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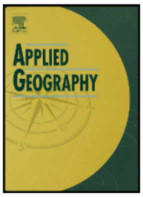

Changes in anthropogenic influence on soils across Europe 1990–2018

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ABSTRACT

Soils have been widely transformed and degraded by human activities. The area occupied by soils that remain unmodified is decreasing, while recent rural outmigration and land abandonment provide new opportunities for soil restauration across larger area.Little is known about the spatial distribution of both near-natural and anthropogenically influenced soils on large scales. We here present a new methodology to assess soil naturalness across Europe combining CORINE land cover and anthropogenic diagnostic features of the World Reference Base (WRB) for soils. Based on these features, we defined soil naturalness groups, ranging from dominantly natural to dominantly anthropogenic soils. This yielded a European soil naturalness map for the year 2018, covering 37 countries. Using the dataset resurveys, we spatially assessed changes in land cover in 1990–2018 and used these to estimate changes in soil naturalness. On average, 50.74% of the examined soil surface was classified as natural or near-natural, 41.66% of the surface was moderately, but recognizably transformed by human activities, while 4.43% of the soils were found to be strongly affected or created by human activities. Over the study period, increased anthropogenic influence on soils was stated for 42 745 km^2 (0.18% of the surface studied area), decreasing influence for 14 248 km^2 (0.06%). Hotspots of increasing anthropogenic influence were found in regions with rapid development, while hotspots of decreasing influence were often associated with land abandonment.Our approach allows recognizing areas of changes in soil naturalness, and can be used to inform soil protection initiatives on the European level.

1. Introduction

Soils play an important role in ecosystem functioning. They provide provisioning ecosystem services such as water retention, regulating services such as carbon sequestration and provisioning services such as nutrient cycling or habitat provision (Adhikari & Hartemink, 2016). Soils serve as archives of the customs and activities of humans over history and thus also provide cultural services (Yaalon & Arnold, 2000).

Despite the importance of soils for the persistence of ecosystems and humanity, soils have been widely transformed and degraded. Since the emergence of the first settlements and the expansion of soil cultivation, human activities constitute an important soil forming factor (Dudal, 2005). Soils are affected by various anthropogenic influences (AI) across extensive areas (Mendyk et al., 2016). This is mirrored in their taxonomy (Waroszewski et al., 2015; Świtoniak et al., 2016). We here consider anthropogenic impacts all local or distant human activities that change (directly or indirectly) measurable and detectable properties of soils. However, it is not possible to reflect all anthropogenic impacts in the soil taxonomical status.

The area occupied by soils that remain unaffected by AI is decreasing. By 1990, ca. 15% of the world's soils were in some way degraded (Oldeman, 1992, pp. 19–36), more recently, figures of up to 33% have been suggested (Nachtergaele at al. 2011). Current rates of erosion on agricultural land are an order of magnitude higher than that of natural erosion or soil formation processes (Ter, 2012). The main factors that induce soil transformation are deforestation (Sewerniak et al., 2017), drainage (Glina et al., 2016), soil sealing (Mendyk & Charzyński, 2016), construction, mining, and agricultural cultivation (Szilassi et al., 2010).

Amelioration and landfill with excavated material affect a considerable area every year (Dazzi & Lo Papa, 2015; Dudal, 2005).

Soil naturalness (Bossuyt et al., 1999) is an important feature in soil taxonomy, where pedogenic features are related to natural soil forming factors as principal criteria in the classification process (IUSS WG IUSS Working Group WRB, 2015). Anthropogenic soil features

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are considered unambiguous indicators (Certini & Scalenghe, 2011) of the 'Anthropocene' as an epoch of Earth's history dominated by anthropogenic processes (Hamilton, 2015, 2016; Hamilton & Grinevald, 2015).

Despite the fact that anthropogenic activities are a widely accepted soil-forming factor, most soil databases and soil maps do not contain information about anthropogenic contributions to soil development and on the grade of anthropogenic transformation - even in highly urbanized areas. According to the basic principles of soil surveys, soils should be described and classified as found *in situ* (IUSS 2015). However, this principle is often neglected, and soils are frequently assigned to taxonomical classes based on site conditions without dedicated fieldwork, thereby assuming near-natural soil types and ignoring anthropogenic impacts. The main reasons for this are the often lower economic importance of anthropogenic soils (Dazzi & Lo Papa, 2015, with the exception of irrigated soils, e.g., paddy field soils), and the lack of an elaborate classification terminology (Krasilnikov et al., 2009).

As a result, knowledge gaps about the distribution and extent of anthropogenically modified and near-natural soils remain across all of Europe. The state of 'soil naturalness' has rarely been surveyed over larger areas.

Since soil naturalness itself is not monitored, surveyed, and evaluated by pedological information systems, we here develop a procedure to compile information on soil naturalness from remote sensing data on very large scales. "Remote sensing data is now used to monitor soil features such as soil moisture (Mohanty et al., 2017), colour (Eldeiry & Garcia, 2008), salinity (Escadafal, 1993) and others, but so far, not method was available to assess combined human impacts on soils over very large areas."

2. We aimed

(1) To develop an objective and reproducible classification system of soil naturalness,
(2) To map soil naturalness across Europe by combining land cover and soil classification data,
(3) To identify hotspots of change in soil naturalness for the period 1990–2018,
(4) To relate changes in soil naturalness on the country level to socio-economic and biophysical conditions.

