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LUCAS 2015 Topsoil Survey

Presentation of dataset and results

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Contents

Acknowledgements	ii
Abstract	iii
1 Introduction	1
2 LUCAS sampling methodology and laboratory analysis	2
3 Soil data evaluation	5
3.1 Agreement of the data format with the specifications of the call for tender for laboratory analysis in LUCAS 2015	5
3.2 Identification and registration of samples in LUCAS 2015	6
3.3 Evaluation of soil data and pedological criteria in LUCAS 2015	7
3.4 Closeness of sampling locations in paired samples between surveys	11
4 The LUCAS 2015 Topsoil dataset	12
4.1 Structure and description of the dataset	12
4.2 Spectral database	14
4.3 X-Ray diffraction dataset	14
5 Spatial representation of soil properties in the EU-28.....	15
5.1 Organic carbon.....	18
5.2 Nitrogen, phosphorus, and potassium.....	28
5.3 pH and carbonates.....	53
5.4 Electrical conductivity	68
6 Conclusions.....	69
References	71
List of figures	73
List of tables	74

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Abstract

This report accompanies the release of the LUCAS 2015 soil dataset. It presents an overview of the laboratory analysis data and provides a detailed description of the results for the EU-28 territory. The report describes the spatial variability of soil properties by land cover (LC) class and a comparative analysis of the soil properties by NUTS 2 regions.

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) supports the specific needs of the European Commission by collecting data that characterises soil condition and health in relation to land use practices and other activities (e.g. industrial emissions) 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 European Union (EU), addressing all major land cover types simultaneously, in a single sampling period (generally 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, together with additional laboratory analysis. This capacity reflects 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. At that time, the main LUCAS survey was planned for 23 EU Member States (MS). Bulgaria, Cyprus, Malta and Romania were excluded, while Croatia was not a MS at the time.

The initial premise for the soil module was to collect a baseline dataset on a range of soil characteristics such as organic matter content, nutrient status, fertility, acidification and soil pollution (metals).

An approach was developed to collect samples from 10% of the sites where field visits (i.e. verification) were to be carried out as part of the main LUCAS Survey. In 2009, this gave 235,000 possible locations for 23,500 soil samples. At the end of the survey, about 20,000 had been collected from a depth of 20 cm following a common sampling procedure. 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 same procedure, sampling method and analysis standards were extended in 2012 to Bulgaria and Romania, where samples were collected from about 2,000 locations.

In 2015, the survey was carried out for all twenty-eight EU MS. Of the locations sampled in 2009 and 2012, 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.

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. Switzerland also participated following standard LUCAS protocols.

Overall, 27,069 locations were selected for the soil sampling of LUCAS 2015, of which 22,631 were collected in the EU-28, with a further 1,271 samples being collected from other countries. After the removal of samples that could not be identified or mislabelled, the LUCAS 2015 Soil dataset contains 21,859 unique records. 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 main LUCAS 2015 microdata, which is made available by EUROSTAT..

The results for Switzerland and Western Balkan Countries will be presented separately.

A parallel report presents an assessment of changes in soil properties between 2009 and 2015

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

1 Introduction

Soil is a key component of the biosphere that delivers fundamental ecosystem services that support human well-being. These services are classified as 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). In order to ensure that soil delivers these ecosystem services, it is necessary to develop pan-European policies for a sustainable land and soil management while preventing degradation. The development of such policies should be based on land and soil monitoring networks that are able to provide evidence of the impact of land use and cover changes in soil properties both in space and in time. In this context, the topsoil assessment module of the LUCAS (Land Use and Cover Area Frame Survey) programme is the only mechanism for the harmonised monitoring (common sampling procedure and standard analysis methods) of topsoils at the European Union (EU) level.

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 and land cover, 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, Cyprus, Malta and Romania were not included). Ten percent of these points were selected for the soil survey. At the end of the survey, soil samples were taken in about 20,000 points. In LUCAS 2012, the soil survey was conducted in Romania and Bulgaria, where circa 2,000 points were sampled. The details and outcomes of the 2009 and 2012 surveys are fully documented in Tóth et al. (2013).

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 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, Croatia, Montenegro, North Macedonia, and Serbia. Switzerland also participated following standard LUCAS protocols.

In total, 27,069 locations were selected for sampling. Samples were eventually collected from 23,902 locations, of which 22,631 were in the EU. Soil samples were collected from a depth of 20 cm following a common sampling procedure.

As for LUCAS 2009 and 2012 surveys, all samples were analysed for physical and chemical properties in a single laboratory using the same ISO analytical methods (¹). In addition, electrical conductivity (EC) was included for the first time. Clay mineralogy data was extracted through X-Ray Diffraction from 400 samples (not discussed in this report).

The aim of this report is to:

- (1) present the dataset of the LUCAS 2015 Topsoil Survey
- (2) provide a detailed description of the results in for the EU.

The results include a characterization of the spatial variability of soil properties by land cover class and a comparative analysis of the soil properties by NUTS 2 regions.

The results for Switzerland and Western Balkan Countries will be presented in separate reports.

(¹) coarse fragments, particle-size distribution, organic carbon (OC), carbonates (CaCO₃), nitrogen (N), phosphorus (P), potassium (K), cation exchange capacity (CEC), pH and multispectral spectroscopy

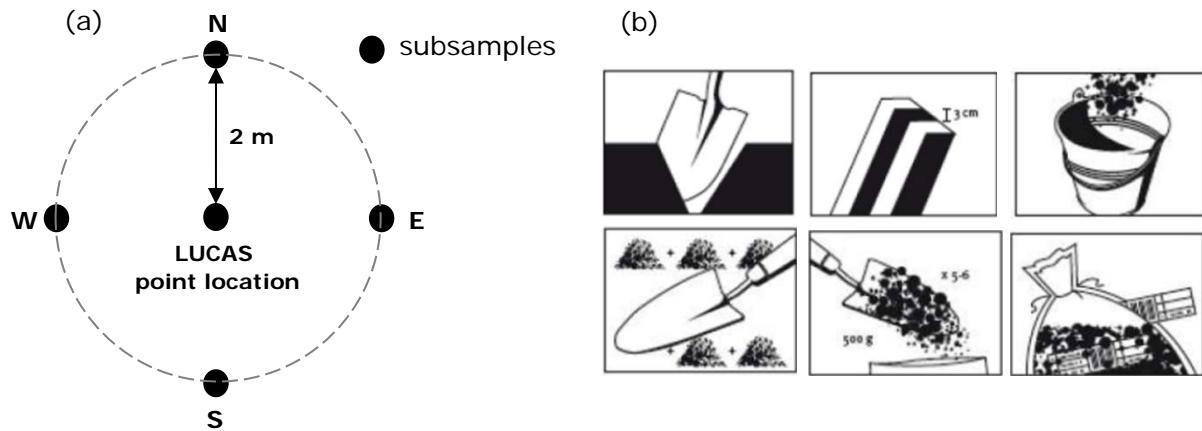
2 LUCAS sampling methodology and laboratory analysis

The sampling in 2015 was carried out following the common procedure established for the 2009 and 2012 surveys (²).

In summary, a composite sample of approximately 500 g was taken from five subsamples collected with a spade at each LUCAS point. The first subsample was collected 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 1a).

Before collecting 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 1b, 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 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 1. (a) LUCAS sampling schema and (b) summary of the sampling procedure



The samples were then sent to a central laboratory (³) where physical and chemical properties were analysed according to standard ISO methods (except for extractable Potassium). Table 1 shows the soil properties measured, together with the methods used. For properties measures in the 2009 and 2012 LUCAS campaigns, the laboratory methods were the same.

Particle-size analysis was not performed on samples from revisited point (i.e. points sampled in 2009/2012 and 2015) as this property can be regarded as stable during the interval between surveys.

(²) <http://ec.europa.eu/eurostat/documents/205002/6786255/LUCAS2015-C1-Instructions-20150227.pdf>

(³) SGS Hungária Kft, Nyíregyháza, Hungary

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

Soil properties	Method	Description
Coarse fragments	ISO 11464:2006	Sieving to separate coarse fragments (2–60 mm) from fine earth fraction
Clay, silt and sand contents	ISO 11277:1998 ISO 13320:2009	Sieving and sedimentation method (in 2009 and 2012) Laser diffraction (in 2015 only)
pH in CaCl ₂ and in H ₂ O	ISO 10390:2005	Glass electrode in a 1:5 (V/V) suspension of soil in H ₂ O and CaCl ₂
Electrical Conductivity	ISO 11265:1994	Metal electrodes in aqueous extract of soil
Organic carbon content	ISO 10694:1995	Dry combustion (elementary analysis)
Carbonates content	ISO 10693:1995	Volumetric method
Phosphorus content	ISO 11263:1194	Spectrometric determination of P soluble in sodium hydrogen CaCO ₃ solution
Total nitrogen content	ISO 11261:1995	Modified Kjeldahl method
Extractable potassium content	USDA-NRCS, 2004	Atomic absorption spectrometry after extraction with NH ₄ OAc
Cation exchange capacity	ISO 11260:1994	Using barium chloride solution to saturate samples and extract cations
Multispectral spectroscopy	Soil Spectroscopy Group	Diffuse reflectance measurements
Clay mineralogy	X-ray diffraction	X-ray diffraction patterns of oriented aggregates (only in 2015)

As part of the quality control measures, the efficiency of the LUCAS sampling for topsoil monitoring was assessed. A detailed description of this study is presented in Fernandez-Ugalde et al. (2020).

The main conclusion of the study was that the LUCAS spade sampling is an efficient and cost-effective method for topsoil monitoring at regional/continental scale, although a better control of litter removal in woodland and sampling depth in all LC classes is needed.

3 Soil data evaluation

Data validation processes aims to provide certain guarantees of accuracy, completeness and consistency to data. Based on the methodology developed by Hiederer et al. (2008) for other pan-European soil databases, three aspects were assessed for the LUCAS 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. For each of these aspects, various tests were carried out:

- agreement of the data format with the specifications indicated in the call for tender of LUCAS 2015 (Compliance check, section 3.1),
- control of the identification and registration of samples in the LUCAS 2015 survey (Conformity check, section 3.2),
- evaluation of soil data and application of pedological criteria in the LUCAS 2015 survey (Conformity check, section 3.3),
- assessment of closeness of sampling locations in paired samples between the 2009/2012 and 2015 surveys (Uniformity check, section 3.4),
- assessment of the comparability of soil data between 2009/2012 and 2015 surveys (Uniformity check, section 3.5).

Furthermore, Hiederer (2018) performed a detailed validation of OC data, as it is a key property for all customer DGs due to its implications for climate change mitigation, assessing the impact of agricultural practices and the supply of ecosystem services.

3.1 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 2015 survey ⁽⁴⁾ includes the following conditions:

- Data generated in the laboratory for each soil sample shall be linked to the Soil ID in the dataset,
- Data of core soil properties ⁽⁵⁾ shall be delivered in an Excel (or 100 % Excel-compatible) workbook,
- Core soil properties shall be presented in columns following the order specified in the technical document,
- Units and number of decimals for each core soil property shall also follow the technical specifications,
- Additional soil properties (multispectral data and clay mineralogy) shall be delivered separately, following the specific indications for their data presentation.

The laboratory delivered the dataset of core soil properties in an Excel file with four sheets, one for each group of samples identified in the technical specifications. Group 1 includes potentially organic or organic-rich samples, Group 2 comprises mineral samples collected in georeferenced points previously sampled in 2009 or 2012 surveys, Group 3 contains mineral samples collected in new plots, and Group 4 contains soil samples in which clay mineralogy was analysed. Samples in Group 4 shall be included in Group 3, because they were collected in points sampled also in 2009 or 2012 surveys.

The information of each soil sample is linked to its Soil ID in the dataset, so that soil information can be attributed to a monitoring point in the LUCAS 2015 database of Eurostat through the Soil ID. Soil properties are ordered in columns in the dataset as indicated in the technical specifications, except for silt and sand that are interchanged. Data of soil properties are expressed in pertinent units and with the number of decimals requested in the technical specifications. The laboratory added two extra columns to the dataset with Client ID (i.e. internal identification of samples in the laboratory) and member state of origin of soil samples. As requested, the laboratory delivered the data of additional soil properties separately with the proper format.

⁽⁴⁾ Tender reference number: JRC/IPR/2016/H.5/0004/OC (<https://etendering.ted.europa.eu/cft/cft-search.html>).

⁽⁵⁾ Coarse elements, clay, silt, sand, pH in CaCl₂, pH in H₂O, organic carbon, carbonates, phosphorus, nitrogen, extractable potassium, cation exchange capacity

The technical specifications do not include indications neither for the coding of missing data nor for data outside detection limits. From the dataset it can be concluded that empty fields indicate missing data. This is the case of contents of coarse elements, clay, silt and sand in samples from Groups 1, 2 and 3, in which these properties were not analysed. Regarding the detection limits, the laboratory provided the values for the methods used to analyse the soil properties in the Final Report.

3.2 Identification and registration of samples in LUCAS 2015

The LUCAS soil points in the EU-28 MS are identified by unique Point IDs. These Point IDs are used in every survey to record agro-environmental data relating to the points in the Data Management Tool (DMT) managed by Eurostat. Furthermore, topsoil 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, every topsoil 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.

Overall, 23,902 samples were taken in LUCAS 2015, from which 22,631 were taken in the EU-28 MS. In all, 241 samples in the EU-28 MS had repeated Soil IDs in the LUCAS 2015 survey. We were able to identify 58 out of these samples using the Point ID and member state in the DMT (Table 4). For the rest of the samples, it was not possible to find unique links between the soil data and the agro-environmental information.

During the laboratory analysis, 589 samples, which Soil IDs were not recorded in the DMT, were found through the EU-28 MS. Thus, it was not possible to relate these samples to any Point ID. On the opposite, there were 130 Soil IDs recorded in the DMT but the samples were not received (Table 2).

After the removal of samples that could not be identified, the LUCAS 2015 Soil dataset has 21,859 unique records with soil and agro-environmental data.

Table 2. Identification of samples taken in LUCAS 2015 in the EU-28 member states.

Identification of samples	N samples affected
Samples taken	22,631
Repeated Soil IDs	241
Recovered Soil IDs	58
Soil IDs not recorded in the DMT	589
Soil IDs recorded in the DMT but no physical samples available	130
Unique Soil ID / Point ID combinations	21,859

3.3 Evaluation of soil data and pedological criteria in LUCAS 2015

The limits of detection of the analytical methods were used to filter the data of soil properties and highlight the presence of values outside possible ranges in the dataset of the 2015 survey. Table 3 gives an overview of these outsider values in the dataset.

Table 3. Summary of outsider values per soil property in the dataset of the LUCAS 2015 survey.

Soil parameter	LOD ¹	Range actual values	N samples <LOD ¹	% of the data
pH-CaCl ₂	2-10	2.6-10	0	0
pH-H ₂ O	2-10	3.2-10.4	1	0
Electrical conductivity (mS m ⁻¹)	0.1	0.3-969	0	0
Organic carbon (g kg ⁻¹)	2.0	0.1-560.2	71	0.3
Carbonates (g kg ⁻¹)	1.0	0-976	11478	49
Phosphorous (mg kg ⁻¹)	10.0	0-1017.6	5464	23
Total nitrogen (g kg ⁻¹)	0.2	0-38.5	14	0
Extractable potassium (mg kg ⁻¹)	10.0	0-10030.9	136	0.6
Cation exchange capacity (cmol+ kg ⁻¹)	2.0	0-173.3	382	1.6

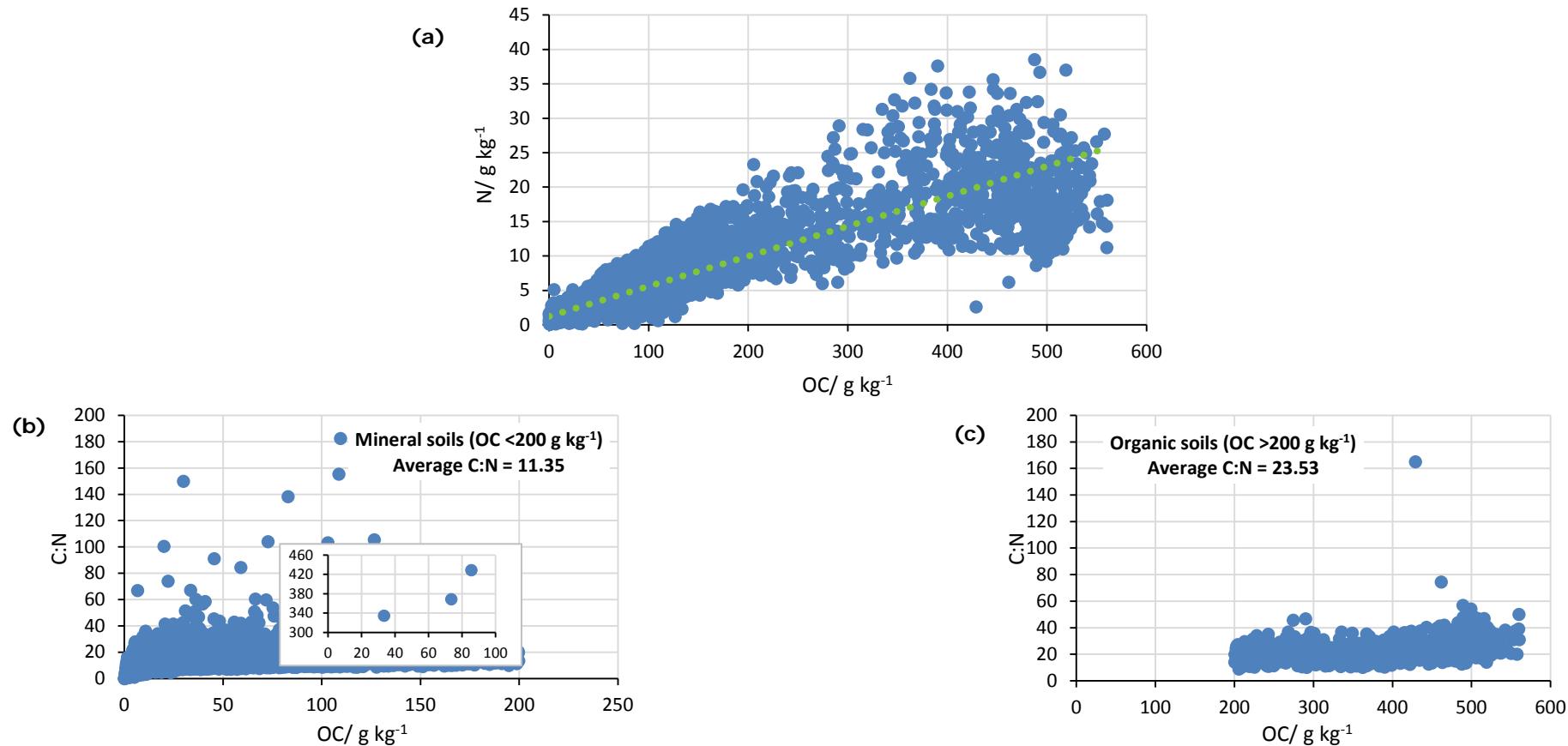
(¹) LOD : limit of detection.

The ranges of values reported for soil properties are within reasonable limits for soils in Europe. In fact, they are similar to those in the 2009 and 2012 surveys. The high number of outlier values for CaCO₃ is due to the use of the value “0” to indicate the absence of CaCO₃ in soil samples with low pH (pH<7). The value “0” has been substituted by “NA” in the dataset. Soil samples with the P content below the limit of detection are mainly located in woodland (36 %), and grassland and cropland most likely not subject to fertiliser applications (19 % and 21 %, respectively).

A range of correlations between soil properties were assessed for verifying coherence of the raw data from the soil point of view. These correlations include:

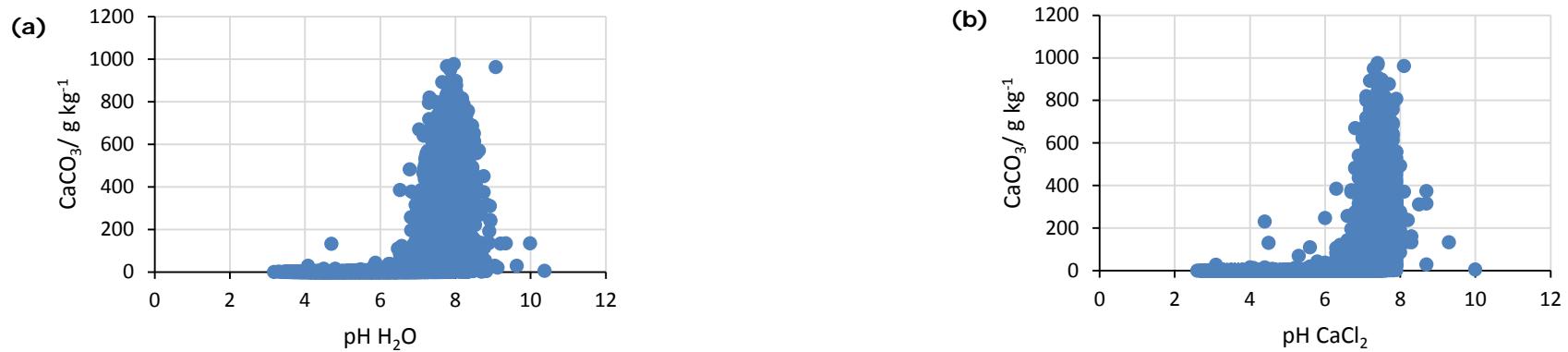
- Correlation between OC and N. A close relationship exists between OC and N levels in soil. The higher the OC concentration, the greater the N concentration (Figure 2a). Moreover, the C-to-N ratio is relatively stable across different soil types. Overall, mineral soils generally have a C-to-N ratio close to 12:1 (Figure 2b), while organic-rich soils shall have a C-to-N ratio close to 30:1 (Figure 2c). 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 2. (a) Relation between OC and N in the whole dataset, (b) relation between OC and C-to-N ratio in mineral soils and (c) relation between OC and C-to-N ratio in organic soils



— 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 3 shows (i) that pH in H_2O ranges between 3.4 and 10.4 while pH in CaCl_2 ranges between 2.6 and 10.0 in LUCAS 2015 samples, and (ii) that soil samples with pH around 7.0 – 8.5 have the greatest contents of CaCO_3 .

Figure 3. Relation between pH and carbonates (CaCO_3) in the whole dataset: (a) pH-H₂O, (b) pH-CaCl₂



— *Correlations between CEC and clay and OC.* Cation exchange capacity is the total capacity of soils to hold exchangeable cations. Soils with higher organic matter content and/or clay tend to have greater CEC, because organic matter and clay minerals have negatively charged sites on their surfaces where cations are adsorbed by electrostatic force. Figure 4 shows a positive, though not strong, correlation between OC and CEC, and clay and CEC. This is because soil CEC not only depends on the OC and clay content, but also on the degree of decomposition of organic matter and mineral composition of clay fraction. Apart from OC and clay, soil pH also influences CEC.

Figure 4. (a) Relation between OC and CEC in the whole dataset and (b) relation between clay and CEC in new LUCAS sampling points (i.e. points that were sampled for the first time in 2015)



- *Coherence of particle size distribution data:* Mineral fraction <2 mm in soil can be split in three size fractions: sand (2–0.05 mm), silt (0.05–0.002 mm) and clay (<0.002 mm). In the LUCAS 2015 survey, these three fractions were measured only in new LUCAS sampling points (i.e. points sampled for the first time in the LUCAS survey) because sand, silt and clay contents in soil are considered to be stable in the short to medium term. To validate the data, the sum of mass of the three fractions shall be equal to 100 %. In the LUCAS 2015 dataset, the sum of sand, silt and clay fractions ranged between 99 % and 101 % because the contents of the three fractions were rounded to the nearest whole number.

Overall, the raw soil data followed the expected trends for assessed correlations. Thus, it can be concluded that the data is coherent from the pedological point of view.

3.4 Closeness of sampling locations in paired samples between surveys

The LUCAS soil points for the topsoil module were selected from the LUCAS regular grid based on land use and terrain information, as indicated in the introduction chapter. Each of these soil points has its theoretical coordinates in the LUCAS grid. For the first topsoil survey in 2009, the triplet concept was used to design the survey (Tóth et al., 2013). Briefly, the surveyors received a list of three alternative sites from the LUCAS grid that have common characteristics of slope, aspect and LC within the surveyed area (this group of site is referred to as triplets). A soil sample was collected from only one of the sites of a triplet. As a general rule, the sample had to be taken in the first site of each triplet. The surveyor had to take the sample in the exact location. If this was not possible, the surveyor had to move to the next site in the triplet to collect the sample (⁶). This triplet concept was also used in the LUCAS 2012 survey for Bulgaria and Romania. In the 2009 survey, 26 % of the sampling locations were at a distance less than a meter from the LUCAS soil points, 76 % of the locations were at a distance less than 5 m and 96 % of them were located less than 100 m from their LUCAS soil point. In the 2012 survey, 34 out of 1,454 sampling locations (2.3 %) were taken at a distance greater than 100 m from the LUCAS soil points in Bulgaria and Romania. According to the instructions, points should be monitored as close as possible (at a distance less than 100 m), always on the same field parcel.

