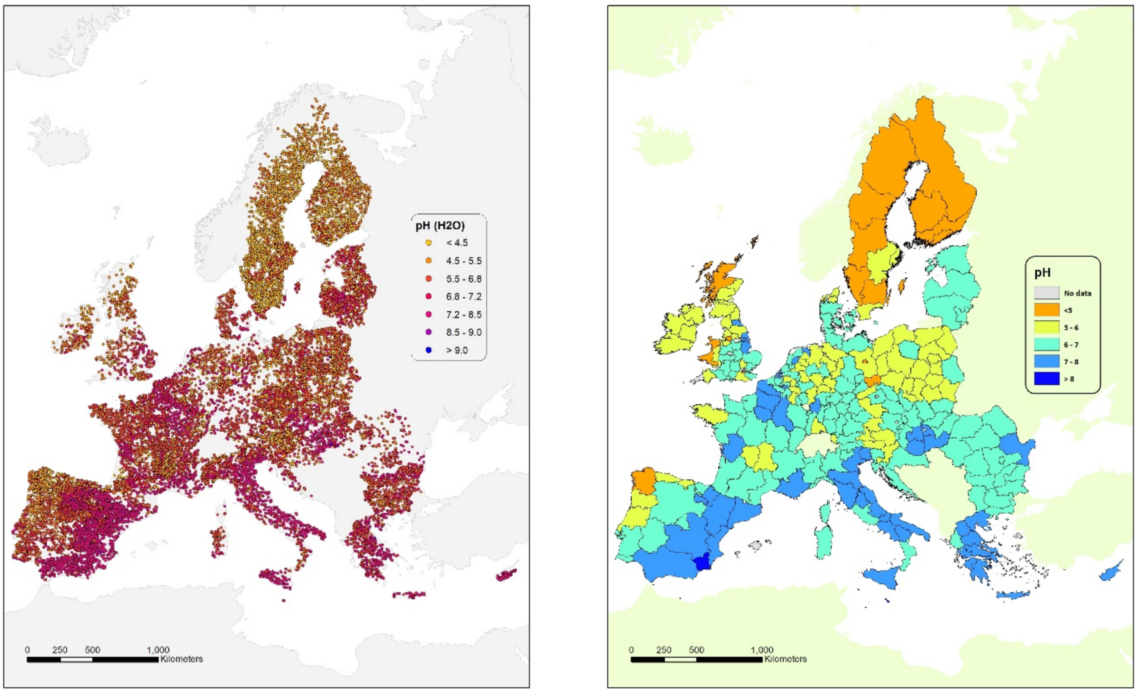


Figure 44 pH in H_2O in cropland presented (a) as point data and (b) average aggregated at NUTS 2 level

(a) (b)

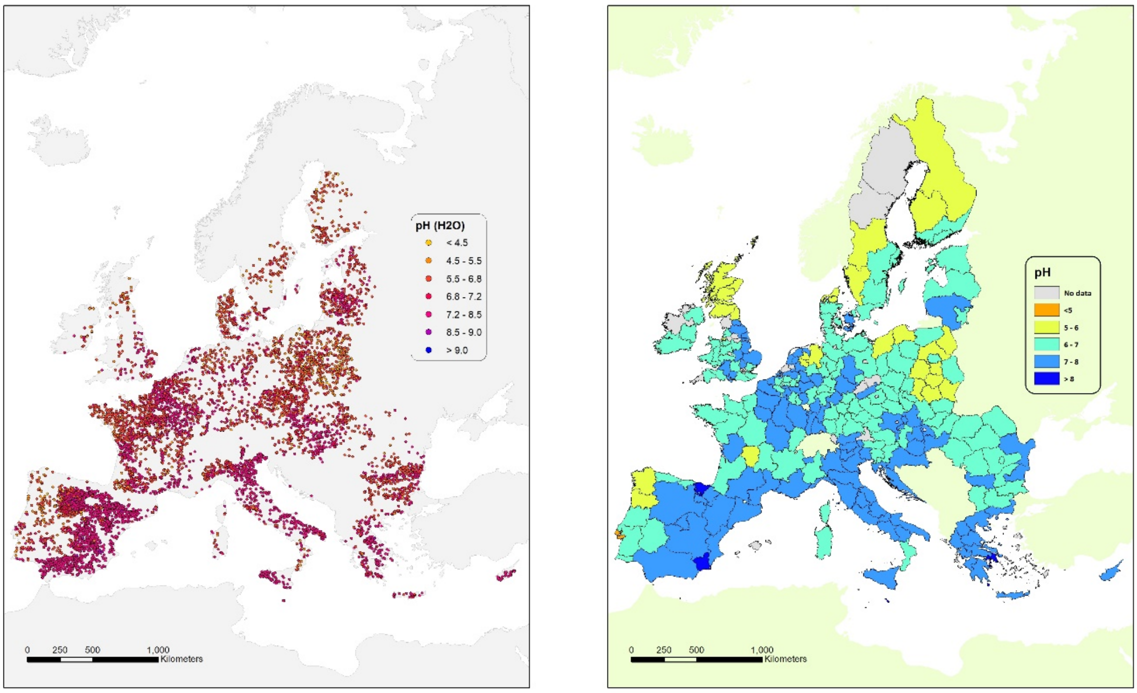


Figure 45 pH in H_2O in grassland presented (a) as point data and (b) average aggregated at NUTS 2 level

(a) (b)

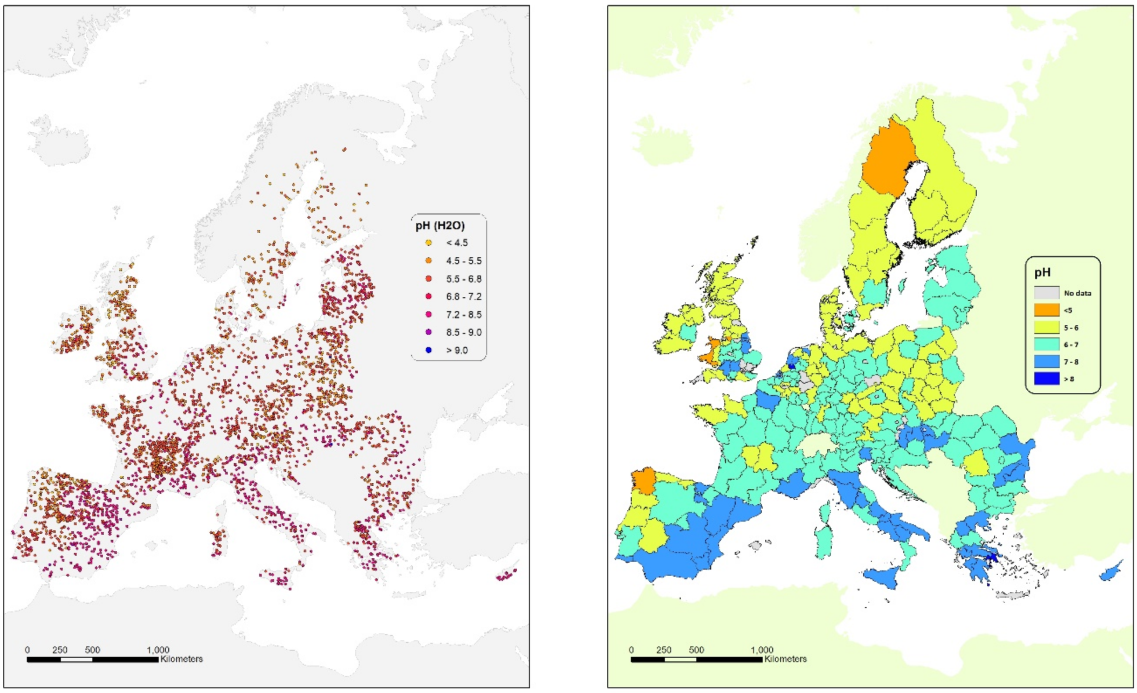


Figure 46 pH in H2O in woodland presented (a) as point data and (b) average aggregated at NUTS 2 level

(a) (b)

