

HOW AGRICULTURAL CROP CLASSES RELATE TO SOIL TAXONOMIC DIVERSITY: AN EXAMPLE OF TWO CONTRASTING LANDSCAPES IN LATVIA

Marks Arnolds Župerka¹, Solvita Rūsiņa¹, *Raimonds Kasparinskis^{1,2}

¹University of Latvia, Latvia

²Latvia University of Life Sciences and Technologies, Latvia

*Corresponding author's e-mail: raimonds.kasparinskis@lbtu.lv

Abstract

The spatial composition of different soil types has traditionally been evaluated through soil mapping and broad-scale regional assessments of soil properties. However, mathematical quantification of soil taxonomic diversity in agricultural landscapes with varying management intensities remains largely unexplored. To address this gap, we applied Shannon Diversity Index at landscape level and potential pedodiversity index (PD_H) at a 30 × 30 m cell resolution in two distinct agricultural landscapes in Latvia – Taurene and Platone municipalities – characterized by different soil formation conditions, topography, heterogeneity of soil cover, land-use structure and farming practices. Soil mapping data based on the World Reference Base for Soil Resources (WRB) system was used. Soil taxonomic diversity at the municipality level was assessed using a single Shannon Diversity Index for each area, calculated separately for first-level reference soil groups without qualifiers and second-level classification with qualifiers. Cropping classes were determined using dominant crop types over a 9-year period (2015–2023) and grouping crop types into classes. At the broad soil classification level, the upland landscape of Taurene showed higher soil taxonomic diversity than Platone, aligning with its more complex soil formation factors and processes. However, at a more detailed classification level, Platone exhibited slightly higher diversity, contradicting established theoretical expectations for such landscapes. Study results of both agricultural landscapes show that the highest soil taxonomic diversity values were observed in areas of temporary grasslands sown in arable land.

Keywords: taxonomy, pedodiversity, Shannon index, land use, moving window.

Introduction

In Europe, soils are subjected to various threats, including water and wind erosion, the reduction of organic matter in both mineral and organic soils, as well as soil compaction (Stolte et al., 2016). Within the framework of the European Union Soil Strategy for 2030, the importance of soil research is emphasized not only as a means to improve soil conditions but also to mitigate the climate impact of soil management practices (Panagos et al., 2022). Rasmussen (2022) identifies the study of soil spatial distribution, its properties, and the processes occurring within it as one of the key priorities in contemporary soil science research.

There are numerous studies worldwide on the patterns of soil spatial distribution (McBratney, 1998), highlighting the significance of various environmental factors in shaping soil processes, morphology, and properties. Furthermore, soil processes and their interactions under different environmental conditions vary considerably, contributing to the diversity of soils (Targulian & Krasilnikov, 2007).

Measuring soil diversity (*syn.* pedodiversity) is inherently complex and lacks a universal approach (Usher, 1983). As a result, multiple research methodologies and classification systems have been developed. Ibáñez et al. (1995) proposed a framework based on the prevailing biological diversity classification, categorizing soil diversity into four hierarchical levels depending on the spatial scale of analysis: micro-scale diversity at the polypedon level, α -scale diversity representing soil associations at a medium scale, γ -scale diversity at the landscape or watershed level, and ϵ -scale diversity referring to soil diversity at a geographical regional level. In contrast, Mikhailova et al. (2021) provided an example of

dividing soil diversity into four distinct types: taxonomic diversity, which encompasses variation in soil groups, types, and subtypes; genetic diversity, referring to the diversity of soil genetic horizons; parametric diversity, which accounts for differences in soil physical and chemical properties; and functional diversity, which describes variability in soil characteristics under different land use conditions. This soil diversity classification aligns more closely with contemporary trends in soil research.

Significant uncertainties persist regarding the application of specific soil classification systems in determining spatial distribution patterns. As a result, soil scientists often disagree on the extent to which environmental factors influence soil distribution at regional and local scales (Gray et al., 2009). Incomplete knowledge of environmental conditions can sometimes lead to an overestimation or underestimation of soil formation processes, complicating the use and comparison of different classification systems (Reintam, 2002; McBratney et al., 2003).