We presumed that land cover classes can be characterized by particular anthropogenic soil characteristics, which could be also expressed during classification according to the World Reference Base for Soil Resources, WRB (IUSS WG IUSS Working Group WRB, 2015). According to the number and character of these anthropogenic features we distinguished "soil naturalness grades", which allowed to gain an overview on soil naturalness state and its changes in European countries. We suggest the developed soil naturalness classification allows to classify and evaluate the naturalness of ecosystems, and applicable in decision-making in conservation, similar to hemeroby-based concepts in vegetation and land-use science (Steinhardt et al., 1999).

3. Material and methods

3.1. Data sources

We combined two established international databases for our analyses. The CORINE (Coordination of Information on the Environment) land cover database (EEA, 1995) contains information on land use and land-use change across Europe at high spatial resolution. The WRB database (World Reference Base for Soils Resources, IUSS WG IUSS Working Group WRB, 2015) contains information on soil taxonomy for across Europe.

The CORINE Land Cover project was initiated by the European Environmental Agency in 1985, mainly for environmental management purposes and to produce consistent and reproducible data regarding the state of environment in the Member States of the European Community (Commission of the European Communities 1985). It also serves to coordinate the compilation of data and the organization of information at the national level. The data are available on a spatial scale of 1:100 000 for Europe, and additionally on a scale of 1:50 000 for some of the member states (Büttner et al., 2004). Land cover (LC) classes were derived using classifications of Landsat, SPOT and Sentinel satellite imagery. In CORINE (CLMS, 2018), 44 LC classes at three hierarchical levels are distinguished. In our analyses, we used data available at 1:100 000 scale and the associated LC classes (CLC100), in order to work at an identical resolution across Europe. The CORINE LC database for years 1990, 2000, 2006, 2012 and 2018 is available as vector dataset, raster dataset or in the form of interactive maps (CLMS, 2018). For consecutive CORINE LC surveys, a database of LC changes (CHA 1990–2000; CHA 2000–2006; CHA 2006–2012; CHA 2012–2018) is available. For our analyses, we harnessed the vector datasets (polygons) of all four periods of LC changes and the LC data of the latest, 2018 survey (CLC 2018). The most important characteristics of these datasets are summarized in Table 1. CORINE LC data have been used successfully to answer a wide range of questions regarding land-use change on regional or country level (Hazeu & de Wit, 2004; Jones et al., 2011; Liga et al., 2014; Nalej, 2015; Pazúr et al., 2014; Pelorosso et al., 2009; Petrişor et al., 2014; Petrişor, 2012; Schaffert & Steensen, 2017), or in Europe-wide comparisons (Feranec et al., 2010; Feranec & Soukup, 2013; Jones et al., 2007; Kupková, Bičik, & Najman, 2013; Schmidt et al., 2014).

The World Reference Base of Soil Resources working group elaborated soil diagnostic methods (IUSS WG IUSS Working Group WRB, 2015) based on soil features and developed a soil taxonomic classification. This taxonomy also contains information on recognizable anthropogenic soil features. This allows to assess the anthropogenic impact on soil formation and transformation. Many of the diagnostic features are connected with distinct human activities and land management. For example, soils with cultivated topsoils to a depth of 20 cm are described with an added 'Aric' qualifier, soils showing signs of long-term cultivation such as a orchards and gardens are classified as 'Hortic', soils superimposed by human-made solid materials as 'Ekranic' and soils of agricultural terraces as 'Escalic'. Separate reference groups are used for soils that developed under strong anthropogenic influence, e.g. at the surfaces of construction or mining waste. The classification is generally based on diagnostic materials, properties, and soil horizons.

4. Geographical coverage

Since the start of the CORINE project in 1985, political change resulted in changing country borders. Country-wide CORINE datasets were corrected and updated in many cases, e.g. after Czechoslovakia was split into Czech Republic and Slovakia in 1993, or for the successor states of former Socialist Federal Republic of Yugoslavia. Numerous countries were included after the first survey, during the 1990s, therefore datasets are available only from 2000 onwards (Table 1). We excluded those countries from our analysis, for which no data were available for more than one time step (Fig. 1), and most of the European 'ministates', like Andorra, Monaco, Vatican state and San Marino. This resulted in the inclusion of 38 European countries in analysis (Table 1). For nine countries (Albania, Bosnia and Herzegovina, Cyprus, Finland, Iceland, Macedonia, Norway, Sweden and Switzerland) the data of the first survey (1990) are not available (Fig. 1), therefore averages for this time and changes between 1990 and 2000 were estimated excluding these countries.

5. Data analysis

We combined CORINE LC data and WRB soil diagnostic groups to define four groups of soil-naturalness (Table 2). We then assigned all

Table 1
CORINE land cover (CLC) and land cover change (CLCC) datasets applied in this study and their specifications.

Dataset	CLCC1990-2000 change 1990–2000	CLCC2000-2006 change 2000–2006	CLCC2006-2012 change 2006–2012	CLC2012 change 2012–2018	CLC2018
Satellite data	Landsat-5 SS/TM & Landsat-7 ETM	Landsat-7 ETM & SPOT-4/5 and IRS P6 LISS III dual date	SPOT-4/5 and IRS P6 LISS III dual date & IRS P6 and RapidEye LISS III dual date	IRS P6 and RapidEye LISS III dual date	Sentinel-2 and Landsat-8 for gap filling
Change mapping	boundary displacement min. 100 m; change area for existing polygons ≥5 ha; for isolated changes ≥25 ha	boundary displacement min.100 m; all changes ≥5 ha are to be mapped			
Min. mapping unit/width	25 ha/100 m				
Dissemination policy	as agreed at the start of project	free access	free access	free access	free access
Number of countries involved in this study	29	38	38	37****	
Countries involved in this study	Austria, Belgium, Bulgaria, Croatia, Czech Republic, Denmark, Estonia, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Montenegro, Netherlands, Poland, Portugal**, Romania, Serbia, Slovakia, Slovenia, Spain, Turkey, United Kingdom***	Albania [a], Austria, Belgium, Bosnia and Herzegovina [a], Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Liechtenstein, Lithuania, Luxembourg, Macedonia [a], Malta, Monte Negro, Netherlands, Norway, Poland, Portugal**, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom***		Albania [a], Austria, Belgium, Bosnia and Herzegovina [a], Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Liechtenstein, Lithuania, Luxembourg, Macedonia [a], Malta, Monte Negro, Netherlands, Norway, Poland, Portugal**, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, United Kingdom***	