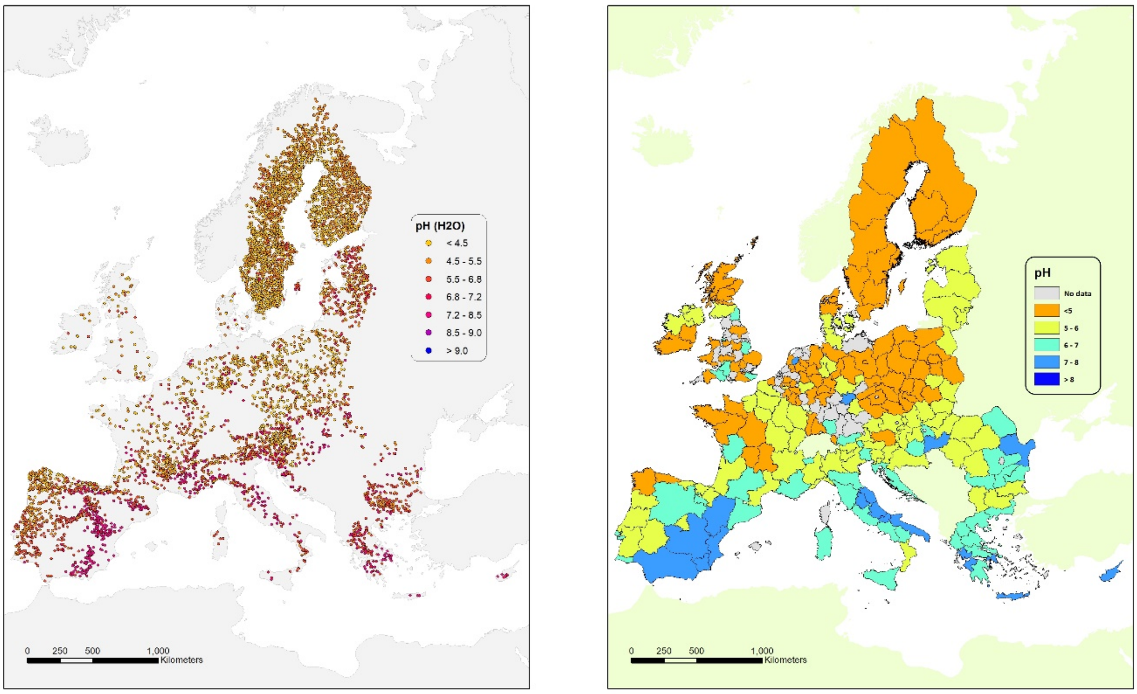


Table 41 Summary of pH in H_2O in cropland points

Climatic zone	*N* points	Mean	Median	Std dev	NUTS 2 with highest pH in H_2O	NUTS 2 with lowest pH in H_2O
Boreal to sub-boreal	210	6.2	6.2	0.7	EE00 *N* points = 48 mean = 6.7 median = 6.5	FI1D *N* points = 37 mean = 5.7 median = 5.8
Atlantic	1438	6.8	6.8	0.8	FRJ1 *N* points = 3 mean = 8.1 median = 8.1	SE23 *N* points = 3 mean = 5.3 median = 5.4
Sub-oceanic	814	7.0	7.2	0.8	EL53 *N* points = 3 mean = 8.3 median = 8.4	ES43 *N* points = 5 mean = 5.7 median = 5.7
Sub-continental (northern)	1430	6.4	6.5	0.9	DEG0 *N* points = 13 mean = 7.3 median = 7.5	PL82 *N* points = 7 mean = 6.1 median = 5.9
Sub-continental (southern)	754	6.9	6.9	0.9	HU12 *N* points = 15 mean = 7.9 median = 8	PL82 *N* points = 7 mean = 6.1 median = 5.9
Temperate mountainous	170	6.8	6.8	0.9	FRL0 *N* points = 6 mean = 8.0 median = 7.8	RO12 *N* points = 14 mean = 5.8 median = 5.6
Mediterranean (semi-arid)	1916	7.7	7.7	0.7	EL30 *N* points =5 mean = 8.2 median = 8.2	PT16 *N* points = 4 mean = 5.6 median = 5.5
Mediterranean (temperate to sub-oceanic)	615	7.6	7.6	0.9	ES62 *N* points = 6 mean = 8.3 median = 8.2	ES11 *N* points = 6 mean = 4.8 median = 4.6

Table 42 Summary of pH in $CaCl_2$ in cropland points

Climatic zone	*N* points	Mean	Median	Std dev	NUTS 2 with highest pH in $CaCl_2$	NUTS 2 with lowest pH in $CaCl_2$
Boreal to sub-boreal	218	5.6	5.6	0.7	EE00 *N* points =48 mean = 6.2 median = 6.1	SE31 *N* points = 7 mean = 5.1 median = 5.1
Atlantic	1438	6.3	6.4	0.8	FRJ1 *N* points = 3 mean = 7.5 median = 7.5	SE23 *N* points = 3 mean = 4.8 median = 4.8
Sub-oceanic	814	6.6	6.8	0.8	EL53 *N* points = 3 mean = 7.6 median = 7.8	ES43 *N* points = 5 mean = 5 median =4.9
Sub-continental (northern)	1430	5.9	6.0	0.9	DEG0 *N* points = 13 mean = 6.8 median = 7.0	PL82 *N* points = 5 mean = 4.7 median = 4.8
Sub-continental (southern)	754	6.3	6.3	0.9	AT12 *N* points =33 mean = 7.2 median = 7.3	RO32 *N* points = 5 mean = 5.4 median = 5.4
Temperate mountainous	170	6.3	6.4	0.9	FRL0 *N* points = 3 mean = 7.3 median = 7.4	RO12 *N* points = 14 mean = 5.4 median = 5.4
Mediterranean (semi-arid)	1916	7.1	7.4	0.8	EL30 *N* points = 5 mean = 7.6 median = 7.7	PT16 *N* points = 4 mean = 4.8 median = 4.7
Mediterranean (temperate to sub-oceanic)	615	7.0	7.4	0.9	ES62 *N* points = 6 mean = 7.6 median = 7.6	ES11 *N* points = 6 mean = 4.2 median = 4.2

Table 43. Summary of pH in H_2O in grassland points

Climatic zone	*N* points	Mean	Median	Std dev	NUTS 2 with highest pH in H_2O	NUTS 2 with lowest pH in H_2O
Boreal to sub-boreal	167	5.8	5.9	0.9	EE00 *N* points = 28 mean = 6.5 median = 6.4	UKM7 *N* points = 3 mean = 4.5 median = 4.5
Atlantic	716	5.9	5.8	0.9	UKF3 *N* points = 6 mean = 7.2 median = 7.3	UKL1 *N* points = 21 mean = 4.9 median = 4.9
Sub-oceanic	789	6.2	6.1	0.9	ES61 *N* points = 3 mean = 7.9 median = 8.0	ES11 *N* points = 10 mean = 4.8 median = 4.7
Sub-continental (northern)	704	6.0	5.9	0.8	RO22 *N* points = 6 mean = 7.3 median = 7.5	SE31 *N* points = 4 mean = 5.3 median = 5.4
Sub-continental (southern)	355	6.6	6.5	0.9	HU33 *N* points = 20 mean = 7.7 median = 7.7	PL82 *N* points = 16 mean = 5.8 median = 5.4
Temperate mountainous	413	6.2	6.2	1.0	EL52 *N* points = 4 mean = 8.0 median = 8.0	PL21 *N* points = 11 mean = 5.0 median = 4.8
Mediterranean (semi-arid)	539	7.1	7.4	1.0	ES62 *N* points = 4 mean = 8.0 median = 8.0	ES43 *N* points = 17 mean = 6.0 median = 6.0
Mediterranean (temperate to sub-oceanic)	261	7.0	7.5	1.1	ITI1 *N* points = 3 mean = 8.0 median = 7.9	ES11 *N* points = 3 mean = 5.0 median = 4.8