Previous research has made significant contributions to the statistical assessment of STD, particularly in forest ecosystems. For example, Samec et al. (2018) study conducted in the Czech Republic has provided valuable insights into the diversity of forest soils, offering a methodological framework for similar investigations. An innovative methodology for evaluating STD was introduced in the studies by Vacek et al. (2020) and Vašát et al. (2023). These works propose a new method of analysis – the potential pedodiversity index (PD_H). This approach is based on the widely used Shannon diversity (entropy) index (Shannon, 1948), which is extensively applied in

ecology and landscape research. The index is calculated within raster cells using the moving window method, which uses a fixed geometric shape to repeatedly scan the area, calculating local values within each window as it moves across the territory, allowing for a spatially explicit assessment of STD. PD_H is defined as a pressure of the surroundings on the soil unit change at a particular soil point location (Vacek et al., 2020).

Based on these foundations, our study aims to further explore STD the context of agricultural land use in Latvia. Agricultural practices influence soil properties, biodiversity, and ecosystem functions, thereby shaping soil diversity at both local and regional scales (Trivedi et al., 2016, Briones & Schmidt, 2017). Intensive land use can lead to soil homogenization, loss of taxonomic diversity, and degradation of soil functions, whereas low-intensity or diversified land use may enhance soil heterogeneity and resilience (Burton et al., 2023). Studies on soil diversity in relation to agricultural intensity help to assess the impact of land management practices on soil sustainability, inform precision agriculture strategies, and support policy-making for sustainable land use planning. Therefore, our aim was to assess the soil taxonomic diversity and its possible relationship with different agricultural crop classes in two contrasting landscapes in Latvia.

Materials and Methods

For the geospatial analysis of STD, publicly available soil mapping data from the 'E2SOILAGRI' project were used, based on the WRB system (IUSS Working Group WRB, 2022). The data cover the Taurene and Platone municipalities (Figure 1) at a 1:10,000 scale. Data are available on the national geospatial information portal (www.geolativija.lv) under a CC 4.0 license and on the Latvian open data portal (www.data.gov.lv) under a CC 1.0 license State Plant Protection Service, 2024 (Valsts augu aizsardzības dienests, 2024). Soil mapping was conducted by the University of Latvia, Faculty of Geography and Earth Sciences, during 2021–2023 (Nikodemus et al., 2023). Platone and Taurene represent contrasting pedological environments. Platone is located in Zemgale lowland plain into transition zone between the Baltic Ice lake sands (in northern part) and clay sediments of the meltwater basins in glacial lowland (in southern part); furthermore, alluvial sandy sediments are distributed in certain areas (Geological map of Latvia, 1981; Zelčs & Markots, 2004; Zelčs et al., 2011) and represent low topographic variation, ranging in elevation from just 0.7 to 24 meters above sea level. This flat terrain fosters relatively homogeneous soil formation processes.

In contrast, Taurene features a glacial deposits and undulated topography (Geological map of Latvia, 1981; Zelčs & Markots, 2004; Zelčs et al., 2011), with elevations between 175 and 256 meters above sea level. Its pronounced relative elevation changes,

combined with diverse microclimatic and geological conditions, drive spatially heterogeneous pedogenesis, resulting in more complex soil properties and distributions.

STD at municipality level was analysed by calculating a single Shannon's diversity index for each study area for the first level classification for unique reference soil groups without qualifiers and separately for the second level classification with qualifiers. The soil mapping process did not encompass all potential qualifiers for the relevant soil groups (Nikodemus et al., 2023), which may lead to a simplified representation of actual STD. For spatial data visualization, ArcGIS desktop software was used (ESRI, 2020).