[a] Coppin, Jonckheere, Nackaerts, Muys, & Lambin, 2004 based on the satellite images taken in late 1990s; **Madeira and Azores Islands included; ***Guernsey and Jersey Islands included, ****Turkey was added in 2019.

CORINE LC classes to a single soil naturalness group. This was done by considering the anthropogenic processes, which are reflected in taxonomy and diagnostics found in the WRB.

To our first group (no soils) we assigned CORINE LC classes without soil development, namely mineral extraction sites, glaciers and water courses and bodies, because our analysis considered only terrestrial areas. “No soils” is not a category of anthropogenic impact, but was necessary to be introduced as we aimed to calculate country-wide estimates of anthropogenically influenced soil area.

Our second group (dominantly natural or close to natural soils) comprised LC classes in which dominantly or exclusively natural soil forming processes prevail. The first and the second group therefore did not contain any soils that are characterized by anthropogenic features in the WRB (Table 2). In the LC classes included in this group, the surface is covered by natural or near-natural vegetation. The land is not used by humans, or at very low intensity, so that the AI is not reflecting in the soil classification status. This group contains all forests, natural grasslands, moors, heathlands, bogs, and marshes. Also sand dunes, bare rocks, salines, and intertidal flats were allocated to this group, because they are formed by natural processes and some initial soil development is observable on them (classified as Regosol, Arenosol, Leptosol or Gleysol in the WRB). Finally, burnt areas were included in this group, because they appear dominantly in forests, shrub- or grasslands, and only rarely on built-up or cultivated areas.

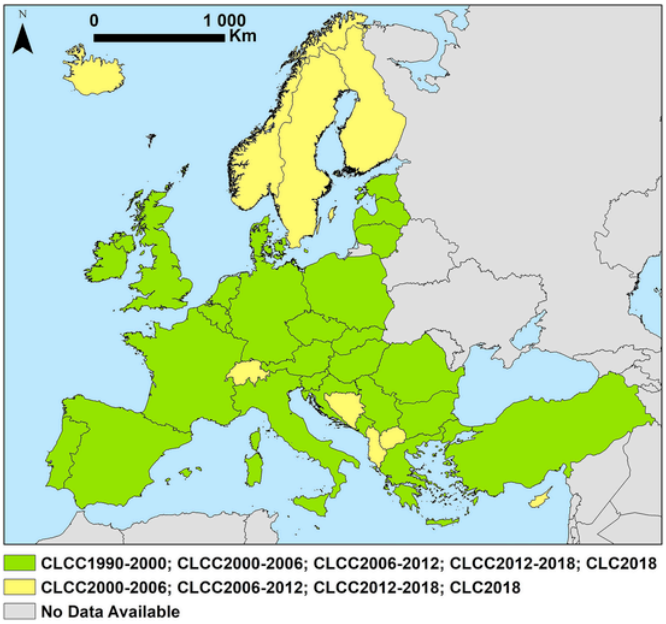

Fig. 1. Geographical scope of the study and applied CORINE datasets. For details on the used CORINE land cover and change (CLCC) datasets, see `Table 1`

In the third group (soils with significant anthropogenic influences), we considered LC classes with soils that show significant AI based on soil diagnostic features: LC classes of agricultural areas such as cropland, vineyards, plantations, olive groves, complex cultivation patterns and agricultural patch-like areas with remnants of natural vegetation. Pastures were also included, considering the trampling effect of livestock that leads to soil compaction and sometimes erosion. Typical for this LC group is the constant disturbance of topsoil and mixing of soil horizons, which leads to recognizable characteristic features in soil profiles. These are mirrored in the classification, but not at the highest level (reference soil group).

The forth group (Dominantly anthropogenic soils) contains LC classes in which AI are the dominant soil-forming factors: soils are developed on anthropogenic substrates, or rich in artefacts, mining or construction waste (technogenic soils), their physical-chemical characteristics are considerably influenced by human activities. The soils of these LC classes reflect the AI not only by certain diagnostic features indicating anthropogenic activities, but the WRB reference groups itself, in which most belong, are anthropogenic by definition (Anthrosols and Technosols). We included not only residential built up areas, industrial, commercial, and traffic zones, but also recreational facilities and urban green areas, because their soils have usually been filled in with mixed material from often distant areas making the natural soil horizon development unrecognizable.

Once we had linked CORINE classes and soil diagnostic features, we reclassified the CORINE LC polygons (2018 dataset, scale 1:100 000, in ETRS 1989, Lambert azimuthal equal-area (LAEA) projection) in ArcGIS 10.4.1, assigning a naturalness class to each CORINE land cover category. This resulted in a current soil naturalness map of Europe. To reveal changes in soil naturalness across Europe, the LC Changes datasets of CORINE (CLCC) were used. These contain information on polygons, in which the LC classes of two consecutive CORINE LC maps differs, i.e. LC change was detected. To each LC conversion, polygon information about the initial LC and the change class was assigned. This was done to assess whether the LC conversion resulted in a considerable change in soil naturalness between survey periods. If the LC class before and after the LC change was still in the same soil naturalness group, no soil naturalness change was assumed. If the LC change re-

Table 2
Soil naturalness grades of European soils produced by assigning WRB diagnostic features to CLC100 CORINE land-cover classes.