Table 44 Summary of pH in CaCl2 in grassland points

Climatic zone	***N* points**	**Mean**	**Median**	**Std dev**	**NUTS 2 with highest pH in $CaCl_2$**	**NUTS 2 with lowest pH in $CaCl_2$**
Boreal to sub-boreal	167	5.3	5.4	1.0	E00 *N* points = 28 mean = 6.1 median = 5.8	SE33 *N* points = 9 mean = 4.1 median = 4.3
Atlantic	716	5.4	5.3	0.9	UKF3 *N* points = 6 mean = 6.8 median = 7.0	UKL1 *N* points = 21 mean = 4.5 median = 4.5
Sub-oceanic	789	5.8	5.6	0.9	ES61 *N* points = 3 mean = 7.5 median = 7.5	ES11 *N* points = 10 mean = 4.4 median = 4.4
Sub-continental (northern)	704	5.5	5.4	0.9	RO22 *N* points = 6 mean = 6.8 median = 7.1	SE22 *N* points = 12 mean = 4.7 median = 4.8
Sub-continental (southern)	355	6.0	6.0	1.0	RO22 *N* points = 8 mean = 7.2 median = 7.3	HU23 *N* points = 4 mean = 5.3 median = 5.3
Temperate mountainous	413	5.7	5.7	1.0	EL52 *N* points = 4 mean = 7.3 median = 7.4	PL21 *N* points = 11 mean = 4.7 median = 4.5
Mediterranean (semi-arid)	539	6.5	7.0	1.1	ES22 *N* points = 4 mean = 7.6 median = 7.6	PT11 *N* points = 7 mean = 5.3 median = 5.3
Mediterranean (temperate to sub-oceanic)	261	6.5	7.1	1.1	ES24 *N* points = 19 mean = 7.4 median = 7.5	ES11 *N* points = 10 mean = 4.4 median = 4.4

Table 45 Summary of pH in H2O in woodland points

Climatic zone	*N* points	Mean	Median	Std dev	NUTS 2 with highest pH in H_2O	NUTS 2 with lowest pH in H_2O
Boreal to sub-boreal	2096	4.6	4.5	0.6	EE00 *N* points = 87 mean = 5.6 median = 5.8	SE23 *N* points = 5 mean = 4.3 median = 4.2
Atlantic	374	4.9	4.6	0.9	NL23 *N* points = 4 mean = 7.0 median = 7.2	UKM6 *N* points = 3 mean = 4.1 median = 3.9
Sub-oceanic	693	5.6	5.4	1.2	ES62 *N* points = 4 mean = 7.9 median = 8.0	BE34 *N* points = 5 mean = 4.3 median = 4.2
Sub-continental (northern)	1146	4.7	4.5	0.8	LT02 *N* points = 76 mean = 5.6 median = 5.7	FI1B *N* points =4 mean = 4.0 median = 4.0
Sub-continental (southern)	275	5.9	5.8	1.2	HU33 *N* points = 6 mean = 7.5 median = 7.5	AT22 *N* points = 55 mean = 4.6 median = 4.3
Temperate mountainous	665	5.8	5.7	1.1	ES21 *N* points = 3 mean = 7.3 median = 7.2	AT22 *N* points = 55 mean = 4.6 median = 4.3
Mediterranean (semi-arid)	427	6.6	6.5	1.0	EL30 *N* points = 10 mean = 7.9 median = 8.0	PT11 *N* points = 6 mean = 5.6 median = 5.6
Mediterranean (temperate to sub-oceanic)	324	6.2	6.0	1.3	ES24 *N* points = 26 mean = 7.7 median = 7.8	ES11 *N* points = 7 mean = 4.6 median = 4.7

Table 46 Summary of pH in CaCl2 in woodland points

Climatic zone	*N* points	Mean	Median	Std dev	NUTS 2 with highest pH in $CaCl_2$	NUTS 2 with lowest pH in $CaCl_2$
Boreal to sub-boreal	2096	3.9	3.8	0.7	EE00 *N* points = 28 mean = 6.1 median = 5.8	SE23 *N* points = 5 mean = 3.4 median = 3.2
Atlantic	374	4.3	4.0	1.0	UKF3 *N* points = 6 mean = 6.8 median = 7.0	UKM6 *N* points = 3 mean = 3.3 median = 3.3
Sub-oceanic	693	5.1	4.8	1.3	ES61 *N* points = 3 mean = 7.5 median = 7.5	BE34 *N* points = 5 mean = 3.7 median = 3.5
Sub-continental (northern)	1146	4.1	3.8	0.9	RO22 *N* points = 8 mean = 7.2 median = 7.3	FI1B *N* points = 4 mean = 3.2 median = 3.2
Sub-continental (southern)	275	5.3	5.1	1.3	RO22 *N* points =6 mean = 6.9 median = 7.1	AT22 *N* points = 8 mean = 3.8 median = 3.7
Temperate mountainous	665	5.2	5.0	1.2	EL52 *N* points = 4 mean = 7.3 median = 7.4	AT22 *N* points = 55 mean = 3.9 median = 3.7
Mediterranean (semi-arid)	427	6.0	5.9	1.1	ES22 *N* points = 4 mean = 7.6 median = 7.5	PT11 *N* points = 6 mean = 4.7 median = 4.6
Mediterranean (temperate to sub-oceanic)	324	5.7	5.5	1.4	ES24 *N* points = 19 mean = 7.4 median = 7.5	ES11 *N* points = 7 mean = 4.0 median = 4.0

Figure 47 Carbonates content (all 2018 LUCAS Soil Module points) presented (a) as point data and (b) average aggregated at NUTS 2 level

(a) (b)

