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High resolution mapping of topsoil properties in the Western Balkans using the LUCAS soil survey

Authors:

Cristina Arias-Navarro[1], Bexhet Islamaj[2], Dragana Vidojevic[3], Pandi Zdruli[4], Felipe Yunta-Mezquita[1], Panos Panagos[1], Piotr Wojda[1], Arwyn Jones[1]

[1] European Commission, Joint Research Centre (JRC), Ispra, Italy

[2] Geoinformation Centre for the Western Balkans, Tirana, Albania

[3] Environmental Protection Agency, Republic of Serbia

[4] Mediterranean Agronomic Institute of Bari, Italy

Correspondence email:

Cristina.ARIAS-NAVARRO@ec.europa.eu

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Abstract

The Western Balkans are undergoing rapid socio-economic and environmental change as national policies converge with those of the European Union (EU). In line with the EU Soil Monitoring Law, a robust, spatially explicit baseline of soil health is required to support both national decision-making and the region's EU accession process. This study presents the first EU-wide comparable, high-resolution (500 m) digital soil maps for five Western Balkan countries (Albania, Bosnia-and-Herzegovina, Montenegro, North Macedonia and Serbia).

A total of 955 field-sampled points from the Land Use and Cover Area frame Survey (LUCAS) soil campaign were analysed for pH (H_2O and $CaCl_2$), electrical conductivity, organic carbon, carbonate, phosphorus, total nitrogen, extractable potassium, cation exchange capacity and texture fractions (clay, sand, silt, coarse fragments). Gaussian Process Regression (GPR) was selected because it provides a statistically rigorous framework for (i) integrating the same set of ancillary covariates used in EU-wide soil mapping, thereby ensuring methodological comparability, and (ii) delivering full predictive-variance surfaces alongside the mean predictions. Results reveal distinct regional gradients and identify the dominant environmental drivers of soil variability across the Western Balkans.

The generated maps constitute a comprehensive baseline for monitoring soil quality, informing agro-environmental research, and guiding policy development in the context of EU enlargement.

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Graphical Abstract

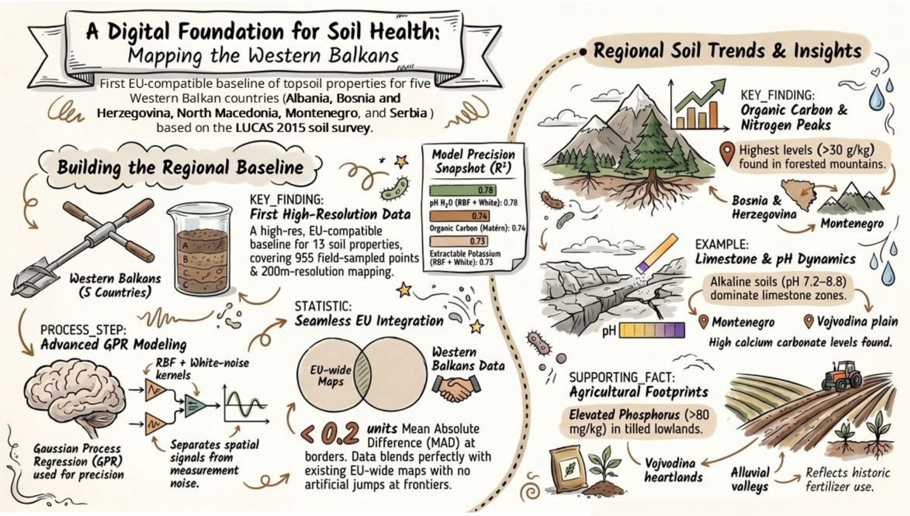

Image generated using NotebookLM and subsequently modified by the authors.

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1. Introduction

The European Union (EU) is fully committed to the integration of the Western Balkans, a region comprising six countries—Albania, Bosnia and Herzegovina, Kosovo[1], Montenegro, North Macedonia, and Serbia—progressing at different speeds toward EU membership (De Munter, 2024). A crucial aspect of this integration process is the alignment with EU environmental and climate policies, notably chapter 27 of the EU acquis, which covers environmental protection and climate change (Belis *et al.*, 2024). The Green Agenda for the Western Balkans is a strategic framework adopted in 2020 to drive climate neutrality and environmental sustainability in the region by 2050. It focuses on five key pillars: climate action, clean air, clean water, clean land, and a healthy environment, which are aligned with the ambitions of the European Green Deal (EC, 2020). Soil health is central to this agenda, aligning with the EU's Soil Strategy for 2030 and the Soil Monitoring and Resilience Directive which aims to enhance soil protection, remediation, and sustainable management practices (EC, 2025). This Directive provides an opportunity for the Western Balkan countries to harmonize their soil policies with those of the EU (Arias-Navarro *et al.*, 2025).

The Land-Use/Cover Area frame Survey (LUCAS) provides the most extensive harmonised soil observation network in Europe, yet many peripheral regions including the Western Balkans, remain unmapped at continental resolution (Arias-Navarro *et al.*, 2026). The European Commission's Joint Research Centre (JRC) under its enlargement and integration programme, launched the first soil sampling campaign in the Western

[1] This designation is without prejudice to positions on status and is in line with United Nations Security Council resolution 1244 and the International Court of Justice opinion on the Kosovo declaration of independence.

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Balkans in 2015 (LUCAS WB 2015). This campaign collected soil samples from Albania, Bosnia and Herzegovina, North Macedonia, Montenegro, and Serbia (Arias-Navarro *et al.*, 2024, 2026). The LUCAS WB 2015 soil dataset provides a versatile foundation for a range of applications, from evaluating soil health and ecosystem services to calibrating land-surface and climate models (Arias-Navarro *et al.*, 2026). Within the EU, LUCAS soil data are most frequently employed to model soil-related properties at regional scales (Panagos *et al.*, 2022b). Digital-soil-mapping (DSM) techniques have become the preferred means of delivering spatially explicit soil information to researchers, policy-makers and industry sector (Chen *et al.*, 2022; Lagacherie, 2025) . Gaussian Process Regression (GPR) is a particularly powerful statistical approach for DSM, offering flexible non-linear modelling and explicit quantification of prediction uncertainty (Wang *et al.*, 2024). Using the LUCAS top-soil database for the EU together with GPR, (Ballabio *et al.*, 2016, 2019) produced EU-wide maps of physical and chemical soil properties. The present study adapts their EU methodology to the Western Balkans, a region characterised by marked lithological, climatic and land-cover heterogeneity. By combining the LUCAS WB 2015 observations with GPR, we generate pan-Western-Balkan maps of top-soil attributes, each accompanied by quantitative uncertainty estimates and a fully reproducible suite of GIS products.

2. Materials and Methods

2.1. Study area and reference data

The LUCAS topsoil survey is the soil-sampling component of the EU-wide Land Use/Cover Area frame Survey (LUCAS). It was introduced in 2009 to create a harmonised, pan-European dataset of the physical, chemical and biological properties

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of the uppermost 0–20 cm of soil (Orgiazzi *et al.*, 2018). LUCAS topsoil run in 2009 (2012 for Bulgaria and Romania), 2015, 2018 and 2022 with around 20,000 samples analysed in each campaign. The European Commission's Joint Research Centre (JRC) under its enlargement and integration programme, launched the first soil sampling campaign in the Western Balkans in 2015. The study area comprises five Western Balkans countries, covering Albania, Bosnia and Herzegovina, Montenegro and North Macedonia and Serbia. Within this region, 955 soil sampling points were collected during the LUCAS 2015 soil campaign of which 337 points (≈ 35.3 %) were located in cropland, 344 points (≈ 36.0 %) in woodland, 72 points (≈ 7.5 %) in shrubland, 196 points (≈ 20.5 %) in grassland and a marginal 6 points (≈ 0.6 %) in other land-cover types (Arias-Navarro *et al.*, 2026)(Figure 1).

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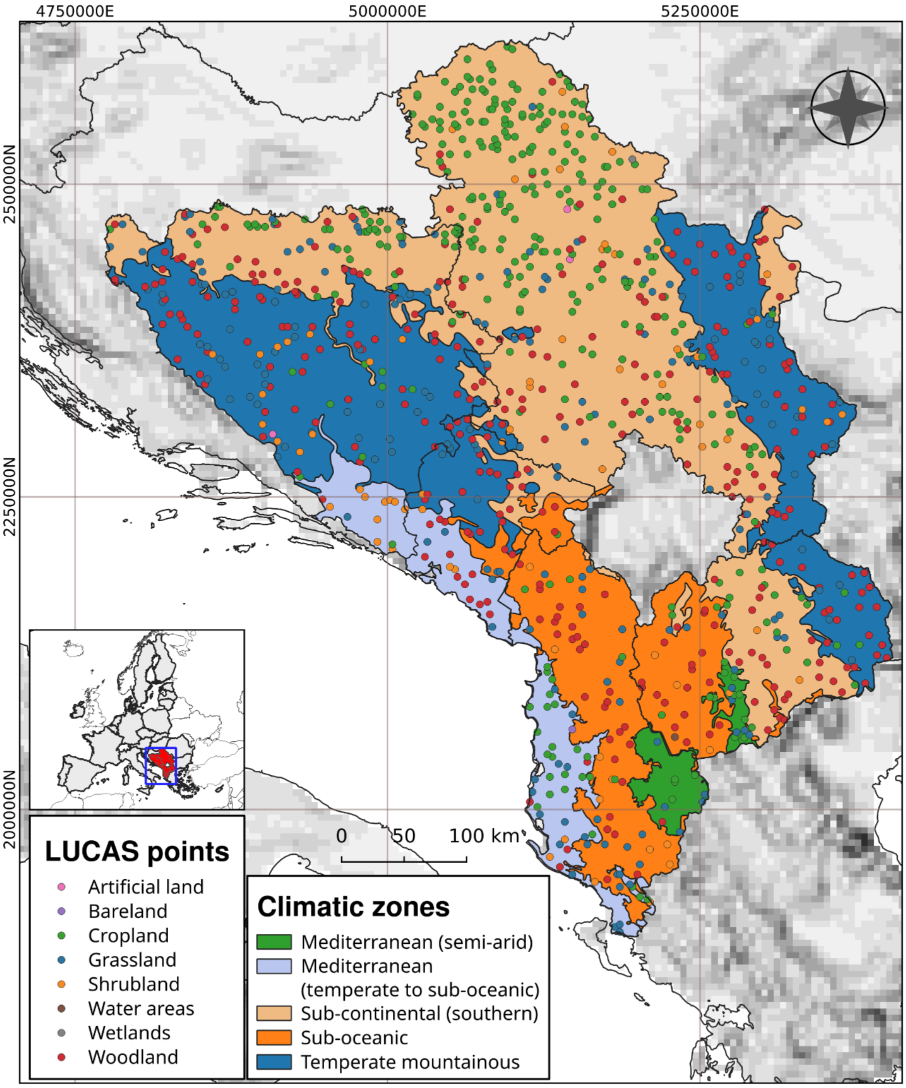