To examine the relationship between STD and agricultural land-use, the Potential Pedodiversity Index (PD_H) was calculated at a fine-scale 30 × 30 m cell resolution, but only using the first-level classification (Reference Soil Groups without qualifiers). PD_H was the main method of assessing STD in this article. Since municipality-level soil mapping was conducted at a 1:10,000 scale, with a minimum elementary soil contour size of 0.3 ha the initial vector data were rasterized at a 30-meter resolution. A 300-meter radius was selected for the moving window analysis. The analysis was conducted using R programming language in R Studio version 4.4.2. Following packages were used: 'sf' for spatial data operations (Pebesma, 2018; Pebesma & Bivand, 2023), 'dplyr' for data manipulation, 'terra' (Hijmans, 2024a) and 'raster' (Hijmans, 2024b) for raster file management, 'ggplot2' for visualization (Wickham, 2016), 'doParallel' for multi-core processing (R Core Team, 2024), 'FSA' for post-hoc testing (Ogle et al., 2025), 'agricolae' for reference diversity index calculations (De Mendiburu, 2021), and 'nortest' for performing normality tests on large datasets (Gross & Ligges, 2015).

The mathematical foundation of the PD_H index is based on the Shannon diversity index (Shannon, 1948), adapted for soil data (Vacek et al., 2020). The PD_H index was calculated initially by determining the proportion (P_a) of cells occupied by each soil type relative to the total number of soil cells (P_{at}) within the defined search window. Results were then log-transformed, and the product of P_a and P_{at} was multiplied by this transformed value. Finally, these individual contributions were summed and multiplied by -1 to yield the PD_H index (Equation 1). PD_H calculation codelines can be found in associated master's thesis annex section (Župerka, 2025).

$$PD_H = - \sum_{i=1}^s \frac{P_a}{P_{at}} \ln \frac{P_a}{P_{at}} \quad (1)$$

where:

PD_H – potential pedodiversity index,

P_{a_i} – number of cells occupied by a given soil type within the search window;

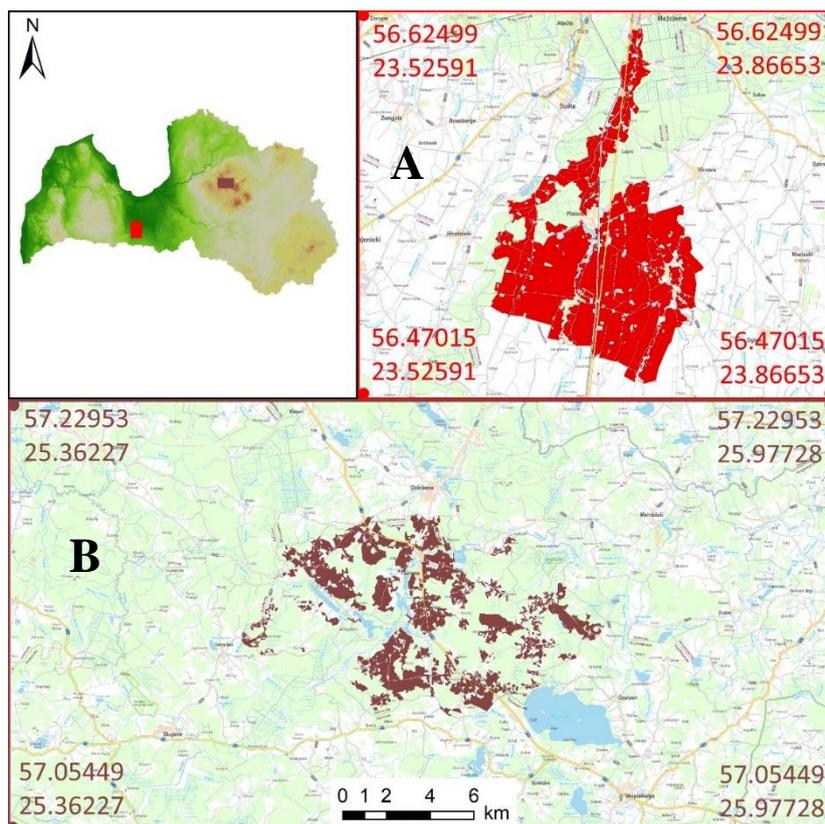
P_{at} – total number of cells occupied by all soil types within the search window.