Soil naturalness grades	Land cover classes (CLC100)	Applicable diagnostic features according WRB 2014 indicating anthropogenic influences		
		Reference groups	Diagnostic horizons, properties and materials	Qualifiers
No soils	1.3.1 Mineral extraction sites 3.3.5 Glaciers and perpetual snow 5.1.1 Water courses 5.1.2 Water bodies 5.2.1 Coastal lagoons 5.2.2 Estuaries 5.2.3 Sea and ocean	–	–	–
Dominantly natural or close to natural soils	3.1.1 Broad-leaved forest 3.1.2 Coniferous forest 3.1.3 Mixed forest 3.2.1 Natural grasslands 3.2.2 Moors and heathland 3.2.3 Sclerophyllous vegetation 3.2.4 Transitional woodland-shrub 3.3.1 Beaches, dunes, sands 3.3.2 Bare rocks 3.3.3 Sparsely vegetated areas 3.3.4 Burnt areas 4.1.1 Inland marshes 4.1.2 Peat bogs 4.2.1 Salt marshes 4.2.2 Salines 4.2.3 Intertidal flats	–	–	–

Table 2 (*Continued*)

Soil naturalness grades	Land cover classes (CLC100)	Applicable diagnostic features according WRB 2014 indicating anthropogenic influences		
		Reference groups	Diagnostic horizons, properties and materials	Qualifiers
Soils with significant anthropogenic influences	2.1.1 Non-irrigated arable land 2.1.2 Permanently irrigated land 2.1.3 Rice fields 2.2.1 Vineyards 2.2.2 Fruit trees and berry plantations 2.2.3 Olive groves 2.3.1 Pastures 2.4.1. Annual crops associated with permanent crops 2.4.2 Complex cultivation patterns 2.4.3 Land principally occupied by agriculture, with significant areas of natural vegetation 2.4.4 Agro-forestry areas	Anthrosol	Anthraquic horizon Hortic horizon Hydragric horizon Irragric horizon Terric horizon Anthric properties	Anthraquic Anthric Aric Densic [a] Drainic Escalic Hortic Hydragric Irragric Murshic Relocatic Terric
Dominantly anthropogenic soils	1.1.1 Continuous urban fabric 1.1.2 Discontinuous urban fabric 1.2.1 Industrial or commercial units 1.2.2 Road and rail networks and associated land 1.2.3 Port areas 1.2.4 Airports 1.3.2 Dump sites 1.3.3 Construction sites 1.4.1 Green urban areas 1.4.2 Sport and leisure facilities	Anthrosol Technosol	Hortic horizon Terric horizon Anthric properties Artefacts Technic hard material	Anthric Archaic Densic [a] Drainic Ekranic Garbic Hortic Hyperartefactic Isolatic Linic Relocatic Spolic Technic Toxic Transportic Urbic

[a] May be result of both, natural and anthropogenic processes.

sulted in a soil naturalness class change, increasing or decreasing human impact on soils was assumed. From the initial and resulting LC classes of conversions we compiled a LC change matrix (Table 3).

The CLCC polygons were then reclassified according to this matrix (Table 3) in the GIS, and plotted separately for each change period (1990–2000, 2000–2006, 2006–2012, and 2012–2018). LC changes were assigned to three different possible directions according to their influence on soil naturalness. In Table 3, zero (0) indicates LC conversions where no significant changes in order of soil naturalness are expected. LC conversions where the degree of anthropogenic influence (and therefore number of anthropogenic diagnostic features in soil) is expected to increase were marked with +1, those where anthropogenic influence is expected to decrease was marked with −1. These changes are obvious when natural or semi-natural vegetation is converted to cultivated land, or when artificial surface cover elements appear. In the opposite case, when cultivated land was abandoned (and as soil regeneration starts), the diagnostic change in soils was not as evident, and might remain only a potential change. However, numerous studies show, that the regeneration of soils after abandonment takes place in particular cases much more rapidly than expected (Kalinina et al., 2015). Within a few years or decades soil recovery was obvious due to a decrease in nutrient contents (Kalinina et al., 2009; Oktaba & Kusińska, 2012), increased carbon sequestration (Carolan & Fornara, 2016; Devine et al., 2014; Kalinina et al., 2013; Wertebach et al., 2017; Zhao et al., 2015), increased aggregate stability (An et al., 2013), and an emerging formation of soil horizons (Kalinina et al. 2013, 2014). The extent of LC changes with increasing, decreasing and unchanged intensity of anthropogenic influences on soils was aggregated to country level (resulting in a change area in km^2) and

Table 3
Evaluation matrix of LC changes in order of the soil naturalness grade.