Figure 1 Distribution of sampling points in Western Balkans

2.2 Modelling workflow and used covariates

To create detailed maps that illustrate the distribution and characteristics of topsoil properties across the Western Balkan Countries we rely on Gaussian Process

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Regression (GPR), as specified in Ballabio et al 2019 for the EU. GPR was performed with two alternative covariance functions (Kuok *et al.*, 2025). The first is the Radial Basis Function (RBF) kernel, also known as the squared-exponential kernel, which assumes an infinitely differentiable underlying function and therefore yields very smooth predictions. The second is the Matérn kernel, a more flexible generalisation of the RBF that introduces an additional smoothness parameter (v). By varying v, the Matérn kernel can represent functions ranging from rough (v = ½, equivalent to an exponential kernel) to increasingly smooth (v → ∞, converging to the RBF) (Ballabio *et al.*, 2019). Both kernels were evaluated in the modelling workflow to assess the impact of the smoothness assumption on the prediction of soil chemical properties. Supplementary Information (SI) describes the methods and kernels applied in the given code, explaining the optimization processes and the choices for kernels used to achieve optimal results. Five well-documented Python scripts are also provided, detailing the chosen kernel and its corresponding parameters, predicting the chemical properties, predicting the grid of points, making spatial and statistical analysis and QA/QC of the predicted data and maps.

Table 1. Overview of covariates used

Covariate	**Variables**	**Source**
NUTS-2 boundaries	Statistical reporting units; used for spatial joins.	Eurostat
Country borders	Clipping and country-level aggregation.	GADM
Climatic zones	Primary driver of soil chemistry (acidification, leaching).	National climatology agencies
Pedoclimate zones	Combines parent material and climate; provides WRB codes.	National soil agencies

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CORINE-CLC 2018	Land-cover influences organic matter and nutrient cycling.	Copernicus
Digital Elevation Model (DEM)	Elevation (POINT_Z) and derived terrain indices (slope, valley-bottom flatness).	Copernicus (30 m)
MODIS reflectance (bands 1-7, 2009)	Principal-component-derived vegetation indices (NDVI, EVI) capture biomass and moisture.	NASA
WorldClim bioclimatic variables	Temperature and precipitation gradients.	WorldClim v2.1 (1 km)

A regular point grid with 500 m spatial resolution was created over the study extent (≈ 480 000 points). For each grid point a spatial join retrieved all covariate values (Table 1), yielding a feature vector x. All covariates were re-projected to EPSG:4326 and resampled to a common 250 m grid (the compromise between MODIS 500 m, DEM 25 m and WorldClim 1 km resolutions). The resulting matrix X constitutes the input for GPR.

The modelling workflow employed the 955 LUCAS points as the reference dataset, of which 80 % were allocated to a training set and the remaining 20 % were held out as an independent validation set; the split was performed in a stratified manner with respect to CORINE land-cover classes to preserve the proportional representation of the main land-use types. During hyper-parameter optimisation a repeated ten-fold cross-validation (k = 10) was applied, allowing the estimation of model stability across multiple data partitions. Model performance was assessed using the root-mean-square error (RMSE), mean absolute error (MAE) and the coefficient of determination (R^2). For each raster cell of the study area the posterior mean and variance of the predicted chemical property were derived, yielding a mean raster that was subsequently

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resampled to a 200 m resolution and a variance raster that quantifies prediction uncertainty and was employed for continuity checks across the map.

The predicted values, together with the original measured points, were first transformed into Thiessen (Voronoi) polygons, each polygon inheriting the chemical attribute of its seed point. Polygons intersecting areas outside the WB5 domain, as well as water bodies, urban zones and transport networks, were subsequently removed by clipping with the CORINE land-cover and hydrography layers. The resulting clean polygon layer was then rasterised to GeoTIFF format at a spatial resolution of 200 m × 200 m, with each raster band containing the mean predicted value of a single chemical property.

2.3 Comparative Analysis of Western Balkans and EU-Level Soil Property Results

Standardised colour ramps, identical to those employed in the EU-wide LUCAS maps (Ballabio *et al.*, 2016, 2019), were applied enabling straightforward visual comparison with the broader European dataset. To verify that the newly generated soil-property layers for the Western Balkans blend seamlessly with the existing EU-27 LUCAS-derived products (Ballabio et al., 2016, 2019), a systematic edge-effect analysis was carried out. Raster values for each variable were extracted at a 1-km buffer on either side of the political frontiers that separate the study area from the neighbouring EU-27 cells. For each property the mean absolute difference (MAD) between the Western-Balkan values and the corresponding LUCAS values was then calculated.

3. Results

3.1. Model performance

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The RBF + White kernel consistently outperformed the Matérn kernel for properties with strong measurement noise (pH, EC, carbonate, P, K, CEC). The additive white-noise component allows the model to separate genuine spatial signal from laboratory variability, resulting in lower RMSE and more stable optimisation (see SI). The Matérn kernel delivered marginally better results for smoother, texture-related variables (OC, N, sand, silt). Its flexibility in controlling smoothness (ν parameter) is advantageous when the underlying process exhibits intermediate roughness.

Table 2 Summary of the performance of the two kernels for each soil property.

Property	**Best kernel**	**RMSE**	**MAE**	**R^2**
pH H_2O	RBF + White	0.67	0.44	0.78
pH $CaCl_2$	RBF + White	0.69	0.46	0.76
Electrical Conductivity	RBF + White	0.91	0.63	0.71
Organic Carbon	Matérn	0.69	0.48	0.74
Carbonate	Matérn	0.88	0.61	0.62
Phosphorus	RBF + White	0.91	0.58	0.70
Total Nitrogen	Matérn	0.73	0.51	0.68
Extractable Potassium	RBF + White	0.89	0.57	0.73
Cation Exchange Capacity	RBF + White	0.80	0.55	0.69
Clay %	RBF + White	0.78	0.51	0.71
Sand %	Matérn	0.67	0.44	0.73
Silt %	Matérn	0.74	0.48	0.70
Coarse Fragments	Matérn	0.86	0.60	0.66

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While both kernels enable GPR to perform well (Table 2), the RBF+White Kernel demonstrates superior performance overall. As a result, the maps and final predictions presented in this study are based on the RBF+White Kernel combination.

3.2. Prediction uncertainty

Another aspect of the analysis involves comparing the predicted values with the trained values. While these values are not expected to be identical, they should converge. To verify this, a spatial joint was performed between each predicted point and the nearest trained point (955 points from the LUCAS WB database). This allows for an assessment of how the predicted values compare to the training data (Tyralis & Papacharalampous, 2024). The analysis reveals that most predicted values are closely aligned with their corresponding trained values, with some variations (SI). The mean prediction-variance across the region is 0.12 units for pH H_2O and 0.21 units for EC. A limitation of the training data concerns the absence of several categorical levels, which is attributable to the modest sample size. The presence of unseen WRB and pedoclimate classes introduces localized uncertainty, especially in the Dinaric-Alpine sector where codes such as ‘CH’, ‘AB’ and ‘HS’ are common. The lack of training observations for these categories reduces the statistical power of the GPR model in the corresponding grid cells, leading to higher prediction variance and lower reliability for those locations, as reflected in the variance raster. Although the attributes were retained because they convey valuable environmental information, users should interpret predictions for cells belonging to the unseen categories with caution. Future LUCAS sampling campaigns are recommended to target these under-represented WRB and pedoclimate classes in order to enhance the robustness and accuracy of the spatial predictions. Variance

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rasters (SI) reveal higher uncertainty in mountainous, sparsely sampled zones (e.g. the Dinaric Alps) and in heterogeneous land-cover mosaics (urban–agricultural interfaces).

3.3 Quantitative edge-effect assessment

A systematic edge-effect analysis was performed to confirm that the new Western-Balkan soil-property layers integrate smoothly with the existing EU-27 (+UK) LUCAS products (Ballabio et al., 2019). Values for each soil property were extracted from a 1 km buffer on both sides of the borders, and the mean absolute difference (MAD) was calculated. For all properties the MAD was < 0.2 units, demonstrating a statistically indistinguishable transition and no artificial discontinuities (Rindskopf & Shiyko, 2010). In addition to the numeric edge-effect test, a qualitative continuity check was performed. The final maps were displayed side-by-side with the EU maps for the adjacent EU member states. Particular attention was paid to the alignment of colour classes, the smoothness of isocontours and the absence of abrupt jumps at national borders and at NUTS-2/3 administrative limits. Because LUCAS maps are typically terminated at the outermost national boundary, the continuity assessment focused on the internal borders where the two products meet. A further comparison was undertaken for each chemical attribute to confirm both visual coherence (colour palette alignment) and geographical continuity. The analysis excluded land-cover types that are not represented in the LUCAS soil-property framework – namely urban areas, permanent water bodies and major transport networks – as these were deliberately masked during map production. For the remaining land surface, the colour gradients of the Western-Balkan layers were harmonised to the LUCAS palette by applying the same quantile-based break-points used in the European dataset. This ensured that, for

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example, a pH value of 6.5 is rendered with the identical hue in both the Balkan and the EU maps. All continuity maps (Figures S1 – S8) demonstrate a high degree of spatial consistency with the continental products. The quantitative edge-effect results (MAD < 0.2 units) together with the visual continuity checks confirm that the Western-Balkan layers can be integrated into pan-European analyses without introducing artefacts. This harmonised dataset therefore provides a reliable basis for cross-regional studies of soil quality, land-use change and climate-impact assessments across the whole of Europe.

3.4 Spatial patterns of topsoil properties

3.4.1 Soil Organic Carbon

The map of OC content in the Western Balkan shows the smallest values (10-20 g/kg) in central Serbia, North Macedonia and south-eastern Albania (Figure 2).