The classification of cropping classes was based on dominant crop types observed over a 9-year period (2015–2023), which we use as a proxy for recent land-use practices. Spatial data were sourced from the Field Register of the Rural Support Service (RSS, Lauku atbalsta dienests, 2025), comprising land parcels and their associated crop types from 2015 to 2023. Crop

types are encoded using a standardized three-digit, three-level hierarchical classification based on crop characteristics and usage (LR Ministru Kabinets, 2023). For analysis, second-level groups were used for grasslands and first-level groups for other crops. Crop types were then grouped into classes and used in further analysis (Table 1).

Figure 1

Study areas and reference bounding box coordinates (decimal degrees): A – Platone Municipality, B – Taurene Municipality



The Anderson-Darling normality test confirmed that the distribution of PD_H values in both territories deviated significantly from normality. Consequently, the non-parametric Wilcoxon rank-sum test was employed to assess whether the median PD_H values differed significantly between the two territories. The Kruskal-Wallis rank-sum test was used to evaluate

differences across all crop groups. To further investigate specific pairwise differences between groups, a post-hoc Dunn’s test with Bonferroni correction for multiple comparisons was conducted. Welch’s ANOVA was used to assess differences between diversity values variances of two territories.

Table 1

Classification of agricultural land into agricultural crop classes

CC*	Crop type	Crop names and codes after Cabinet of Ministers of the Republic of Latvia (Latvijas Republikas Ministru Kabinets, 2023)
1	Fallow	Green manure fallow (612)
2	Vegetables	Starch potatoes (825), Potatoes not elsewhere specified (820), Other unspecified cabbages (870), Table beets, chard / leaf beets (844), Onions, shallots, chives, Welsh onions and Japanese bunching onions (846), Garlic (847)
3	Fabaceae fields Legumes	Red clover (723), White clover (724), Alfalfa (726), Field beans (410), Peas (420), Soybean (443)
4	Permanent grasslands**	Permanent grasslands (710)

CC*	Crop type	Crop names and codes after Cabinet of Ministers of the Republic of Latvia (Latvijas Republikas Ministru Kabinets, 2023)
5	Permanent crops (orchards, short-rotation coppice, energy crops)	Apple trees (911), Pear trees (912), Sweet and sour cherries (932), Plum trees (914), Aronia (918), Sea buckthorn (919), Blackcurrants (922), Quince bushes (928), Fruit trees and berry bushes (except strawberries), each occupying less than 0.1 ha in a continuous area (950), Woody plant nurseries on agricultural land (640)
6	Others (not specifically classified)	Other crops sown pure in arable land (872), Mustard, including white mustard (215), Various crops in small arable areas or multiple crops grown in a continuous field, each occupying less than 0.1 ha, or areas used for flower cultivation (811)
7	Temporary grasslands sown in arable land***	Mixture of grasses or forage herbs (including protein crops) sown in arable land (720), Mixture of grasses and legumes sown in arable land, with legumes >50% (760)
8	Grain crops	Oats (140), Oats with grass or legume undersowing (141), Spring wheat (111), Winter wheat (112), Spring barley (131), Spring barley with grass or legume undersowing (133), Winter barley (132), Rye (121), Cereal and pea mixture with peas >50% (445), Other unspecified maize (741)
9	Oil and fibre crops	Winter rapeseed (212)
10	Single-species grass swards	Red oat grass for seed production (735)

*CC – agricultural land crop class; ** - Permanent grasslands are grassland areas that until 2014 were declared as permanent meadows and pastures. Areas declared as permanent grasslands include those that for five consecutive years have been declared as arable land sown with mixtures of grasses and/or fodder herbs (such as timothy, alfalfa, vetch, sainfoin, eastern galega, rough hawkbit) or as pure grass sown fields, or as pure fodder herb fields. In addition to permanent grasslands, areas recognized as biologically valuable grasslands or grasslands important for biodiversity — such as protected grassland habitats or bird habitats resulting from the cessation of agricultural activities — are also declared as permanent grasslands (Latvijas Republikas Ministru Kabinets, 2023). ***Temporary grasslands sown in arable land are grassland areas that have been declared for less than five consecutive years as mixtures of grasses or forage herbs (including protein crops) sown in arable land (code 720), or as mixtures of grasses and legumes sown in arable land with legumes comprising more than 50% (code 760).