In the 2015 survey, 80.6 % (17,613 out of 21,859) of the sampling locations of the 2009 and 2012 surveys were revisited. A maximum distance of 100 m, always from the same LC class as observed in the soil point, was allowed between the baseline samples collected in the 2009/2012 surveys and their paired samples collected in the 2015 survey (⁷). Altogether, 80 % of the sampling locations in 2015 were at a distance less than 10 m from their baseline sampling locations in 2009/2012. The percentage increased to 96.5 % when considering a distance less than 100 m between the sampling locations in 2009/2012 and in 2015. Among the 620 locations at a distance greater than 100 m between 2009/2012 and 2015, 362 were at a distance between 100 and 200 m and the rest at a distance between 200 m and 1 km from their baseline location. Surveyors gave different reasons to explain the inaccessibility to the LUCAS soil points for the topsoil sampling. The most common difficulties were the presence of high crops and dense vegetation, ground conditions (mainly waterlogged conditions, and stoniness), presence of fences, refusal of landowner and presence of roaming and dangerous animals.

(⁶) LUCAS 2009. Instructions for Surveyors:
<http://ec.europa.eu/eurostat/documents/205002/208938/LUCAS+2009+Instructions/8ffdb9d8-b911-40b6-8f9a-8788bf696aa3>

(⁷) LUCAS 2015. Instructions for surveyors:
<http://ec.europa.eu/eurostat/documents/205002/6786255/LUCAS2015-C1-Instructions-20150227.pdf>

4 The LUCAS 2015 Topsoil dataset

4.1 Structure and description of the dataset

The LUCAS 2015 Topsoil dataset represents laboratory analysis of the samples taken in the 2015 survey. After controlling for the identification of samples (see section 3.2), the dataset has 21,859 unique records with soil and agro-environmental data for the EU-28 MS. Table 4 shows the distribution of points by member state and by Land Cover (LC) class.

Table 4: Allocation of LUCAS 2015 sampling locations.

Country	Points	Cropland	Grassland	Woodland	Wetland	Shrubland	Bareland	Other
Austria	543	118	167	237	1	8	9	3
Belgium	146	88	25	29	1	0	3	0
Bulgaria	536	256	125	128	0	19	8	0
Croatia	114	12	27	60	0	15	0	0
Cyprus	76	34	14	5	0	20	2	1
Czech Republic	440	223	110	99	1	3	4	0
Denmark	222	166	28	23	2	1	1	1
Estonia	194	55	38	94	0	3	2	2
Finland	1149	174	51	892	3	19	8	2
France	3050	1581	785	549	2	71	54	8
Germany	1687	837	411	405	2	9	19	4
Greece	643	284	119	156	1	65	15	3
Hungary	412	261	74	57	1	4	11	4
Ireland	197	14	148	15	12	5	3	0
Italy	1642	794	362	409	0	46	27	4
Latvia	310	86	103	114	0	3	4	0
Lithuania	352	173	93	74	0	4	8	0
Luxembourg	13	5	3	5	0	0	0	0
Malta	3	3	2	0	0	0	1	0
The Netherlands	172	85	58	23	2	1	1	2
Poland	1377	699	332	310	1	4	31	0
Portugal	447	112	96	167	0	56	12	4
Romania	1085	452	438	173	0	17	4	1
Slovakia	228	100	47	76	0	4	0	1
Slovenia	147	12	33	99	0	2	0	1
Spain	4027	1918	605	763	0	380	352	9
Sweden	1903	154	109	1551	13	56	16	4
United Kingdom	744	277	350	68	7	30	10	2

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⁽⁸⁾. The field data consist of land cover, land use and environmental parameters associated with the individual points surveyed⁽⁹⁾.

As outlined in Table 5, soil data are reported in 12 fields (columns). A limited number of supplementary data have been extracted from the LUCAS Microdata to provide land cover and land use context to users of the soil data (Table 6).

Particle-size data (coarse fragments, sand, silt and clay) are only available for points that were sampled for the first time in 2015.

The soil dataset is made available in a variety of formats (e.g. CSV, Excel and SHAPE) to help users. Data can be downloaded through the European Soil Data Centre (ESDAC) using the following URL: <https://esdac.jrc.ec.europa.eu/resource-type/datasets>.

An additional supplementary dataset containing ancillary environmental information for the soil sampling locations (e.g. climate, topographic setting, soil regions, NATURA 2000 sites, etc.) is also available to download from ESDAC.

Soil data for the Western Balkan countries and Switzerland will be published in a separate dataset and accompanied by a similar report. Both the dataset and the report will be available through ESDAC.

Table 5. Soil fields in the LUCAS 2015 Topsoil dataset.

Field	Description
Point_ID	LUCAS Point Identifier – link to Eurostat LUCAS Microdata
Coarse	% of coarse fragments (>2mm)
Clay	% of clay particles
Sand	% of sand particles
Silt	% of silt particles
pH_CaCl ₂	pH – measured in calcium chloride
pH_H ₂ O	pH – measured in water
EC	Electrical conductivity (miliSiemens per meter – mS m ⁻¹)
OC	Organic carbon content (g kg ⁻¹)
CaCO ₃	Calcium carbonate content (g kg ⁻¹)
P	Total phosphorus (g kg ⁻¹)
N	Total nitrogen (g kg ⁻¹)
K	Extractable potassium (g kg ⁻¹)

⁽⁸⁾ <https://ec.europa.eu/eurostat/web/lucas/data/primary-data/2015>

⁽⁹⁾ <https://ec.europa.eu/eurostat/web/lucas/data/database>

Table 6. Non-soil fields in the LUCAS 2015 Topsoil dataset.

Field	Description
LC	Primary land cover
LU	Primary land use
NUTS_0	NUTS 0 Code
NUTS_1	NUTS 1 Code
NUTS_2	NUTS 2 Code
NUTS_3	NUTS 3 Code
LC0_Desc	Description of primary land cover
LC1_Desc	Description of secondary land cover
LU1_Desc	Description of primary land use

4.2 Spectral database

Diffuse high resolution reflectance spectra were collected for all samples in the visible (400 to 780 nm) and the near infrared (780 to 2500 nm) regions with 0.5 nm spectral resolution. The measurements were carried out following the protocol of the Soil Spectroscopy Group¹⁰ with a FOSS Rapid Content Analyzer¹¹. This technology has proven its efficiency to predict OC and N, clay content and mineral composition and water retention properties in large set of soil samples (Cécillon and Brun, 2007; Stenberg et al., 2010; Blaschek et al., 2019). Many studies have also shown the potential of visible and near infrared spectroscopy to predict pH, nutrients, CaCO₃ and heavy metals in soil samples. One scope of the spectral data collected through LUCAS-Soil is to contribute to the development of a spectral library that would help to improve the calibration and robustness of prediction of soil properties using this technology. A preliminary assessment of 2015 spectral data have shown that they are in line with the 2009/12 spectral data and that spectral data of both surveys are comparable.

4.3 X-Ray diffraction dataset

The mineralogical composition of the clay fraction was analysed through X-ray diffraction (XRD) in 400 samples selected according to their texture and land cover class. Moreover, this subset was representative for the chemical properties (OC, N, P, K, CaCO₃ and pH) of the LUCAS topsoil dataset. The XRD patterns were obtained from oriented aggregates of clay fractions in the following conditions: air-drying, ethylene glycolation, heating at 110°C, 350°C and 550°C, saturation with Mg and K ions, and solvation with glycerol. Interpretation and quantification of XRD patterns was carried out with the NEWMOD software. Chemical properties of clay minerals affect nutrient availability (Guo and Gifford, 2002) and OC turnover (Singh and Schulze, 2015) in soil. The aim of this study is to assess at EU scale the potential role of clay minerals on the OC content and nutrient supply in soils.

⁽¹⁰⁾ <http://groups.google.com/group/soil-spectroscopy>

⁽¹¹⁾ XDSTM Rapid Content Analyzer User Manual, FOSS 2010

5 Spatial representation of soil properties in the EU-28

Point data of each soil property is presented on four maps: one for the whole dataset and three for cropland, grassland and woodland points separately. No maps of bareland, shrubland and wetland are shown due to the low number of points. We used the same ranging of values, based on pedological and agrochemical criteria, as in the presentation report of LUCAS 2009 Topsoil Survey (Tóth et al., 2013a) to characterise soil properties in the maps.

Maps of aggregated data at NUTS 2 level are also presented for all points and for the main LC classes separately (cropland, woodland, and grassland). Overall, the NUTS classification of 2013 (¹²) has 276 regions for the EU-28 MS at level 2. The LUCAS 2015 Soil survey was carried out in 253 of these regions, although the number of regions sampled is lower when considering each LC class separately (Table 7). For data aggregation, we only considered NUTS 2 regions with at least 3 samples taken: the 98% of the regions sampled when considering the whole dataset, 92% of the regions for cropland, 90% of the regions for grassland, 84% of the regions for woodland, 38% of the regions for bareland, 49% of the regions for shrubland and 16% of the regions for wetland.

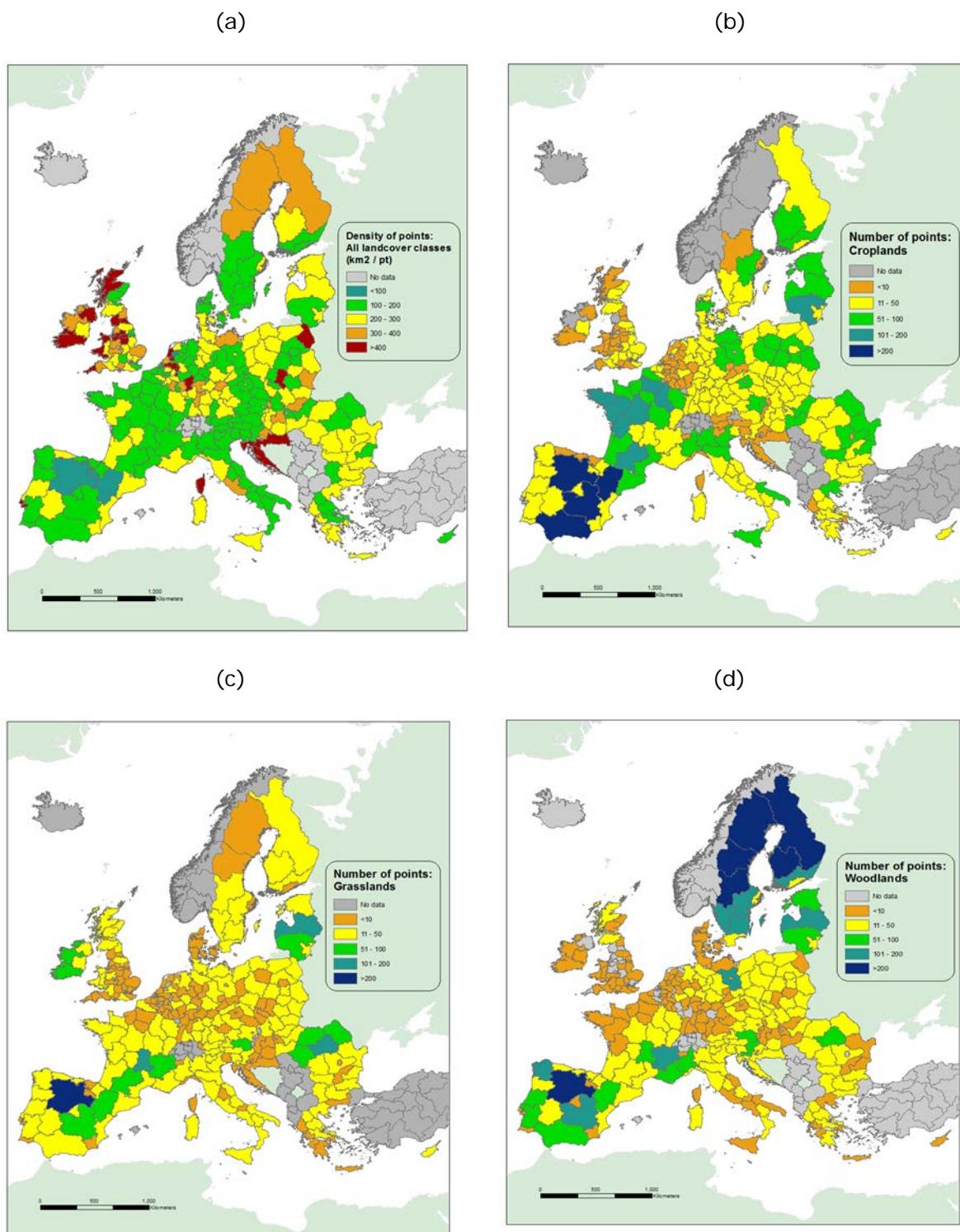
As shown in Table 7, the median values of sampling density in NUTS 2 regions were below the 295.2 km² per sample observed in woodland. These values of sampling density can be considered acceptable, at least for the assessment of soil organic carbon content, as proposed by Jandl et al. (2011) and Panagos et al. (2013). Jandl et al (2011) suggested that a minimum sampling density of one sample for every 300 km² 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 km² could be reasonable for LUCAS Soil survey to measure soil organic carbon. Based on these studies, we considered a minimum density of 250 km² per sample a reasonable preliminary indicator for the confidence level of the LUCAS 2015 Soil survey to measure chemical soil properties. According to this criterion, the sampling density can be sufficient in more than 50% of NUTS 2 regions both when considering the whole dataset and the different LC classes separately (Table 7, Figure 5). The % of regions with a minimum sampling density of 250 km² per sample was slightly below the 50% in woodland and shrubland (Table 7).

Table 7. Summary statistics of sampling density in NUTS 2 regions.

	N of NUTS 2 regions sampled	Sampling density (km² per sample)		% of NUTS 2 regions with density <250 km² per sample
		Mean of NUTS 2 regions	Median of NUTS 2 regions	
Whole dataset	253	257.2	209.1	69
Cropland	238	144.4	117.7	91
Grassland	244	268.5	217.6	61
Woodland	230	446.3	295.2	40
Bareland	122	364.6	182.3	67
Shrubland	129	433.8	275.6	46
Wetland	24	802.7	222.5	54

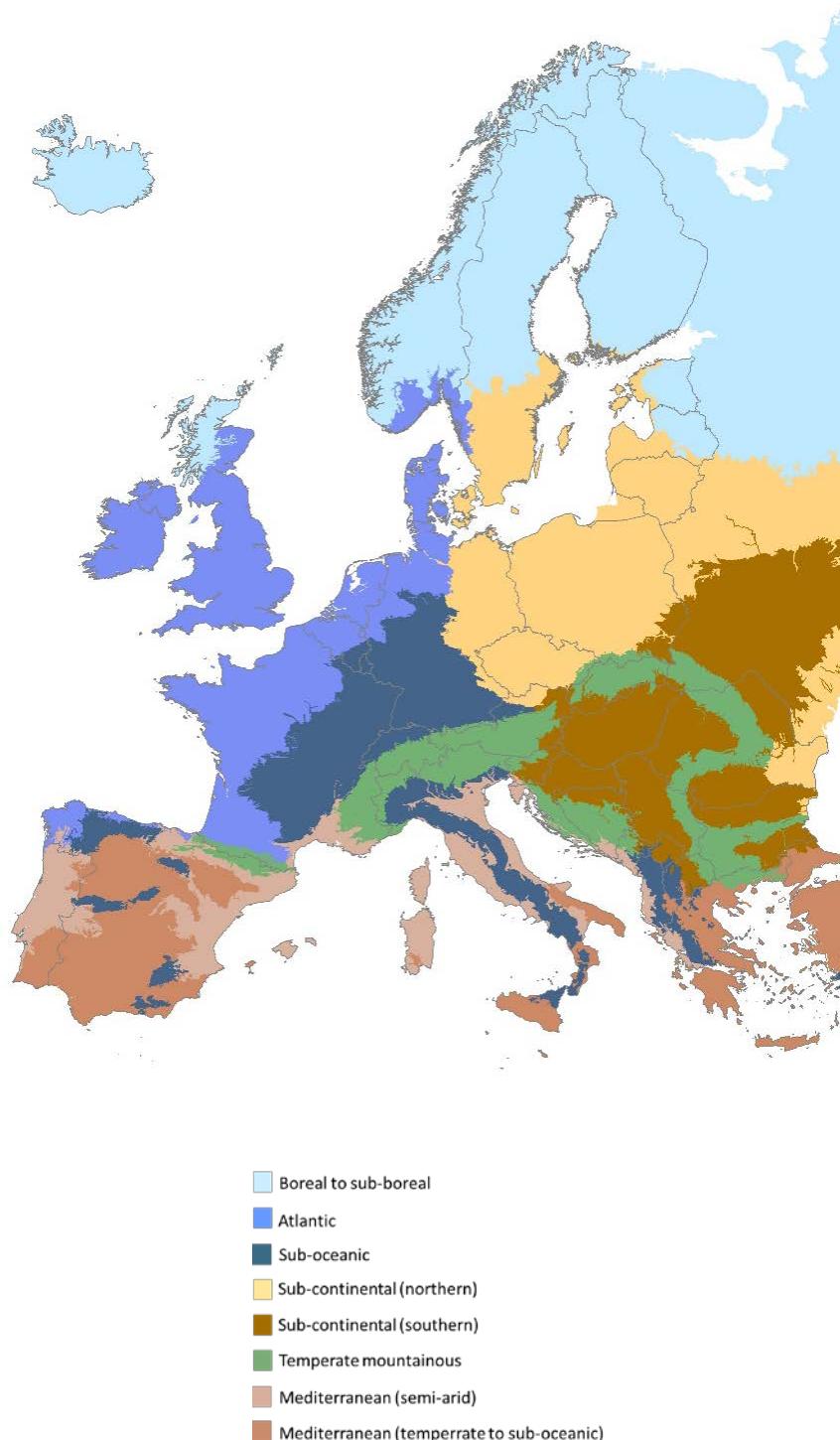
(¹²) Regional data of LUCAS 2105 is presented based on NUTS 2013 classification at the Eurostat webpage. Thus, we decided to use the same classification to describe LUCAS 2015 soil data in this report

Figure 5. (a) Sampling density in NUTS 2 regions for the complete dataset; number of points in each NUTS2 Region for (b) cropland, (c) grassland, (d) woodland



Both point data and aggregated data are described following the climatic zones for soil quality assessment identified in Tóth et al. (2013b) (Figure 6), as it was done in the report of LUCAS 2009 Topsoil Survey (Tóth et al., 2013a).

Figure 6. Climatic zones identified in Tóth et al. (2013b)



5.1 Organic carbon

Spatial variability of organic carbon (OC) content depends on the climate and the share of land cover (i.e. vegetation type) across the EU. Organic carbon was the highest in the boreal zone, most of the Atlantic zone, and the temperate mountainous zone. It was intermediate in the sub-oceanic zone and lowest in the Mediterranean and sub-continent zones (Figure 7). Wetland, woodland, shrubland and grassland were the main LC classes in zones with the highest OC content. On the contrary, cropland and bareland were the more common LC class in zones with the lowest OC content (Figures 8 to 10).

Points in **wetland** recorded the highest levels of OC (mean = 336.1 g kg⁻¹, median = 459.8 g kg⁻¹). According to their OC contents, these points are classified as organic (OC > 200 g/kg, Figure 11). Wetland points were located in the boreal, Atlantic, sub-oceanic, northern sub-continent and temperate mountainous zones. Overall, 49 points were sampled under wetland in 24 out of 276 NUTS 2 regions. The NUTS 2 region with the largest number of wetland points (twelve) was IEO1 (mean OC = 471.9 g kg⁻¹, median OC = 524.3 g kg⁻¹), followed by SE31 with six points (mean OC = 465.7 g kg⁻¹, median OC = 469.8 g kg⁻¹). In UKM3 region, with three points, OC content was lower (mean OC = 248.9 g kg⁻¹, median OC = 237.9 g kg⁻¹) (Table 8). This suggest a great variability of OC content in wetland from one region to another most likely due to differences on management practices and local climatic conditions. The remaining 21 regions had less than three samples or low sampling densities in wetland. It has to be noted that four wetland points had low OC contents (<20 g kg⁻¹). A similar situation was also observed in the LUCAS 2009 Soil survey (de Brogniez et al., 2015).

Table 8. Summary of organic carbon in wetland points.

Climatic zone	N points	Mean (g kg ⁻¹)	Median (g kg ⁻¹)	Std dev (g kg ⁻¹)	NUTS 2 with highest OC content (g kg ⁻¹) (1)	NUTS 2 with lowest OC content (g kg ⁻¹) (1)
Boreal to sub-boreal	18	416.7	480.2	145.6	SE31 mean = 465.7 median = 469.8	SE33 mean = 400.4 median = 479.5
Atlantic	25	348.7	470.3	224.5	IE01 mean = 471.9 median = 524.3	

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

Overall, OC content in **woodland** points was also high (mean = 88.2 g kg⁻¹, median = 37.9 g kg⁻¹). Organic carbon content was higher in north-western climatic zones (boreal, Atlantic, sub-oceanic and northern sub-continent) than in the south-eastern climatic zones (Mediterranean and southern sub-continent) (Table 9, Figure 8). In the north-western climatic zones, OC content ranged from 344.1 g kg⁻¹ (median = 396.0 g kg⁻¹) in NUTS 2 region IE01 in the Atlantic zone to 10.1 g kg⁻¹ (median = 10.1 g kg⁻¹) in PL33 in the northern sub-continent zone (Table 9). In south-eastern zones, OC content ranged from 91.0 g kg⁻¹ (median = 99.6 g kg⁻¹) in NUTS 2 region SI04 in the southern sub-continent zone to 7.3 g kg⁻¹ (median = 6.9 g kg⁻¹) in CY00 in the semi-arid Mediterranean zone (Table 9). The temperate mountainous zone had OC levels similar to the north-western zones (Table 9, Figure 8).

These results of wetland and woodland show that the cooler and more humid conditions in boreal, Atlantic, temperate mountainous and sub-oceanic zones prevent litter decomposition and promote accumulation of OC in soil. It has to be noted that, in general, points from northern boreal zone had lower OC contents than points from southern boreal zone (Figure 8). Possible explanations for these low OC contents include the temperature and moisture conditions, and the quantity and quality of litter (Hanewinkel et al., 2013). Trees growing under colder and drier zones (i.e. northern boreal) tend to produce less litter and poorer in nutrients than those growing in wetter and/or warmer zones (Berg & Meentemeyer, 2002). Similarly, the cold and dry climate in the eastern sub-continent zones limits the production and quality of litter in woodland. In the southern Mediterranean zones, the warmer and drier conditions accelerate organic matter decomposition that explains the lower OC content.

Table 9. Summary of organic carbon in woodland points.

Climatic zone	N points	Mean (g kg ⁻¹)	Median (g kg ⁻¹)	Std dev (g kg ⁻¹)	NUTS 2 with highest OC content (g kg ⁻¹) (1)	NUTS 2 with lowest OC content (g kg ⁻¹) (1)
Boreal to sub-boreal	2040	118.1	38.6	158.6	UKM6 mean = 167.5 median = 104.4	SE33 mean = 89.9 median = 20.4
Atlantic	438	82.3	46.0	100.8	IE01 mean = 344.1 median = 396.0	FR61 mean = 25.3 median = 21.0
Sub-oceanic	848	61.1	45	54.5	BE33 mean = 151.7 median = 176.3	EL64 mean = 22.4 median = 20.6
Sub-continental (northern)	1246	79.7	37.4	113.4	FI1C mean = 224.6 median = 129.9	PL33 mean = 10.1 median = 10.1
Sub-continental (southern)	298	32.5	24.5	28.6	SI04 mean = 91.0 median = 99.6	HU10 mean = 8.9 median = 5.3
Temperate mountainous	874	69.4	46.9	72.1	DE21 mean = 160.4 median = 179.0	BG32 mean = 12.8 median = 16.6
Mediterranean (semi-arid)	438	28.8	20.5	27.5	EL43 mean = 73.7 median = 93.3	CY00 mean = 7.2 median = 6.9
Mediterranean (temperate to sub-oceanic)	391	41.4	32.3	33.2	FR83 mean = 73.9 median = 59.6	PT18 mean = 11.7 median = 9.1

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

Organic carbon content in **grassland** points followed a similar trend to the woodland points (north-western to south-eastern). The mean OC content of grassland points in the EU was 40.0 g kg⁻¹ (median = 27.5 g kg⁻¹), although a large variability of OC content was observed within climatic zones and NUTS 2 regions. The highest OC contents were observed in the Atlantic zone, followed by sub-oceanic zone (Table 10, Figure 9). In these zones, OC content ranged from 168.7 g kg⁻¹ (median = 51.6 g kg⁻¹) in the NUTS 2 region DE93, in the Atlantic zone, to 10.0 g kg⁻¹ (median = 7.4 g kg⁻¹) in EL61, in the sub-oceanic zone (Table 8). The temperate mountainous zone and the northern sub-continental zones had OC levels similar to the Atlantic and sub-oceanic zones (Table 10). Organic carbon content was the lowest in points from Mediterranean and southern sub-continental zones (Table 10, Figure 9). Organic carbon content ranged from 62.0 g kg⁻¹ (median = 62.9 g kg⁻¹) in the NUTS 2 region SI04, in Mediterranean temperate to sub-oceanic zone, to 8.1 g kg⁻¹ (median = 7.2 g kg⁻¹) in EL52, in semi-arid Mediterranean zone (Table 10). The spatial variability of OC in grassland reflects the distribution of various types of grassland and climatic conditions in the EU, ranging from permanent grassland that dominates the north and north-western cool and humid regions to dry and desert-like grassland that predominates in the southern and south-eastern. Steppic/mesic dry grassland dominates the boreal zone.

Table 10. Summary of organic carbon in grassland points.