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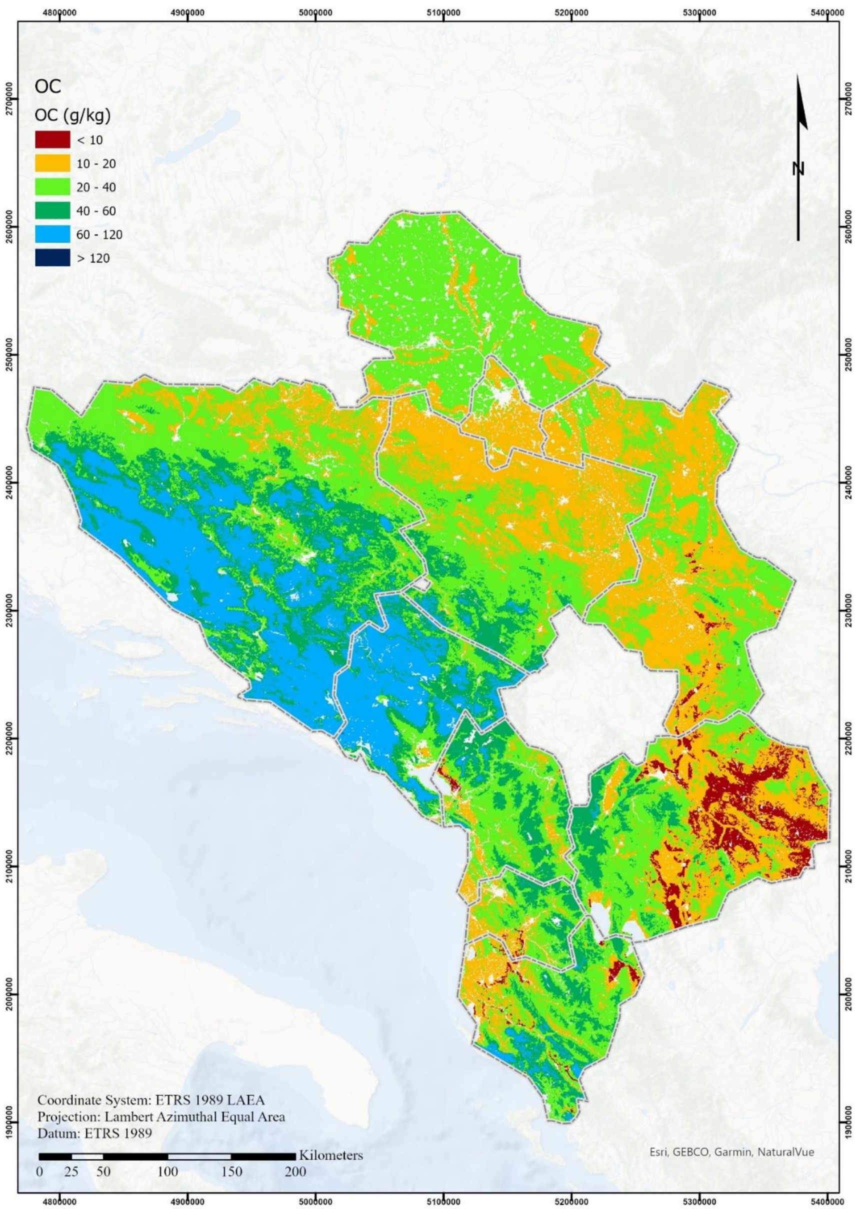

Figure 2 Spatial Distribution of Soil Organic Carbon (OC). The base map was designed and developed by Esri | Powered by Esri.

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The highest concentrations of organic carbon (OC) were recorded in Bosnia and Herzegovina and Montenegro, predominantly on forested slopes and in mountainous catchments. In Montenegro, the prevailing soil type is the limestone-dolomitic black soil (Calcomelanosols), which is characteristically rich in OC and consequently exhibits a high cation-exchange capacity (CEC) (Spalevic, 2024). These soils are mainly covered by natural meadows and pastures, with a smaller proportion allocated to vegetable and field crops such as potatoes, rye, barley and wheat. Conversely, the territory of North Macedonia displays the lowest OC contents in the dataset, a pattern that is strongly modulated by land use. Recent field work in the Ohrid Valley showed that the top-soil layer (0–20 cm) of forest land contains, on average, 6.81 % OC, whereas the same depth under grassland holds only 4.07 % (Mukaetov & Poposka, 2023) . Arable soils that are subject to continuous human disturbance exhibit the most depleted OC stocks, with mean values of 2.5 % under annual field crops and 2.61 % under perennial crops. The North-Macedonian case is representative of a broader West ern Balkan gradient: ecosystems that experience limited anthropogenic pressure (forests, natural pastures and shrublands) accumulate the greatest amounts of OC, whereas intensively cultivated soils that receive little or no organic amendment show a pronounced decline in carbon stocks. A similar trajectory has been documented for the Chernozem soils of Serbia, where several decades of unsustainable agricultural practices have led to a substantial loss of SOC (Marković *et al.*, 2025). Overall, OC concentrations in arable land across the Western Balkans are low, typically ranging between 10 and 20 g/kg. A clear decreasing trend emerges when moving from forested areas (highest OC) to semi-natural pastures and finally to cultivated fields (lowest OC). These observations

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are consistent with the European-wide spatial patterns reported by (de Brogniez *et al.*, 2015), who identified the lowest predicted carbon contents in Mediterranean countries and in regions of France, Germany, Poland, the Czech Republic, Slovakia and Hungary where arable and permanent crops dominate the landscape. Intensive management practices such as frequent tillage, high fertiliser inputs and limited residue return, accelerate the mineralisation of soil organic matter, thereby further reducing OC levels (Just *et al.*, 2023). In summary, the present analysis confirms that the distribution of top-soil OC in the Western Balkans follows the well-established European gradient, with natural, low-intensity land uses acting as carbon reservoirs and intensive agriculture representing a major driver of OC depletion.

3.4.2 Topsoil nitrogen and C:N ratio

The top-soil nitrogen (N) distribution in the Western Balkans closely mirrors that of soil organic carbon (OC).

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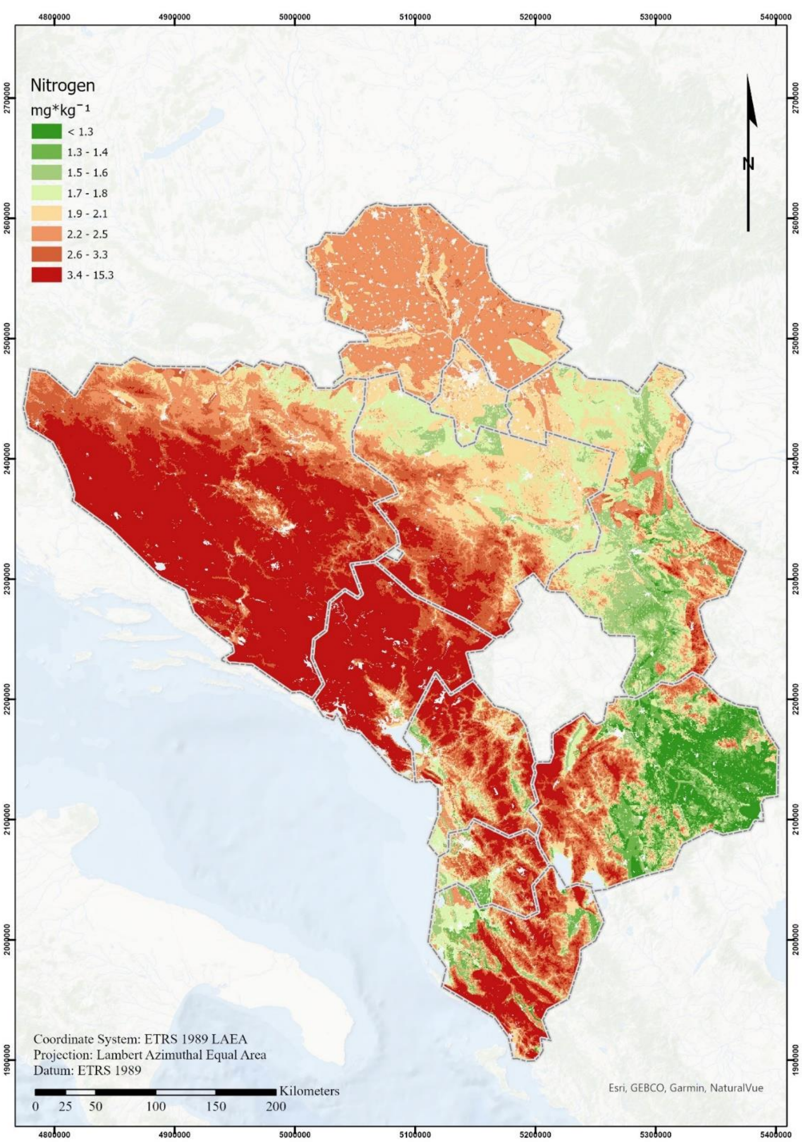

Figure 3 Spatial distribution of Total Nitrogen (N). The base map was designed and developed by Esri | Powered by Esri.

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Figure 3 shows that forests and grasslands, particularly the mountainous forests of Bosnia-Herzegovina, Montenegro and other high-altitude zones, exhibit the highest N concentrations, whereas agricultural soils display markedly lower values. Across the region, soils with higher OC also contain larger N confirming a strong positive correlation between the two variables (Gaudel *et al.*, 2025). The observed CN coupling (Figure 4) can be interpreted through the hierarchical environmental controls described by Gaudel et al. (2025). Clay-rich soils, which dominate many forested catchments, provide organo-mineral protection that stabilises organic matter and maintains C/N stoichiometric balance, whereas the sandier, less protected soils of cultivated areas promote rapid microbial mineralisation and consequently C/N imbalance (Amorim *et al.*, 2022; Islam *et al.*, 2022). Climate further modulates these patterns with higher mean annual temperatures accelerate microbial N demand and decomposition, especially in coarse-textured soils, amplifying N losses in agricultural lands (Dove *et al.*, 2021; Huang *et al.*, 2021).