Results and Discussion

Shannon's diversity index at municipality level

The number of unique Reference Soil Groups (RSG) was consistent across both territories, with 12 groups present in each. Similarly, the number of unique soil and principal qualifier combinations showed only a slight difference between the two territories: Platone had 223 unique combinations, while Taurene had 208. The Shannon's Diversity Index for broad RSGs without qualifiers was 1.90 for Taurene and 1.35 for Platone. Thus, at broad soil classification level Taurene area was assessed as more diverse than Platone area. This is in line with previous studies showing much higher diversity of soil formation processes and their driving factors in heterogeneous upland areas (Kasparinskis & Nikodemus, 2012; Nikodemus et al., 2024) where small-scale topographic variability can significantly influence soil formation and heterogeneity (Groß et al., 2023). In Platone, the largest soil areas were dominated by Luvisols and Planosols, which covered 62% and 12% of the total mapped area, respectively, while other RSGs each constituted less than 10%. In contrast, dominant RSGs distribution in Taurene exhibited greater diversity, with the three most prevalent RSGs being Luvisols (33%), Retisols (19%), and Phaeozems (14%).

The Shannon's Diversity Index for RSGs with qualifiers was 3.72 for Taurene and 3.92 for Platone. These results contrast with our results based on RSGs without qualifiers.

These findings are in line with recent literature on local scale, e.g. Nikodemus et al. (2024), which underscores the challenges of mapping regions with complex

topography, e.g. Taurene, where high STD complicates spatial capture. At broader mapping scales, small-scale soil variations – and consequently specific qualifiers – may not be adequately captured, potentially contributing to the lack of distinct patterns observed at the municipal level. The higher overall STD recorded in Taurene without considering qualifiers, contrasted with greater soil group diversity observed in Platone when qualifiers are included, suggests a need for more detailed soil mapping. This would ensure that ecologically relevant soil variations, particularly in geomorphologically complex and heterogeneous areas such as Taurene, are accurately represented. Previous research has demonstrated that small-scale topographic variability can significantly influence soil formation and heterogeneity (Groß et al., 2023).

However, studies on STD in our region remain scarce, and no well-established reference values exist for agricultural lands. For the Boreal biogeographical region, the reported Shannon index is 3.27 for the second-level WRB groups and 2.49 for the first-level WRB groups (Ibáñez et al., 2013). However, this coarse-scale values cannot be compared to landscape-level results. Thus, we could not compare our results to draw more detailed conclusions.

Potential pedodiversity index at cell level

The absolute differences between PD_H in the two territories were minimal as well, with Taurene showing a slightly higher overall index values compared to Platone. Statistically significant differences between the medians of the two territories ($W > 8 \cdot 10^8$, $p < 0.001$) were observed. The median

PD_H value for Taurene was 0.93, while for Platone, it was 0.86. Welch's ANOVA also indicated significant differences in group variances ($F_{(84,889)} = 328.1, p < 0.001$), a finding supported by the histograms. The spatial distribution of the index displayed a more distinct pattern in Platone, with the highest PD_H values located in the northern part of the municipality. In contrast, Taurene exhibited no clear spatial patterns (Figure 2). Higher STD in northern part of Platone area could be explained by soil genesis and geological formation of area, e.g. varying soil texture of the soil parent material (Kasparinskis & Nikodemus, 2012). According to geological map of Latvia (1981) – area of Platone municipality is located in Zemgale lowland into transition zone between the Baltic Ice lake sands (in northern part) and clay sediments of the meltwater basins in glacial lowland (in southern part); furthermore, alluvial sandy sediments are distributed in certain areas (Zelčs & Markots, 2004). The contact zone of diverse or double-sided soil parent material (clay in subsoil and

sand in topsoil) is characterized by heterogeneity conditions, e.g. higher variety of soil formation processes (e.g., accumulation of organic matter, podzolization, increase of soil moisture conditions, gleying, etc.) instead of homogeneous clay sediments (in southern part of Platone municipality area).