Climatic zone	N points	Mean (g kg ⁻¹)	median (g kg ⁻¹)	Std dev (g kg ⁻¹)	NUTS 2 with highest OC content (g kg ⁻¹) (1)	NUTS 2 with lowest OC content (g kg ⁻¹) (1)
Boreal to sub-boreal	176	66.4	29.5	98.9	UKM6 mean = 150.3 median = 62.3	SE32 mean = 39.1 median = 31.3
Atlantic	945	58.3	39.0	71.1	DE93 mean = 168.7 median = 51.6	DEA4 mean = 18.9 median = 21.4
Sub-oceanic	1004	43.0	35.1	33.7	FR81 mean = 85.3 median = 61.4	EL61 mean = 10.0 median = 7.4
Sub-continental (northern)	767	40.7	21.4	68.0	DE91 mean = 169.6 median = 44.3	PL32 mean = 13.2 median = 11.9
Sub-continental (southern)	509	24.2	20.1	19.4	HU21 mean = 81.0 median = 88.6	HU23 mean = 12.1 median = 10.8
Temperate mountainous	513	38.7	31.2	35.2	ITH3 mean = 74.8 median = 57.4	EL51 mean = 5.6 median = 6.5
Mediterranean (semi-arid)	531	17.3	13.4	17.9	ES23 mean = 31.6 median = 21.2	EL52 mean = 8.1 median = 7.2
Mediterranean (temperate to sub-oceanic)	300	24.5	17.2	20.2	SI04 mean = 62.0 median = 62.9	ES43 mean = 12.1 median = 11.4

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

Organic carbon content in **cropland** points decreased from north-western to south-eastern, as occurred with woodland and grassland points. Organic carbon content in cropland points was on average 17.6 g kg⁻¹ (median = 14.3 g kg⁻¹). The lowest contents of OC were measured notably in points from the semi-arid Mediterranean and the southern sub-continental zones (Table 11, Figure 10). Organic carbon content ranged from 23.4 g kg⁻¹ (median = 22.2 g kg⁻¹) in NUTS 2 region EL30 to 8.9 g kg⁻¹ (median = 6.6 g kg⁻¹) in PT11 in the semi-arid Mediterranean zone (Table 11). In the southern sub-continental zone, OC content ranged from 21.7 g kg⁻¹ (median = 17.5 g kg⁻¹) in AT11 to 10.8 g kg⁻¹ (median = 9.5 g kg⁻¹) in PL31 (Table 9).

Dry and warm climatic conditions in the semi-arid Mediterranean zone hinder agricultural production (mainly cereal and permanent crops such as vineyards, olive groves and fruits trees) and OC accumulation in this zone. Besides, soils in this climatic zone have, in general, low agricultural potential (e.g. Calcisol, Leptosol, Arenosol) and soil management practices also prevent agricultural production. In the southern sub-continental zone, soils have a larger agricultural potential (e.g. Luvisol) and climatic conditions are more appropriate for agricultural production. However, the intensive management practices of soils in agriculture increase the mineralization of organic matter and, as a result, reduce OC accumulation.

Table 11. Summary of organic carbon in cropland points.

Climatic zone	N points	Mean (g kg ⁻¹)	Median (g kg ⁻¹)	Std dev (g kg ⁻¹)	NUTS 2 with highest OC content (g kg ⁻¹) (1)	NUTS 2 with lowest OC content (g kg ⁻¹) (1)
Boreal to sub-boreal	251	48.1	25.8	71.9	FI1D mean = 110.7 median = 47.3	SE31 mean = 24.2 median = 27.3
Atlantic	1948	18.8	15.3	14.6	IE01 mean = 78.8 median = 28.1	FR81 mean = 6.5 median = 6.3
Sub-oceanic	1123	19.8	16.2	14.7	ITH4 mean = 45.2 median = 31.8	ES23 mean = 11.1 median = 10.5
Sub-continental (northern)	1681	17.1	13.9	19.2	SE11 mean = 78.0 median = 24.8	PL11 mean = 10.3 median = 9.8
Sub-continental (southern)	978	16.7	16.1	7.1	SK04 mean = 17.8 median = 16.3	HU22 mean = 15.0 median = 13.3
Temperate mountainous	207	20.8	16.1	16.7	AT21 mean = 43.7 median = 24.4	EL52 mean = 9.6 median = 8.1
Mediterranean (semi-arid)	2046	12.6	10.8	8.7	EL30 mean = 23.4 median = 22.2	PT11 mean = 8.9 median = 6.6
Mediterranean (temperate to sub-oceanic)	734	16.3	13.0	14.4	ES11 mean = 46.8 median = 33.5	ES21 mean = 6.6 median = 4.2

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

The highest OC contents were observed in points from the Atlantic zone, northern sub-continental, sub-oceanic, temperate mountainous and temperate to sub-oceanic Mediterranean zones (Table 11, Figure 10). The highest and lowest mean OC contents in the Atlantic zone were 78.8 g kg⁻¹ (median = 28.1 g kg⁻¹) in NUTS 2 region IE01 and 6.5 g kg⁻¹ (median = 6.3 g kg⁻¹) in FR81, where root crops are common (Table 11). In points from the northern sub-continental, sub-oceanic and temperate to sub-oceanic Mediterranean zones, largely dedicated to cereal production, OC content ranged from 78.0 g kg⁻¹ (median = 24.8 g kg⁻¹) in the NUTS 2 region SE11, in the northern sub-continental zone, to 6.6 g kg⁻¹ (median = 4.3 g kg⁻¹) in ES21, in the northern temperate to sub-oceanic zone (Table 9). The cooler and more humid conditions in these zones and more adapted soils for agricultural production (e.g. Luvisol, Phaeozem, Cambisol) in the Atlantic, southern sub-continental and sub-oceanic zones can explain the larger accumulation of OC in soil.

Mean OC content was 16.9 g kg^{-1} (median = 11.9 g kg^{-1}) in **barelанд** points and 49.1 g kg^{-1} (median = 29.1 g kg^{-1}) in **shrubland** points (Tables 12 and 13). It has to be noted that a large number of bareland and shrubland points were located in southern countries, especially in Spain. Most of these bareland points were under agricultural use, while shrubland points were in unused and abandoned areas.

Table 12. Summary of organic carbon in bareland points.

Climatic zone	N points	Mean (g kg ⁻¹)	Median (g kg ⁻¹)	Std dev (g kg ⁻¹)	NUTS 2 with highest OC content (g kg ⁻¹) (1)	NUTS 2 with lowest OC content (g kg ⁻¹) (1)
Boreal to sub-boreal	19	56.6	28.9	67.9		
Atlantic	58	26.8	13.8	53.3		
Sub-oceanic	48	20.3	13.8	14.6		
Sub-continental (northern)	63	20.9	13.6	48.9	LT00 mean = 25.5 median = 19.2	PL34 mean = 7.9 median = 7.1
Sub-continental (southern)	22	16.3	16.1	4.6		
Temperate mountainous	9	22.3	12.1	25.7		
Mediterranean (semi-arid)	330	11.4	9.5	8.8	ITF4 mean = 15.6 median = 16.0	ES30 mean = 6.1 median = 5.4
Mediterranean (temperate to sub-oceanic)	54	18.0	15	13.1		

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

Table 13. Summary of organic carbon in shrubland points.

Climatic zone	N points	Mean (g kg ⁻¹)	Median (g kg ⁻¹)	Std dev (g kg ⁻¹)	NUTS 2 with highest OC content (g kg ⁻¹) (1)	NUTS 2 with lowest OC content (g kg ⁻¹) (1)
Boreal to sub-boreal	81	94.9	26.2	140.5	UKM6 mean = 224.5 median = 170.8	SE32 mean = 31.9 median = 23.6
Atlantic	61	113.3	61.2	139.2		
Sub-oceanic	170	50.7	37.3	43.7	ES12 mean = 151.3 median = 143.1	ITG1 mean = 17.9 median = 21.8
Sub-continental (northern)	21	49.3	23.9	59.1		
Sub-continental (southern)	32	24.3	23.4	11.1		
Temperate mountainous	48	57.8	43.5	51.1		
Mediterranean (semi-arid)	263	25.4	20.8	18.7	PT11 mean = 48.7 median = 40.6	EL53 mean = 13.2 median = 12.3
Mediterranean (temperate to sub-oceanic)	169	40.3	31.4	38.6	ES11 mean = 71.9 median = 68.3	ES43 mean = 17.6 median = 12.0

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

Figure 7. Organic carbon content (all points) presented (a) as point data and (b) average aggregated at NUTS 2 level

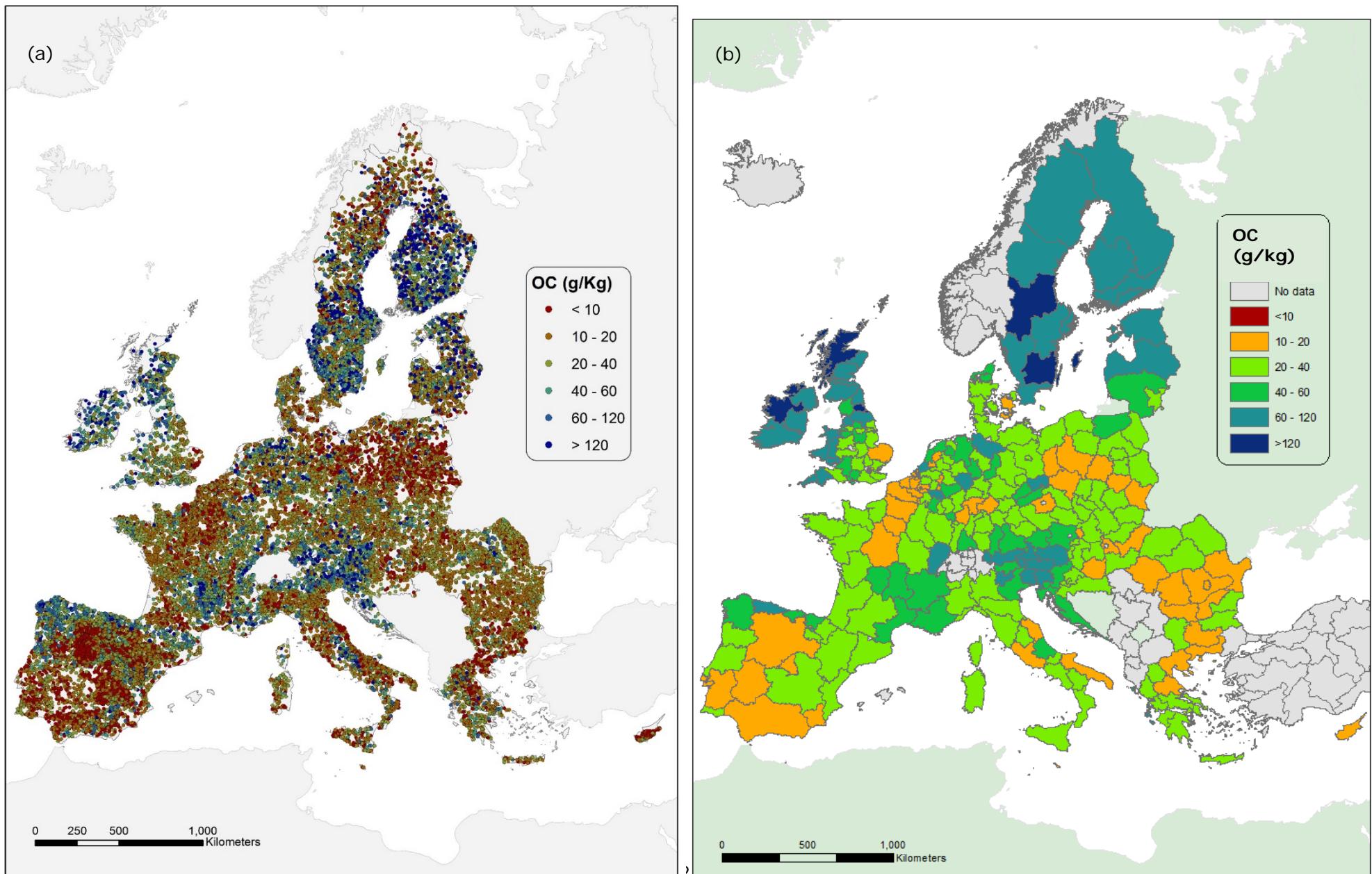


Figure 8. Organic carbon content in woodland: (a) point data and (b) average aggregated at NUTS 2 level

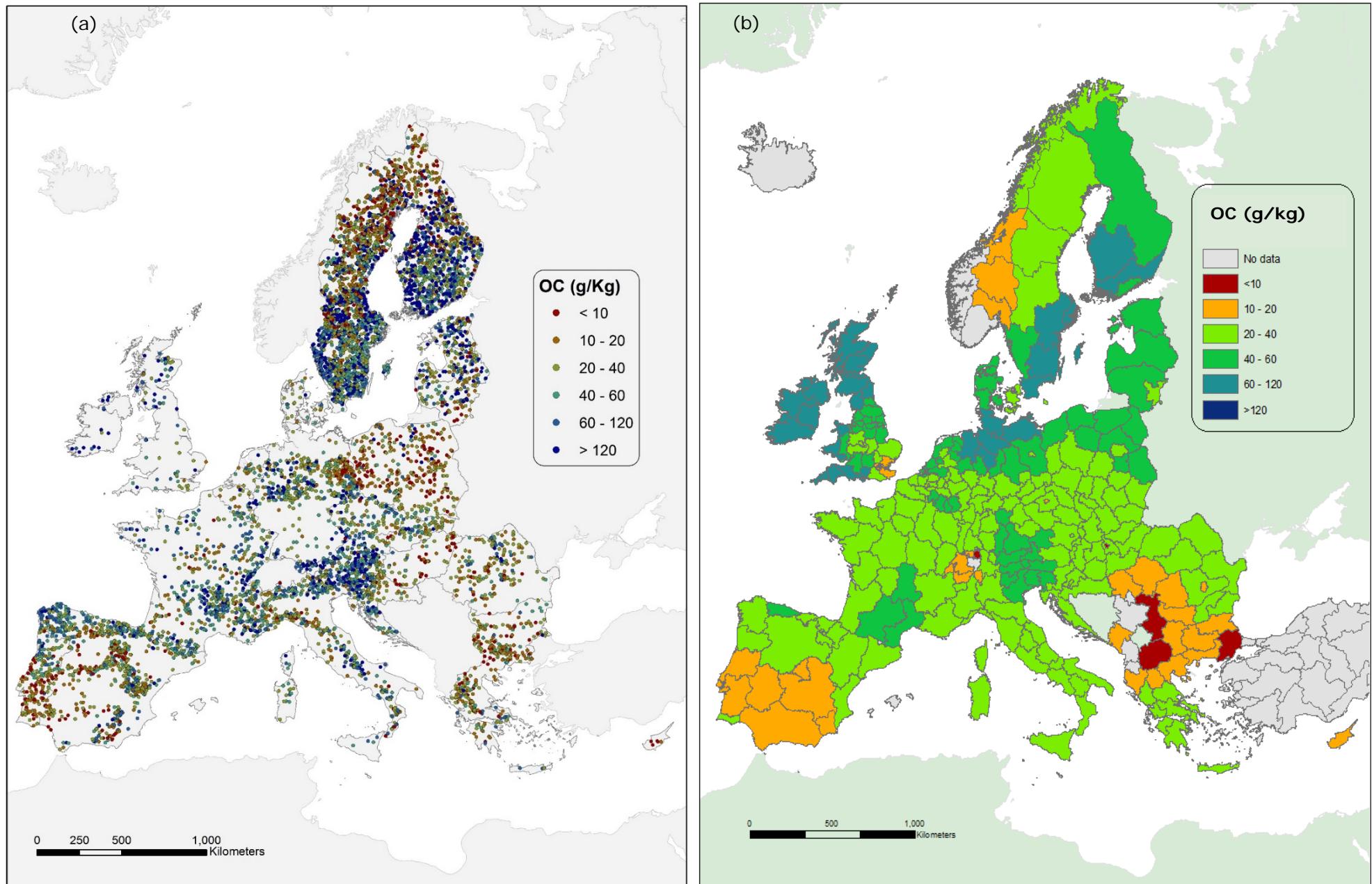


Figure 9. Organic carbon content in grassland: (a) point data and (b) average aggregated at NUTS 2 level

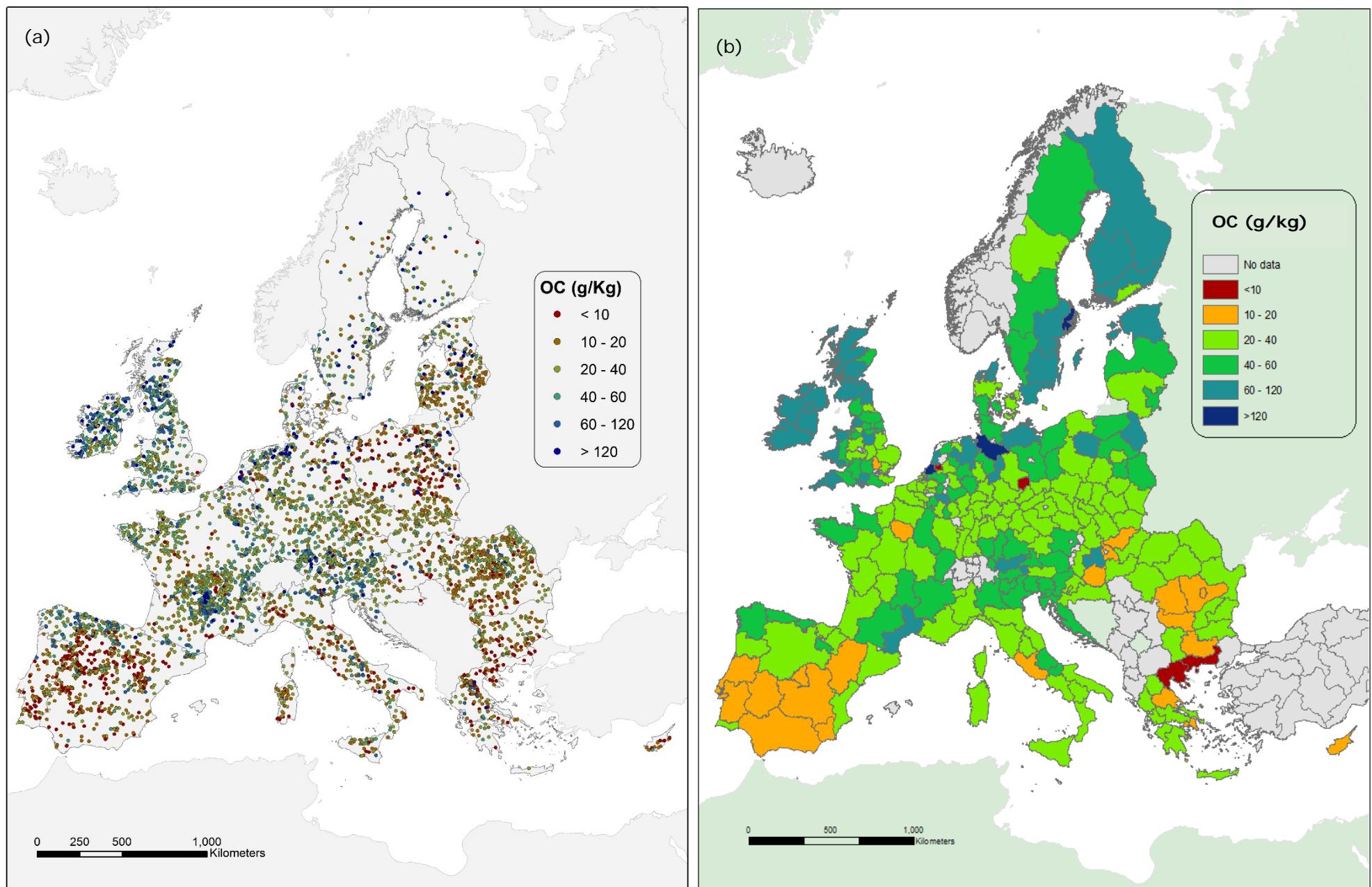


Figure 10. Organic carbon content in cropland: (a) point data and (b) average aggregated at NUTS 2 level

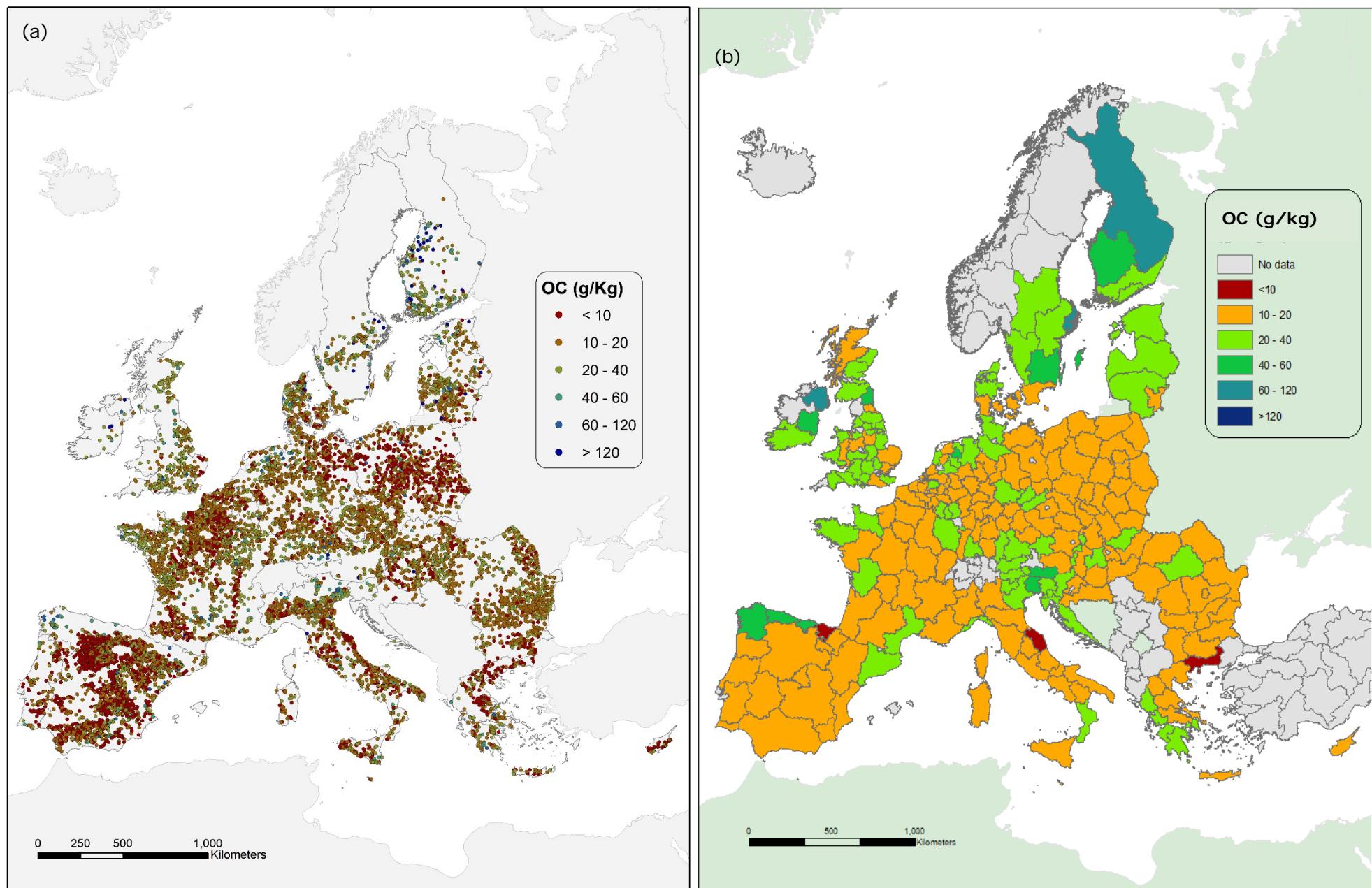
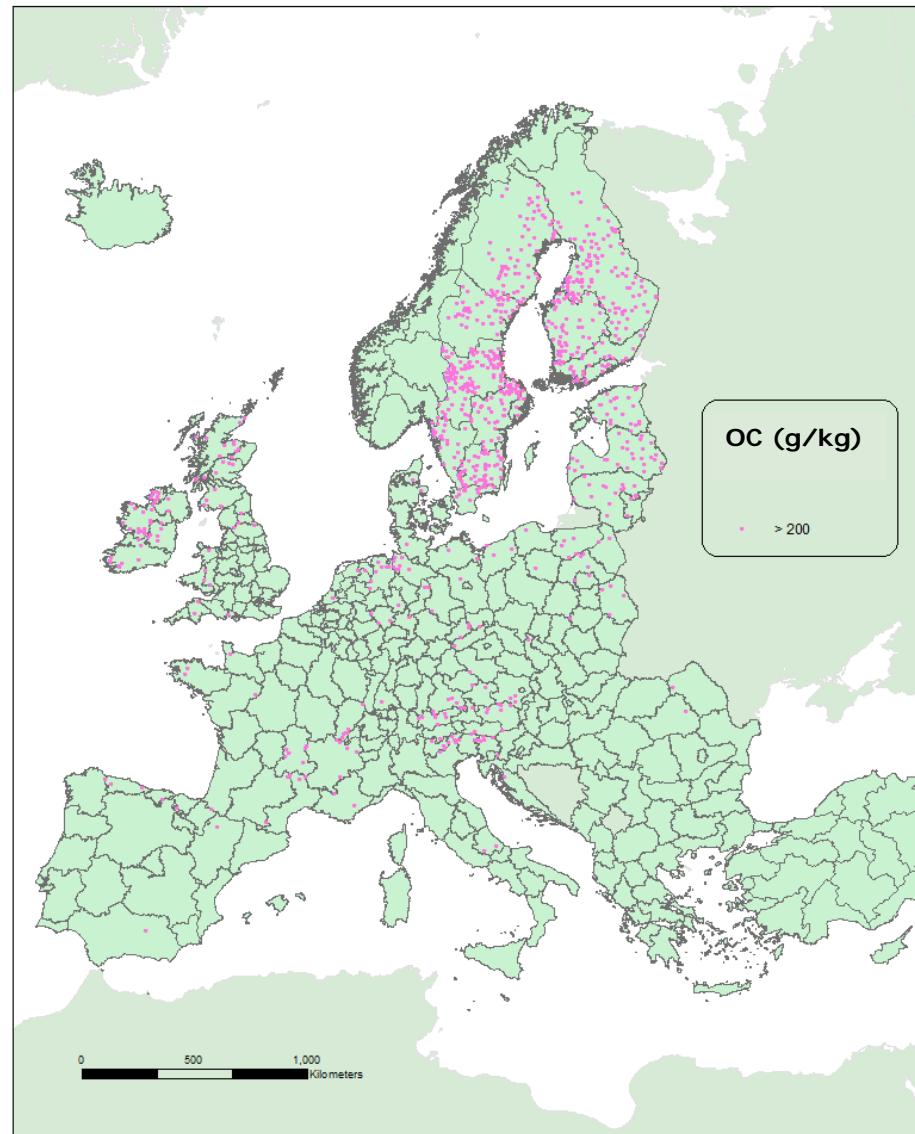


Figure 11. Spatial distribution of organic-rich soils



5.2 Nitrogen, phosphorus, and potassium

Nitrogen content

The spatial distribution of nitrogen (N) (Figure 12) is highly correlated with that OC, given that N is a main component of soil organic matter. Figures 7 and 15 show that many OC-rich soils are also N-rich, at least in terms of absolute quantities, although their C/N ratio can vary. Given this relation, it is clear that LC and climate are the main drivers of the spatial distribution of N as it occurs with that of OC. As observed for OC, (i) N content decrease from north-western to south-eastern climatic zones and (ii) it was lower in cropland (mean = 1.7 g kg⁻¹, median = 1.4 g kg⁻¹) and bareland (mean = 1.3 g kg⁻¹, median = 1.0 g kg⁻¹) than in woodland (mean = 3.2 g kg⁻¹, median = 2.1 g kg⁻¹), grassland (mean = 3.4 g kg⁻¹, median = 2.6 g kg⁻¹) and wetland (mean = 11.2 g kg⁻¹, median = 10.5 g kg⁻¹). Nitrogen content in shrubland was in between cropland and woodland (mean = 2.4 g kg⁻¹, median = 1.7 g kg⁻¹). Lower contents both of OC and N in cropland and bareland than in other LC classes are the result of a reduced storage of organic residues in soil under these LC classes due to vegetation type and management practices.