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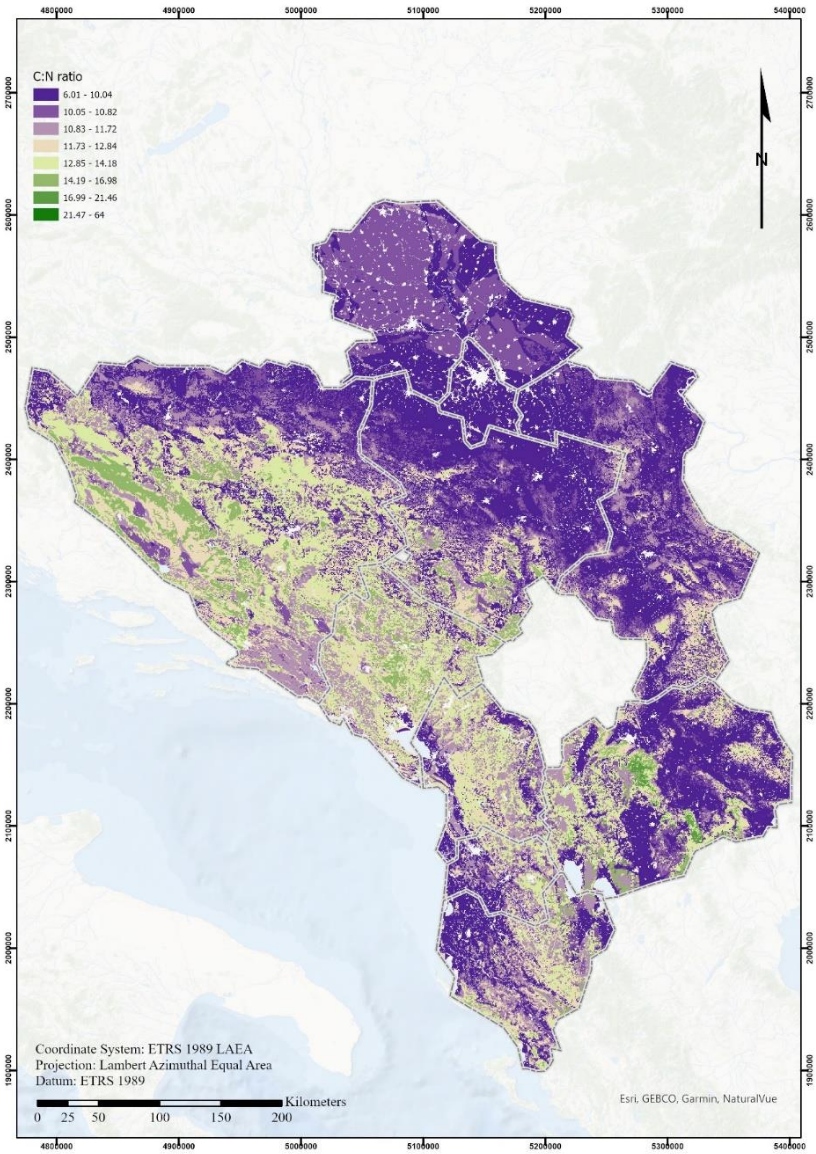

Figure 4 Spatial distribution of C/N ratio. The base map was designed and developed by Esri | Powered by Esri.

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These findings are consistent with broader European observations. Ballabio et al. (2019) reported that EU forests and grasslands generally possess higher N contents than croplands, a pattern echoed in the Western Balkans. Likewise, (Matschullat *et al.*, 2018) demonstrated that the spatial distribution of soil C, N, and C/N ratios across European agricultural soils is primarily driven by natural processes rather than by anthropogenic inputs. When the effect of organic fertiliser application is excluded, the Western Balkan data confirm that vegetation cover, climate, and soil texture are the dominant controls on N distribution, underscoring the limited role of direct human amendments in shaping regional soil N stocks.

3.4.3 Topsoil available phosphorus and extractable potassium

The map of soil available phosphorus (P) distribution in the Western Balkans (Figure 5) shows a clear trend in which land use has a strong influence, with most agricultural areas having higher levels of available P. The higher P content in croplands is indicative of fertilisation, particularly in highly productive soils under intensive cultivation such as the Chernozems of Serbia and the Republic of Srpska and for the low-lying areas of Albania, Bosnia, Montenegro and North Macedonia. This pattern is especially evident in the Vojvodina region of Serbia. Readily accessible P in central Serbia is low, in agreement with previous research indicating that 61 % of soil samples contain low P levels ($\leq$ 60 g kg^{-1}) (Mrvić *et al.*, 2023). These low-P areas are largely covered by forests, meadows and pastures. High total P concentrations are found mainly on Vertisols, alluvial soils and rendzinas (Phaeozems).

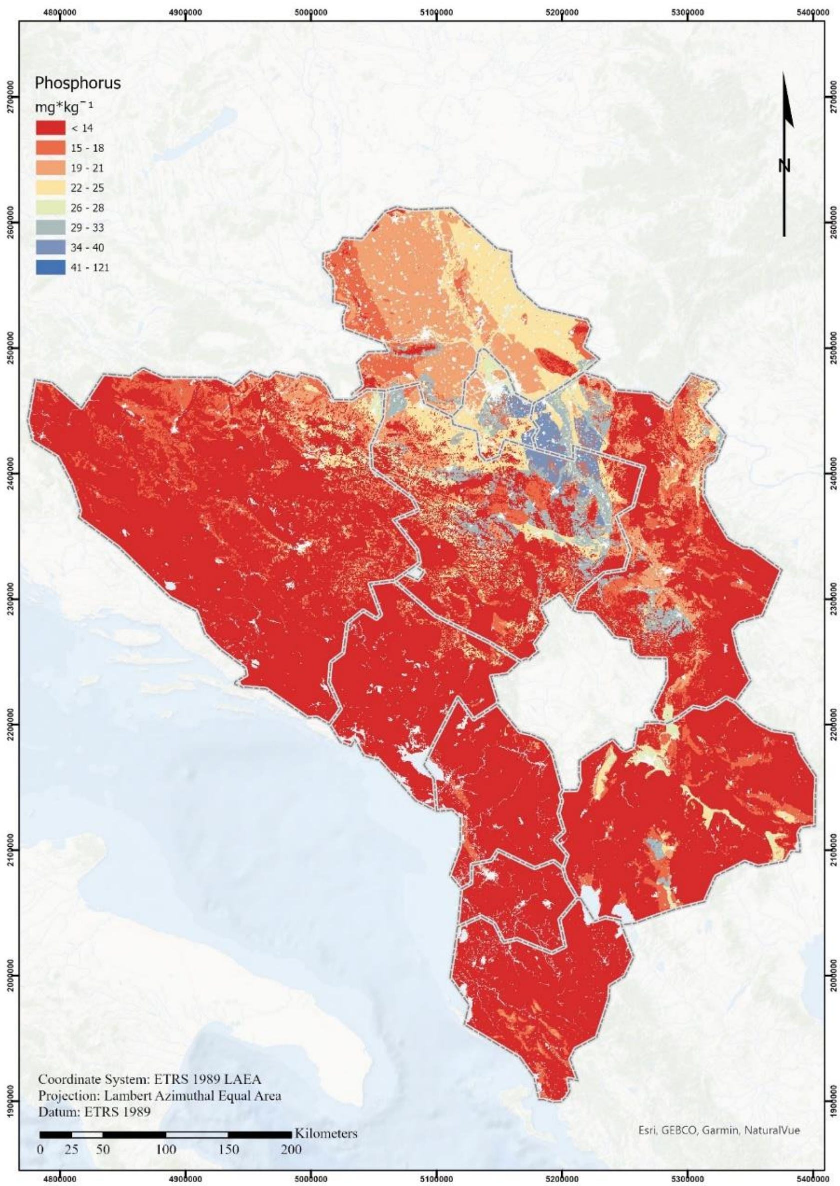

Figure 5. Spatial Distribution of Phosphorus (P Olsen). The base map was designed and developed by Esri | Powered by Esri.

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In general, areas with natural land cover and those dominated by permanent crops have lower available P levels. When compared with EU data, van Eynde et al (2025) report that, using an optimal range of 20-40 mg/kg, 33 % of EU-27 agricultural land has high P, 50 % is within the optimal range and 17 % is low, reflecting historical fertilisation (Sattari et al., 2012; van Dijk et al., 2016). The spatial distribution of current P-management strategies shows large variation between and within countries, with higher P concentrations in northern and central Europe and more heterogeneous, often lower, concentrations in southern and eastern parts. Ballabio (2019) found a similar land-use signal for Italy where most agricultural areas, particularly the Po plain, have higher P than the national average, whereas natural land cover and permanent-crop zones have lower concentrations. In that study climate, rather than geology, was identified as the main driver because wetter regions receive larger fertiliser inputs (Potter *et al.*, 2010). Together, the Western Balkan results, the EU-wide assessments (Ballabio *et al.*, 2019; Panagos *et al.*, 2022a) emphasise that soil types, land use, crop types and fertilisation inputs are the primary determinant of soil P levels. However, the Western Balkans are characterised by generally low baseline P stocks, which may constrain crop productivity over medium and long periods unless targeted fertilisation or soil-amendment strategies are implemented.

The spatial pattern of soil potassium (K) in the Western Balkans (Figure 6) is mainly controlled by the chemistry of the parent material and by climate. Sandy, relatively young soils – for example those found in the northeastern part of the region – show lower than average K concentrations because their coarse texture provides little capacity for cation exchange and because K is easily leached. A similar leaching effect is observed in Portugal and north-western Spain, where higher rainfall intensifies K loss

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from the soil profile (Ballabio et al., 2019). In contrast, soils with a higher proportion of clay retain K more efficiently; consequently, the distribution of K closely follows that of clay content.