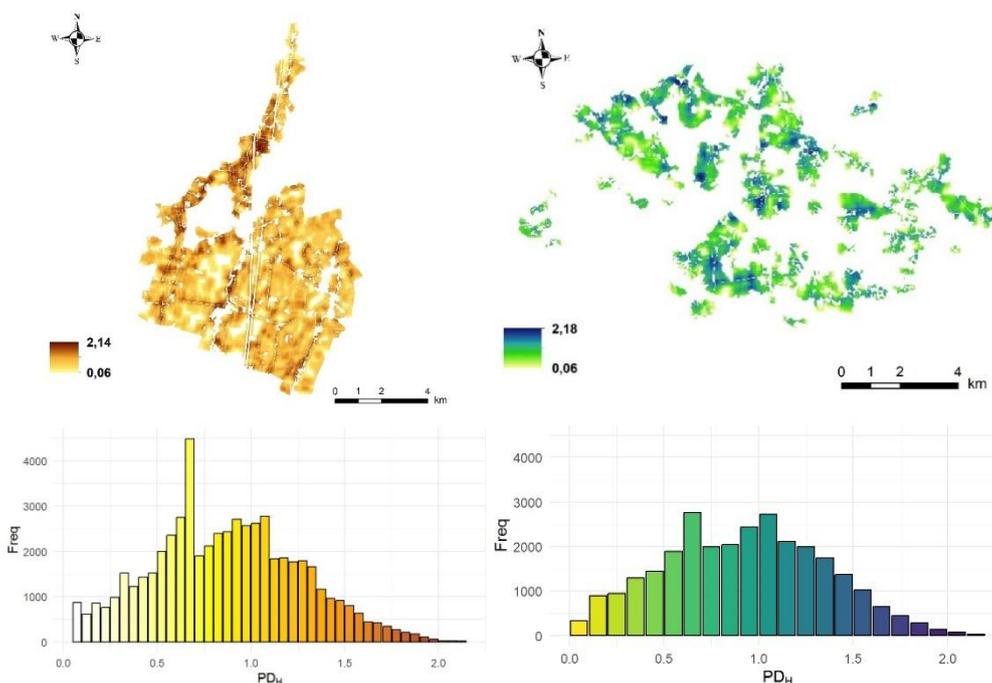
In Taurene area such relationships are not visible. However, soil diversity is being provided mainly by undulated topography and glacial deposits (Geological map of Latvia, 1981; Zelčs & Markots, 2004; Zelčs et al., 2011).

Relationship between soil taxonomic diversity and agricultural crop classes

It is well established that the local soil biodiversity decreases with increasing agricultural land use intensity (Tsiafouli et al., 2015). In addition, intensive agriculture drives profound changes in soil properties to the degree that the soil can no longer be considered representative of its undisturbed counterpart (Amundson et al., 2003).

Figure 2

Potential soil diversity index in Platone (left) and Taurene (right) and value distribution histograms (Freq on y axis indicates number of 30x30m cells)



Our two study regions differed considerably in agricultural crop class composition (Figure 3). Only 28% of the Taurene Municipality area was used for agriculture, and almost 82% of this area corresponded to the 4th class – permanent grasslands. On the contrary, 45% of the Platone Municipality was covered by agricultural lands, and 86% of them were intensively used and corresponded to the 8th class – grain crops. Statistical tests confirmed significant differences between group medians ($\chi_{(9)} = 3,118.9, p < 0.001$). Post-hoc testing revealed several significant

differences between the cropping groups, with group 10 (single-species grass swards) exhibiting the lowest PD_H values compared to the others, while group 7 (temporary grasslands sown in arable land) showed the highest values in the range (Figure 4). Furthermore, no significant differences in soil groups were found across cropping classes. Permanent grasslands in Taurene had much higher PD_H values than those in Platone, even though they belong to the same land-use class. This unexpected difference suggests that STD hardly explains land use patterns. Therefore, other

factors related to land use – such as historical land management, crop rotation, fertilization, or farmer decisions - should be considered in future analyses to gain a deeper understanding of the relationship between STD and crop choices.