CORINE LC classes	after conversion	(1.3.1)(3.3.5) (5.1.1)(5.1.2) (5.2.1)(5.2.2) (5.2.3)	(1.1.1)(1.1.2) (1.2.1)(1.2.2) (1.2.3)(1.2.4) (1.3.2)(1.3.3) (1.4.1)(1.4.2)	((2.1.1)(2.1.2) (2.1.3)(2.2.1) (2.2.2)(2.2.3) (2.3.1)(2.4.1) (2.4.2)(2.4.3) (2.4.4)	(3.1.1)(3.1.2)(3.1.3)(3.2.1) (3.2.2)(3.2.3) (3.2.4)(3.3.1) (3.3.2)(3.3.3) (3.3.4)(4.1.1) (4.1.2)(4.2.1) (4.2.2)(4.2.3)
before conversion	**Soil naturalness grade**	**No soils**	**Soils with high intensity of AI (anthropogenic soils)**	**Soils with moderate intensity of AI**	**Soils with low intensity of AI (natural or close to natural soils)**
(1.3.1)(3.3.5) (5.1.1)(5.1.2) (5.2.1)(5.2.2) (5.2.3)	**No soils**	0	−1	−1	−1
(1.1.1)(1.1.2) (1.2.1)(1.2.2) (1.2.3)(1.2.4) (1.3.2)(1.3.3) (1.4.1)(1.4.2)	**Soils with high intensity of AI (anthropogenic soils)**	+1	0	−1	−1
(2.1.1)(2.1.2) (2.1.3)(2.2.1) (2.2.2)(2.2.3) (2.3.1)(2.4.1) (2.4.2)(2.4.3) (2.4.4)	**Soils with moderate intensity of AI**	+1	+1	0	−1
(3.1.1)(3.1.2) (3.1.3)(3.2.1) (3.2.2)(3.2.3) (3.2.4)(3.3.1) (3.3.2)(3.3.3) (3.3.4)(4.1.1) (4.1.2)(4.2.1) (4.2.2)(4.2.3)	**Soils with low intensity of AI (natural or close to natural soils)**	+1	+1	+1	0

0 = unchanged intensity of anthropogenic impacts, +1 = increasing intensity of anthropogenic impacts, −1 = decreasing intensity of anthropogenic impacts.

also expressed as proportion (%) of the country area, separately for each of the investigation periods.

In a final step, we identified European hotspots of soil naturalness change. We defined hotspots as areas of fast increasing or decreasing, severe anthropogenic impact (AI) on soils. A vector grid of rectangular cells with 10 × 10 km resolution was overlaid onto the maps of patches (from the vector layer) with increasing and decreasing AI over the study period in ArcGIS 10.4.1. To each 10 × 10 km cell the number of LU conversions within the cell that showed increasing AI, and the number of patches that exhibited decreasing AI was assigned, for all study periods separately. For both types of change and the four periods (1990–2000; 2000–2006; 2006–2012; 2012–2018) those cells that had larger values than the upper quartile in each period, were defined as hotspots of soil naturalness loss and recovery, respectively. For these hotspots it was then calculated, in how many of the four periods they fulfilled the hotspots criterion according to the definition above. Hotspot grid cells, which were classified as hotspots in more than one period were delimited and mapped. After that, we joined the attributes from grid cell features to patches based on the spatial relationship. Finally, we calculated summary statistics for all fields in a feature class.

6. Results

6.1. Soil naturalness grades 2018

On average, 3.17% of the surface area in the 37 countries included in the study was classified as having ‘no soil‘. Countries with a high cover of glaciers, rocky terrain, and large water bodies reached above-average values in this category, e.g. Iceland, Finland, and Norway (Fig. 3). Soils with little anthropogenic disturbance or transformation (i.e. natural or near-natural soils) were primarily found in Iceland, Norway, Sweden, and in mountain or upland areas (Fig. 2). Moderately disturbed soils prevailed over large areas of intensive agriculture, such as Denmark, Ireland, Netherlands, Hungary, northern France, the UK, Germany, and Poland. Highly transformed soils were concentrated in urban conglomerations, especially in the Benelux states (Online Supplementary Material: Table S1, Fig. S1).

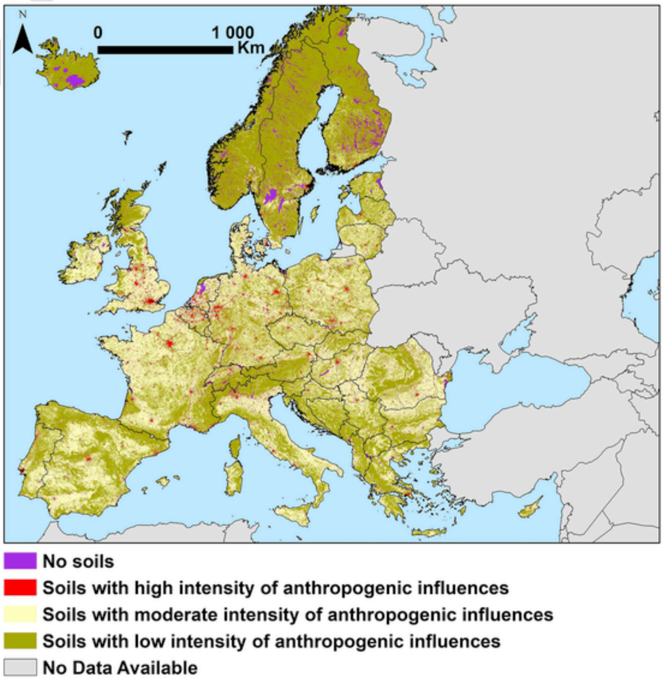

Fig. 2. Spatial distribution of soil-naturalness across Europe around 2018.