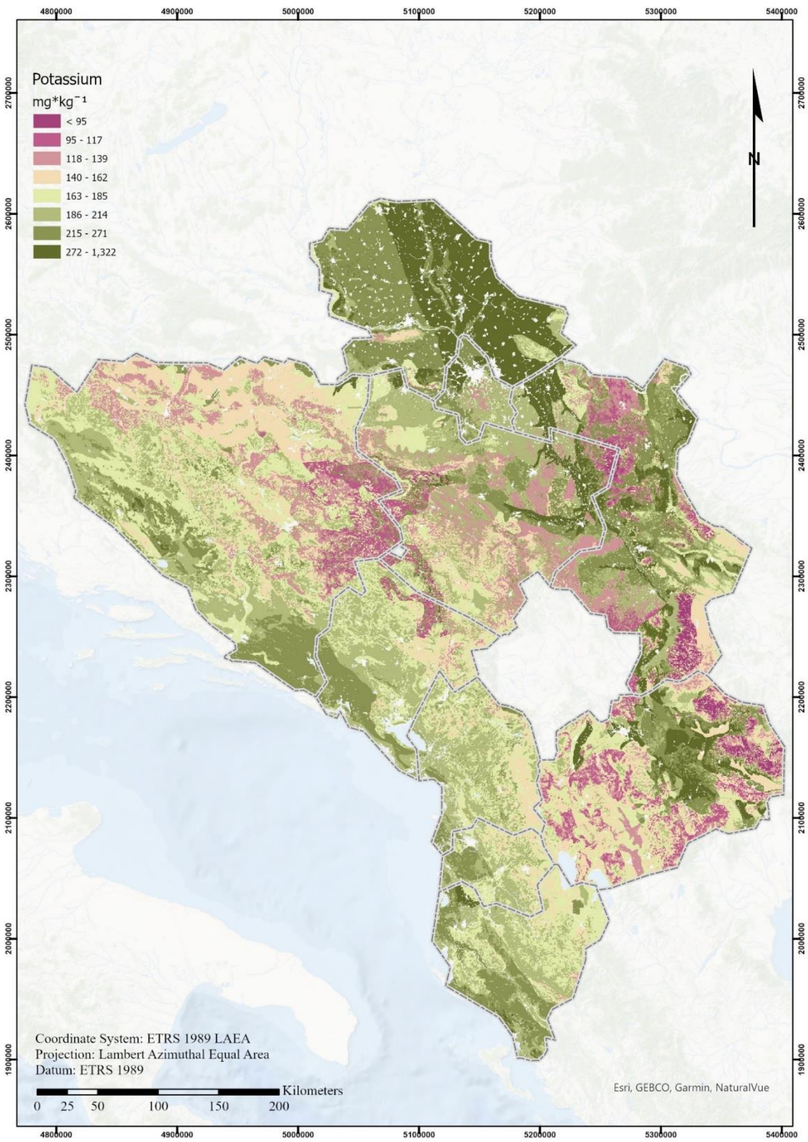

Figure 6 Spatial Distribution of extractable Potassium (K). The base map was designed and developed by Esri | Powered by Esri.

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When the Western Balkan pattern is placed in the broader European context (Ballabio, 2019), several similarities and differences become apparent. Across the EU the overall K status is considerably higher than that of P, yet distinct low-K zones are still present (Ballabio *et al.*, 2019). In the Balkans, lower than average K values (140 -162 mg/kg) are recorded in eastern Bosnia and Herzegovina, central and southeastern Serbia, and North Macedonia, reflecting the same light-texture, leaching-prone soils described above. Conversely, the western part of Albania and the Pannonian plain of Serbia exhibit relatively higher K concentrations, consistent with the presence of more clay-rich, less leached soils.

Both the regional and EU-wide analyses underline the role of soil pH: as pH increases, K concentrations tend to rise, although the correlation is weak (Mrvic et al., 2009). Very high K concentrations are found in a limited number of samples and are linked to intensive fertilisation, especially in soils under vegetable and fruit crops. Poorly fertilised arable lands and soils with a lighter mechanical composition therefore continue to show depleted K pools.

Overall, the Western Balkan K distribution confirms the broader European finding that parent material and texture set the baseline K availability, while climate-driven leaching and agronomic inputs modulate the observed concentrations. The presence of low-K zones in the region suggests a need for targeted fertilisation strategies, particularly on sandy, low-clay soils, to avoid nutrient deficiencies that could limit agricultural productivity in the medium- to long-term.

3.4.4 pH (H_2O and $CaCl_2$)

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According to the pH distribution maps (Figure 7 and Figure 8), the Western Balkan is separated into several main zones: northern Serbia, southern Albania and the central part of North Macedonia with higher pH values (pH in H_2O 7.2-8.8). Higher pH values (pH in H_2O 6.8-7.1) are also present in the southeastern part of Bosnia and Herzegovina.

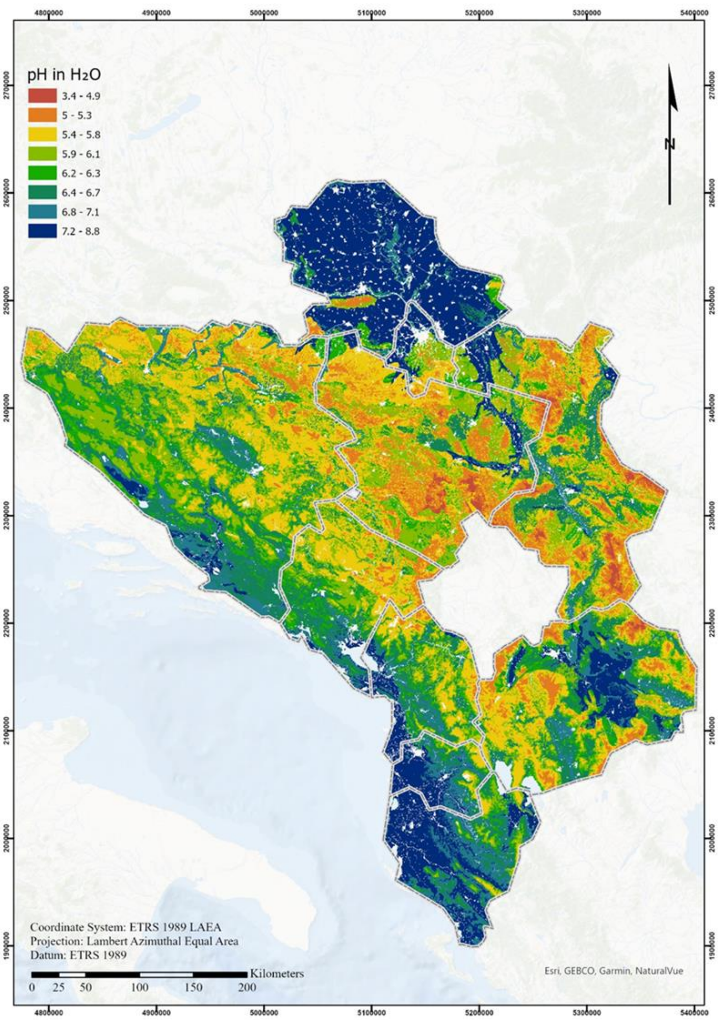

Figure 7 Spatial Distribution of pH in H_2O. The base map was designed and developed by Esri | Powered by Esri.

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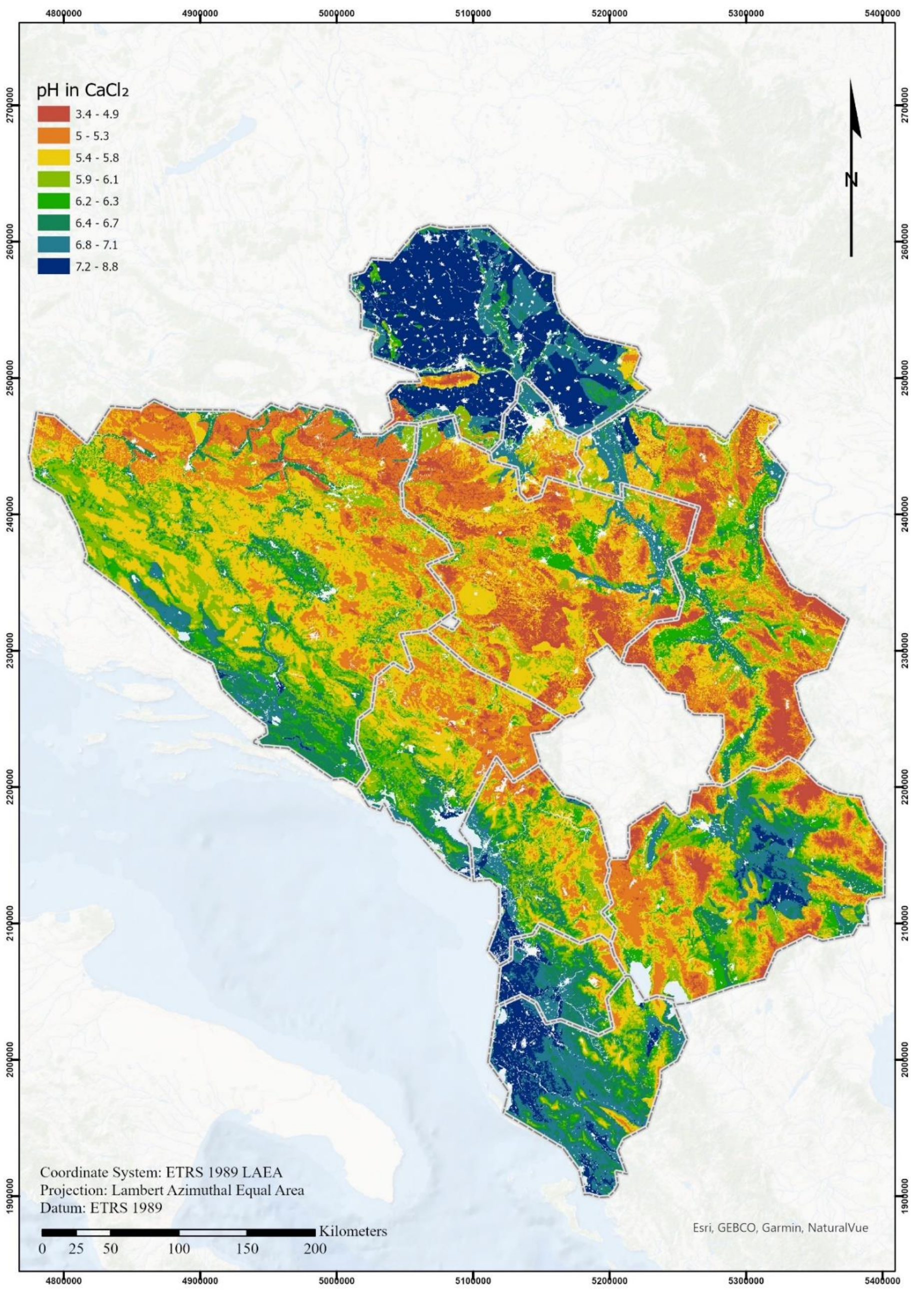

Figure 8. Spatial Distribution of pH in $CaCl_2$. The base map was designed and developed by Esri | Powered by Esri.