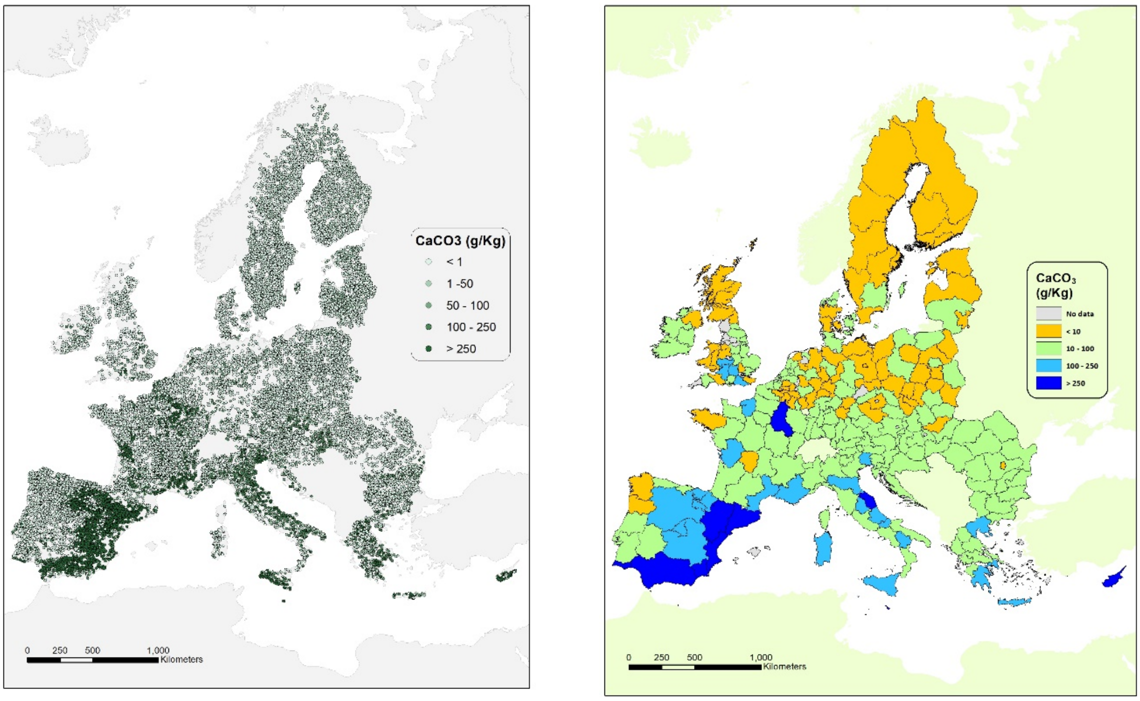


Table 47 Summary of CaCO3 content in cropland points

Climatic zone	***N* points**	**Mean (g kg-1)**	**Median (g kg-1)**	**Std dev (g kg-1)**	**NUTS 2 with highest $CaCO_3$ content in cropland (g kg^{-1})** (1)	**NUTS 2 with lowest $CaCO_3$ content in cropland (g kg^{-1})** (1)
Boreal to sub-boreal	41	9.7	2.0	17.4	FI19 *N* points = 46 mean = 56.4 median = 47.6	SE31 *N* points =7 mean = 22.4 median = 19.4
Atlantic	663	110.0	10.0	194.7	NL21 *N* points = 4 mean = 113.4 median = 77.1	SE23 *N* points = 3 mean = 23.5 median = 23
Sub-oceanic	488	112.5	52.5	150.4	BE34 *N* points = 3 mean = 84.0 median = 83.5	ITI1 *N* points = 7 mean = 14.4 median = 13.3
Sub-continental (northern)	521	16.4	4.0	34.0	DE23 *N* points = 5 mean = 105.7 median = 100.8	RO22 *N* points = 24 mean = 12.8 median = 9.7
Sub-continental (southern)	403	38.2	12.0	58.7	SI03 *N* points = 6 mean = 52.0 median = 46.1	RO22 *N* points = 21 mean = 14.7 median = 9.6
Temperate mountainous	90	64.5	16.5	104.1	SK02 *N* points = 8 mean = 58.5 median = 59.1	FRK2 *N* points = 3 mean = 12.8 median = 13.7
Mediterranean (semi-arid)	1658	222.4	192.5	198.1	EL30 *N* points = 3 mean = 83.8 median = 38.1	PT18 *N* points = 20 mean = 22.3 median = 17.1
Mediterranean (temperate to sub-oceanic)	508	227.7	191.0	184.8	ES11 *N* points = 6 mean = 61.2 median = 52.7	ITI2 *N* points = 3 mean = 14.3 median = 15.2

Table 48 Summary of $CaCO_3$ content in grassland points

Climatic zone	***N* points**	**Mean (g kg-1)**	**Median (g kg-1)**	**Std dev (g kg-1)**	**NUTS 2 with highest $CaCO_3$ content in grassland (g kg^{-1})** (1)	**NUTS 2 with lowest $CaCO_3$ content in grassland (g kg^{-1})** (1)
Boreal to sub-boreal	33	13.2	9.0	14.4	UKM6 *N* points = 6 mean = 52.5 median = 36.8	FI1B *N* points = 3 mean = 25.5 median = 19
Atlantic	209	52.6	3.0	113.6	UKF1 *N* points = 6 mean = 106.5 median = 84.1	FRI2 *N* points = 3 mean = 15.8 median = 16.9
Sub-oceanic	308	64.5	5.0	111.9	DE22 *N* points = 3 mean = 76 median = 86.7	ITI1 *N* points = 3 mean = 15 median = 13
Sub-continental (northern)	171	19.3	3.0	52.6	PL91 *N* points = 8 mean = 72.4 median = 29.0	RO22 *N* points = 3 mean = 18.2 median = 19.5
Sub-continental (southern)	156	44.4	11.0	84.8	BG32 *N* points = 3 mean = 59.8 median = 44.4	RO22 *N* points = 8 mean = 13.0 median = 6.5
Temperate mountainous	197	62.9	7.0	122.2	ITH3 *N* points = 4 mean = 65.6 median = 37.7	RO42 *N* points = 3 mean = 9.5 median = 9
Mediterranean (semi-arid)	352	174.9	106.0	197.6	EL64 *N* points = 6 mean = 109 median = 27.3	ITG2 *N* points = 4 mean = 16.8 median = 14
Mediterranean (temperate to sub-oceanic)	171	179.3	138.0	168.5	PT11 *N* points = 15 mean = 54.8 median = 62	FRJ1 *N* points = 6 mean = 15.3 median = 13.9

Table 49 Summary of $CaCO_3$ content in woodland points

Climatic zone	***N* points**	**Mean (g kg-1)**	**Median (g kg-1)**	**Std dev (g kg-1)**	**NUTS 2 with highest $CaCO_3$ content in woodland (g kg^{-1})** (1)	**NUTS 2 with lowest $CaCO_3$ content in woodland (g kg^{-1})** (1)
Boreal to sub-boreal	1400	2.0	1.0	5.6	UKM6 *N* points = 3 mean = 42.0 median = 18.5	SE12 *N* points = 20 mean = 20.9 median = 18.4
Atlantic	239	15.7	1.0	78.7	BE21 *N* points = 4 mean = 108.4 median = 90.2	FRC1 *N* points = 3 mean = 11.2 median = 10.6
Sub-oceanic	548	37.2	2.0	97.7	DE14 *N* points = 4 mean = 57.5 median = 30.3	FRI11 *N* points =6 mean = 13.1 median = 12.3
Sub-continental (northern)	719	2.1	1.0	6.5	AT31 *N* points = 5 mean = 64.8 median = 33.2	CZ02 *N* points =7 mean = 15.8 median = 14.9
Sub-continental (southern)	197	24.2	2.0	64.4	RO41 *N* points = 6 mean = 48.4 median = 18.7	RO42 *N* points = 5 mean = 10.3 median = 8.2
Temperate mountainous	511	36.6	2.0	93.7	AT32 *N* points = 13 mean = 34.8 median = 27.3	RO12 *N* points = 3 mean = 11.4 median = 12.4
Mediterranean (semi-arid)	351	78.7	2.0	161.7	EL65 *N* points = 8 mean = 66.3 median = 24.1	EL53 *N* points = 8 mean = 15.6 median = 15.7
Mediterranean (temperate to sub-oceanic)	264	97.4	3.0	169.2	ES11 *N* points = 3 mean = 55.7 median = 15.2	ITI1 *N* points = 3 mean = 11.4 median = 11.4

4.9 Electrical conductivity

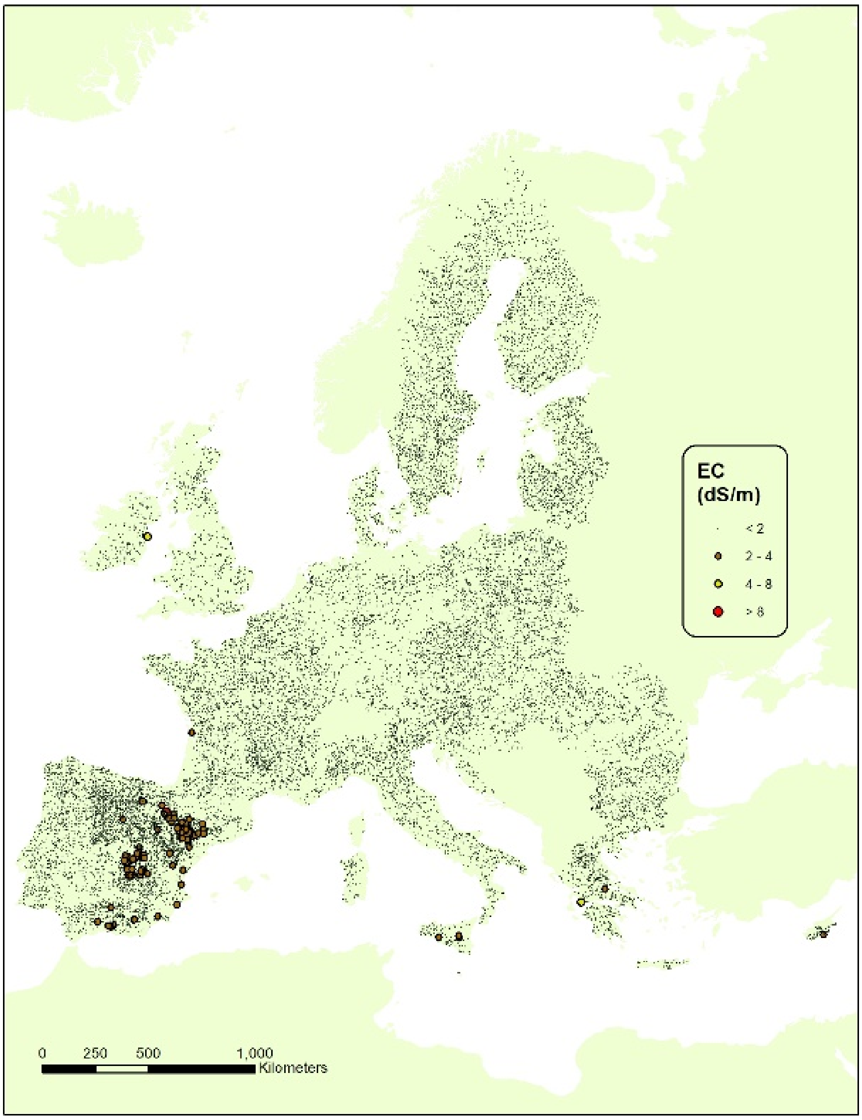
Soil electrical conductivity (EC) is a measure of the amount of salts in soil (salinity). It is also an excellent indicator of nutrient availability and loss, soil texture, and available water capacity. Excessive salt levels hinder plant growth by affecting the soil and water balance.