Woodland, grassland and wetland showed a relatively large proportion of points with high content (>3 g kg⁻¹) in the Atlantic, temperate mountainous and sub-oceanic zones, and in some regions of the boreal and northern sub-continental zones (Figures 13 and 15, Tables 14 to 16). Average N content in woodland was >3 g kg⁻¹ in 65% of NUTS 2 regions in these climatic zones, ranging from 3.0 g kg⁻¹ (median = 2.7 g kg⁻¹) in NL23 region to 16.0 g kg⁻¹ (median = 16.8 g kg⁻¹) in IE01 region both from the Atlantic zone. In grassland, average N content was high in 72% of the NUTS 2 regions, ranging from 3.0 g kg⁻¹ (median = 3.0 g kg⁻¹) in FR62 to 12.9 g kg⁻¹ (median = 12.5 g kg⁻¹) in NL33 both from the Atlantic zone. In wetland, average N content was >3.0 g kg⁻¹ in 81% of the NUTS 2 regions in these climatic zones, ranging from 15.1 g kg⁻¹ (median = 12.4 g kg⁻¹) in SE33 region from boreal zone to 17.8 g kg⁻¹ (median = 17.0 g kg⁻¹) in the IE01 region of the Atlantic zone. These N contents agree 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 from Scandinavia and the mountain areas clearly stand out for their high N content. Climate is also a key factor to explain the accumulation of N under grassland in the Atlantic zone, especially in the United Kingdom and Ireland. The cool and humid conditions in these countries favours organic matter accumulation, which results in high contents of OC and N in topsoil

Table 14. Summary of nitrogen in wetland points.

Climatic zone	N points	Mean (g kg ⁻¹)	Median (g kg ⁻¹)	Std dev (g kg ⁻¹)	NUTS 2 with highest OC content (g kg ⁻¹) (1)	NUTS 2 with lowest OC content (g kg ⁻¹) (1)
Boreal to sub-boreal	18	15.1	13.7	6.7	SE31 mean = 16.4 median = 16.3	SE33 mean = 15.1 median = 12.4
Atlantic	25	13.6	15.7	8.4	IE01 mean = 17.9 median = 17.0	

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

Table 15. Summary of nitrogen in woodland points.

Climatic zone	N points	Mean (g kg ⁻¹)	Median (g kg ⁻¹)	Std dev (g kg ⁻¹)	NUTS 2 with highest OC content (g kg ⁻¹) (1)	NUTS 2 with lowest OC content (g kg ⁻¹) (1)
Boreal to sub-boreal	2040	5.4	2.1	6.9	UKM6 mean = 8.7 median = 6.5	SE33 mean = 4.0 median = 1.1
Atlantic	438	4.9	3.3	4.6	IE01 mean = 16.0 median = 16.8	NL21 mean = 1.8 median = 1.6
Sub-oceanic	848	4.3	3.4	3.1	ITF2 mean = 9.8 median = 8.8	EL53 mean = 1.6 median = 1.0
Sub-continental (northern)	1246	4.2	2.5	4.9	FI1C mean = 10.0 median = 6.6	PL43 mean = 0.9 median = 0.8
Sub-continental (southern)	298	2.7	2.3	1.9	SI04 mean = 6.2 median = 6.7	HU10 mean = 0.9 median = 0.6
Temperate mountainous	874	4.6	3.7	3.7	DE21 mean = 10.2 median = 10.0	BG32 mean = 1.5 median = 1.6
Mediterranean (semi-arid)	438	2.1	1.7	1.5	EL43 mean = 4.9 median = 5.7	CY00 mean = 0.8 median = 0.6
Mediterranean (temperate to sub-oceanic)	391	2.9	2.5	1.9	ES11 mean = 4.6 median = 4.2	PT18 mean = 0.9 median = 0.8

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

Table 16. Summary of nitrogen in grassland points.

Climatic zone	N points	Mean (g kg ⁻¹)	Median (g kg ⁻¹)	Std dev (g kg ⁻¹)	NUTS 2 with highest OC content (g kg ⁻¹) (1)	NUTS 2 with lowest OC content (g kg ⁻¹) (1)
Boreal to sub-boreal	176	4.5	2.4	5.7	UKM6 mean = 9.6 median = 5.4	SE33 mean = 2.3 median = 1.8
Atlantic	945	5.2	4.1	4.1	NL33 mean = 12.8 median = 12.5	DEA4 mean = 2.1 median = 2.2
Sub-oceanic	1004	4.4	3.8	2.9	BE33 mean = 7.4 median = 6.3	EL61 mean = 1.0 median = 1.0
Sub-continental (northern)	767	3.6	2.2	5.1	SE11 mean = 9.2 median = 9.5	PL32 mean = 1.3 median = 1.2
Sub-continental (southern)	509	2.5	2.2	1.6	HU21 mean = 8.5 median = 9	BG42 mean = 1.4 median = 1.3
Temperate mountainous	513	3.9	3.3	2.8	ES22 mean = 7.1 median = 3.6	EL51 mean = 0.8 median = 0.9
Mediterranean (semi-arid)	531	1.8	1.4	1.4	EL64 mean = 3.2 median = 2.0	PT16 mean = 1.0 median = 0.9
Mediterranean (temperate to sub-oceanic)	300	2.3	1.8	1.7	SI04 mean = 5.9 median = 6	ITI3 mean = 1.4 median = 1.2

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

Nitrogen content in **cropland** was especially low in the northern sub-continental and Mediterranean zones (Figure 14, Table 17). Eighty-eight percent of NUTS 2 regions in these zones had N contents <3 g kg⁻¹, ranging from 0.7 g kg⁻¹ (median 0.8 g kg⁻¹) in the NUTS 2 region ES62 of the temperate Mediterranean zone to 2.7 (median 2.3) in the NUTS 2 region ES51 of the semi-arid Mediterranean zone. The N map produced by Ballabio et al. (2019) showed also low N contents in these zones. In the Mediterranean zones, the warm and/or dry conditions accelerate organic matter decomposition, which can explain the lower N content compared to other cropland areas in the EU. Soil texture also plays a role in preserving organic matter and, thus, OC and N. Areas with coarser soils, such as most of cropland in the northern sub-continental Poland, tend to have less N even if other factors are favourable (e.g. climate). It must be noted that different fertilization practices at regional and national scale can influence the spatial distribution of N in soils under cropland.

In **shrubland**, points with high N content (>3 g kg⁻¹) were distributed across all climatic zones (Table 19). Some **bareland** points (approximately 5% of the points) also presented high N contents (Table 18). The atmospheric deposition of N could explain these high contents of N in shrubland and bareland, that generally are not subject to fertilization (Erisman & de Vries, 2000, Stevens et al., 2010).

Table 17. Summary of nitrogen in cropland points.

Climatic zone	N points	Mean (g kg ⁻¹)	Median (g kg ⁻¹)	Std dev (g kg ⁻¹)	NUTS 2 with highest OC content (g kg ⁻¹) (1)	NUTS 2 with lowest OC content (g kg ⁻¹) (1)
Boreal to sub-boreal	251	3.4	2.3	3.6	FI1D mean = 6.2 median = 3.3	LV00 mean = 2.2 median = 1.6
Atlantic	1948	2.1	1.8	1.2	IE01 mean = 7.8 median = 3.5	FR81 mean = 1.1 median = 1.1
Sub-oceanic	1123	0.2	1.9	1.1	BE34 mean = 3.4 median = 3.7	ES23 mean = 1.1 median = 0.9
Sub-continental (northern)	1681	1.8	1.5	1.4	SE11 mean = 4.6 median = 2.6	PL11 mean = 1.1 median = 1.1
Sub-continental (southern)	978	1.8	1.8	0.7	RO12 mean = 2.4 median = 2.4	BG42 mean = 1.3 median = 1.2
Temperate mountainous	207	2.2	1.9	1.5	AT21 mean = 4.1 median = 2.5	EL52 mean = 1.1 median = 1.0
Mediterranean (semi-arid)	2046	1.3	1.2	0.7	ES51 mean = 2.7 median = 2.3	ES43 mean = 1.0 median = 0.9
Mediterranean (temperate to sub-oceanic)	734	1.6	1.4	1.1	ES11 mean = 3.6 median = 3.1	ES62 mean = 0.7 median = 0.7

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

Table 18. Summary of nitrogen in bareland points

Climatic zone	N points	Mean (g kg ⁻¹)	Median (g kg ⁻¹)	Std dev (g kg ⁻¹)	NUTS 2 with highest OC content (g kg ⁻¹) (1)	NUTS 2 with lowest OC content (g kg ⁻¹) (1)
Boreal to sub-boreal	19	3.1	1.9	2.9		
Atlantic	58	2.5	1.8	2.9		
Sub-oceanic	48	2.0	1.6	1.2		
Sub-continental (northern)	63	1.8	1.5	2.1	DE00 mean = 2.3 median = 2.3	PL37 mean = 0.9 median = 0.9
Sub-continental (southern)	22	1.8	1.8	0.4		
Temperate mountainous	9	1.7	1.5	1.4		
Mediterranean (semi-arid)	330	1.1	1.0	0.6	EL63 mean = 1.8 median = 0.9	ES30 mean = 0.68 median = 0.6
Mediterranean (temperate to sub-oceanic)	54	1.6	1.3	0.7		

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

Table 19. Summary of nitrogen in shrubland points.

Climatic zone	N points	Mean (g kg ⁻¹)	Median (g kg ⁻¹)	Std dev (g kg ⁻¹)	NUTS 2 with highest OC content (g kg ⁻¹) (1)	NUTS 2 with lowest OC content (g kg ⁻¹) (1)
Boreal to sub-boreal	81	3.9	1.3	4.9	UKM6 mean = 8.8 median = 8.7	SE32 mean = 1.5 median = 0.9
Atlantic	61	6.7	4.9	6.2	ES12 mean = 10.7 median = 10.2	ITG1 mean = 1.8 median = 2.2
Sub-oceanic	170	4.1	3.2	3.2		
Sub-continental (northern)	21	3.9	2.4	4.1		
Sub-continental (southern)	32	2.6	2.6	1.1		
Temperate mountainous	48	4.7	3.4	3.5		
Mediterranean (semi-arid)	263	2.2	1.9	1.4	EL30 mean = 4.0 median = 4.2	EL53 mean = 1.5 median = 1.1
Mediterranean (temperate to sub-oceanic)	169	3.1	2.6	2.4	ES11 mean = 4.3 median = 4.3	PT16 mean = 1.8 median = 1.3

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

Figure 12. Nitrogen content (all points) presented (a) as point data and (b) average aggregated at NUTS 2 level

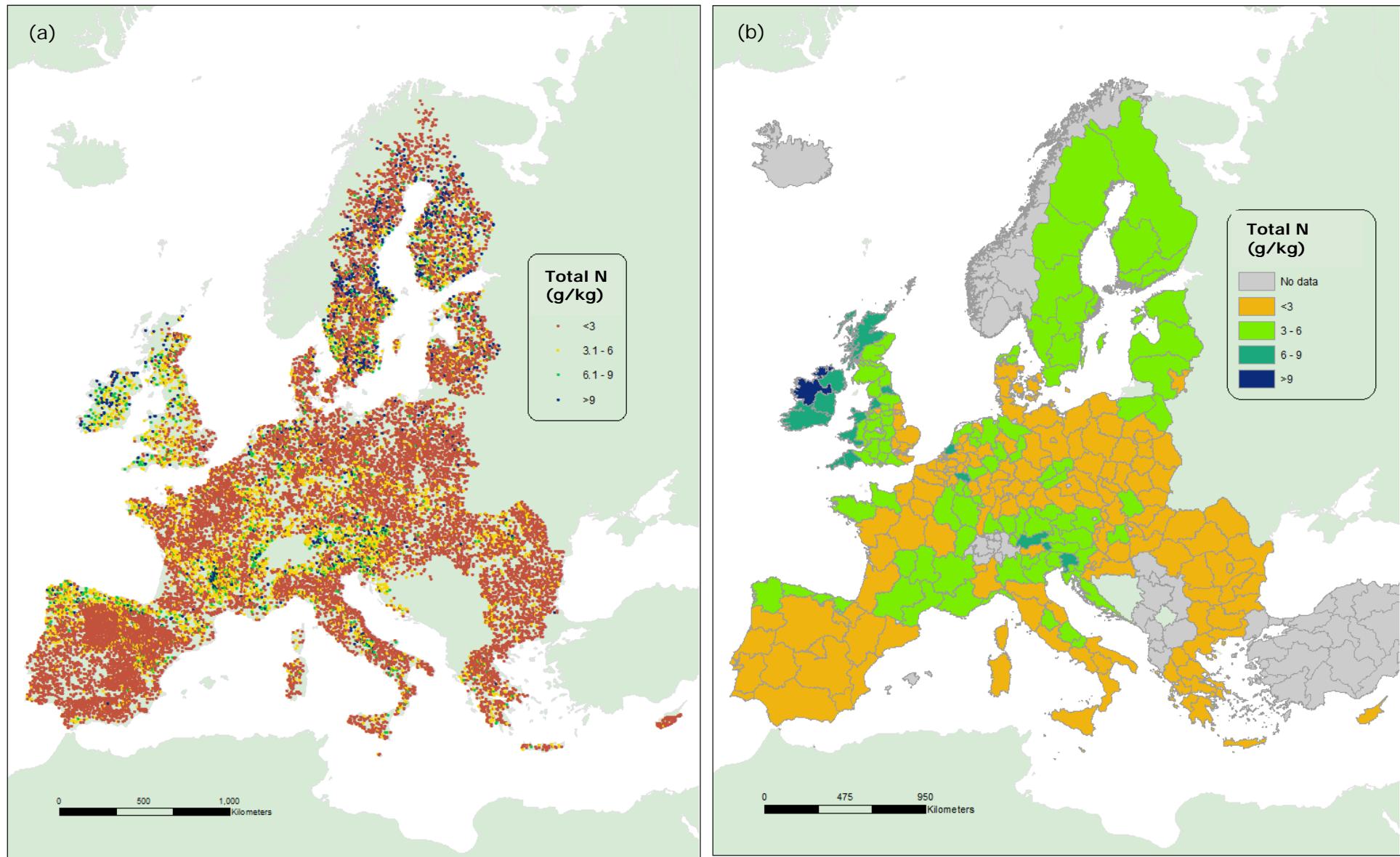


Figure 13. Nitrogen content in woodland: (a) point data and (b) average aggregated at NUTS 2 level

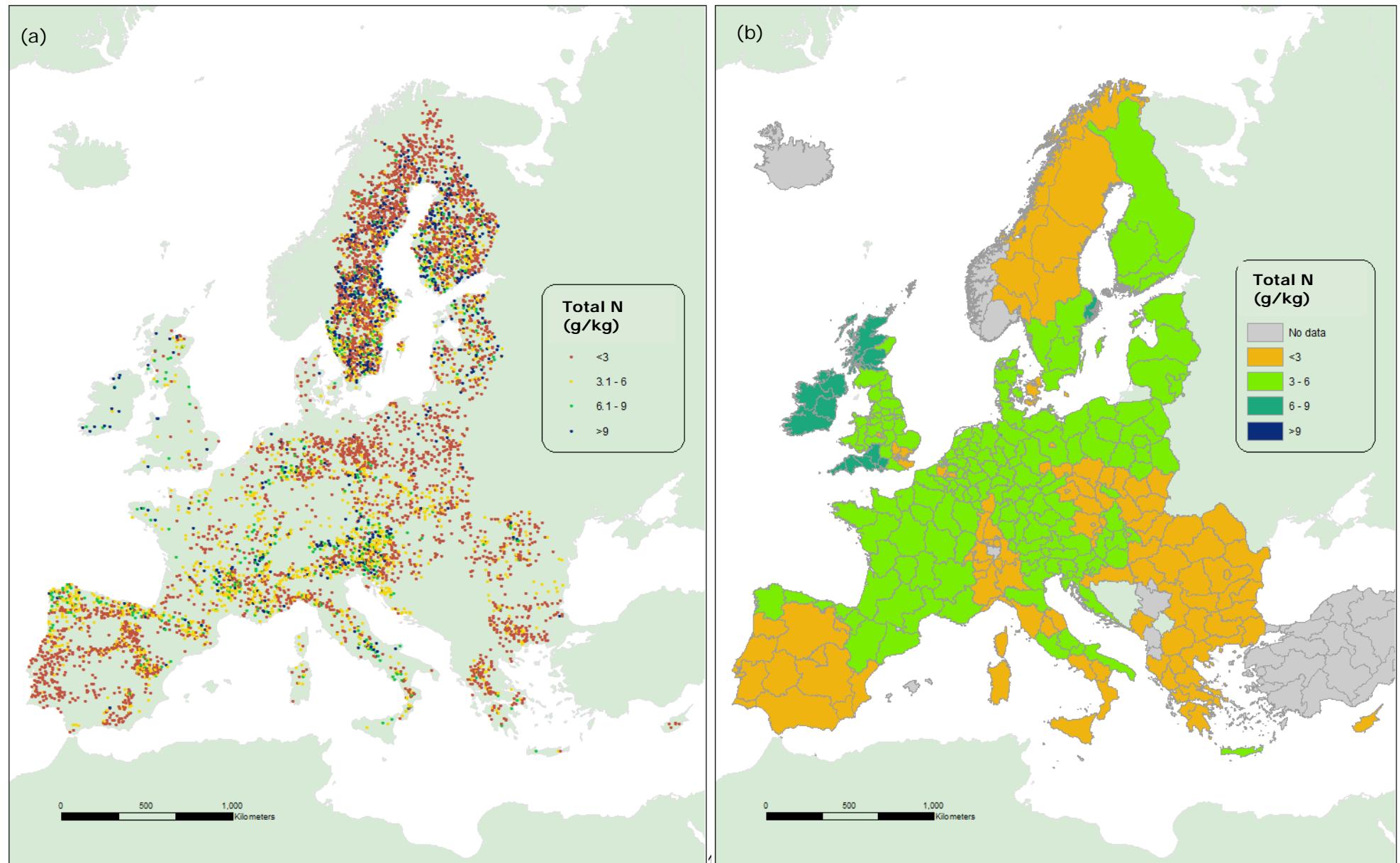


Figure 14. Nitrogen content in cropland: (a) point data and (b) average aggregated at NUTS 2 level

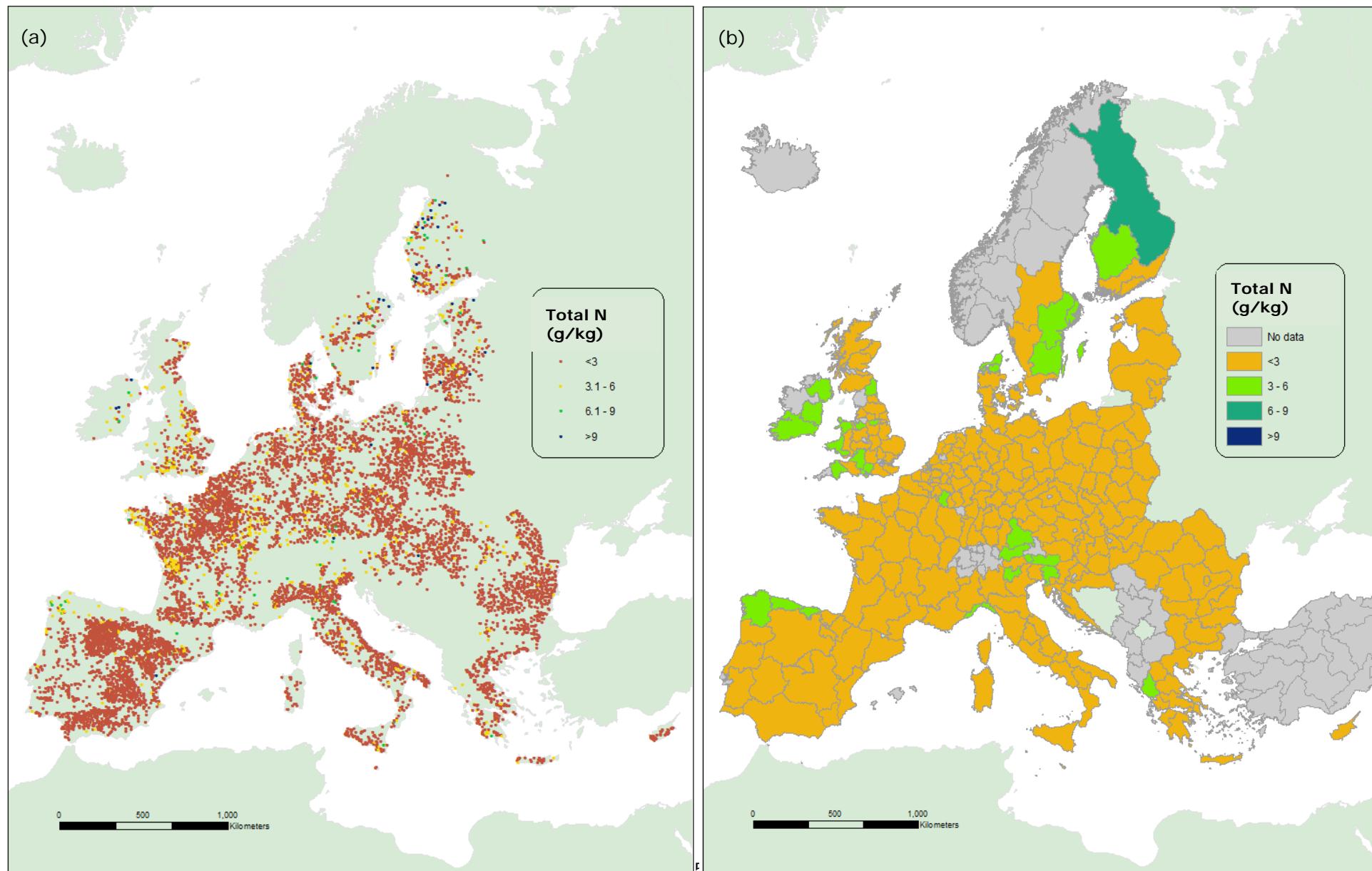
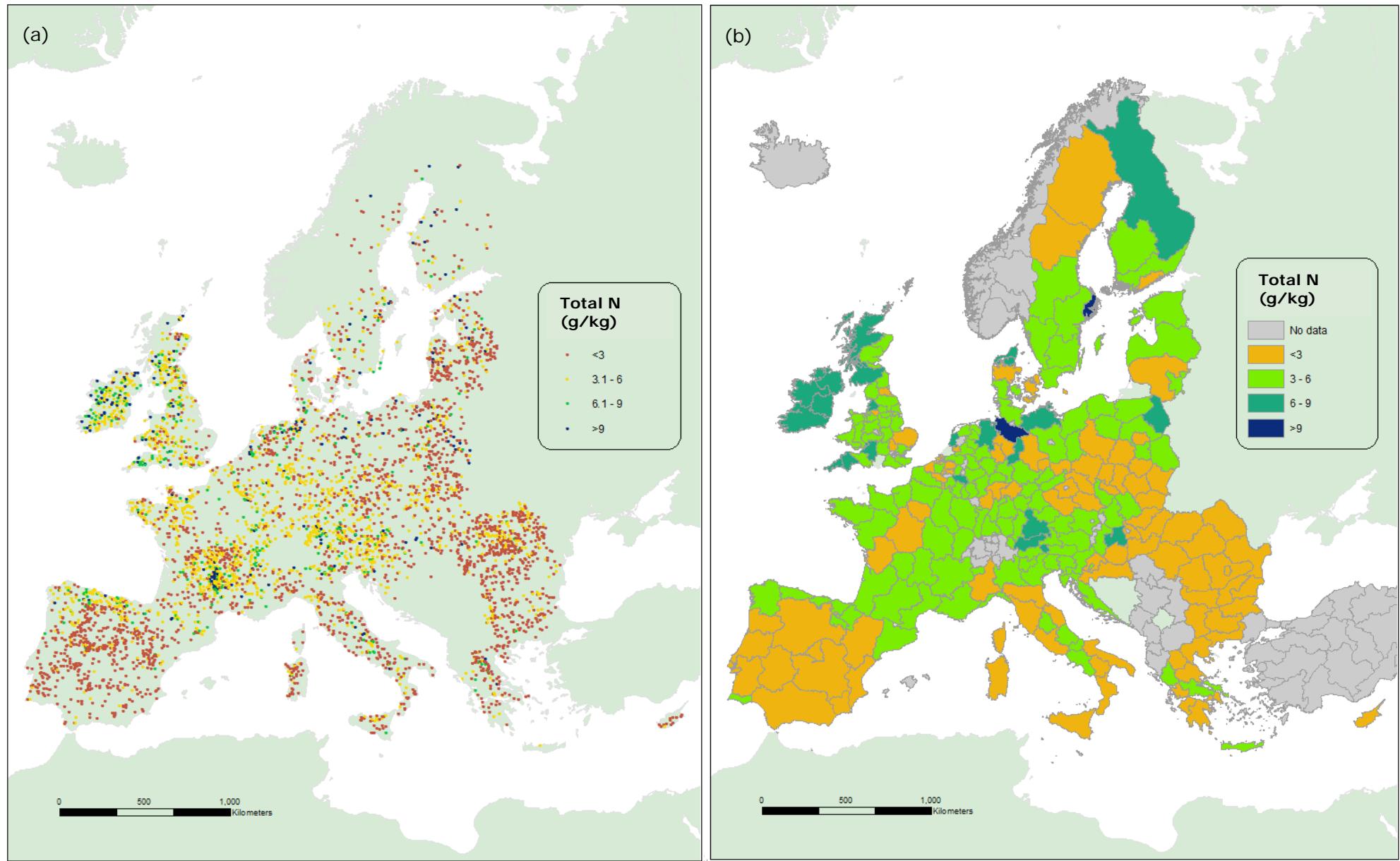