The results show that acidic soils are predominant in the central Serbia and northern Albania. These findings are consistent with previous research which indicates that pH

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values in KCl in central Serbia range from 2.5 to 7.6, with an average of 5.2 (Tomić *et al.*, 2025). Highly acidic soils are widely distributed particularly in areas with acidic parent materials or agroecological conditions that promote acidification and soil degradation. Extensive areas of highly acidic soils are found in southern Serbia, particularly south of Leskovac. These soils are most prevalent in mountainous regions where acidic substrates dominate (Mrvić *et al.*, 2023). In the Vojvodina region, alkaline soils are dominant, pH values in KCl ranging from 7.2 to 8.2 (SEPA, 2025). The primary Chernozem zone in Serbia is situated in the Vojvodina region, marking the westernmost extension of the Southern European Chernozem zone. The parent material of chernozem consists of loess, a type of sediment rich in varying levels of calcium carbonate(You *et al.*, 2023). Acid soils in Bosnia and Herzegovina occupy 44.12% of the total soil area of the country with prevailing District Cambisols (28.73%), Luvisols (6.90 %), and pseudogleys (4.64 %) (Markovic et al., 2015) that are classified as Stagnosols in the WRB. Overall, these data are comparable with the results of this study.

From a geographical point of view, Montenegro is generally divided into three regions which share climatic, lithologic, hydrographic and vegetation characteristics: Coastal Montenegro, Central Montenegro and North(east)ern Montenegro which is reflecting acid pH values. Most of the soils in Montenegro are shallow, with low plant and nutritional potential. Calcomelansols (Limestone-dolomite, Leptosol in WRB classification), is the most widespread soil type in Montenegro and covers around 50% of the country territory (Fustic & Djuretic, 2000; Spalevic, 2024). They are formed on hard and compact limestones and dolomites and belong to dry and warm, very porous soils with a high content of supra capillary pores. They are very permeable to water and well aerated, which often leads to a deficit of water in the soil for plants. These soils are

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mainly dominated by xerophytic vegetation where plants often suffer from drought due to strong water permeability and shallow soil depth. The reactions of these soils are neutral to slightly acidic. In the higher mountains they are more acidic because the bases are washed away, and at lower altitudes, they are neutral to slightly acidic because there is no leaching of organic matter. North Macedonia has a complex geology and extensive configuration, including many geological formations of different ages and different geological and granular compositions, which have resulted in a large variety of soil types (Stafilov & Šajn, 2016) and influence the chemical properties of the soil. Albania has both alkaline and acidic soils. Most of the basic ones are located along Adriatic and Ionian costs often associated with saline and sodic soils that overall have higher pH values, often above 8 or 8.5. Instead, acidic soils are mostly located in the Northeast and Southeast regions where the large distribution of ultrabasic rocks influence also soil formation and soil properties. Serbia, Albania, Montenegro and North Macedonia host also a specific soil type, in WRB is Chromic Vertisol (in local language known as *smonitsa*) that are characterized by high content of Magnesium and relatively low pH values (Zdruli *et al.*, 1997).

The spatial patterns revealed by the pH maps indicate that regional acidity is primarily governed by the underlying geology together with the prevailing climatic regime. Areas underlain by calcareous lithologies consistently exhibit higher pH values, whereas siliceous or acidic parent materials correspond to lower pH. Superimposed on this geological control, temperature and precipitation gradients modulate soil solution chemistry: warmer, drier zones tend to retain higher alkalinity, while cooler, wetter regions promote leaching of basic cations and thus lower pH. Consequently, the

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combined influence of bedrock composition and climate emerges as the dominant driver of top-soil pH at the Western-Balkan scale.

3.4.5 Calcium carbonate ($CaCO_3$)

Calcium carbonate ($CaCO_3$) concentrations are largely controlled by the lithology of the parent material and prevailing climatic conditions (Ghanem *et al.*, 2025). Across the Western Balkan territory, $CaCO_3$ concentrations are modulated by both land-cover type and climate (Figure 9). Croplands, especially those situated in temperate to sub-oceanic Mediterranean settings, tend to accumulate higher carbonate levels than woodlands or grasslands. In the Western Balkans, the landscape is dominated by a spectrum of calcareous substrates, ranging from massive limestones in Albania and Montenegro to calcareous sandstones, claystones, siltstones and shales. The fertile Chernozem soils of Serbia, recognised among the world's most productive soils, also contain appreciable $CaCO_3$, a feature that, together with the presence of mull-calcic horizons rich in organic matter, promotes prolonged humification and stabilisation of organic carbon (Eckmeier *et al.*, 2007). In the Mediterranean climate of Albania and Montenegro, the shallow petrocalcic horizons (≈ 50 cm depth) of these calcareous soils provide an optimal medium for olive cultivation, a practice that has persisted for centuries owing to the favourable match between soil quality and land use (Dur *et al.*, 2024). Low pH values and reduced $CaCO_3$ concentrations are observed in acidic lithologies, a pattern that is clearly reflected in the pH distribution maps (Figure 7, Figure 8).

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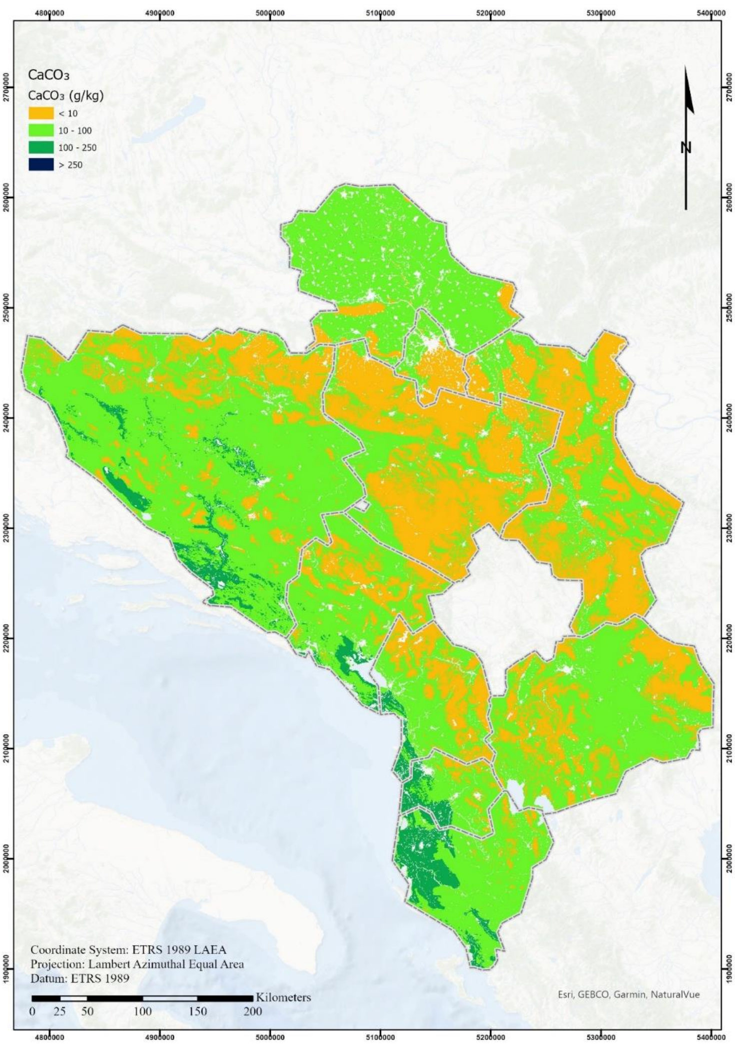

Figure 9. Spatial Distribution of $CaCO_3$. The base map was designed and developed by Esri | Powered by Esri.

The Mediterranean climate has also conditioned soil formation on calcareous parent material, a factor highlighted in European Commission assessments (Anastasiou *et al.*, 2015) . Calcareous agricultural soils now account for more than one-third of the world's arable land and underlie distinctive agro-ecosystems that support globally important crops such as grapes, olives and almonds, contributing to the region's status as a biodiversity hotspot (Francaviglia *et al.*, 2017; Ghanem *et al.*, 2025). Soil inorganic

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carbon (SIC) is the second largest component of total soil carbon (TC) worldwide (Zamanian *et al.*, 2016, 2021; Khalidy *et al.*, 2022) . In arid and semi-arid environments, SIC—predominantly as $CaCO_3$—dominates the TC pool, with concentrations in the upper 2 m of soil exceeding those of soil organic carbon (SOC) by a factor of 10–17. This highlights the pivotal role of carbonate reservoirs in global carbon dynamics and underscores the need for targeted assessment of SIC in Mediterranean calcareous landscapes. In spite its relevance, very few studies have developed a set of specific soil quality indicators for the Mediterranean Region.

3.4.6 Cation-Exchange Capacity (CEC)

Cation exchange capacity (CEC) is a principal indicator of soil fertility because it controls the retention and availability of plant-available cations (Goda *et al.*, 2025). In the present work the spatial pattern of CEC is governed chiefly by the distribution of clay and organic matter in the topsoil. Accordingly, CEC exerts a strong influence on soil-structure stability, nutrient dynamics, pH regulation and the response of soils to fertilisers and other ameliorants (Goda *et al.*, 2025). Observed CEC values range from the low capacities typical of sandy soils to the high capacities of clay-rich and organic soils. Figure 10, when examined alongside the CEC map, clearly shows a positive correlation between clay content and CEC, confirming the dominant influence of soil texture. Figure 10 presents the measured CEC values, with a positive correlation with clay content, confirming the dominant role of texture. Geomorphology further modulates CEC with areas of sediment accumulation displaying consistently higher capacities, a pattern that is evident in northern Serbia, southern Albania and the southeastern part of Bosnia and Herzegovina, and that mirrors the situation reported for

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the wider European domain (Ballabio et al., 2019). In the latter study, elevated CEC values were associated with low-lying, fluvial landscapes in the Netherlands, northern Germany and Poland, where alluvial deposits enrich the soil in fine particles.

The geochemistry of the parent material also contributes to CEC variability. Beyond limestone, soils developed on calcareous and marl substrates tend to accumulate clay as carbonate leaching removes the more soluble phases, leaving the more stable clay minerals behind. This mechanism, described by Ballabio et al. (2019), concurs with the high CEC values recorded in the study area’s calcareous terrains. Conversely, Mediterranean croplands under semi-arid conditions exhibit lower CEC, reflecting their coarser texture and reduced clay-organic matter content.