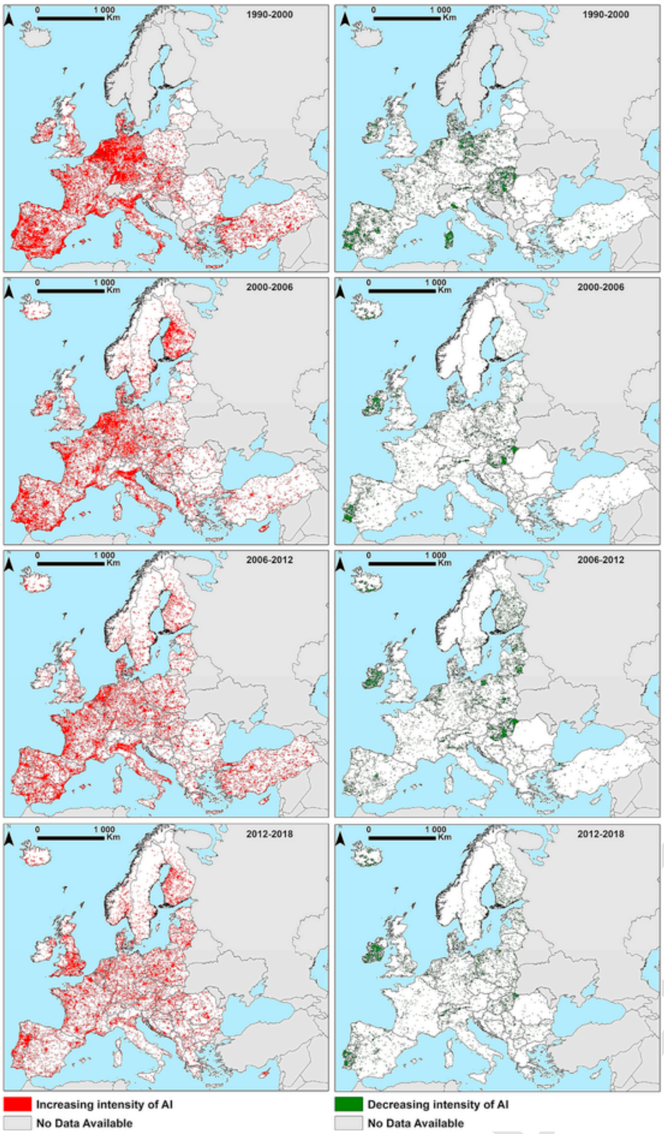

Fig. 3. Spatial patterns of changes in anthropogenic influences (AI) on soils across Europe, for the four periods with increasing AI (left panel) and decreasing AI (right panel).

7. Changes in the intensity of anthropogenic influences on soils since 1990

Total LC changes were highest during the period 1990–2000, when on average 2.68% of the area of all countries included were affected by change. In the following three periods, 2000–2006, 2006–2012, and 2012–2018, the average LC changes were lower (1.37%, 1.34%, and 1.24%, respectively). However, the first period is longer than the second, and only 29 countries were included in the analysis of the first period compared to 38 in the second.

In 1990–2000, nine countries showed an above-average (>2.68%) proportion of areas with any kind (unchanged AI, increasing AI, and decreasing AI summarized) of LC change. The largest LC changes were detected in Portugal, Ireland, and Czech Republic. In 2000–2006, LC changes exceeded the average for the period (>1.37%) in 16 countries (Figs. 3 and 4; Online Supplementary Material: Table S3), with the strongest changes observed in Cyprus, Sweden, and Portugal. In the third period, 2006–2012, LC changes were most pronounced in Sweden, Portugal, and Estonia (Figs. 3 and 4). In 2012–2018, LC changes exceeded the average for the period (>1.24%) in 9 countries (Fig. 4; Online Supplementary Material, Table S3). LC changes with increasing intensity of AI happened on average on 0.39% of the 29 countries in the period 1990–2000.

LC changes with decreasing intensity of AI were 0.15% averaged for the 31 countries between 1990 and 2000, but similarly to total LC changes and LC changes with increasing AI in further three investigated periods it was lower, 0.8% for 2000–2006, 2006–2012, and 2012–2018 periods. The largest relative growth of LC changes with decreasing AI was detected in Hungary, the Netherlands, and Portugal. Between 2000 and 2006, LC changes with decreasing intensity of AI were especially pronounced in Ireland, Hungary, and Portugal. In the last period, the share of LC with decreasing intensity of AI reached or exceeded the average value (0.12%) in eight countries (Fig. 4, Online Supplementary Material: Table S3).

Summarized over the four investigation periods, LC changes with increasing human impact on soils were highest in the Netherlands, Portugal, and Cyprus, and lowest in Sweden, Norway, and Switzerland. Decreasing intensity of anthropogenic influence was most pronounced in Portugal, Hungary, and the Netherlands. The smallest areas of this sort of LC changes were detectable in Sweden (0.01%), Norway (<0.01%), and Liechtenstein (<0.01%) (Fig. 4, Online Supplementary Material: Table S2, Table S3).

The largest part of LC changes in most of the covered countries was neutral concerning the grade of anthropogenic influences. Across all countries, a total of 346320.24 km^2 (5.85% of the investigated area) was subject to LC change between 1990 and 2018. LC changes indicating decreasing human impacts on soil were identified on 14247.6 km^2 (0.24% of the study area), and at country level it was dominant only in few countries, such as Iceland and Switzerland. Summed up, on 42744.2 km^2 (0.72% of the study area) LC changes with increasing human impacts were detected. Only in a few countries (e.g. in Netherlands, Malta, Liechtenstein), the LC changes with increasing anthropogenic impact exceeded the proportion of LC changes classified as neutral concerning the intensity of anthropogenic influences.

8. Hotspots of soil naturalness change between 1990 and 2018

The number of 10 × 10 km cells with a higher number of CLCC polygons than the upper quartile value (hotspots) for both increasing and decreasing AI for all four investigated periods are shown in Table 4.

The consistency of increasing and decreasing AI change through the four periods was variable, with a large proportion of the grid cells being classified as part of a hotspot in only period. The number of single and multi-period hotspots of increasing and decreasing AI are counted in Table 5.