Figure 15. Nitrogen content in grassland: (a) point data and (b) average aggregated at NUTS 2 level



Phosphorus content

The map with all point data (Figure 16) shows that phosphorus (P) content was highest in the Atlantic, sub-oceanic and northern sub-continental zones, and lowest in the Mediterranean and southern sub-continental zones. This spatial distribution of P is clearly influenced by land cover, with higher contents of P in cropland soils than in grassland and woodland soils (Figures 17, 18 and 19).

Overall, 79% of **woodland** points had low P contents ($<40 \text{ mg kg}^{-1}$) and only 5% of the points fell in the highest category of $>80 \text{ mg kg}^{-1}$. The average P content in the various climatic zones ranged from 35.3 mg kg^{-1} in the northern sub-continental zone to 9.0 mg kg^{-1} in the semi-arid Mediterranean zone, showing a north-southern decreasing trend (Table 20, Figure 17). Moreover, the median values ranged from 27.5 mg kg^{-1} to 6.4 mg kg^{-1} in the climatic zones, which means that more than 50% of the points at each zone had low P contents (Table 20). A similar situation was observed in **shrubland**, with 89% of the points with low contents of P and only 2.5% of the points in the highest category of P content, and **bareland**, with 76% of the points in the lowest P categories and 4% in the highest category (see Tables 21 and 22 for summary statistics). Woodland, shrubland and bareland are not normally subjected to fertilization practices, which explains the low content of P in these LC classes.

On the contrary, higher contents of P in **cropland** points (Figure 18) are indicative of fertilization. P content in cropland decreased from northern to southern zones, ranging from 52.7 mg kg^{-1} (median = 45.3 mg kg^{-1}) in the Atlantic zone to 25.8 mg kg^{-1} (median = 18.8 mg kg^{-1}) and 25.7 mg kg^{-1} (median 18.8 mg kg^{-1}) in the southern sub-continental and semi-arid Mediterranean zones, respectively (Table 23). This trend of P content is likely due to greater fertilization rates in wetter climates than in drier climates because P availability and movements are reduced in cool and wet soils. The NUTS 2 regions with the highest P contents ($>80 \text{ mg kg}^{-1}$) were in The Netherlands (mean = 123.8 mg kg^{-1} , median = 119.7 mg kg^{-1} in NL13), Belgium (mean = 107.5 mg kg^{-1} , median = 106.0 mg kg^{-1} in BE21) and in Germany (mean 117.7 mg kg^{-1} , median = 118.8 mg kg^{-1} in DE94). In the Po Valley in Italy, dedicated mainly to agriculture, the proportion of points with high contents of P ($<40 \text{ mg kg}^{-1}$) was also considerable/notable: 30% of the points had high P contents compared to the 20% at national level. This observation agrees with the estimations produced by Ballabio et al. (2019) for the Po Valley based on LUCAS 2009/2012 data.

Grassland points had P contents similar to those observed in cropland. P content in grassland ranged from 55.7 mg kg^{-1} (median = 44.1 mg kg^{-1}) in the Atlantic zone to 19.3 mg kg^{-1} (median = 10.3 mg kg^{-1}) and 18.5 mg kg^{-1} (median = 10.5 mg kg^{-1}) in the southern sub-continental and semi-arid Mediterranean zones (Table 24, Figure 19). These high P contents can be an indicator of fertilization in manged grassland, with higher application rates in northern wet zones as explained for cropland. In the case of naturally acidic grassland, P content can be linked to the high OC contents because soil organic matter provides an important source of P and can maintain P availability.

Phosphorus content in **wetland** was also relatively high: 55.9 mg kg^{-1} (median = 42.6 mg kg^{-1}) in the boreal zone and 41.8 mg kg^{-1} (median = 28.2 mg kg^{-1}) in the Atlantic zone (Table 25). Wetland soils have an inherent ability to store nutrients such as P. In many cases, P is stored in organic forms due to high content of organic matter, poorly decomposed, and low mineral fraction.

Overall, the trends observed for P under different LC classes in LUCAS 2015 confirms the estimates produced for their P map by Ballabio et al. (2019).

Table 20. Summary of phosphorus in woodland points.

Climatic zone	N points	Mean (mg kg ⁻¹)	Median (mg kg ⁻¹)	Std dev (mg kg ⁻¹)	NUTS 2 with highest OC content (mg kg ⁻¹) (1)	NUTS 2 with lowest OC content (mg kg ⁻¹) (1)
Boreal to sub-boreal	2040	33.5	25.0	33.1	UKM6 mean = 61.5 median = 32.1	LV00 mean = 25.5 median = 22.2
Atlantic	438	34.7	24.0	37.9	IE01 mean = 88.3 median = 33.9	FR26 mean = 4.8 median = 6.0
Sub-oceanic	848	21.7	15.6	22.9	DE14 mean = 62.22 median = 20.2	EL53 mean = 0.8 median = 0.0
Sub-continental (northern)	1246	35.3	27.5	28.2	AT31 mean = 94.1 median = 68.3	CZ02 mean = 21.3 median = 20.1
Sub-continental (southern)	298	17.3	11.8	24.8	HU31 mean = 39.9 median = 41.6	BG42 mean = 7.7 median = 7.2
Temperate mountainous	874	18.9	12.1	23.3	PL21 mean = 21.3 median = 20.9	ES24 mean = 3.2 median = 0.0
Mediterranean (semi-arid)	438	9.0	6.4	13.4	EL65 mean = 21.8 median = 14.2	CY00 mean = 1.9 median = 0.0
Mediterranean (temperate to sub-oceanic)	391	12.5	7.3	18.7	ES11 mean = 35.2 median = 17.6	HR03 mean = 2.3 median = 0.0

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

Table 21. Summary of phosphorus in shrubland points.

Climatic zone	N points	Mean (mg kg ⁻¹)	Median (mg kg ⁻¹)	Std dev (mg kg ⁻¹)	NUTS 2 with highest OC content (mg kg ⁻¹) (1)	NUTS 2 with lowest OC content (mg kg ⁻¹) (1)
Boreal to sub-boreal	81	30.4	23.0	24.2	SE31 mean = 38.1 median = 34.1	SE32 mean = 15.5 median = 17.9
Atlantic	61	35.9	24.9	33.5		
Sub-oceanic	170	16.8	11.1	17.2	FR26 mean = 31.5 median = 25.5	EL64 mean = 2.1 median = 0.0
Sub-continental (northern)	21	34.7	31.5	26.3		
Sub-continental (southern)	32	16.4	8.9	21.5		
Temperate mountainous	48	13.1	8.7	14.8		
Mediterranean (semi-arid)	263	6.7	5.4	10.6	ES43 mean = 25.9 median = 10.0	CY00 mean = 1.0 median = 0.0
Mediterranean (temperate to sub-oceanic)	169	12.3	7.9	15.9	ITG2 mean = 31.2 median = 8.1	FR82 mean = 4.2 median = 3.5

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

Table 22. Summary of phosphorus in bareland points.

Climatic zone	N points	Mean (mg kg ⁻¹)	Median (mg kg ⁻¹)	Std dev (mg kg ⁻¹)	NUTS 2 with highest OC content (mg kg ⁻¹) (1)	NUTS 2 with lowest OC content (mg kg ⁻¹) (1)
Boreal to sub-boreal	19	39.1	31.9	28.3		
Atlantic	58	42.8	34.9	35.2		
Sub-oceanic	48	29.5	18.8	27.2		
Sub-continental (northern)	63	40.3	36.2	29.1	PL41 mean = 58.3 median = 53.1	RO22 mean = 9.2 median = 1.5
Sub-continental (southern)	22	25.0	22.5	16.3		
Temperate mountainous	9	23.8	26	15.0		
Mediterranean (semi-arid)	330	20.5	14.5	19.1	EL63 mean = 55.2 median = 59.7	ITF6 mean = 12.5 median = 8.8
Mediterranean (temperate to sub-oceanic)	54	24.6	15.7	34.5		

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

Table 23. Summary of phosphorus in cropland points.

Climatic zone	N points	Mean (mg kg ⁻¹)	Median (mg kg ⁻¹)	Std dev (mg kg ⁻¹)	NUTS 2 with highest OC content (mg kg ⁻¹) (1)	NUTS 2 with lowest OC content (mg kg ⁻¹) (1)
Boreal to sub-boreal	251	45.3	39.8	28.1	FI19 mean = 55.6 median = 49.6	SE31 mean = 22.3 median = 22.9
Atlantic	1948	52.7	45.3	34.2	NL13 mean = 123.8 median = 119.7	SE23 mean = 20.6 median = 18.1
Sub-oceanic	1123	41.8	35.7	29.3	DEA2 mean = 83.7 median = 60.6	ES61 mean = 7.8 median = 5.9
Sub-continental (northern)	1681	45.2	40.5	29.9	DE23 mean = 73.7 median = 70.7	RO22 mean = 11.6 median = 8.6
Sub-continental (southern)	978	25.7	18.8	25.5	HR04 mean = 53.6 median = 43.5	RO22 mean = 13.6 median = 10.9
Temperate mountainous	207	32.4	26.4	25.5	ITH4 mean = 83.4 median = 37.8	FR71 mean = 11.46 median = 9.5
Mediterranean (semi-arid)	2046	25.8	18.8	27.1	ES51 mean = 67.4 median = 44.5	EL63 mean = 9.6 median = 8.4
Mediterranean (temperate to sub-oceanic)	734	29.4	20	34.8	ITF3 mean = 69.6 median = 51.8	ITF4 mean = 9.38 median = 7.1

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

Table 24. Summary of phosphorus in grassland points.

Climatic zone	N points	Mean (mg kg ⁻¹)	Median (mg kg ⁻¹)	Std dev (mg kg ⁻¹)	NUTS 2 with highest OC content (mg kg ⁻¹) (1)	NUTS 2 with lowest OC content (mg kg ⁻¹) (1)
Boreal to sub-boreal	176	35.0	28.0	28.9	FI19 mean = 55.8 median = 54.2	SE32 mean = 18.8 median = 11.1
Atlantic	945	55.7	44.1	39.2	UKD4 mean = 106.2 median = 96.5	SE23 mean = 21.7 median = 21.6
Sub-oceanic	1004	33.9	26.4	29.9	LU00 mean = 71.6 median = 68.9	ES62 mean = 4.7 median = 4.8
Sub-continent (northern)	767	39.4	31.9	32.5	SE11 mean = 71.4 median = 26.7	RO22 mean = 17.3 median = 9.1
Sub-continent (southern)	509	18.5	10.5	30.4	AT12 mean = 32.8 median = 18.2	RO12 mean = 8.8 median = 6.7
Temperate mountainous	513	20.6	13.8	20.9	ITC1 mean = 40.3 median = 23.0	HR03 mean = 2.7 median = 0.0
Mediterranean (semi-arid)	531	19.3	10.3	51.2	EL64 mean = 80.2 median = 9.3	EL63 mean = 7.1 median = 8.1
Mediterranean (temperate to sub-oceanic)	300	20.1	12.5	20.4	PT11 mean = 44.9 median = 32.1	ITF4 mean = 7.9 median = 7.7

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

Table 25. Summary of phosphorus in wetland points.

Climatic zone	N points	Mean (mg kg ⁻¹)	Median (mg kg ⁻¹)	Std dev (mg kg ⁻¹)	NUTS 2 with highest OC content (mg kg ⁻¹) (1)	NUTS 2 with lowest OC content (mg kg ⁻¹) (1)
Boreal to sub-boreal	18	55.9	42.6	43.2	SE31 mean = 42.1 median = 41.7	SE33 mean = 39.2 median = 41.3
Atlantic	25	41.8	28.2	36.1	IE01 mean = 31.8 median = 26.6	

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

Figure 16. Phosphorus content (all points) presented (a) as point data and (b) average aggregated at NUTS 2 level

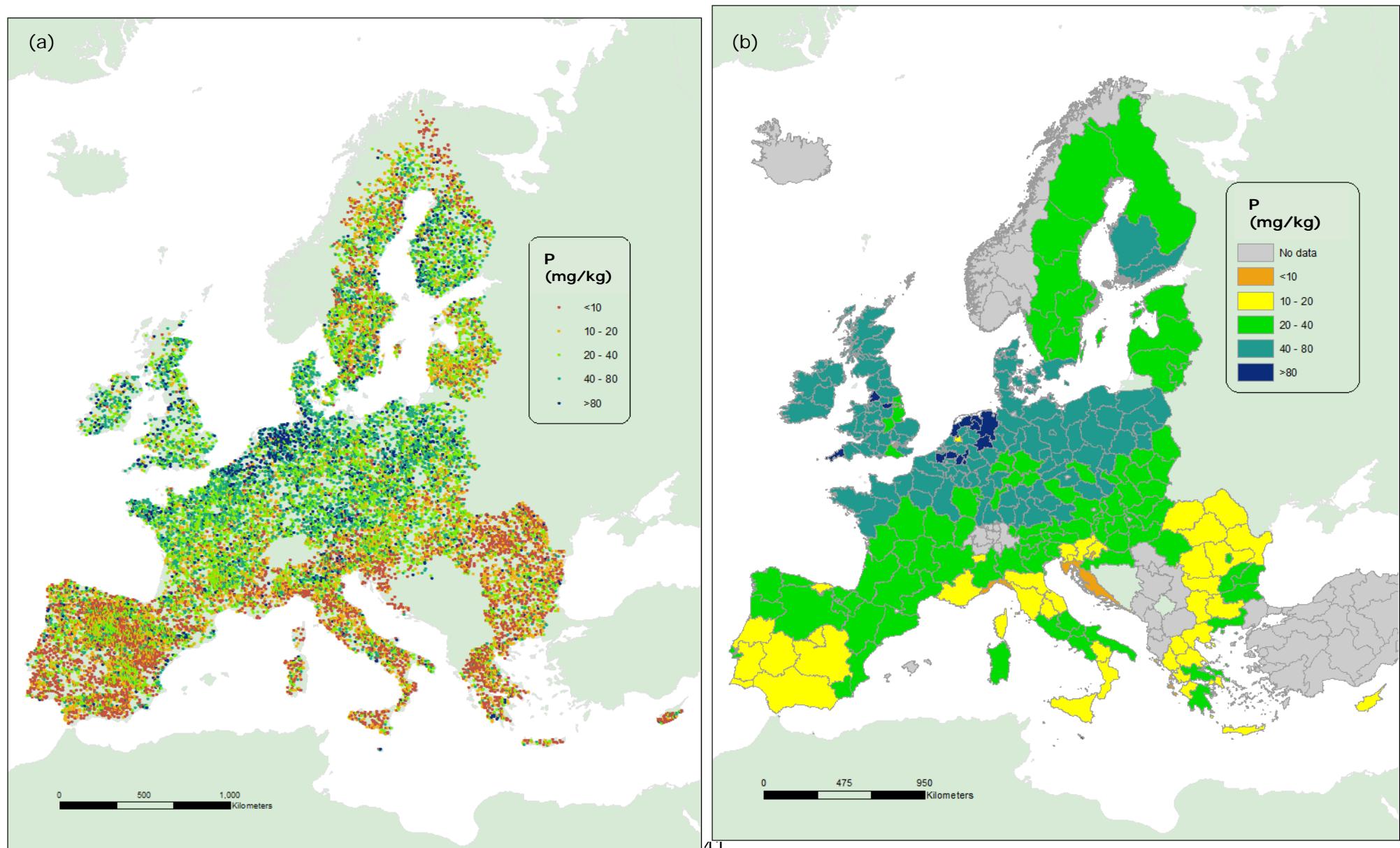


Figure 17. Phosphorus content in woodland: (a) point data and (b) average aggregated at NUTS 2 level

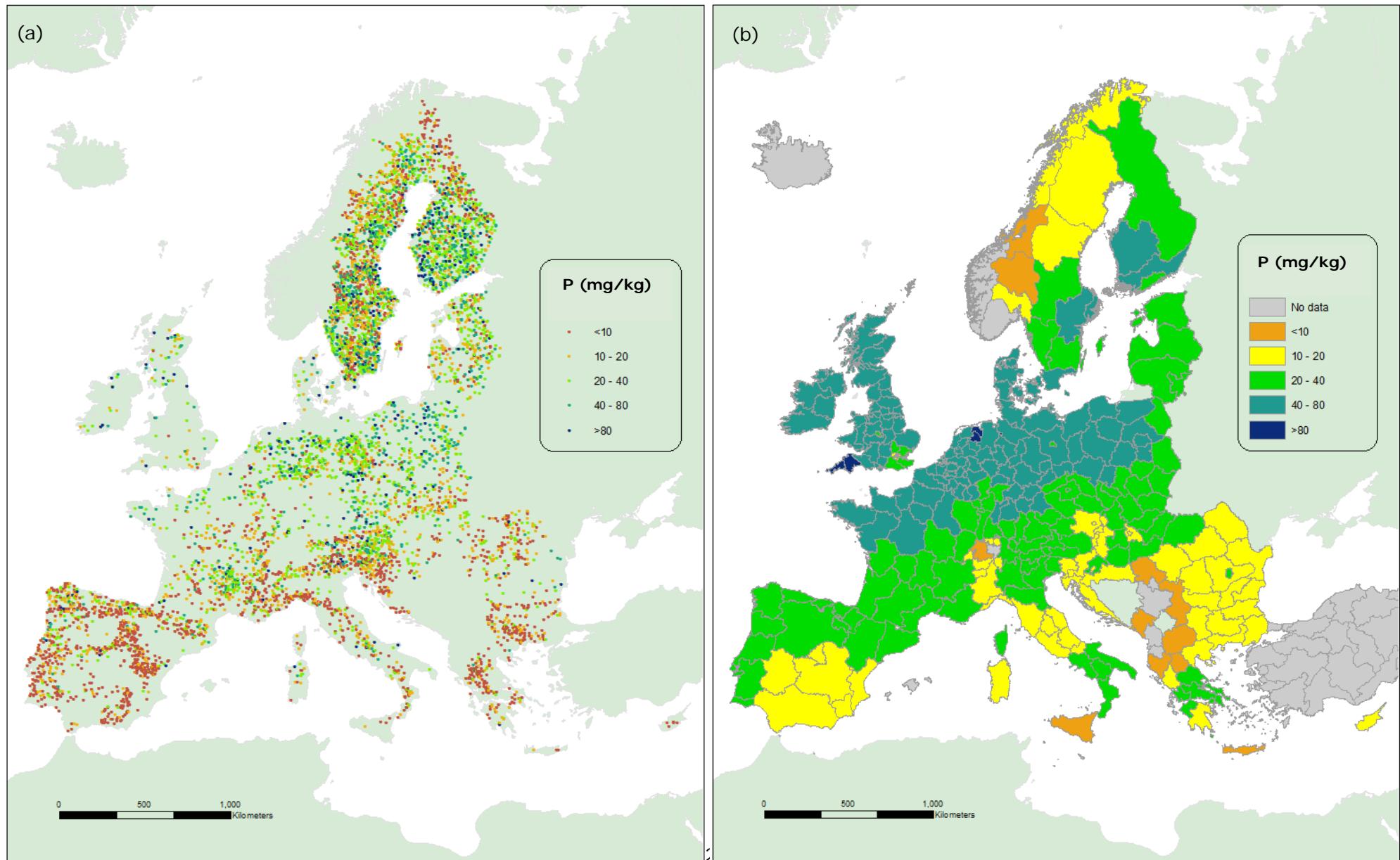


Figure 18. Phosphorus content in cropland: (a) point data and (b) average aggregated at NUTS 2 level