Overall, the Western Balkan CEC pattern aligns with broader European observations where texture, topography and parent-material geochemistry jointly dictate the spatial distribution of cation exchange capacity.

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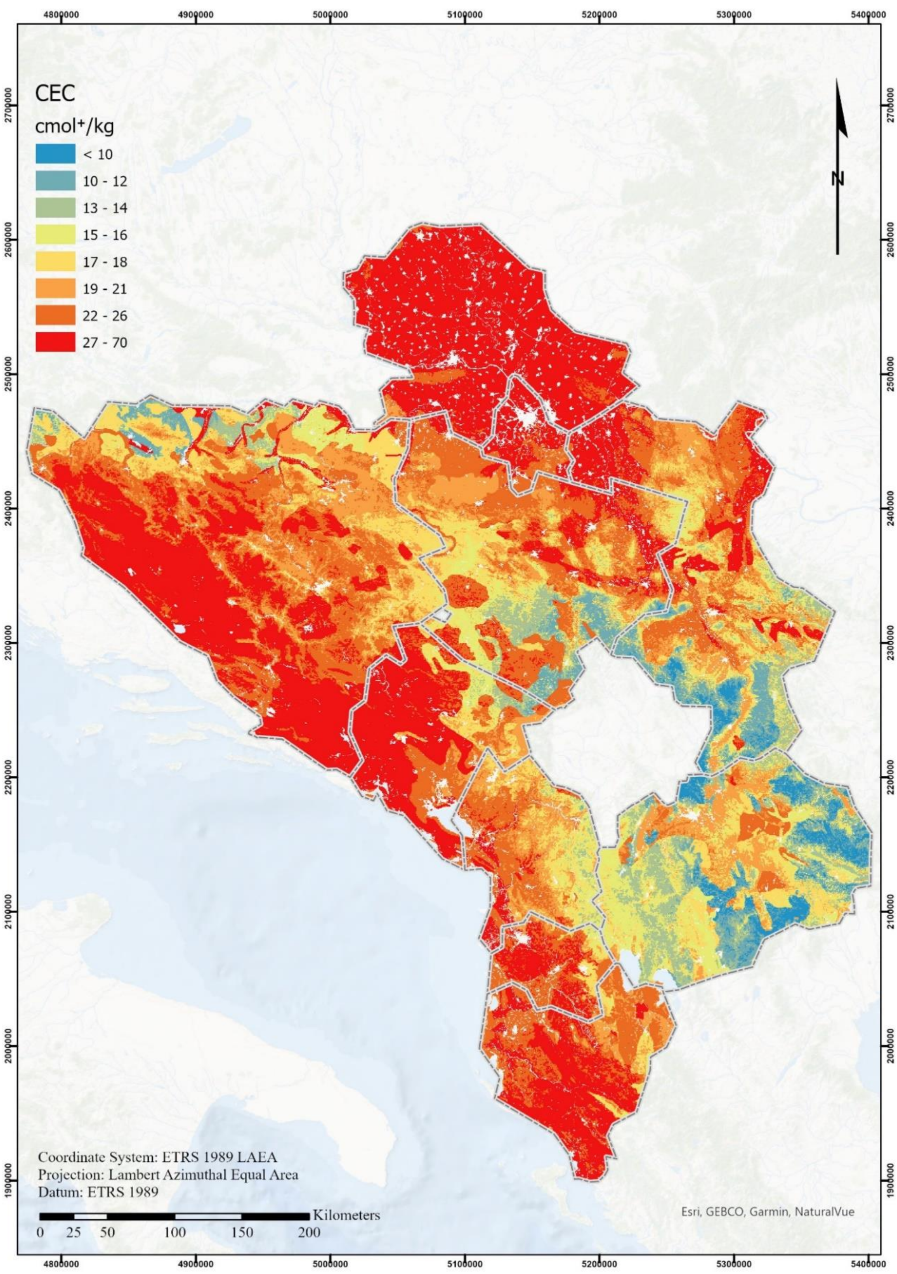

Figure 10. Spatial Distribution of Cation Exchange Capacity (CEC). The base map was designed and developed by Esri | Powered by Esri.

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3.4.7 Soil electrical conductivity (EC)

Soil electrical conductivity (EC) refers to the soil water's ability to transmit an electrical current. This process occurs mainly through water-filled pores and is influenced by the presence of dissolved salts. Positively charged ions (such as Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, and NH_4^{+}) and negatively charged ions (including SO_4^{2-}, Cl^{-}, NO_3^{-}, and HCO_3^{-}) help conduct electricity within the soil. The EC of soil is determined by the concentration of these ions. Several factors affect soil EC, including the quantity and type of soluble salts, soil porosity, texture (particularly clay content and mineral composition), moisture levels, and temperature. Most the areas of Western Balkans have low EC values (Figure 11) however certain areas contain soils with EC values exceeding 4 dS/m, which is classified as saline soil. Saline soils include two large groups of soils, namely Solonchaks (soils with a salic horizon) and Solonetz (Nachtergaele, 2005; Shahid *et al.*, 2018)

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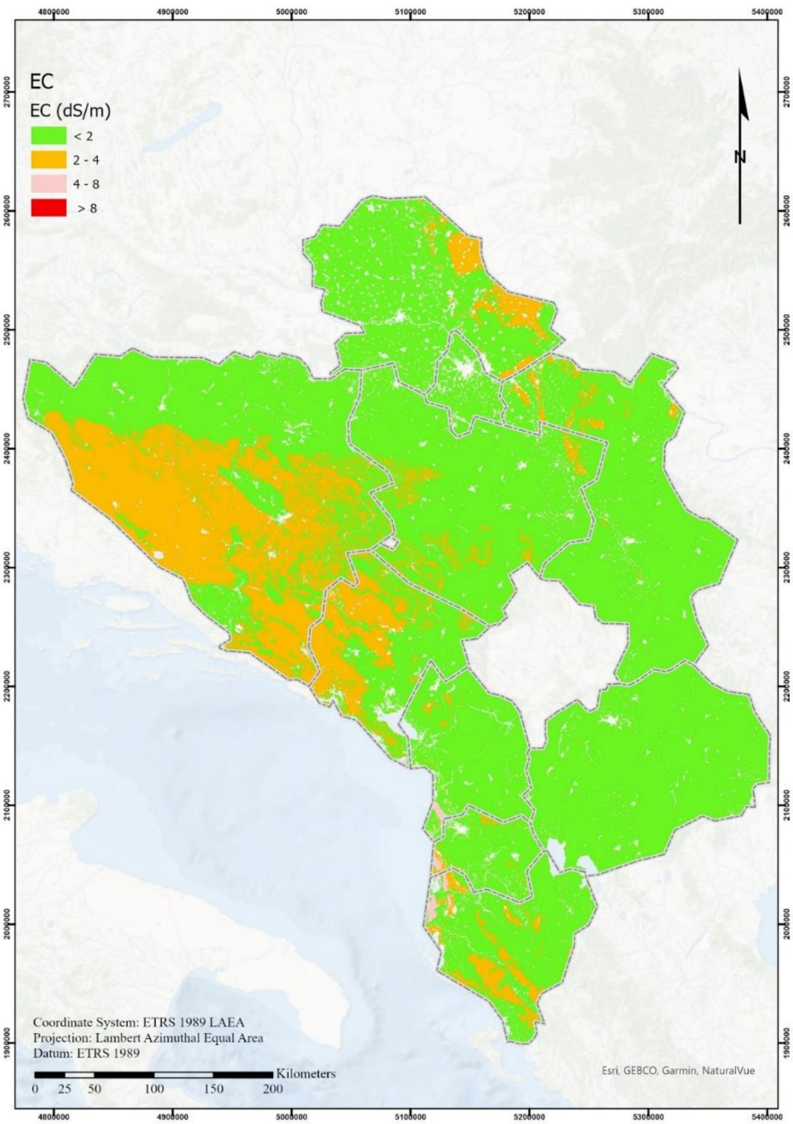

Figure 11. Spatial Distribution of Soil Electrical Conductivity (EC). The base map was designed and developed by Esri | Powered by Esri.

Although the map indicates that saline soils are primarily present in Albania, they are also found in other limited areas of the Western Balkans and represent particularly

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important areas from a biodiversity perspective (Zhang *et al.*, 2024). Until the 90s Albania had about 10,000 ha of saline and sodic soils located in the Western Coastal plans along the Adriatic Sea where the saline groundwater intrusion has caused salinization. According to (Zdruli, 2003), the area may have expanded to more than 15 000 ha by the time of the study, following the complete abandonment of the sites after the political changes of the 1990s. The occurrence of saline soils in northern Serbia, Vojvodina region is not completely related to the climatic conditions. Instead, the formation of saline soils in the Vojvodina region is primarily dependent on local geomorphological and hydrological characteristics (Zeremski *et al.*, 2021). These soils are characterized by poor physical and chemical properties due to a high content of salt and/or adsorbed Na^+ ions which are being used to a limited extent in agricultural production, and more as pastures. According to the results of previous pedological research, saline soils cover about 10% of the total soil surface of Vojvodina (Grujic *et al.*, 2021). In the past, significant effort has been made to protect and preserve saline soil habitats known as "*slatina*" as biologically valuable areas in Serbia. Minor areas of slatina landscapes are now included in protected zones (Zeremski *et al.*, 2021). Examples of areas currently protecting saline soils are the Special Nature Reserves Slano Kopovo and Okanj bara, as well as Nature Park Rusanda, which represents one of the last preserved areas with endangered ecosystems such as salt pans and marshes, as well as saline and steppic meadows with specific Pannonic endemic diversity, involving primarily halophytic flora (Triši & Šteti, 2023).

Finally, there are approximately 11,000 ha saline soils in North Macedonia, mainly found in four valleys (Ovche Pole, Pelagonija, Skopska and Strumica) (Mitrev *et al.*, 2011). Irrigation, particularly in arid regions, is causing increased secondary soil salinization.

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However, the lack of monitoring and research means that the intensity and present extent of salinisation cannot be defined precisely (Mitrev *et al.*, 2011).