Soils containing excessive salts generally occur naturally in dry and warm climates. Salt levels can increase as a result of cropping and irrigation.

Factors affecting EC include soil texture and parent material, climate, and soil management practices (in particular poor use of irrigation, fertilization).

Most of the points across the EU showed low EC, which indicates that they are not saline and that their salt contents are at a minimum (Figure 48). However, Figure 48 shows some salinity hotspots (>4 dS/m) in the Ebro Valley in Spain, Sicily, Cyprus and Greece. The points on the coasts of Ireland and France reflect coastal salt marshes.

Figure 48 Electrical conductivity. Levels > 4 dS/m are considered to have saline conditions.



4.10 Oxalate extractable Fe and Al

The dissolution methods for extracting Al, Fe, Mn, and Si are valuable tools to help determine the chemical forms of these elements in soils. The results are useful in studies of metal mobility or bioavailability in soils.

Figures 49-50 show the locations of the 2,523 samples that were analysed for the presence of organic-complexed Fe and Al in cropland soils through extraction with a 0.1M sodium pyrophosphate solution (Ross & Wang 1993). The extraction solution only slightly dissolves non-crystalline inorganic forms and does not attack silicate minerals and crystalline Fe and Al oxides and hydroxides. Fe and Al levels are quantified by *inductively coupled plasma optical emission spectrometry* (ICP-OES).

Summaries are presented in Tables 50 and 51.

17 samples were not present in the DMT but could be identified through the POINTID code.

- 1 sample with a POINTID not present in the DMT was removed
- 5 samples were identified with comment “Low amount sample” and removed
- 2 samples with null values were removed
- 5 samples with duplicate POINTID and wrong SOIL-ID were removed

2,510 samples have both oxalates values available at the end:

- 5 samples are related to 0-10 cm and not considered
- 2505 samples are related to 0-20 cm (as all the other attributes) and used in the following statistics.
- 92% of the samples are from cropland points.

Figure 49 Point map of Oxalate Extractable Aluminium (all points)

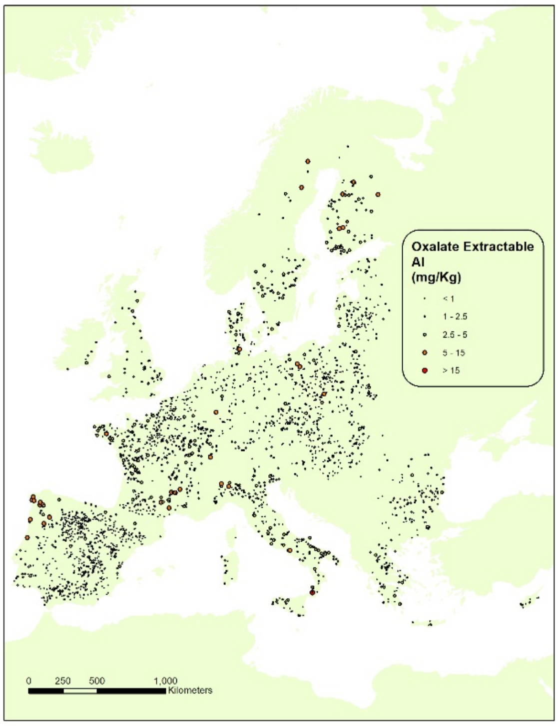


Figure 50 Point map of Oxalate Extractable Iron (all points)

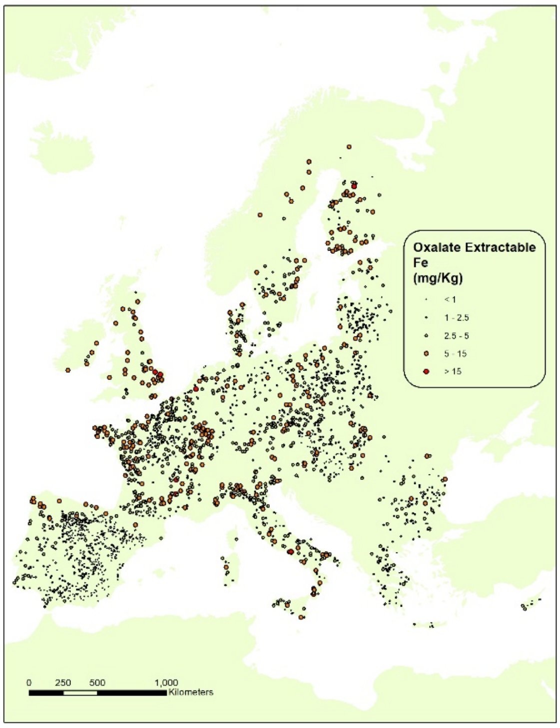


Table 50 Summary of oxalate extractable Aluminum content in the 2018 LUCAS Topsoil survey

Climatic zone	***N* points**	**Mean (mg kg-1)**	**Median (mg kg-1)**	**Std dev (mg kg-1)**	**NUTS 2 with highest Ox Al content (mg kg^{-1})** (1)	**NUTS 2 with lowest Ox Al content (mg kg^{-1})** (1)
Boreal to sub-boreal	101	2.1	1.8	1.6	SE33 *N* points = 7 mean = 3.3 median = 1.8	LV00 *N* points = 5 mean = 0.78 median = 0.8
Atlantic	513	1.3	1.0	1.2	ES11 *N* points = 6 mean = 7 median =6.1	NL23 *N* points = 7 mean = 0.3 median = 0.2
Sub-oceanic	296	1.6	1.2	2.3	ITF6 *N* points = 5 mean = 8.5 median = 2.1	ES42 *N* points = 3 mean = 0.6 median = 0.6
Sub-continental (northern)	489	1.1	0.9	0.7	CZ05 *N* points = 3 mean = 2.1 median = 2.1	DK02 *N* points = 4 mean = 0.6 median = 0.7
Sub-continental (southern)	205	1.0	1.0	0.4	SK04 *N* points = 4 mean = 1.4 median = 1.1	AT12 *N* points = 10 mean = 0.7 median = 0.7
Temperate mountainous	56	1.3	1.0	1.2	ITH2 *N* points = 5 mean = 1.2 median = 1.5	SK02 *N* points = 3 mean = 0.8 median = 0.8
Mediterranean (semi-arid)	637	0.8	0.7	0.6	ITF4 *N* points = 24 mean = 2.1 median = 2.1	ES51 *N* points = 9 mean = 0.4 median = 0.4
Mediterranean (temperate to sub-oceanic)	208	1.3	0.8	1.5	ES11 *N* points = 4 mean = 5.4 median = 5.2	FRL0 *N* points = 3 mean = 0.4 median = 0.4

Table 51 Summary of oxalate extractable Iron content in the 2018 LUCAS Topsoil survey