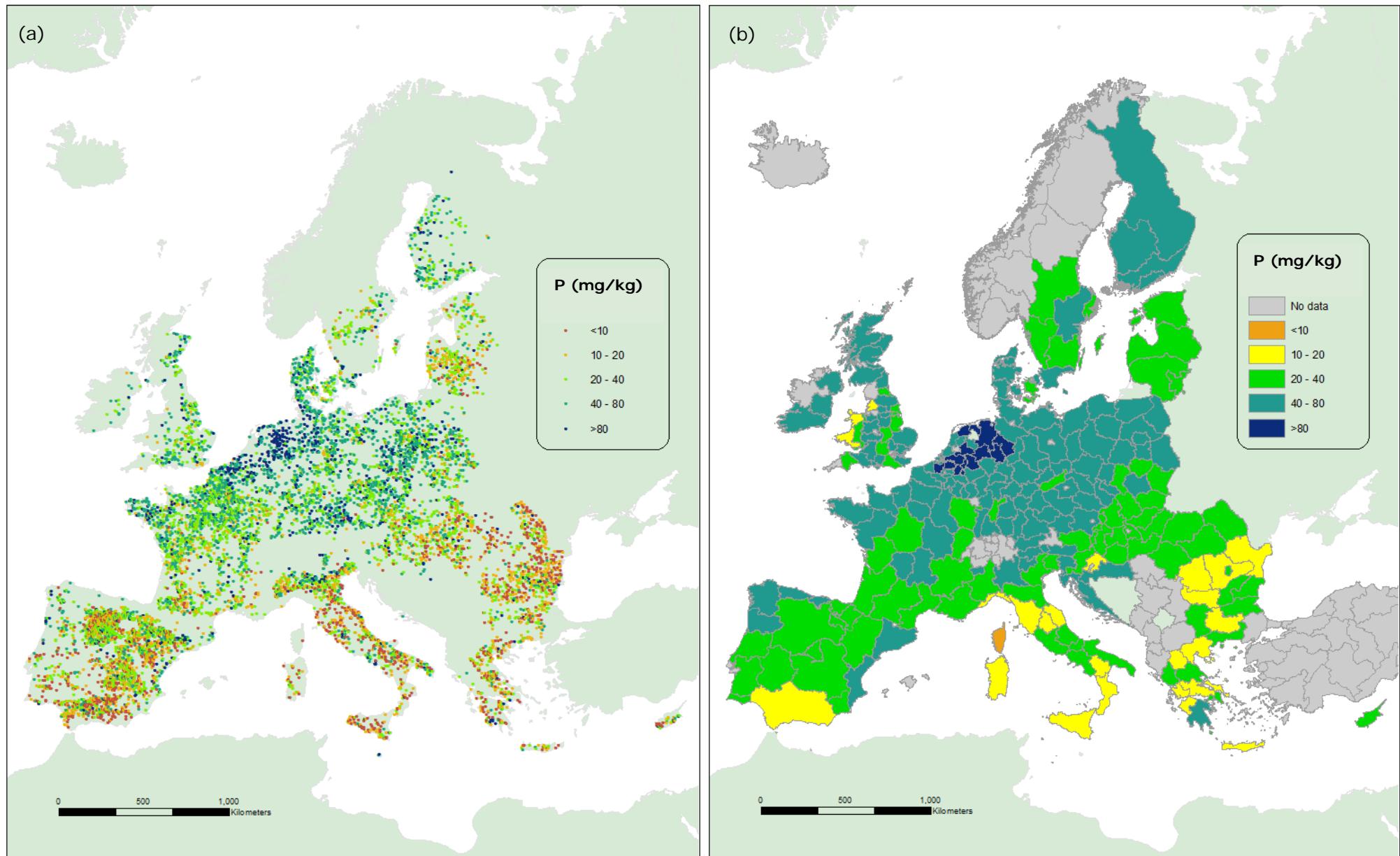
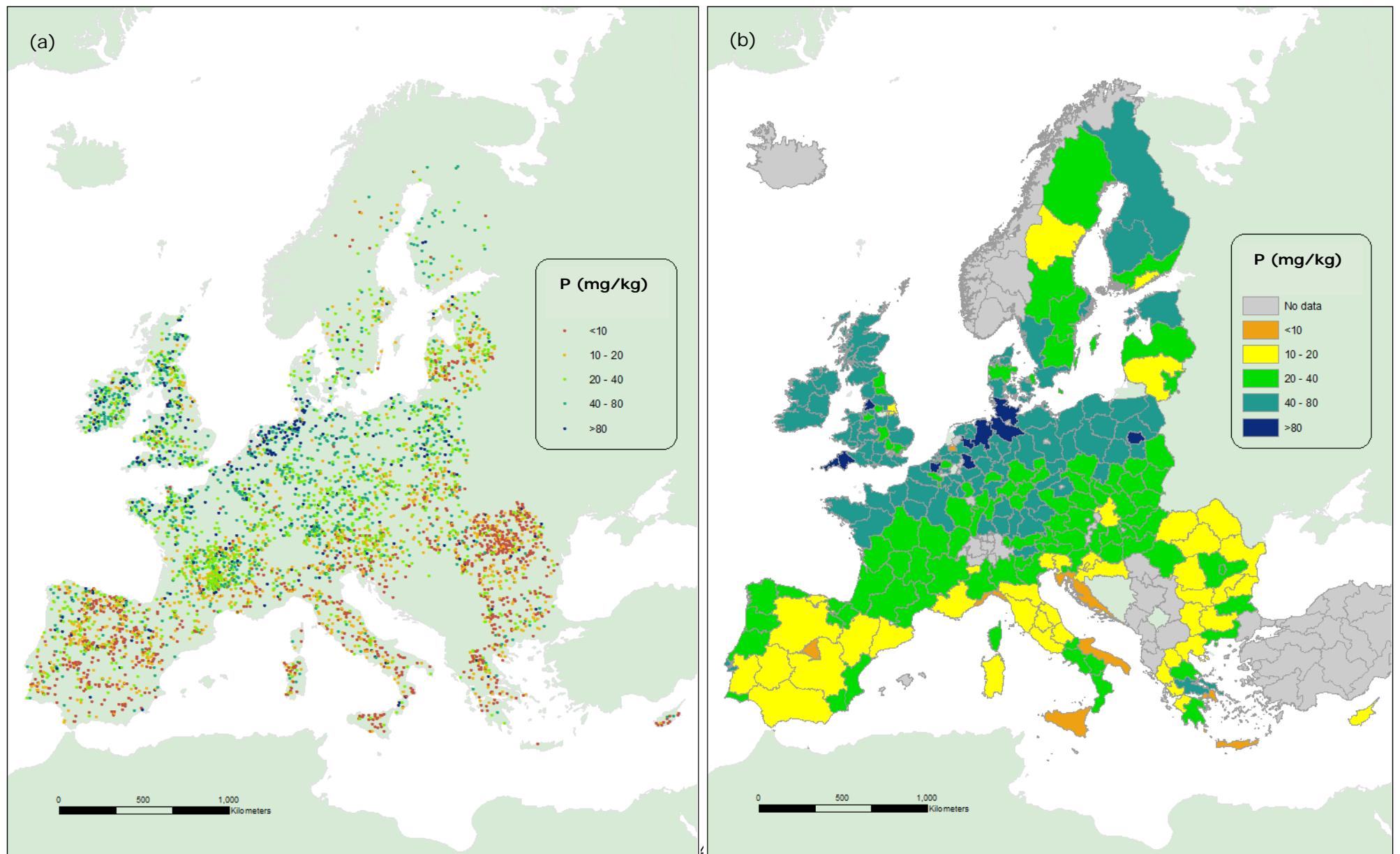


Figure 19. Phosphorus content in grassland: (a) point data and (b) average aggregated at NUTS 2 level



Potassium content

Spatial variability of potassium (K) depends mainly on the parent material (texture and mineralogy) and application of fertiliser. Regarding texture, soils with higher content of clay have a greater capacity to retain K and prevent leaching. These two factors determined the distribution of K in the different LC classes (Figures 20 to 23).

Overall, **woodland** points had low-middle contents of K. Fifty-five percent of the points had K content <100 mg kg⁻¹, and 71% of the points had K content <150 mg kg⁻¹. Potassium content was lowest in the northern sub-continent zone, where soils used to have coarse textures (mean = 86.9 mg kg⁻¹, median = 58.3 mg kg⁻¹), and in the boreal zone, where soils are relatively young and sandy (mean = 113.4 mg kg⁻¹, median = 57.9 mg kg⁻¹) (Figure 21 and Table 26, see Ballabio et al. (2016) for maps of soil texture). Woodland points in Portugal had also quite low contents of K due to their relatively high sand proportion (mean = 67.7 mg kg⁻¹, median = 65.3 mg kg⁻¹). Finally, points in the Atlantic and sub-oceanic zones in northern Spain had also low-middle K contents most likely due to the leaching (Figure 21). Mean K content in northern Spain ranged from 66.4 mg kg⁻¹ (median = 68.9 mg kg⁻¹) in the NUTS 2 region ES13 to 155.5 mg kg⁻¹ (median = 117.8 mg kg⁻¹) in ES21 region.

Potassium contents in **shrubland** were also relatively low, with 50% of the points <150 mg kg⁻¹. In the boreal and Atlantic zones, K contents were lowest (mean = 96.1 mg kg⁻¹ and 169.2 mg kg⁻¹, median = 50.4 mg kg⁻¹ and 129.9 mg kg⁻¹, respectively), due to the presence of soils with coarse texture and/or leaching. In the southern sub-continent zones, in Bulgaria and Romania, K contents in shrubland were relatively high (mean = 272.1 mg kg⁻¹, median = 230.0 mg kg⁻¹) (Table 27). Many soils in this zone have a silty texture, which can explain a better retention of K compared to coarser textures (Ballabio et al., 2016).

Table 26. Summary of potassium in woodland points.

Climatic zone	N points	Mean (mg kg ⁻¹)	Median (mg kg ⁻¹)	Std dev (mg kg ⁻¹)	NUTS 2 with highest OC content (mg kg ⁻¹) (1)	NUTS 2 with lowest OC content (mg kg ⁻¹) (1)
Boreal to sub-boreal	2040	113.4	57.9	262.1	FI19 mean = 156.5 median = 90.4	SE33 mean = 67.6 median = 30.9
Atlantic	438	131.6	87.4	135.1	FRS2 mean = 243.8 median = 149.9	NL22 mean = 22.2 median = 14.9
Sub-oceanic	848	186.8	134.9	362.7	ITC3 mean = 697.3 median = 108.1	BE34 mean = 65.5 median = 55.9
Sub-continent (northern)	1246	86.9	58.3	92.8	FI1C mean = 320.1 median = 416.8	PL43 mean = 21.7 median = 15.5
Sub-continent (southern)	298	158.9	113.0	192.6	BG33 mean = 442.3 median = 329.6	HU10 mean = 63.9 median = 51.4
Temperate mountainous	874	151.9	116.6	120.2	ITH3 mean = 238.3 median = 190.1	ITC2 mean = 33.3 median = 30.9
Mediterranean (semi-arid)	438	185.9	123.2	175.4	EL43 mean = 575.1 median = 392.5	EL52 mean = 99.9 median = 107
Mediterranean (temperate to sub-oceanic)	391	210.5	155.2	255.9	ITI4 mean = 1038.3 median = 333.0	PT18 mean = 57.3 median = 59.0

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

Table 27. Summary of potassium in shrubland points.

Climatic zone	N points	Mean (mg kg ⁻¹)	Median (mg kg ⁻¹)	Std dev (mg kg ⁻¹)	NUTS 2 with highest OC content (mg kg ⁻¹) (1)	NUTS 2 with lowest OC content (mg kg ⁻¹) (1)
Boreal to sub-boreal	81	96.1	50.4	117.2	UKM6 mean = 134.4 median = 148.6	SE32 mean = 54.6 median = 32.5
Atlantic	61	169.2	129.9	137.9		
Sub-oceanic	170	185.8	150.1	124.7	ITF1 mean = 425.9 median = 471.4	ES11 mean = 85.5 median = 66.0
Sub-continental (northern)	21	174.7	149.6	126.0		
Sub-continental (southern)	32	272.1	230	174.5		
Temperate mountainous	48	178.9	159.9	99.5		
Mediterranean (semi-arid)	263	222.9	164.9	189.4	EL30 mean = 480.5 median = 368.6	PT11 mean = 58.1 median = 39.9
Mediterranean (temperate to sub-oceanic)	169	211.9	173.4	175.4	ITG2 mean = 386.2 median = 308.3	PT16 mean = 59.2 median = 47.0

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

Potassium contents in **cropland** and **grassland** points were higher than in woodland points (Figures 22 and 23). In cropland, mean K content ranged from 155.6 mg kg⁻¹ (median = 123.5 mg kg⁻¹) in the northern sub-continental zone to 321.2 mg kg⁻¹ (median = 223.7 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 the temperate Mediterranean zone (Table 28). As indicated before, higher K contents in these LC classes are linked to the application of 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 with sandy and young soils and higher contents in clayey and silty soils of the Atlantic, oceanic and Mediterranean zones (Figures 22 and 23).

The trends observed for K under different LC classes in LUCAS 2015 confirms the estimates produced for their P map by Ballabio et al. (2019).

Table 28. Summary of potassium in grassland points.

Climatic zone	N points	Mean (mg kg ⁻¹)	Median (mg kg ⁻¹)	Std dev (mg kg ⁻¹)	NUTS 2 with highest OC content (mg kg ⁻¹) (1)	NUTS 2 with lowest OC content (mg kg ⁻¹) (1)
Boreal to sub-boreal	176	121.3	88.8	101.9	FI1C mean = 189.3 median = 162.7	SE33 mean = 47.3 median = 42.8
Atlantic	945	205.7	146.9	221.7	UKD1 mean = 423.1 median = 446.2	DK04 mean = 70.6 median = 59.8
Sub-oceanic	1004	224.5	160.5	205.3	ITF3 mean = 616.7 median = 498.8	AT31 mean = 99.9 median = 100.8
Sub-continental (northern)	767	124.9	84	143.0	DEGO mean = 382.2 median = 210.9	PL43 mean = 36.2 median = 35.7
Sub-continental (southern)	509	248.5	180.5	279.5	R022 mean = 399.9 median = 268.9	PL31 mean = 74.7 median = 62.9
Temperate mountainous	513	162.7	119.2	168.9	R022 mean = 590.9 median = 218.3	ITC2 mean = 41.7 median = 29.3
Mediterranean (semi-arid)	531	224.9	150.6	211.2	CY00 mean = 473.6 median = 295.8	PT16 mean = 91.3 median = 78.9
Mediterranean (temperate to sub-oceanic)	300	275.9	161.0	486.8	ITI4 mean = 911.4 median = 184.3	ES43 mean = 80.5 median = 63.2

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

Table 29. Summary of potassium in cropland points.

Climatic zone	N points	Mean (mg kg ⁻¹)	Median (mg kg ⁻¹)	Std dev (mg kg ⁻¹)	NUTS 2 with highest OC content (mg kg ⁻¹) (1)	NUTS 2 with lowest OC content (mg kg ⁻¹) (1)
Boreal to sub-boreal	251	161.1	141.5	104.1	FI18 mean = 253.9 median = 225.5	FI1D mean = 97.6 median = 81.2
Atlantic	1948	201.9	168.7	142.0	FR53 mean = 348.5 median = 301.1	DK04 mean = 92.1 median = 85.5
Sub-oceanic	1123	264.1	227.3	177.8	DE81 mean = 495.0 median = 485	EL52 mean = 68.4 median = 67
Sub-continental (northern)	1681	155.6	123.5	138.3	DEGO mean = 406.6 median = 334.9	PL12 mean = 69.0 median = 56.2
Sub-continental (southern)	978	237.6	195.8	180.5	RO12 mean = 383.0 median = 243.0	PL31 mean = 132.8 median = 123.2
Temperate mountainous	207	199.6	168.9	132.6	CZ07 mean = 340.6 median = 384.9	AT21 mean = 102.3 median = 120.0
Mediterranean (semi-arid)	2046	287.9	227.3	227.3	ITF4 mean = 714.0 median = 674.4	PT11 mean = 134.3 median = 105.9
Mediterranean (temperate to sub-oceanic)	734	321.2	223.7	504.8	ITF3 mean = 1448.2 median = 970.2	ES43 mean = 82.9 median = 63.5

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

Figure 20. Potassium content (all points) presented (a) as point data and (b) average aggregated at NUTS 2 level

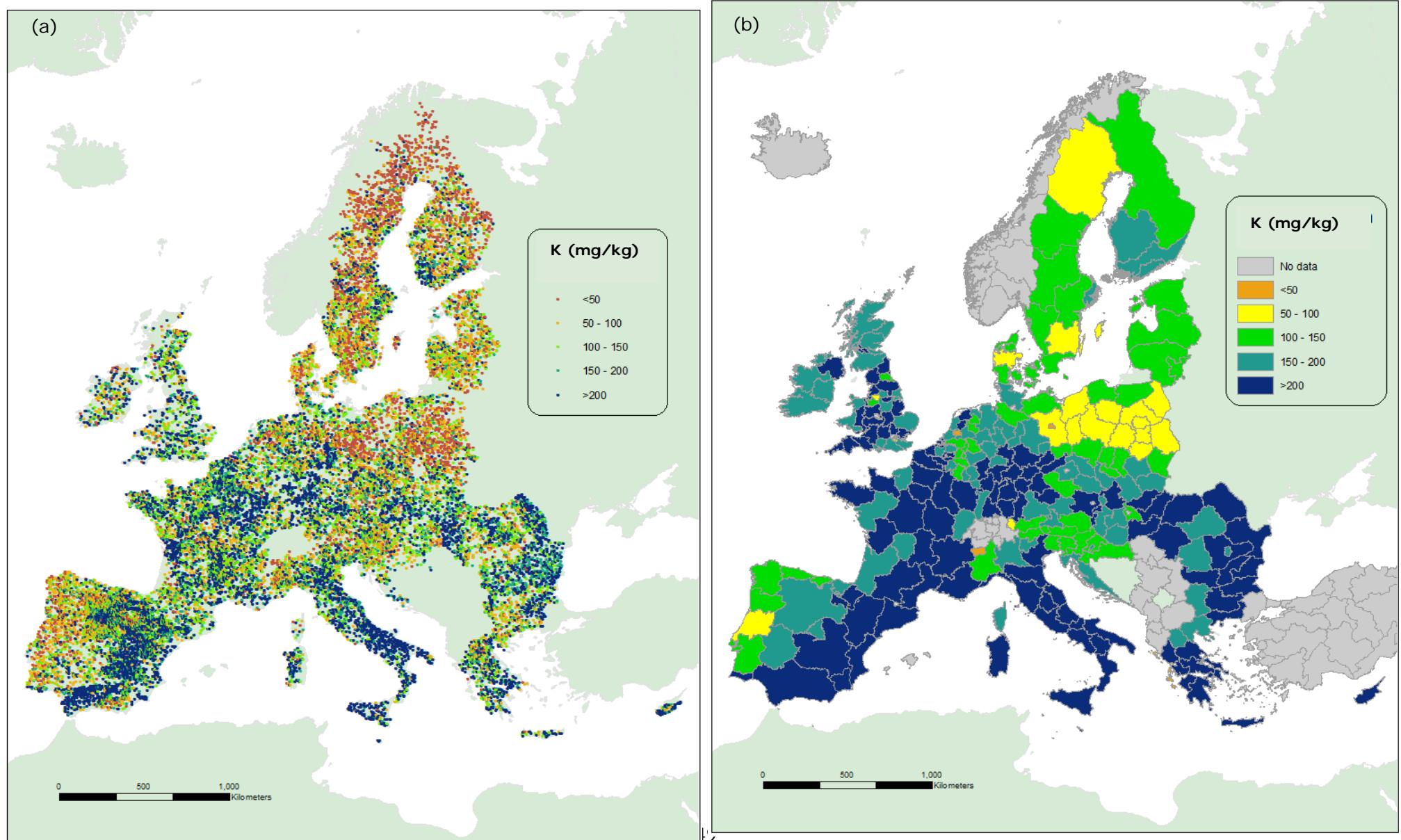


Figure 21. Potassium content in woodland: (a) point data and (b) average aggregated at NUTS 2 level

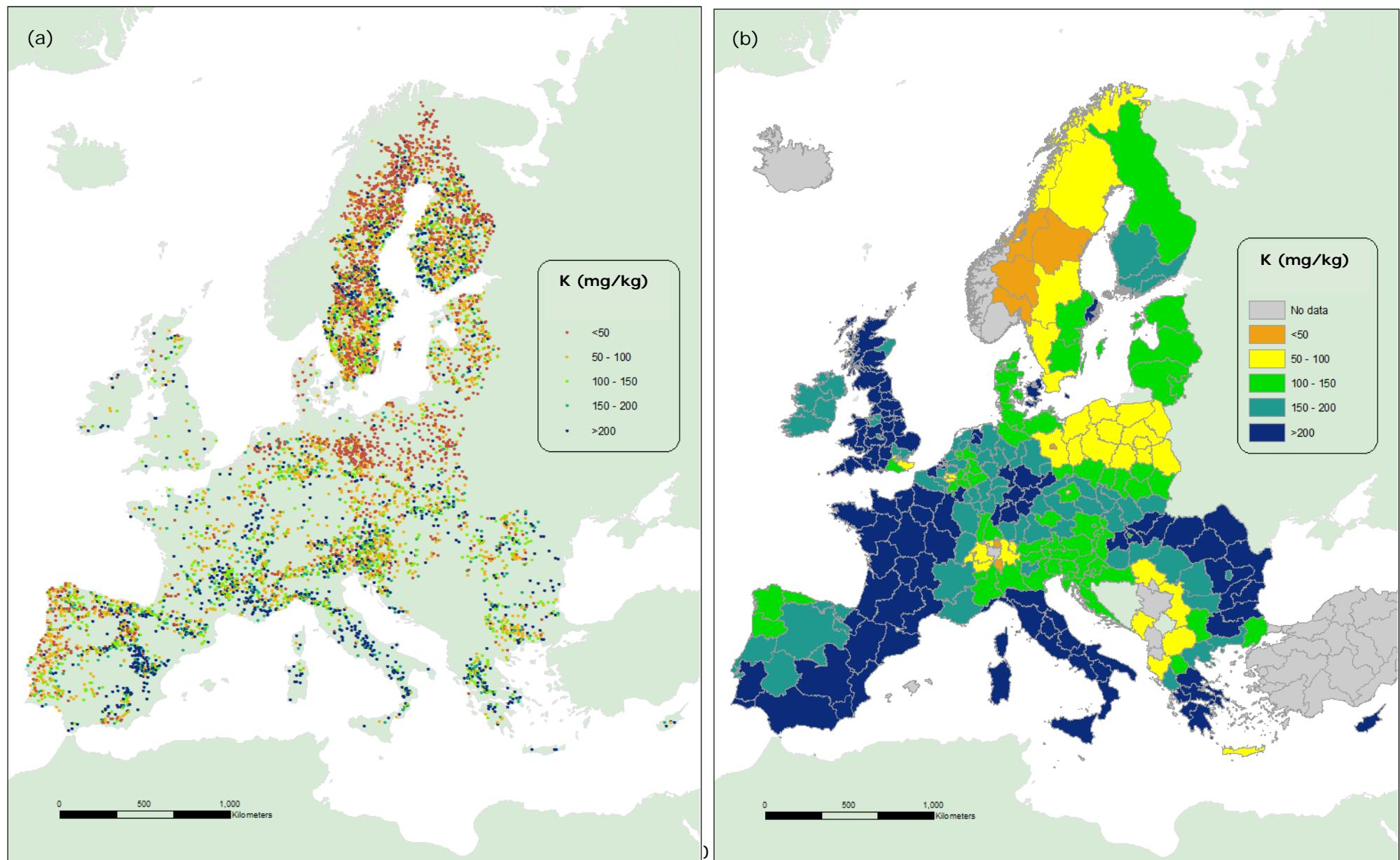


Figure 22. Potassium content in cropland: (a) point data and (b) average aggregated at NUTS 2 level

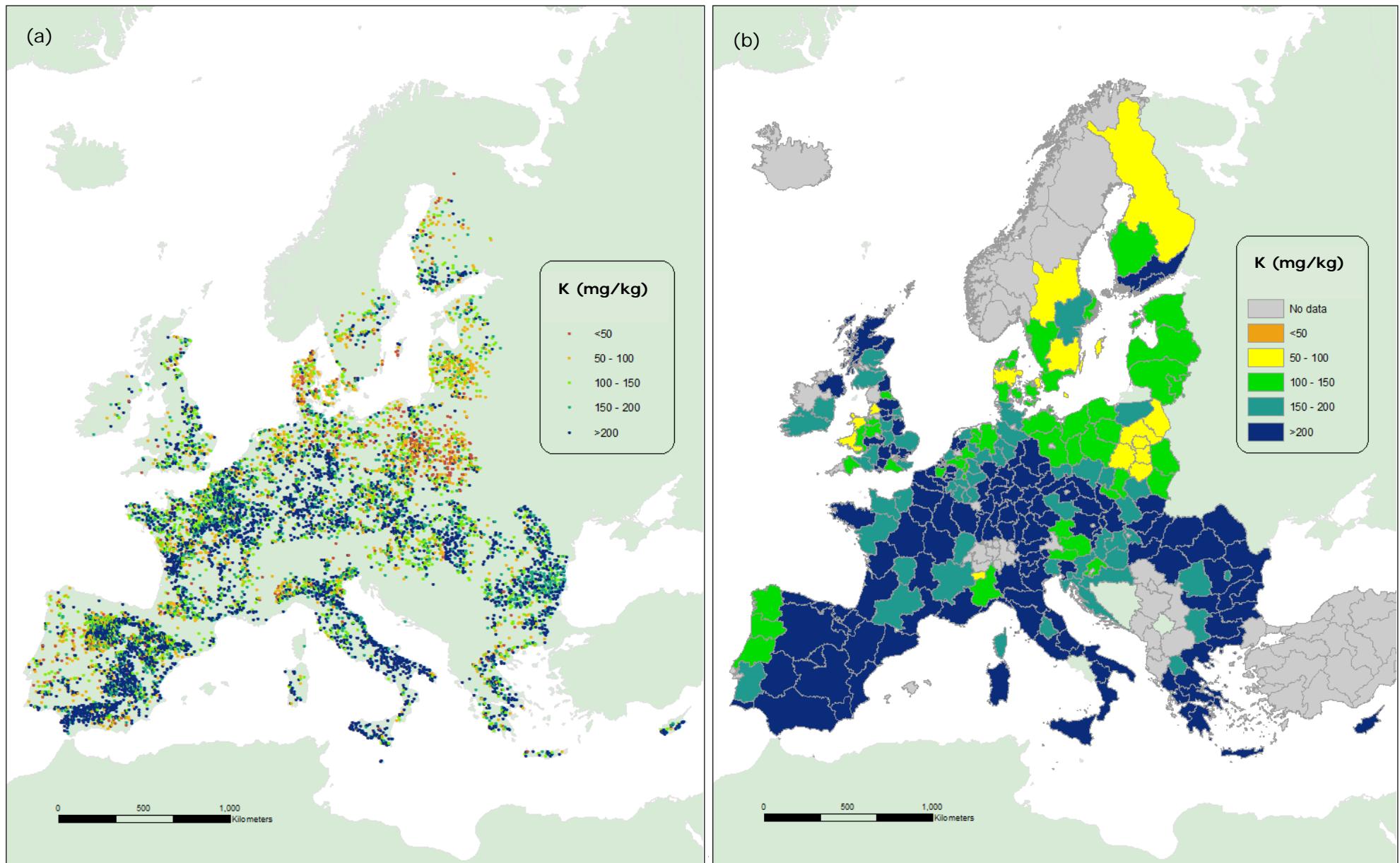
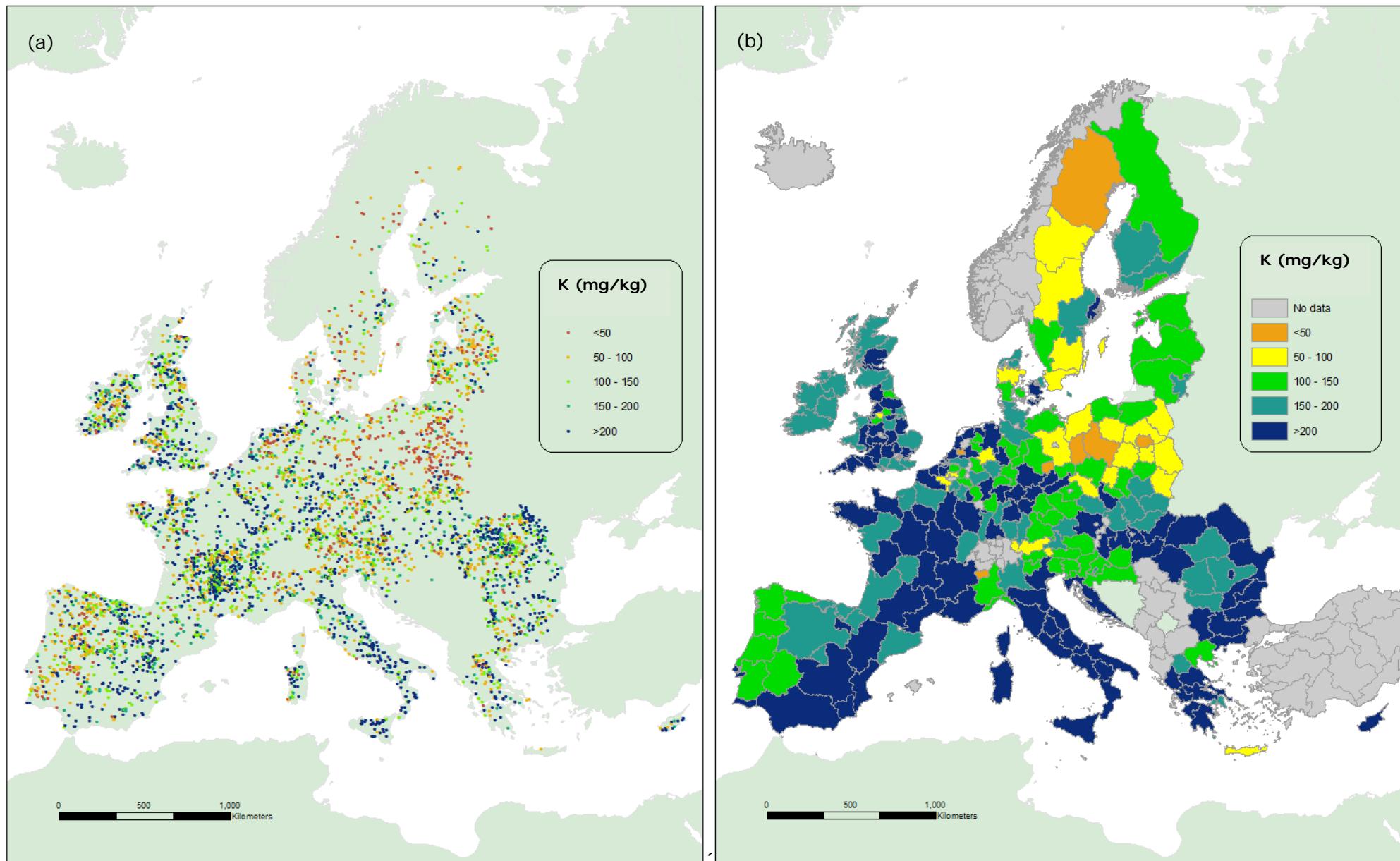