Decreasing human impact on soils during all four investigated periods was detected in the following areas: Longjökull, Hofsjökull, Vatnajöküll, and Skaftatell, areas surrounding large glaciers in Island), the Finnish Lake District, the Irish Plain, Munister (Ireland), Friesland (Netherlands), the North Frisian Islands, Saarland, Lausitz (Germany), the North Bohemian Basin (Czech Republic), Nyírség, Kiskunság (Hungary), the Eastern Alps (Austria, Switzerland, Italy), Lombardy, and Sardinia (Italy), Castile (Spain), Alentejo, and Algarve (Portugal) (Fig. 5b).

9. Discussion

Landscape changes follow polarizing trends across Europe: rural outmigration and increasing urban conglomerations, and land abandonment in marginal areas versus land-use intensification on productive land. Often, a loss of landscape functions and landscape degradation is associated with this polarization (Antrop, 2004; Sluis et al., 2019; Stürck et al., 2015). The mentioned processes are driven by distinct combinations of political, institutional, cultural, and natural forces (Plieninger et al., 2016). EU policies have direct or indirect ef-

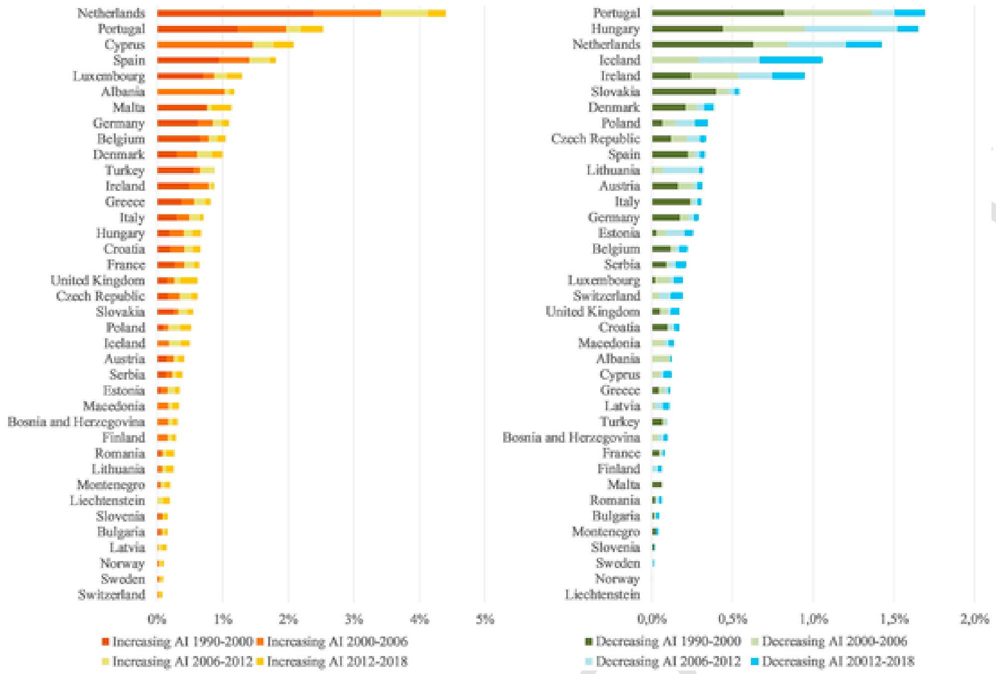

Fig. 4. European countries ranked by the proportion of their area affected by increasing and decreasing anthropogenic influence on soils in the periods 1990–2000, 2000–2006, 2006–2012, and 2012–2018 based on CORINE land cover data.

Table 4
Count of hotspot cells of increasing and decreasing AI in the 4 studied period.

Period	CLCC polygons with increasing AI		CLCC polygons with decreasing AI	
	Value of the upper quartile of polygons within 10 × 10 km cells	Count of 10 × 10 km cells with number of CLCC polygons > upper quartile (hotspots of anthropization)	Value of the upper quartile of poygons within 10 × 10 km cells	Count of 10 × 10 km cells with higher number of CLCC polygons than the upper quartile (hotspots of rewilding)
1990–2000	5	3949	3	1283
2000–2006	4	4315	2	1260
2006–2012	4	3809	2	1677
2012–2018	3	3022	2	1096

Table 5
Number of 10 × 10 km cells classified as hotspot in one or and multiple periods.

Number of studied periods, in which the 10 × 10 km cell were classified as hotspots	Count of 10 × 10 km cells were classified as hotspots	
	of increasing AI	of decreasing AI
1 ×	6351	2855
2 ×	2211	649
3 ×	1010	297
4 ×	323	68

fects on landscape changes, e.g. via agricultural subsidies (Kay et al., 2019; Klijn, 2004, pp. 201–218; Prokopová et al., 2018; Sluis et al., 2019). A change of soil naturalness is both a component and a consequence of land-cover and land-use change, requiring mitigation through governance and management (Panagos et al., 2016).

In our study, an increasing human impact on soils was obvious in dynamic urban regions and regions with a high degree of recent urbanization (i.e. fringes of urban agglomerations, most of the capitals and harbor towns), and along infrastructural networks such as highways (Fig. 5a). Changes were likely driven by various combinations of socio-economic drivers, such as urbanization, economic structural changes, and agricultural intensification (Prokopová et al., 2018). Hotspots proved to be the developing urbanization centers around larger cities, often in Western Europe. Hotspots of decreasing soil naturalness change included areas of intensifying agricultural use (e.g. in Northern Italy), area of deforestation, and regions with infrastructural and economic sprawl e.g. in the Oulu-region, Finland (Country Fact Sheet, 2017).