Climatic zone	***N* points**	**Mean (mg kg-1)**	**Median (mg kg-1)**	**Std dev (mg kg-1)**	**NUTS 2 with highest Ox Fe content (mg kg^{-1})** (1)	**NUTS 2 with lowest Ox Fe content (mg kg^{-1})** (1)
Boreal to sub-boreal	101	4.9	3.5	4.6	FI1D *N* points = 16 mean = 7.1 median = 4.5	LV00 *N* points = 5 mean = 1.4 median = 1.5
Atlantic	513	3.4	2.8	2.5	UKF3 *N* points = 5 mean = 8.5 median = 8.1	FRF2 *N* points = 12 mean = 1.1 median = 0.7
Sub-oceanic	296	3.6	2.9	2.7	FRJ2 *N* points = 6 mean = 6.7 median = 6	ES42 *N* points = 3 mean = 0.6 median = 0.6
Sub-continental (northern)	489	2.5	1.9	1.8	SE21 *N* points = 3 mean = 4.4 median = 3.7	DE80 *N* points = 7 mean = 1.4 median = 1.6
Sub-continental (southern)	205	2.0	1.4	1.8	SK04 *N* points = 4 mean = 7.3 median = 7.5	AT12 *N* points = 10 mean = 0.7 median = 0.7
Temperate mountainous	56	3.0	2.2	2.2	ITH1 *N* points = 5 mean = 3.5 median = 2.5	SK02 *N* points = 3 mean = 1.3 median = 1.4
Mediterranean (semi-arid)	637	1.2	0.8	1.2	ITF6 *N* points = 6 mean = 4.6 median = 3.8	ES62 *N* points = 5 mean = 0.7 median = 0.8
Mediterranean (temperate to sub-oceanic)	208	2.3	1.5	2.6	ITF3 *N* points = 4 mean = 9.5 median = 7.8	ES41 *N* points = 7 mean = 0.6 median = 0.6

4.11 Metals

The concentration of metals in soils is an important criterion for the assessment of environmental quality. In many cases, the concentration of metals in soil simply reflects the mineral characteristics of their parent material. This is known as background concentrations. In most cases, the natural environment has adapted itself to exist with such levels. However, contamination of soil by high concentrations of metals, often introduced through transport, waste streams, or emissions from industrial or agricultural activities, represent a potential threat to environmental well-being, food safety, and human and animal health.

Some metals, at low concentration levels, are essential for living organisms. These include the trace elements cobalt, copper, iron, manganese, molybdenum, selenium and zinc. However, they can become toxic at elevated concentrations. A second group, consisting of arsenic, cadmium, lead, mercury and vanadium (also plutonium, and tungsten but not considered here) do not have any essential function in living organisms and are highly toxic even at low exposure levels.

In 2018, LUCAS points with relatively high concentrations of metals in the 2009/2012 sample were re-analysed, together with an additional set of random points in all MS. In total, 997 samples were analysed for metal concentrations. Some summary statistics are presented in Table 52 (Figure 51). A separate report on changes in metal concentrations is being prepared. Figures 52-62 show the locations of sites according to the elements analysed.

Table 52 Summary of metal content in selected samples (g/mg)

Element	<LOD	Min	Max	Mean	Median	StDev
As	8	1.1	939	33.14	10	79.99
Cd	58	0.2	10.4	0.51	0.4	0.89
Co	1	0.7	182.9	10.87	5.4	22.68
Cr	1	0.9	1203.2	63.13	20.15	133.62
Cu	8	2.3	973.9	40.47	13	89.35
Hg	155*	0.1	4	0.33	0.1	0.72
Ni	11	1	3249.3	87.65	21.4	258.92
Pb	1	2	294.7	26.06	17.9	36.8
Sb	7	0.1	35.9	1.35	0.5	3.9
V	0	1.6	320	42.99	20.6	51.33
Zn	2	3.1	2385	73.37	39.3	186.45

Figure 51 Map of the 997 points for which metal levels were analysed.