Figure 23. Potassium content in grassland: (a) point data and (b) average aggregated at NUTS 2 level



5.3 pH and carbonates

Spatial distribution of soil pH (both of pH in H₂O and CaCl₂) is mainly influenced by lithology and climate. Furthermore, soil management practices (e.g. liming, irrigation) also affect the pH of a soil. As a result of the influence of these factors, topsoil pH tended to be acidic in northern zones and some Atlantic areas, while soil pH was alkaline in Mediterranean zones (Figure 24) (¹³). Greater pH in cropland (mean and median pH in H₂O were 6.8 and 7.1, respectively, and mean and median pH in CaCl₂ were 6.5 and 6.8, respectively) than grassland (mean and median pH in H₂O were 6.0 and 5.8, respectively, and mean and median pH in CaCl₂ were 5.7 and 5.5, respectively) and woodland (mean and median pH in H₂O were 5.1 and 4.7, respectively, and mean and median pH in CaCl₂ were 4.6 and 4.2, respectively).

Woodland points in the boreal zone had very acid pH (<4.5) (Figure 25). The average pH in H₂O was 4.6 (median = 4.5) and the average pH in CaCl₂ was 3.9 (median = 3.9) in this zone (Tables 30 and 31). The iron-humus accumulation on the topsoil of podzols, predominant soil type in the boreal zone, can explain the acid pH of woodland points. Similar values of pH were observed in woodland points in the northern sub-continental zone (Figure 25), where many of those points had podzolic conditions. The average pH in H₂O was 4.6 (median = 4.4) and the average pH in CaCl₂ was 4.1 (median = 3.9) (Table 30). In woodland points of the Atlantic zone, especially in Spain, pH values were also low (Figure 25). The average pH in H₂O was 4.8 (median = 4.5) and the average pH in CaCl₂ was 4.3 (median = 4.0) in this climatic zone (Table 30). Leaching is the main factor explaining the acid pH in woodland in the Atlantic zone. In woodland points in the southern sub-continental, sub-oceanic and temperate mountainous zones, pH values were moderately acid (pH <5.5) (Tables 30 and 31). On the contrary, woodland points in the Mediterranean zones had neutral to alkaline pH (>6.0) (Figure 25, Tables 30). This is most likely due to the abundance of calcareous parent materials in southern Europe.

Cropland points had neutral to alkaline pH in all climatic zones (Figure 26). pH in H₂O ranged from 6.2. (median = 6.3) in the northern sub-continental zone to 7.6 (median = 7.9) in the semi-arid Mediterranean zone (Table 32 and 33). Similarly, pH in CaCl₂ ranged from 6.2 (median = 6.2) in the Atlantic zone to 7.2 (median = 7.5) in the semi-arid Mediterranean zone (Tables 32 and 33). Values of pH were slightly lower in the boreal zone (Tables 32 and 33). Lithology can explain the north-southern increasing trend, as occurred in woodland. Furthermore, soil management practices, such as liming and irrigation, are responsible for the greater pH values in cropland than in woodland.

Overall, **grassland** points showed slightly acid to slightly alkaline pH values. The average pH in H₂O ranged from 5.4 (median = 5.3) in the boreal and Atlantic zones to 6.8 (median = 7.2) in the semi-arid Mediterranean zone (Figure 27, Tables 34 and 35). The average pH in CaCl₂ ranged from 5.1 (median = 4.9) in the boreal zone to 6.4 (median = 6.9) in the semi-arid Mediterranean zone (Figure 27, Tables 34 and 35). Spatial variability of pH reflects the distribution of different grassland types across the EU from desertic calcareous grassland in southern Europe through steppic and mesic grassland in the north-eastern Europe to humid grassland in western Europe.

(¹³) Only maps of pH in H₂O are presented in this report. Maps of pH in CaCl₂ show the same trends as those of pH in H₂O

Table 30. Summary of pH in H₂O in woodland points.

Climatic zone	N points	Mean	Median	Std dev	NUTS 2 with highest OC content (1)	NUTS 2 with lowest OC content (1)
Boreal to sub-boreal	2040	4.6	4.5	0.5	EE00 mean = 5.5 median = 5.4	UKM6 mean = 4.1 median = 4.1
Atlantic	438	4.8	4.5	0.9	NL23 mean = 6.8 median = 7.1	BE21 mean = 4.0 median = 3.9
Sub-oceanic	848	5.5	5.2	1.3	ES62 mean = 7.8 median = 7.8	DEEO mean = 4.0 median = 3.9
Sub-continental (northern)	1246	4.6	4.4	0.8	DEDS mean = 5.5 median = 5.3	CZ08 mean = 4.1 median = 3.9
Sub-continental (southern)	298	5.7	5.4	1.2	HU33 mean = 7.6 median = 7.6	AT22 mean = 4.6 median = 4.5
Temperate mountainous	874	5.6	5.4	1.2	ITC3 mean = 7.2 median = 7.6	CZ07 mean = 4.5 median = 4.4
Mediterranean (semi-arid)	438	6.4	6.2	1.0	CY00 mean = 7.7 median = 7.9	PT11 mean = 5.4 median = 5.3
Mediterranean (temperate to sub-oceanic)	391	6.3	6.4	1.3	ES24 mean = 7.5 median = 7.6	ES11 mean = 4.6 median = 4.6

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

Table 31. Summary of pH in CaCl₂ in woodland points.

Climatic zone	N points	Mean	Median	Std dev	NUTS 2 with highest OC content (1)	NUTS 2 with lowest OC content (1)
Boreal to sub-boreal	2040	4.0	3.9	0.6	EE00 mean = 5.1 median = 5.1	SE23 mean = 3.4 median = 3.3
Atlantic	438	4.3	4.0	1.0	NL23 mean = 6.5 median = 7.0	FR51 mean = 3.4 median = 3.2
Sub-oceanic	848	5.1	4.8	1.3	ES62 mean = 7.4 median = 7.4	BE33 mean = 3.6 median = 3.5
Sub-continental (northern)	1246	4.1	3.9	0.9	DEDS mean = 5.3 median = 4.9	SE22 mean = 3.7 median = 3.6
Sub-continental (southern)	298	5.3	4.9	1.2	HU33 mean = 7.3 median = 7.4	AT22 mean = 4.1 median = 3.9
Temperate mountainous	874	5.3	5.1	1.2	ITC3 mean = 6.9 median = 7.2	CZ07 mean = 4.0 median = 3.9
Mediterranean (semi-arid)	438	6.0	6.0	1.1	CY00 mean = 7.3 median = 7.3	PT11 mean = 4.9 median = 4.7
Mediterranean (temperate to sub-oceanic)	391	5.9	6.1	1.4	ITI2 mean = 7.2 median = 7.2	ES11 mean = 4.0 median = 4.1

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

Table 32. Summary of pH in H₂O in cropland points.

Climatic zone	N points	Mean	Median	Std dev	NUTS 2 with highest OC content (1)	NUTS 2 with lowest OC content (1)
Boreal to sub-boreal	251	5.8	5.7	0.8	EE00 mean = 6.6 median = 6.5	FI1D mean = 5.2 median = 5.4
Atlantic	1948	6.6	6.6	1.0	FR81 mean = 7.8 median = 7.9	SE23 mean = 5.1 median = 5.1
Sub-oceanic	1123	6.9	7.1	0.9	ES23 mean = 8.3 median = 8.2	FR63 mean = 5.3 median = 5.4
Sub-continental (northern)	1681	6.2	6.3	1.0	RO22 mean = 7.7 median = 7.9	SE31 mean = 5.1 median = 5.1
Sub-continental (southern)	978	6.7	6.6	1.0	HU33 mean = 7.6 median = 7.9	PL32 mean = 5.6 median = 5.5
Temperate mountainous	207	6.6	6.6	1.0	EL52 mean = 7.7 median = 7.9	ITC1 mean = 5.0 median = 4.7
Mediterranean (semi-arid)	2046	7.6	7.9	0.8	ES62 mean = 8.1 median = 8.0	PT11 mean = 5.8 median = 5.6
Mediterranean (temperate to sub-oceanic)	734	7.5	7.9	0.9	ES62 mean = 8.3 median = 8.3	ES11 mean = 5.1 median = 5.1

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

Table 33. Summary of pH in CaCl₂ in cropland points.

Climatic zone	N points	Mean	Median	Std dev	NUTS 2 with highest OC content (1)	NUTS 2 with lowest OC content (1)
Boreal to sub-boreal	251	5.4	5.3	0.8	EE00 mean = 6.3 median = 6.3	FI1D mean = 4.9 median = 5.0
Atlantic	1948	6.2	6.3	0.9	NL33 mean = 7.5 median = 7.5	SE23 mean = 4.8 median = 4.7
Sub-oceanic	1123	6.6	6.9	0.9	ES23 mean = 7.7 median = 7.8	FR63 mean = 4.9 median = 5.0
Sub-continental (northern)	1681	5.9	6.0	1.0	RO22 mean = 7.3 median = 7.5	SE31 mean = 4.8 median = 4.9
Sub-continental (southern)	978	6.4	6.4	1.0	HU33 mean = 7.3 median = 7.6	PL32 mean = 5.3 median = 5.1
Temperate mountainous	207	6.3	6.4	1.0	EL52 mean = 7.3 median = 7.5	ITC1 mean = 4.7 median = 4.4
Mediterranean (semi-arid)	2046	7.2	7.5	0.8	ES62 mean = 7.7 median = 7.7	PT11 mean = 5.4 median = 5.4
Mediterranean (temperate to sub-oceanic)	734	7.1	7.5	0.9	ES62 mean = 7.7 median = 7.7	ES11 mean = 4.4 median = 4.5

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

Table 34. Summary of pH in H₂O in grassland points.

Climatic zone	N points	Mean	Median	Std dev	NUTS 2 with highest OC content (1)	NUTS 2 with lowest OC content (1)
Boreal to sub-boreal	176	5.4	5.3	1.0	EE00 mean = 6.4 median = 6.3	SE31 mean = 4.4 median = 4.2
Atlantic	945	5.4	5.3	0.9	UKH1 mean = 7.2 median = 7.4	DE92 mean = 4.3 median = 4.6
Sub-oceanic	1004	6.0	5.8	1.0	ES62 mean = 8.0 median = 8.2	ES11 mean = 5.1 median = 5.1
Sub-continental (northern)	767	5.8	5.7	0.9	RO22 mean = 7.6 median = 7.9	PL32 mean = 4.6 median = 4.5
Sub-continental (southern)	509	6.4	6.3	1.0	HU10 mean = 7.8 median = 8.1	PL32 mean = 5.5 median = 5.3
Temperate mountainous	513	5.9	5.7	1.0	RO22 mean = 7.3 median = 7.7	RO21 mean = 4.8 median = 4.8
Mediterranean (semi-arid)	531	6.8	7.2	1.1	ES62 mean = 8.1 median = 8.0	PT11 mean = 5.8 median = 5.6
Mediterranean (temperate to sub-oceanic)	300	6.7	7.2	1.1	ITI3 mean = 8.0 median = 8.0	PT11 mean = 5.3 median = 5.0

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

Table 35. Summary of pH in CaCl₂ in grassland points.

Climatic zone	N points	Mean	Median	Std dev	NUTS 2 with highest OC content (1)	NUTS 2 with lowest OC content (1)
Boreal to sub-boreal	176	5.1	4.9	1.0	EE00 mean = 6.3 median = 6.3	SE31 mean = 5.1 median = 5.1
Atlantic	945	5.2	5.0	0.9	UKH1 mean = 6.9 median = 7.2	DE92 mean = 4.1 median = 4.6
Sub-oceanic	1004	5.7	5.5	1.0	ES62 mean = 7.6 median = 7.6	ES11 mean = 4.6 median = 4.5
Sub-continental (northern)	767	5.5	5.3	1.0	RO22 mean = 7.1 median = 7.4	PL32 mean = 4.2 median = 4.3
Sub-continental (southern)	509	6.1	6.0	1.0	HU10 mean = 7.4 median = 7.4	PL32 mean = 5.3 median = 5.0
Temperate mountainous	513	5.6	5.4	1.1	RO22 mean = 7.0 median = 7.3	RO21 mean = 4.5 median = 4.5
Mediterranean (semi-arid)	531	6.4	6.9	1.1	ES62 mean = 7.7 median = 7.7	PT16 mean = 4.5 median = 4.6
Mediterranean (temperate to sub-oceanic)	300	6.3	6.9	1.2	ITI3 mean = 7.5 median = 7.6	PT11 mean = 4.8 median = 4.4

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

Figure 24. pH in H₂O (all points) presented (a) as point data and (b) average aggregated at NUTS 2 level

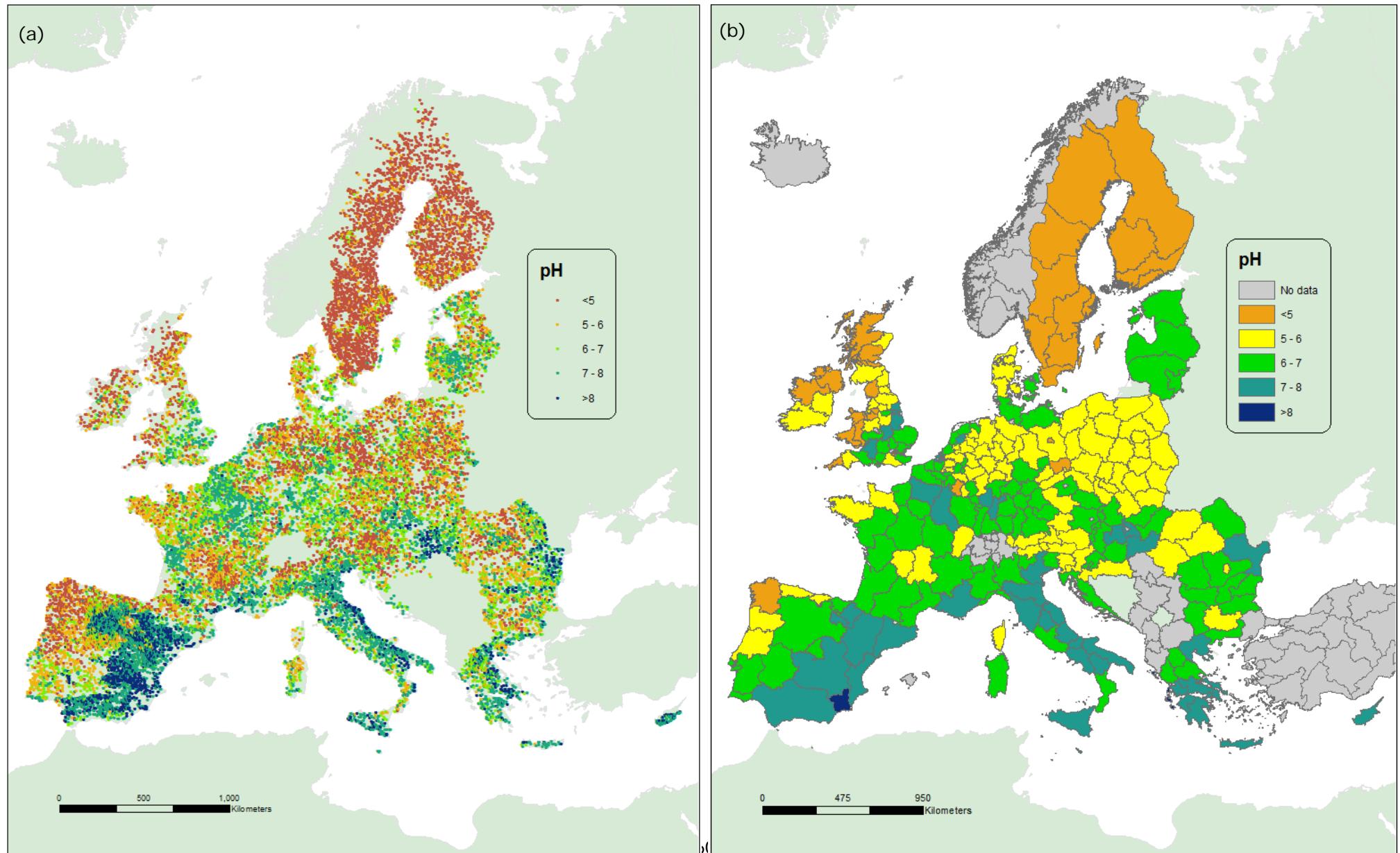


Figure 25. pH in H₂O in woodland: (a) point data and (b) average aggregated at NUTS 2 level

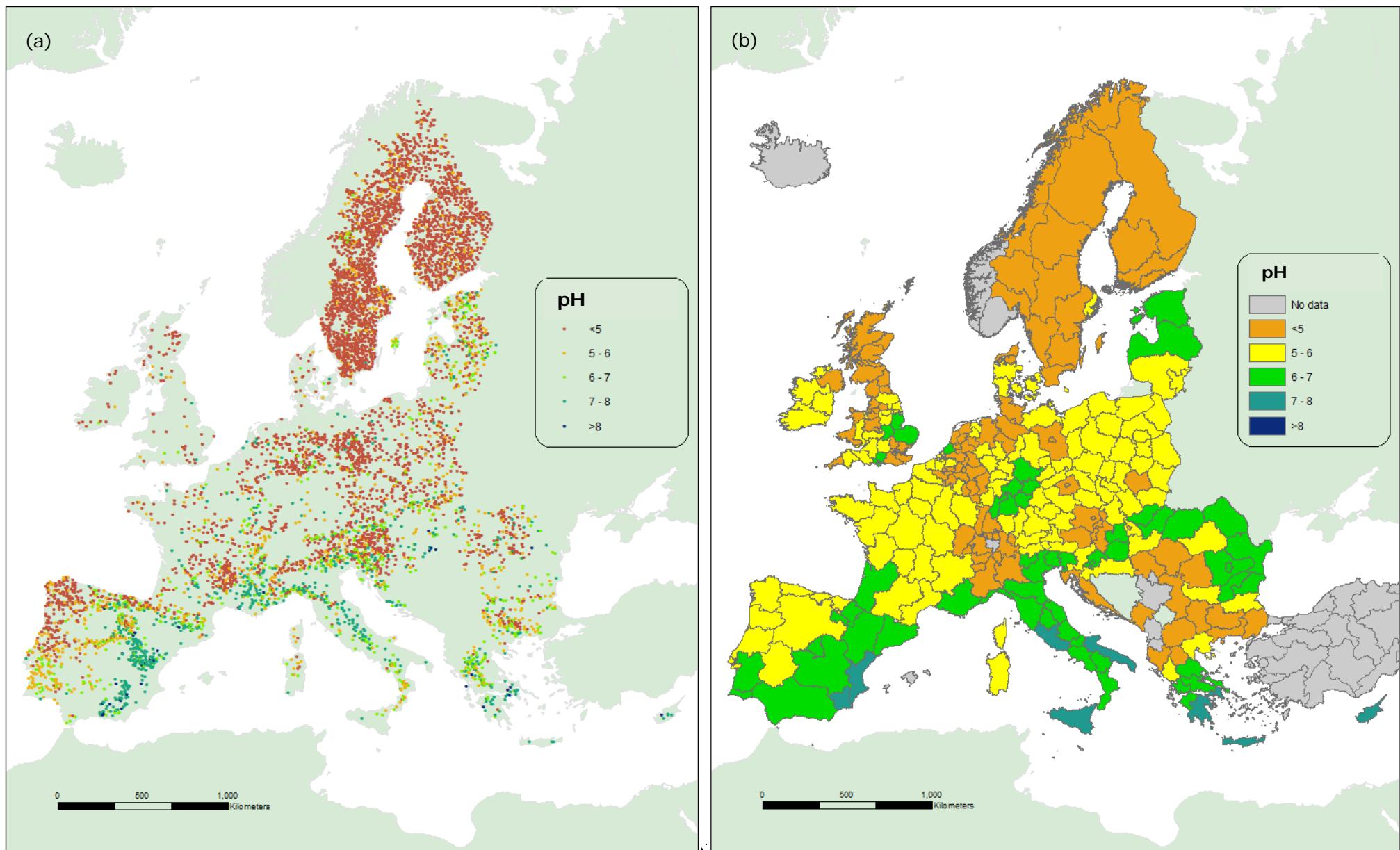


Figure 26. pH in H₂O in cropland: (a) point data and (b) average aggregated at NUTS 2 level