The EC values recorded for the Western Balkan study area are broadly consistent with the patterns described for the wider Mediterranean region, where primary salinisation of soils is widespread on ancient marine sediments and secondary salinisation is increasingly linked to irrigation and land-use change (Daliakopoulos *et al.*, 2016). In the Balkans, the highest EC values (> 4 dS m^{-1}) are found on coastal alluvial terraces and on loess-derived parent materials that retain residual marine salts, mirroring the situation observed in the low-lying, tectonically uplifted basins of Spain and Italy. As in those regions, the presence of soluble Ca^{2+}, Mg^{2+}, Na^{+} and K^{+} ions drive the measured conductivity, and the threshold of 2 dS m^{-1} that defines a saline soil is frequently exceeded where groundwater tables are shallow or where historic sea-spray deposition has left a legacy of salt accumulation. The similarity of the Balkan EC distribution to that of other Mediterranean catchments underlines the dominant role of geological heritage and limited leaching under semi-arid climates in shaping the spatial pattern of salinity. (Rengasamy, 2006; Baldi *et al.*, 2020; Marien *et al.*, 2023; Tao *et al.*, 2024). Most countries exhibit low EC values, indicating limited salinity problems; however, this pattern may also reflect the sparse sampling of areas that are actually affected. Consequently, more detailed, high-resolution EC surveys are required in the region to identify emerging hotspots and to support climate-adaptation strategies that avert a shift from natural to anthropogenic salinisation, a development projected for many dry-land systems under future warming scenarios (Hassani *et al.*, 2021)

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4. Discussion

The distribution of the chemical properties reflects the combined influence of parent material, climate, topography, land-cover and management practices. The most significant patterns are summarized in table 3.

Table 3. Dominant regional controls on soil chemical properties

Property	Dominant controls (regional)
pH (H_2O & $CaCl_2$)	Lithology (presence of carbonate rocks) and precipitation intensity; alkaline soils over limestone, acidic soils where leaching is strong (e.g., humid central Serbia).
Carbonates	Directly linked to the extent of calcareous parent material; high values over the karstic formations of Montenegro and Albania.
Cation Exchange Capaciy	Clay content and organic matter; highest values in alluvial floodplains (Vojvodina) and in soils developed on fine-grained sediments.
Organic carbon & Nitrogen	Vegetation density and land-use; forested and semi-natural areas store more OC and N, whereas intensive arable land shows depletion.
C/N ratio	Balance between carbon inputs (litter) and nitrogen fertilisation; high ratios in undisturbed forests, low ratios where synthetic N fertilisers dominate.
Available Phosphorus	Agricultural intensity and soil-forming processes; higher concentrations in intensively cultivated lowlands, lower in mountainous terrains.
Extractable Potassium	Parent-material chemistry (feldspar, mica weathering) and clay content; elevated in calcareous, clay-rich soils.
Electrical conductivity	Saline groundwater intrusion (coastal Albania) and historic irrigation practices; isolated saline patches in Vojvodina related to alluvial deposits.

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The land-cover mosaic (55.5 % forest/semi-natural, 40.0 % agricultural, 2.8 % artificial) modulates these controls. For instance, the high OC and N stocks in Bosnia-and-Herzegovina and Montenegro are consistent with the large share of forest cover (Spalević 2024). Conversely, the extensive agricultural footprint in Serbia explains the higher P and K levels observed there.

Although the 955 LUCAS 2015 points constitute a solid baseline, the sampling density remains insufficient for the extensive mountainous catchments of the Western Balkans, resulting in elevated prediction variance in those under-sampled areas. In addition, the quality of several ancillary covariates limits model performance; for example, the European Soil Data Base (ESDB) parent-material map is available only at a coarse resolution of approximately 1 km, contributing little to the prediction of texture-related properties, whereas finer-scale geological maps would likely enhance those estimates. Finally, a temporal mismatch exists between the LUCAS 2015 soil samples and the MODIS 2009 imagery used to derive vegetation indices. Although land-cover change in the region proceeds relatively slowly, this discrepancy may introduce minor inconsistencies in the model inputs. Expanding the observational base by incorporating newer LUCAS cycles will increase point density and enable the detection of temporal trends in soil-chemical properties.

Soil health occupies a central position in the Green Agenda for the Western Balkans (EC, 2020), reflecting the EU Soil Strategy for 2030 and the Soil Monitoring and Resilience Directive (EC, 2025). For the Western Balkan states, the soil-monitoring legislation offers a valuable opportunity to harmonise national soil policies with those of the EU (Belis *et al.*, 2024; Arias-Navarro *et al.*, 2025). Recent assessments have

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highlighted both progress and remaining challenges in monitoring soil health in Albania, Bosnia-Herzegovina, Kosovo, Montenegro, North Macedonia and Serbia (Arias-Navarro *et al.*, 2025). By delivering robust, uncertainty-aware topsoil property maps, this work supports the implementation of the Soil Monitoring and Resilience Directive, facilitates the alignment of Western Balkan soil policies with EU standards, and underpins evidence-based decision-making for the green transition envisaged in the Green Agenda. Continued enhancement of soil-monitoring efforts building on the maps presented, will be essential to ensure the long-term sustainability of soil resources in the Western Balkans.

The European Green Deal and the Soil Strategy 2030 have already produced a substantial body of integrated knowledge on soil functions, ecosystem services and the pressures that jeopardise soil health (Arias-Navarro *et al.*, 2023). Building on this momentum, the Horizon Europe "Soil Deal for Europe" mission offers a unique chance to turn research results into concrete tools for the Western Balkans. While participation from the region has increased, with North Macedonia and Serbia now active in Soil-Deal projects, recent analysis identified three persistent barriers: limited institutional capacity, funding gaps and weak integration into European research networks (Hoxha & Gudachi, 2025). Overcoming these obstacles and strengthening partnerships will enable the Western Balkans to both contribute to and benefit from Europe's research and innovation agenda. In this context, the maps produced in the present study constitute a ready-made evidence base for a Western Balkan Soil Degradation Dashboard. By adapting the functionality of the EU Soil Observatory dashboard (Panagos *et al.*, 2024), the new platform will visualise the convergence of scientific evidence across the region, pinpointing hotspots of soil degradation and guiding

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targeted monitoring and policy action. Its open-access architecture will promote data sharing, cross-border collaboration and the harmonisation of soil-health reporting, thereby facilitating the accession processes of the Western Balkans and reinforcing their contribution to the EU Soil Strategy 2030.

5. Conclusions

This study provides baseline maps of top-soil properties for the Western Balkans at a 200 m spatial resolution, encompassing 196, 00 km^2, of which approximately 40 % is agricultural land. The analysis is based on the 955 LUCAS 2015 sampling points – the most extensive and temporally consistent dataset currently available for the region – and identifies the principal drivers of soil-chemical variability. The observed spatial patterns are consistent with previous European investigations (e.g. De Brogniez et al., 2015; Ballabio et al., 2016; Ballabio et al., 2019). The Western Balkans are characterised by heterogeneous lithology, complex geomorphology and diverse climate regimes, which generate considerable spatial complexity. This complexity limits the explanatory power of the available covariates and is compounded by the relatively sparse sampling network. Consequently, the main constraints of the present work are the limited number of observation points and the variable quality of several covariates.

To overcome these limitations, a new LUCAS soil campaign for the Western Balkans – including Kosovo – should be launched promptly. The 2022 topsoil LUCAS campaing of the EU introduces additional variables (soil biodiversity, bulk density, metals and pesticides) that would enable a more comprehensive understanding of the EU biogeochemical and ecological processes. Repeated sampling at fixed locations in

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Western Balkans will generate a harmonised, longitudinal database of chemical, physical and biological soil properties. Such a resource will be invaluable for scientific research, evidence-based policy development and the alignment of Western Balkan monitoring practices with EU standards, as envisaged by the Soil Monitoring and Resilience Directive.

While this work marks a significant step forward, intensified soil-monitoring efforts remain essential to ensure the long-term sustainability of soil resources in the Western Balkans. Strengthening regional cooperation and participation in forthcoming LUCAS campaigns will provide critical insights into soil health and support coordinated soil-protection strategies that are vital for sustainable land-use.

6. Appendices

Supplementary Information (SI): Methodology, Analysis and Maps Generated

7. Data availability and Code availability

LUCAS soil data for the Western Balkans are published in Arias-Navarro et al. 2026 and are available on European Soil Data Centre portal under https://esdac.jrc.ec.europa.eu/. Supplementary Information accompanying this manuscript provides the detailed methodology, the analysis procedures and the complete set of generated maps, the Python scripts used for processing, and a Dockerfile that enables fully reproducible execution of the workflow.

8. Author contribution

Cristina Arias-Navarro: conceptualisation, methodology, investigation, validation, formal analysis, data curation, writing – original draft, writing – review and editing,

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visualisation, project administration.

Bexhet Islamaj: software, data curation, visualisation, formal analysis, writing – original draft.

Dragana Vidojevic: investigation, validation, writing – original draft, writing – review and editing.

Pandi Zdruli: investigation, validation, writing – original draft, writing – review and editing.

Felipe Yunta-Mezquita: conceptualisation, methodology, investigation, validation, formal analysis, visualisation, writing – original draft, writing – review and editing.

Panos Panagos: writing – review and editing, resources, supervision, validation.

Piotr Wojda: supervision, funding acquisition, project administration, resources, conceptualisation, methodology, writing – review and editing.

Arwyn Jones: conceptualisation, methodology, supervision, funding acquisition, project administration, writing – review and editing.

8. Competing interests

The authors declare no conflict of interest. They acknowledge that the manuscript was assisted by Genesis (the GPT@JRC evolution) to improve readability and clarity in selected sections. All content was subsequently reviewed, edited, and approved by the authors, who retain full responsibility for the scientific integrity and conclusions of the paper. The core analysis, findings, and arguments remain in the original work of the author(s). The use of this tool did not influence the research findings or their interpretation

9. Statement on inclusion in global research

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This work, led by soil scientists at the European Commission's Joint Research Centre (JRC) EU Soil Observatory, was carried out in close collaboration with experts from the Western Balkan region, ensuring that the publication reflects the specific needs and challenges of those countries. Field visits and sample collection adhered to the EUROSTAT/LUCAS protocol – the EU-wide, harmonised survey that records land-cover, land-use and soil data on a 2 km grid using standardised questionnaires. All activities were carried out with the informed consent of landowners and local communities.

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Additional support was received from the EU Soil Observatory, also administered by the JRC.

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