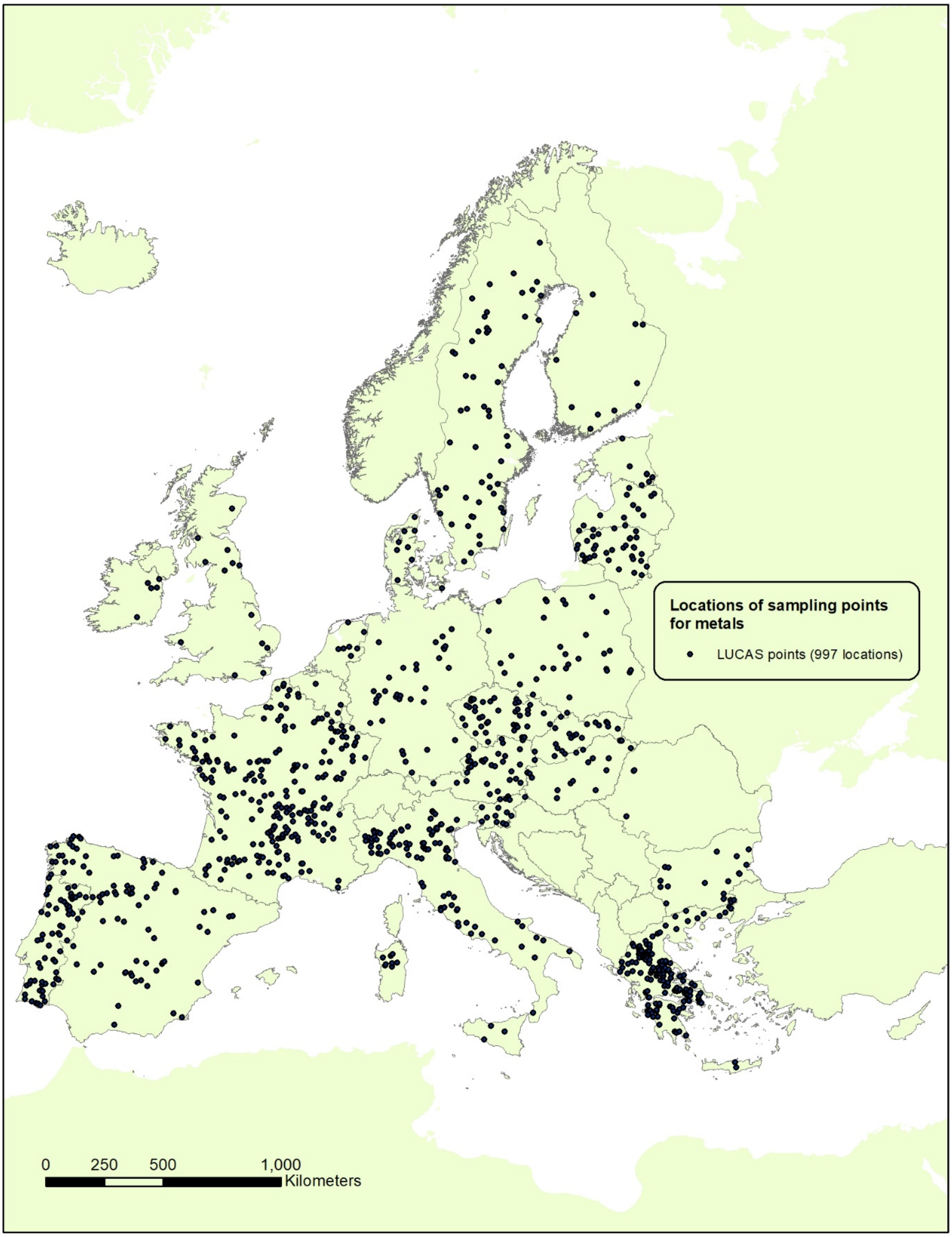


Figure 52 Arsenic analyses

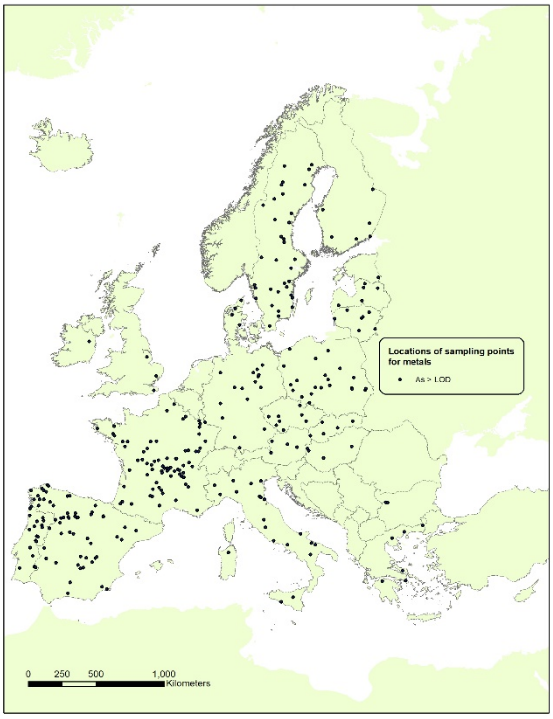


Figure 53 Cadmium analyses

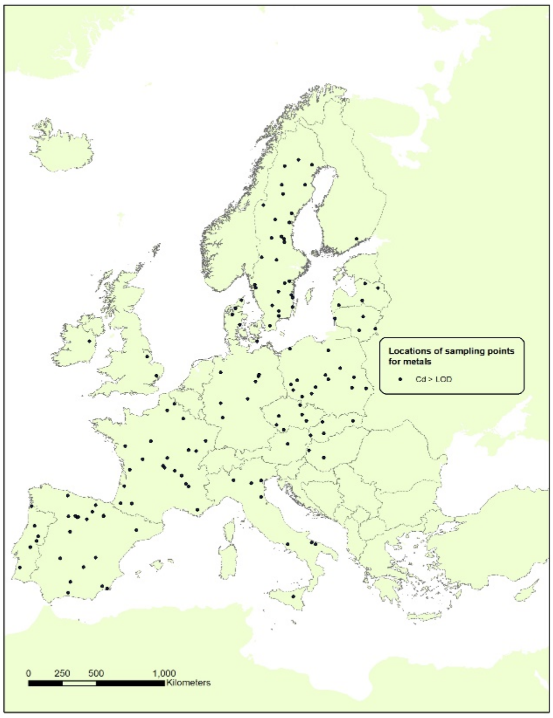


Figure 54 Cobalt analyses

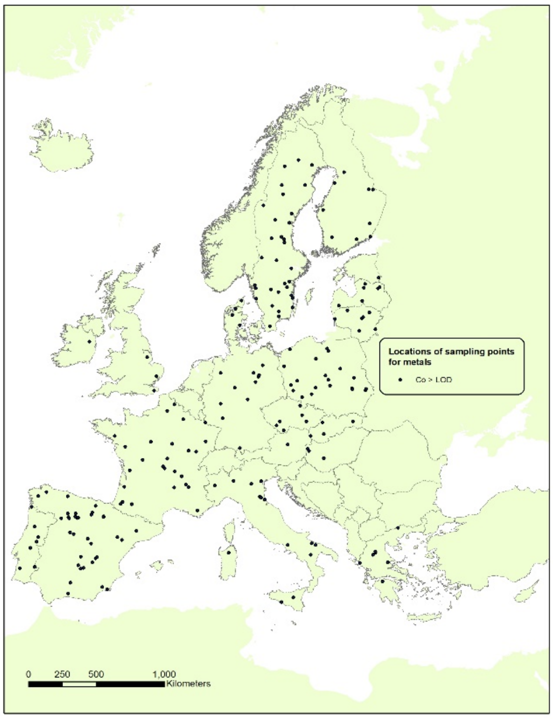


Figure 55 Copper analyses

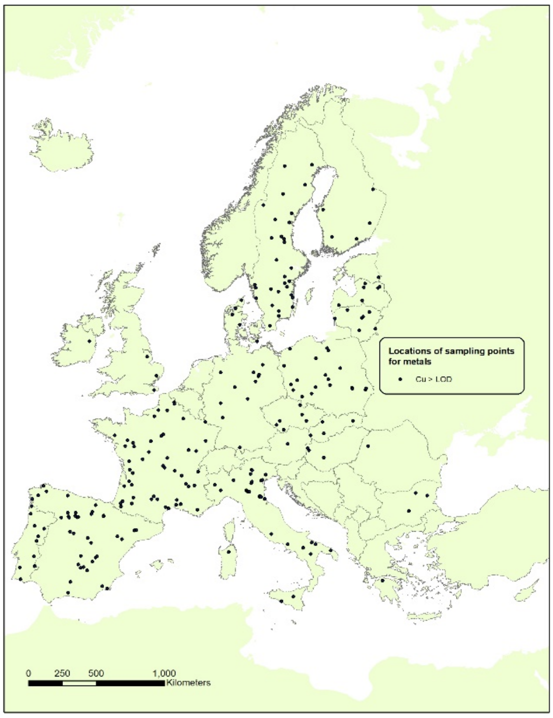


Figure 56 Chromium analyses

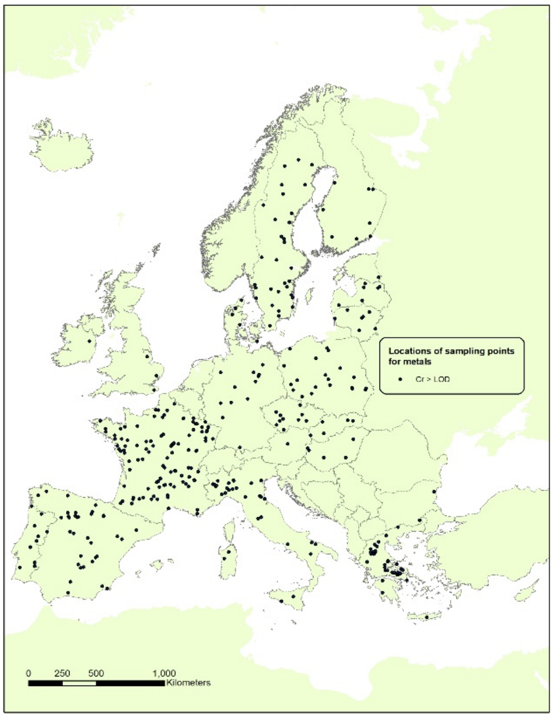


Figure 57 Nickel analyses

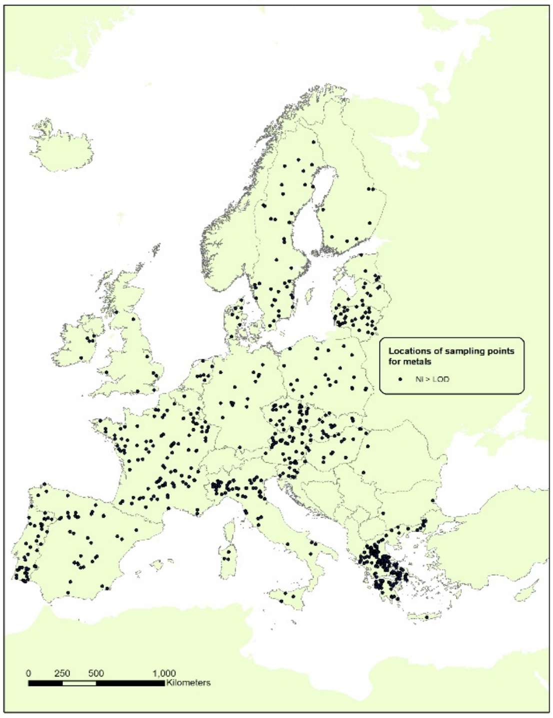


Figure 58 Mercury analyses

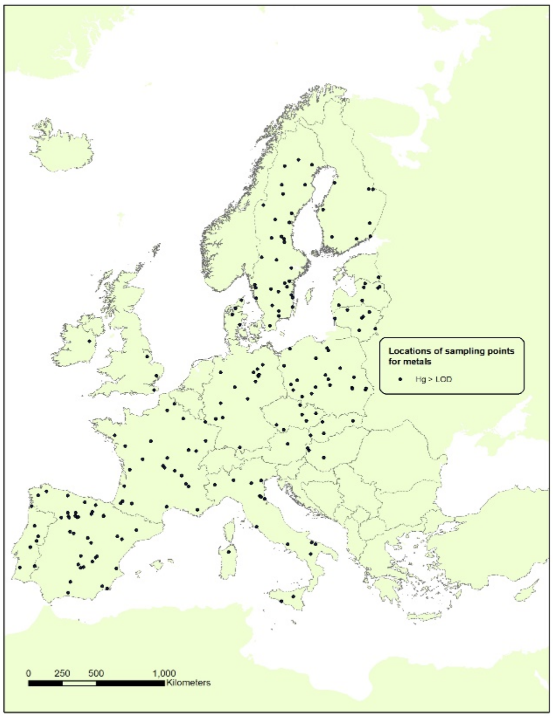


Figure 59 Antimony analyses

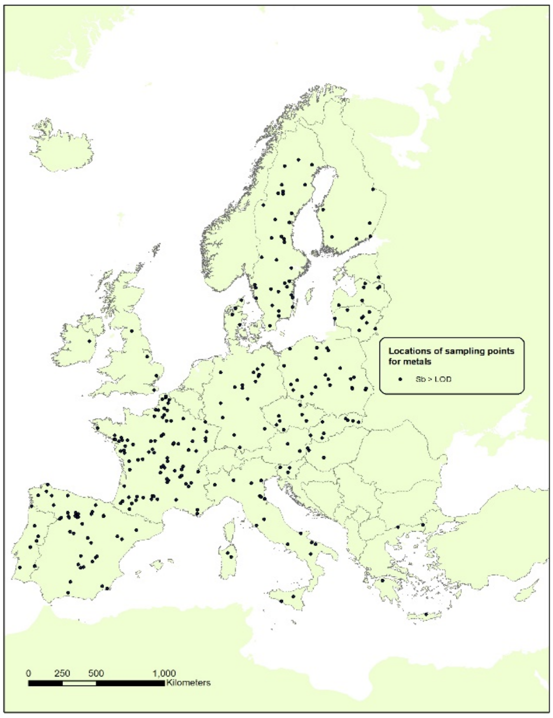


Figure 60 Lead analyses

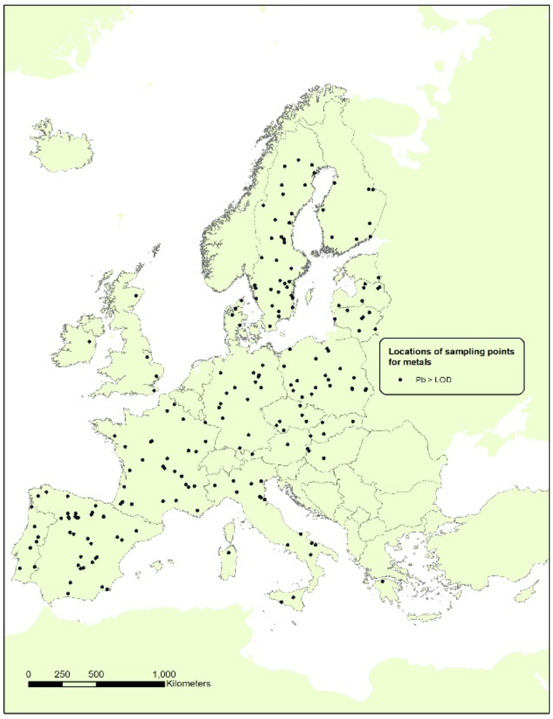


Figure 61 Vanadium analysis

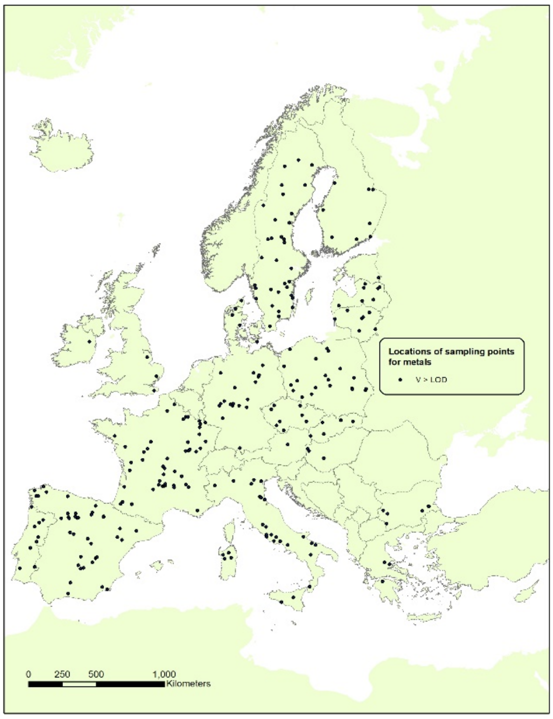
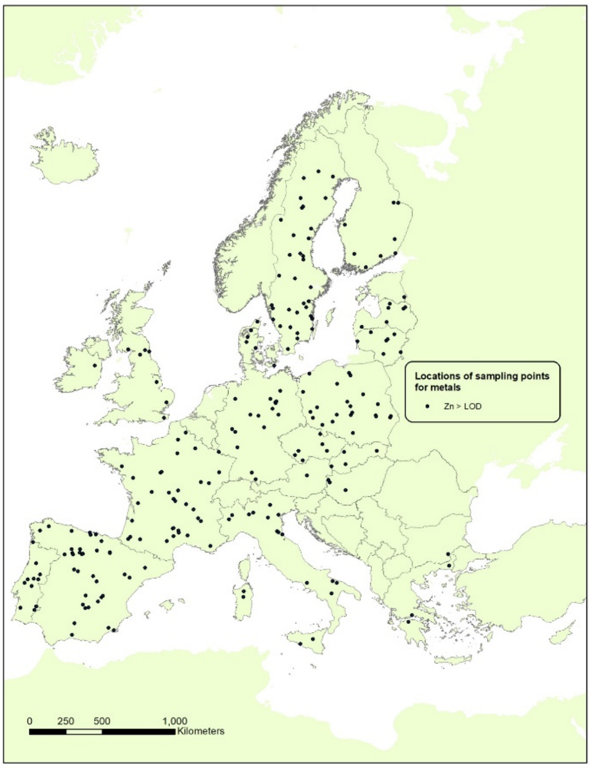


Figure 62 Zinc analyses



5 Conclusions

Regular monitoring provides a unique perspective on pressures affecting soils. In this respect, the soil module of the Land Use/Cover Area frame statistical Survey (generally referred to as LUCAS Soil) collects data that characterises soil conditions and health in relation to land use practices and other activities that are driven by specific policy instruments.

In 2018, the survey was carried out for all twenty-eight EU MS. Of the locations sampled in 2009/2012 and 2015, 90% were maintained. The remaining 10% were substituted by new locations, including new points at altitudes above 1,000 m, which were out of scope of the LUCAS 2009 and LUCAS 2012 surveys.

The LUCAS 2018 Soil dataset has 18,984 unique records with chemical, physical and agro-environmental data covering the 28 Member States of the EU (as in 2018). Samples are identified with their Point ID, which serves to link the soil data with the field data published in the LUCAS portal of Eurostat. The soil dataset is made available in a variety of formats (e.g. CSV, Excel and SHAPE) through the EU Soil Observatory's European Soil Data Centre (ESDAC). A supplementary dataset containing ancillary environmental information (e.g. climate, topographic setting, soil regions, NATURA 2000 sites, etc.) is also available to download from ESDAC.