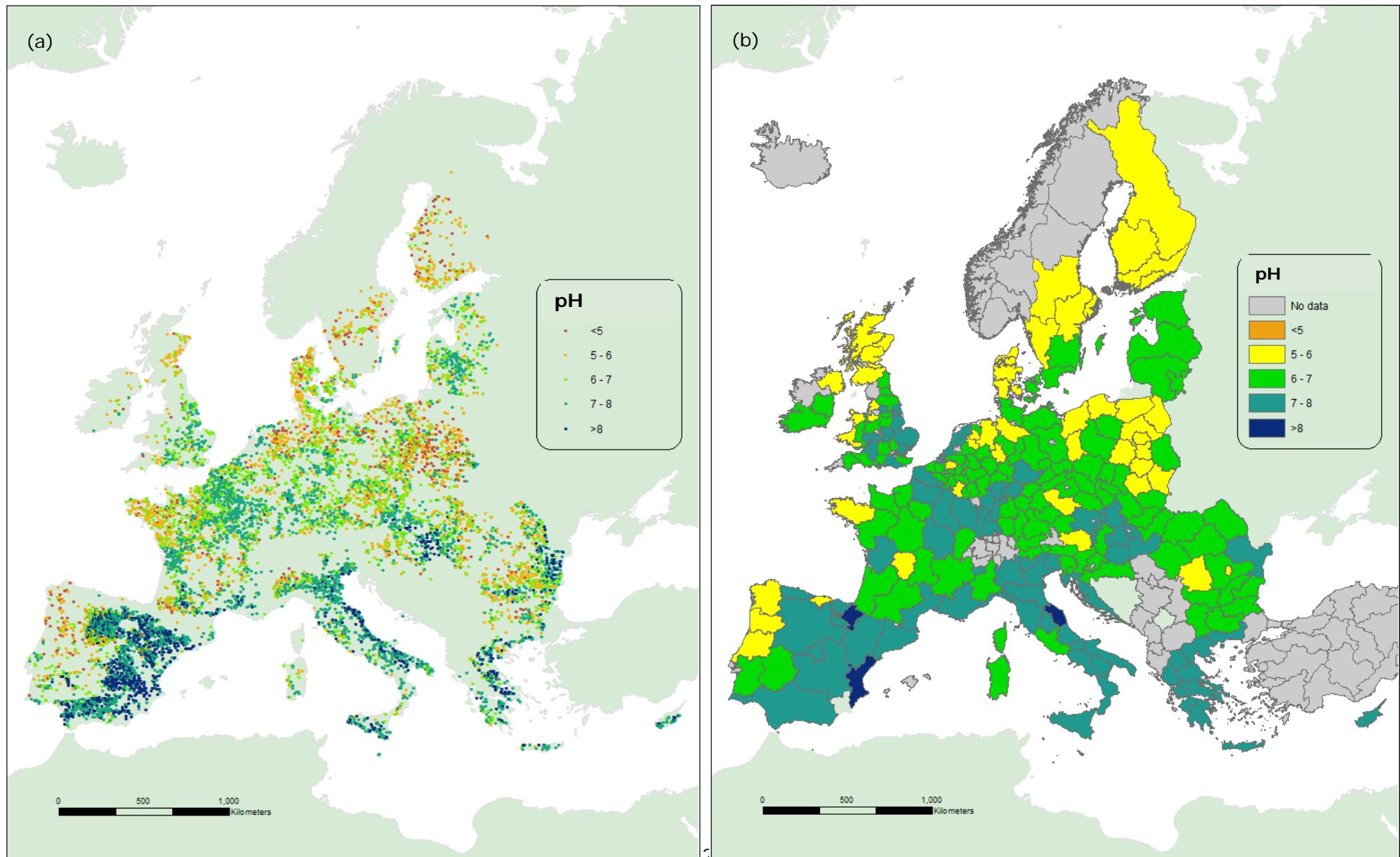
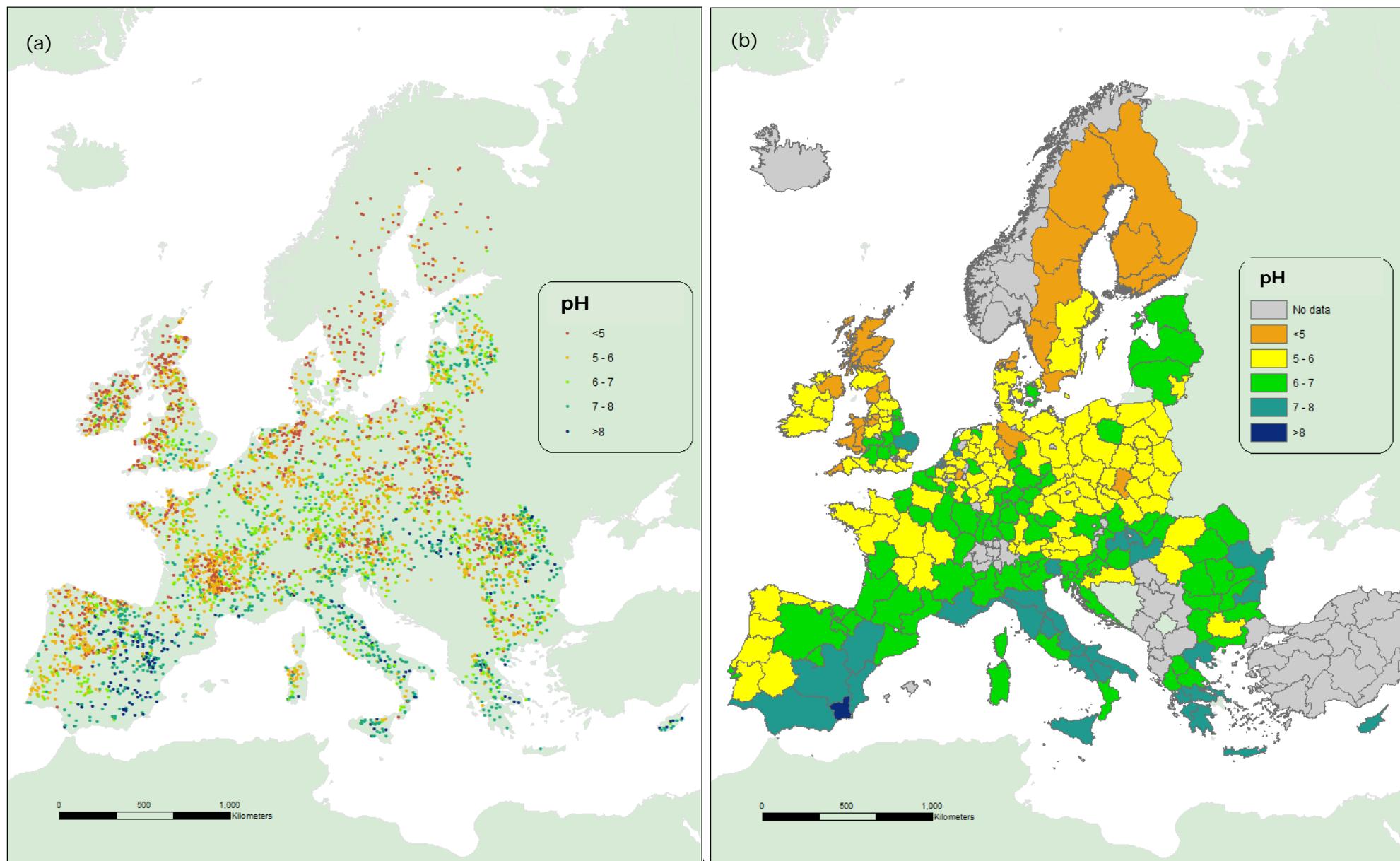


Figure 27. pH in H₂O in grassland: (a) point data and (b) average aggregated at NUTS 2 level



In line with the spatial variability of pH, carbonates were present mainly in points from the Mediterranean zones under cropland, grassland and woodland ($\text{CaCO}_3 > 250 \text{ g kg}^{-1}$, Figures 28). Few areas in the sub-oceanic zone had also important contents of carbonates ($> 100 \text{ g kg}^{-1}$) (Figures \$ \$\$). In the rest of the climatic zones, carbonates content was very low in the three LC classes ($< 1 \text{ g kg}^{-1}$) (Figure 28). This trend on carbonates distribution across the EU depends mainly on the lithology and climate.

Table 36. Summary of CaCO_3 in woodland points.

Climatic zone	N points	Mean (g kg^{-1})	Median (g kg^{-1})	Std dev (g kg^{-1})	NUTS 2 with highest OC content (g kg^{-1}) (1)	NUTS 2 with lowest OC content (g kg^{-1}) (1)
Boreal to sub-boreal	2040	0.5	0.0	7.4	EE00 mean = 7.0 median = 0.0	SE23 mean = 0.0 median = 0.0
Atlantic	438	9.8	0.0	67.8	FR21 mean = 257.7 median = 1.0	UKJ2 mean = 0.0 median = 0.0
Sub-oceanic	848	33.9	1.0	101.7	ES62 mean = 375.5 median = 429.0	DEB1 mean = 0.0 median = 0.0
Sub-continental (northern)	1246	0.7	0.0	3.8	DED5 mean = 3.2 median = 1.0	SE31 mean = 0.0 median = 0.0
Sub-continental (southern)	298	12.0	0.0	34.5	BG33 mean = 65.6 median = 1.0	AT22 mean = 0.0 median = 0.0
Temperate mountainous	874	36.0	1.0	97.6	ITC3 mean = 186.4 median = 104.0	CZ07 mean = 0.0 median = 0.0
Mediterranean (semi-arid)	438	70.3	1.0	152.9	ES24 mean = 245.7 median = 194.5	PT11 mean = 0.0 median = 0.0
Mediterranean (temperate to sub-oceanic)	391	96.7	1.0	170.1	ES52 mean = 282.2 median = 269	PT17 mean = 0.0 median = 0.0

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

Table 37. Summary of CaCO₃ in cropland points.

Climatic zone	N points	Mean (g kg ⁻¹)	Median (g kg ⁻¹)	Std dev (g kg ⁻¹)	NUTS 2 with highest OC content (g kg ⁻¹) (1)	NUTS 2 with lowest OC content (g kg ⁻¹) (1)
Boreal to sub-boreal	251	37.4	0.0	15.1	EE00 mean = 13.8 median = 1.0	SE31 mean = 0.0 median = 0.0
Atlantic	1948	54.5	1.0	151.9	FR21 mean = 519.9 median = 600.5	SE23 mean = 0.0 median = 0.0
Sub-oceanic	1123	64.5	3.0	120.6	ITF1 mean = 311.4 median = 293.0	BE34 mean = 0.0 median = 0.0
Sub-continental (northern)	1681	85.3	0.0	30.9	EE00 mean = 58.0 median = 43.5	SE31 mean = 0.0 median = 0.0
Sub-continental (southern)	978	22.8	1.0	56.5	HU10 mean = 89.9 median = 52.0	RO32 mean = 0.1 median = 0.0
Temperate mountainous	207	39.2	1.0	95.9	FR71 mean = 266.8 median = 301.0	ITC1 mean = 0.0 median = 0.0
Mediterranean (semi-arid)	2046	19.5	1.4	199.5	ES62 mean = 489.7 median = 450.0	PT11 mean = 0.0 median = 0.0
Mediterranean (temperate to sub-oceanic)	734	18.5	1.5	175.6	ES62 mean = 439.3 median = 424.0	ES43 mean = 0.0 median = 0.0

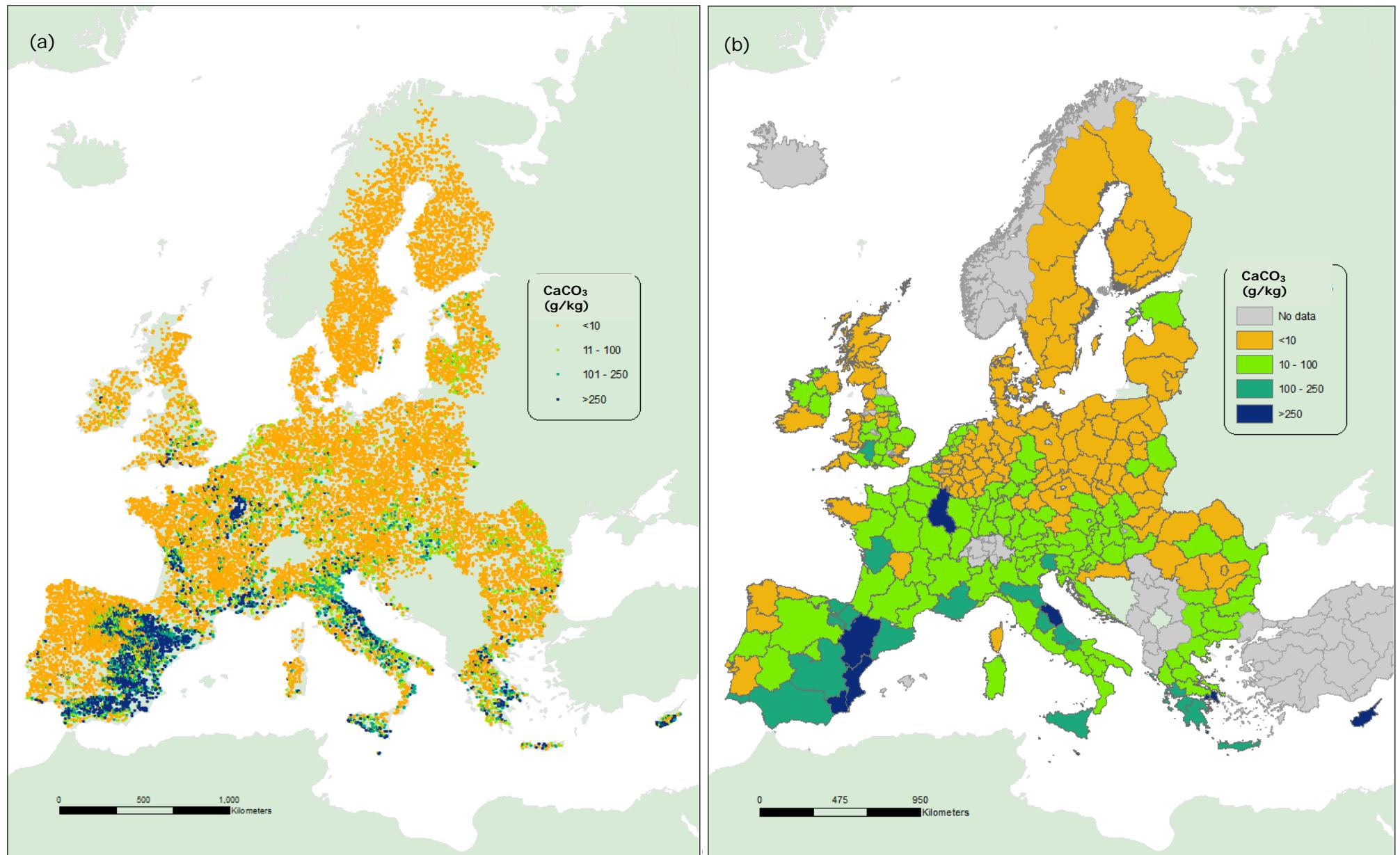
(1) NUTS 2 regions with three or more points were only considered.

Table 38. Summary of CaCO₃ in grassland points

Climatic zone	N points	Mean (g kg ⁻¹)	Median (g kg ⁻¹)	Std dev (g kg ⁻¹)	NUTS 2 with highest OC content (g kg ⁻¹) (1)	NUTS 2 with lowest OC content (g kg ⁻¹) (1)
Boreal to sub-boreal	176	4.8	0.0	21.0	EE00 mean = 13.8 median = 1.0	SE31 mean = 0.0 median = 0.0
Atlantic	945	16.3	0.0	76.4	UKK1 mean = 186.3 median = 12.0	SE23 mean = 0.0 median = 0.0
Sub-oceanic	1004	30.2	0.0	90.8	ES62 mean = 463.7 median = 612.0	DEB1 mean = 0.0 median = 0.0
Sub-continental (northern)	767	8.0	0.0	38.3	RO22 mean = 78.3 median = 32.0	SE31 mean = 0.0 median = 0.0
Sub-continental (southern)	509	20.6	0.0	60.1	PL31 mean = 243.0 median = 77.0	AT22 mean = 0.1 median = 0.0
Temperate mountainous	513	25.2	1.0	75.3	EL52 mean = 271.7 median = 263.0	PL21 mean = 0.1 median = 0.0
Mediterranean (semi-arid)	531	98.9	3.0	168.9	ES24 mean = 347.3 median = 361.5	PT16 mean = 0.0 median = 0.0
Mediterranean (temperate to sub-oceanic)	300	125.3	8.5	174.2	ITF1 mean = 336.8 median = 347.5	PT18 mean = 0.3 median = 0.0

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

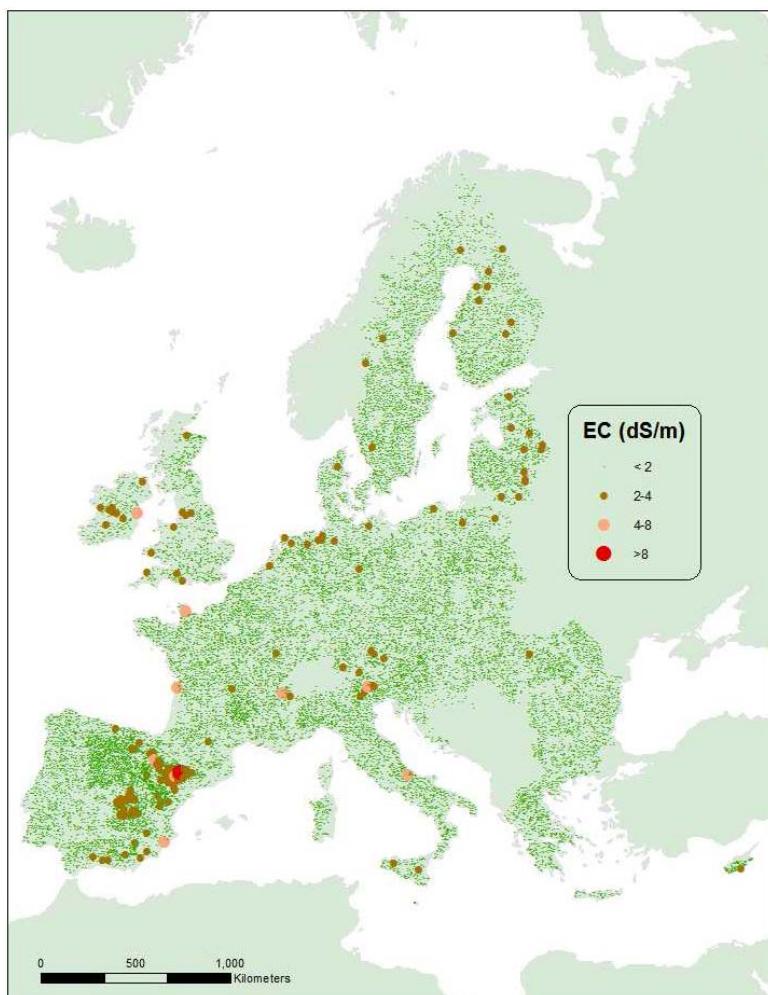
Figure 28. CaCO_3 content (all points) presented (a) as point data and (b) average aggregated at NUTS 2 level



5.4 Electrical conductivity

Electrical conductivity (EC) is primarily used as a measure of the presence and concentrations of salts in soil. 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 were not saline and that their salt contents were at a minimum (Figure 29). However, Figure 29 shows some salinity hotspots (there were 11 points with $EC > 4 \text{ dS m}^{-1}$) in the Ebro Valley in Spain (semi-arid Mediterranean zone, NUTS 2 regions ES22, ES23, ES24 and ES52), in the Adriatic coast (semi-arid Mediterranean zone, NUTS 2 regions ITH3 and ITF1) and in the Atlantic coast in Ireland and France (NUTS 2 regions IE06, FRD1 and FRI3). Curiously, Figure 29 shows also presence of salts in topsoil in a point of the FRK2 region in the sub-oceanic zone. Further investigation showed the site to be a coastal salt marsh. It has to be noted that none of the 11 points were under cropland.

Figure 29. Point map of electrical conductivity (all points)



6 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) supports the specific needs of the European Commission by collecting data that characterises soil condition and health in relation to land use practices and other activities (e.g. industrial emissions) that are driven by specific policy instruments.

In 2015, the survey was carried out for all twenty-eight EU MS. Of the locations sampled in 2009 and 2012, 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 2015 Soil dataset have 21,859 unique records with soil and agro-environmental data for the EU-28 MS. 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 European Soil Data Centre (ESDAC). An additional supplementary reference 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 2015 were compliant with those observed in LUCAS 2009, showing similar trends across the EU and the various land cover classes:

- **Organic carbon, N and P** showed 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 had intermediate contents of OC, N and P.
- Contents of OC and N were greater in wetland, woodland, and grassland than in cropland and bareland. On the contrary, P content was greater in cropland than in woodland and grassland. In wetland, P content was relatively high.
- **Potassium** content tended 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.
- Regarding LC classes, K content was higher in cropland and grassland than in woodland.
- Topsoil **pH** (both in H₂O and CaCl₂) tended to be highly acid in boreal, northern sub-continental and some Atlantic zones, while pH was alkaline in the Mediterranean zones. In accordance with the spatial distribution of pH, high contents of **carbonates** were observed in the Mediterranean zones.
- Greater values of pH in cropland than in grassland and woodland were observed across the EU.
- Most of the points had 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 were observed in the Ebro Valley in Spain, in the Adriatic coast in Italy and in the Atlantic coast in Ireland and France. None of the hotspots were under cropland.

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List of figures

Figure 1. (a) LUCAS sampling schema and (b) summary of the sampling procedure	2
Figure 2. (a) Relation between OC and N in the whole dataset, (b) relation between OC and C-to-N ratio in mineral soils and (c) relation between OC and C-to-N ratio in organic soils.	8
Figure 3. Relation between pH and carbonates (CaCO_3) in the whole dataset: (a) pH-H ₂ O, (b) pH-CaCl ₂ .	9
Figure 4. (a) Relation between OC and CEC in the whole dataset and (b) relation between clay and CEC in new LUCAS sampling points (i.e. points that were sampled for the first time in 2015).	10
Figure 5. (a) Sampling density in NUTS 2 regions for the complete dataset; number of points in each NUTS2 Region for (b) cropland, (c) grassland, (d) woodland	16
Figure 6. Climatic zones identified in Tóth et al. (2013b)	17
Figure 7. Organic carbon content (all points) presented (a) as point data and (b) average aggregated at NUTS 2 level	23
Figure 8. Organic carbon content in woodland: (a) point data and (b) average aggregated at NUTS 2 level	24
Figure 9. Organic carbon content in grassland: (a) point data and (b) average aggregated at NUTS 2 level	25
Figure 10. Organic carbon content in cropland: (a) point data and (b) average aggregated at NUTS 2 level	26
Figure 11. Spatial distribution of organic-rich soils	27
Figure 12. Nitrogen content (all points) presented (a) as point data and (b) average aggregated at NUTS 2 level	33
Figure 13. Nitrogen content in woodland: (a) point data and (b) average aggregated at NUTS 2 level	34
Figure 14. Nitrogen content in cropland: (a) point data and (b) average aggregated at NUTS 2 level	35
Figure 15. Nitrogen content in grassland: (a) point data and (b) average aggregated at NUTS 2 level	36
Figure 16. Phosphorus content (all points) presented (a) as point data and (b) average aggregated at NUTS 2 level	41
Figure 17. Phosphorus content in woodland: (a) point data and (b) average aggregated at NUTS 2 level	42
Figure 18. Phosphorus content in cropland: (a) point data and (b) average aggregated at NUTS 2 level	43
Figure 19. Phosphorus content in grassland: (a) point data and (b) average aggregated at NUTS 2 level	44
Figure 20. Potassium content (all points) presented (a) as point data and (b) average aggregated at NUTS 2 level	49
Figure 21. Potassium content in woodland: (a) point data and (b) average aggregated at NUTS 2 level	50
Figure 22. Potassium content in cropland: (a) point data and (b) average aggregated at NUTS 2 level	51
Figure 23. Potassium content in grassland: (a) point data and (b) average aggregated at NUTS 2 level	52
Figure 24. pH in H ₂ O (all points) presented (a) as point data and (b) average aggregated at NUTS 2 level	60
Figure 25. pH in H ₂ O in woodland: (a) point data and (b) average aggregated at NUTS 2 level	61
Figure 26. pH in H ₂ O in cropland: (a) point data and (b) average aggregated at NUTS 2 level	62
Figure 27. pH in H ₂ O in grassland: (a) point data and (b) average aggregated at NUTS 2 level	63
Figure 28. CaCO_3 content (all points) presented (a) as point data and (b) average aggregated at NUTS 2 level	67
Figure 29. Point map of electrical conductivity (all points)	68

List of tables

Table 1. Methods used for the analysis of physical and chemical properties in topsoil samples.....	3
Table 2. Identification of samples taken in LUCAS 2015 in the EU-28 member states.....	6
Table 3. Summary of outsider values per soil property in the dataset of the LUCAS 2015 survey.....	7
Table 4: Allocation of LUCAS 2015 sampling locations.....	12
Table 5. Soil fields in the LUCAS 2015 Topsoil dataset.....	13
Table 6. Non-soil fields in the LUCAS 2015 Topsoil dataset.....	14
Table 8. Summary of organic carbon in wetland points	18
Table 9. Summary of organic carbon in woodland points	19
Table 10. Summary of organic carbon in grassland points	20
Table 11. Summary of organic carbon in cropland points.....	21
Table 12. Summary of organic carbon in bareland points	22
Table 13. Summary of organic carbon in shrubland points	22
Table 14. Summary of nitrogen in wetland points	28
Table 15. Summary of nitrogen in woodland points	29
Table 16. Summary of nitrogen in grassland points	30
Table 17. Summary of nitrogen in cropland points	31
Table 18. Summary of nitrogen in bareland points	31
Table 19. Summary of nitrogen in shrubland points	32
Table 20. Summary of phosphorus in woodland points	38
Table 21. Summary of phosphorus in shrubland points	38
Table 22. Summary of phosphorus in bareland points	39
Table 23. Summary of phosphorus in cropland points	39
Table 24. Summary of phosphorus in grassland points	40
Table 25. Summary of phosphorus in wetland points	40
Table 26. Summary of potassium in woodland points	45
Table 27. Summary of potassium in shrubland points	46
Table 28. Summary of potassium in grassland points.....	47
Table 29. Summary of potassium in cropland points	48
Table 30. Summary of pH in H ₂ O in woodland points	54
Table 31. Summary of pH in CaCl ₂ in woodland points	55
Table 32. Summary of pH in H ₂ O in cropland points	56
Table 33. Summary of pH in CaCl ₂ in cropland points	57
Table 34. Summary of pH in H ₂ O in grassland points	58
Table 35. Summary of pH in CaCl ₂ in grassland points	59
Table 36. Summary of CaCO ₃ in woodland points	64

Table 37. Summary of CaCO₃ in cropland points.....65

Table 38. Summary of CaCO₃ in grassland points66

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