The extent of areas with reduced intensity of human impacts on soils increases in many European regions (Csorba, 2000, pp. 185–197). The hotspots analysis suggested that there were numerous regions of Hungary, Ireland, Portugal, Iceland, and Italy where anthropogenic influence on soils decreased consistently over several CORINE periods. The determinants of these changes vary strongly between regions. In Hungary, abandonment of arable land was driven by reorganization and abandonment of agriculture on lower quality soils (Csorba, 2000, pp. 185–197). In Ireland, extensive afforestation of former arable fields has been continuing since the middle of 20th century (Whelan, 1997), and was driven by EU forestry policies during the last decades (Forest-Statistics Ireland 2019). In the Mediterranean region the abandonment and transformation of traditionally managed olive groves to other uses was observed in Portugal (Nunes et al., 2012), Sardinia (Balestrieri & Ganciu, 2018) and in Greece (Loumou & Giourga, 2003). Land abandonment that leads to post-agricultural self-restoration of soils is now a process observed across large areas in several European regions (Leal Filho et al., 2017; Navarro & Pereira, 2015, pp. 3–23; Renwick et al., 2013.; Schnitzler, 2014). 'Rewilding' trends driven by agricultural abandonment and rural outmigration pose challenges to landscape planning and man-

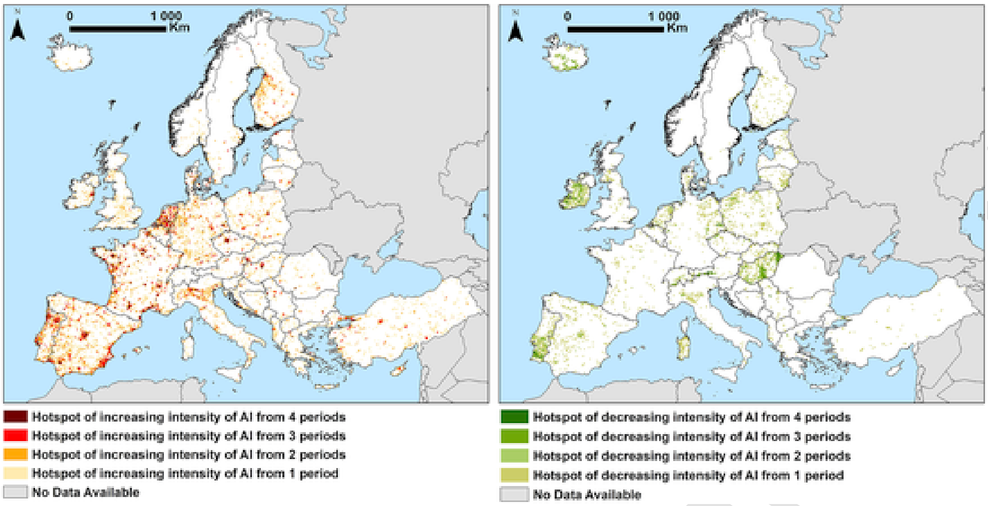

Fig. 5. Hotspots of increasing (left panel) and decreasing (right panel) intensity of AI in one or more of the study periods.

agement in peripheral regions (Pelorosso et al., 2011), with consequences for soil development (An et al., 2013).

Our approach to estimate soil naturalness and changes therein has its limits, because we assumed that land-cover change is the main driver of soil naturalness change. Other factors also affect soil naturalness, such as pollution (Horváth et al., 2018) or changes of groundwater level, and salinization (Ladányi et al., 2016). However, land-cover data often mirror land-use practices (Jie Chen, 2007; Marcotullio et al., 2008, pp. 201–250), which in turn affect soils (Sun et al., 2001; Blum, 2008, pp. 5–10). Soil property and soil- or environmental risk assessments also successfully used CORINE LC data (Bajocco et al., 2012; Bucała et al., 2015; Gardi et al., 2015; Pilaš et al., 2013; Yigini & Panagos, 2016). Furthermore, while some features of anthropogenic influence such as structural compaction, horizon mixing and topsoil depletion are immediately evident in soil profiles, pedogenesis (soil formation, the appearance of horizons) takes decade or more. Therefore, there will also be legacies of land-use changes that will further affect soil formation, suggesting that soil monitoring in the field is still useful despite our advances to remotely identify hotspots of soil change. CORINE data proved a useful tool for comparisons between countries with considerable different natural conditions. Several analyses have found that CORINE LC changes are well explained by changing land use and landscape characteristics on the ground (Olah et al., 2009).

10. Conclusions

Our approach seems justified to analyse soil naturalness change across Europe, at least on a country-wide and European scale. Local case studies that aim at ground-truthing our hotspot analyses, and perhaps include other potential drivers of soil naturalness change except land cover change, seem worthwhile. We show here that on large spatial scales, combining CORINE data and soil classification information can successfully identify hotspots of soil naturalness change.

We assume that our approach underestimates the extent of area affected by human activities. This is because we use LC data of the present period and not historic land cover data. In many cases, formerly strongly influenced areas (cultivated lands, settlements etc.) were abandoned, and are now subject to spontaneous revegetation (Mendyk et al., 2016). In these cases, current land cover hides the formerly more intense anthropogenic impact on soils. Field surveys and soil profile description could reveal anthropogenic soil features in such cases. Because such detailed soil information in higher spatial resolution is currently lacking, our approach seems useful on larger scales for a first assessment of soil naturalness, its spatial variability and temporal changes.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apgeog.2020.102294.

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