The results of topsoil properties for LUCAS 2018 are consistent with those observed in LUCAS 2009 and 2015, showing similar trends across the EU and the various land cover classes:

— Organic carbon, N and P show a decreasing north-western to south-eastern trend, with higher contents in the boreal, Atlantic and northern sub-continental zones and lower contents in the Mediterranean and southern sub-continental zones. Temperate mountainous and sub-oceanic zones have intermediate contents of OC, N and P.

— Contents of OC and N are greater in wetland, woodland and grassland than in cropland and bareland. On the contrary, P content is greater in cropland than in woodland and grassland. In wetland, P content is relatively high.

— Potassium content tends to be lower in northern than in southern Europe, with lowest contents in boreal and northern sub-continental zones and highest contents in semi-arid Mediterranean and southern-sub-continental zones.

— K content is higher in cropland and grassland than in woodland.

— Topsoil pH (both in H_20 and $CaCl_2$) tends to be highly acid in boreal, northern sub-continental and some Atlantic zones, while pH is alkaline in the Mediterranean zones. In accordance with the spatial distribution of pH, high contents of carbonates are observed in the Mediterranean zones.

— Higher values of pH in cropland than in grassland and woodland are observed across the EU.

— Most of the points have low electrical conductivity values (<4 dS m-1), demonstrating limited salinity problems. However, this may also be attributed to insufficient sampling on affected areas.

— Some salinity hotspots are observed in the Ebro Valley in Spain, in the Adriatic coast in Italy and in the Atlantic coast in Ireland and France.

Data can be downloaded from

https://esdac.jrc.ec.europa.eu/content/lucas2018-topsoil-data

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