Current research trends show that major land use intensity studies have not even listed STD as a factor (Marcos-Martinez et al., 2017; Van Vliet et al., 2015),

yet the assessment and conservation of soil diversity as an important part of the European natural heritage is gaining increasing recognition (Ibáñez et al., 2013). Thus, we call for greater integration of different aspects of soil diversity including STD into land use research, policy frameworks, and sustainable agricultural practices to ensure its protection and long-term ecological resilience.

Figure 3
Agricultural crop classes in Platone (left) and Taurene (right)

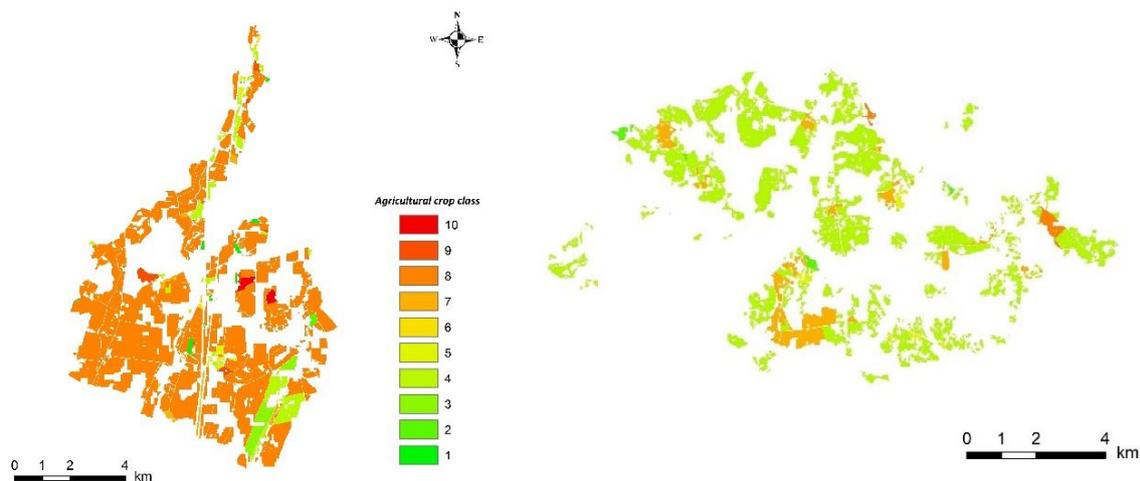
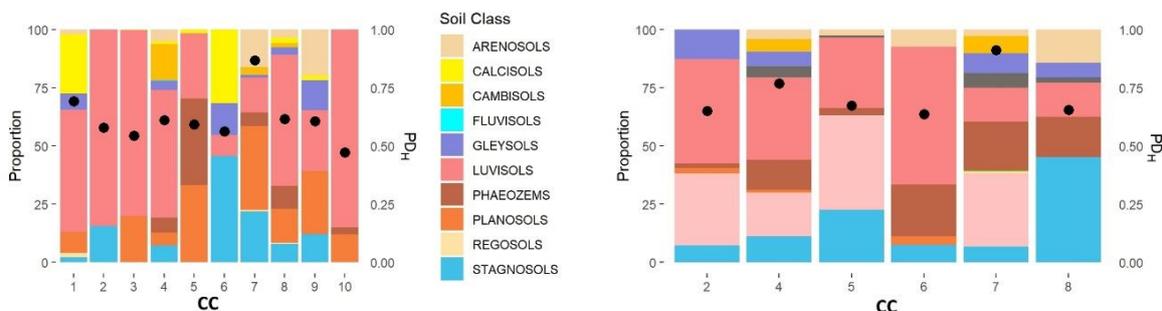


Figure 4
Soil taxonomic composition and median PD_H index (black points) in different cropping classes in Platone (left) and Taurene (right). The codes for cropping classes are the same as in Table 1



It is important to note that PD_H index cannot be used in the same way as Shannon Diversity, because it does not directly measure diversity in a given area but rather shows a tendency for diversity to change in relation to nearby areas (Vacek et al., 2020). Therefore, high PD_H values should not be interpreted in the same manner as a regular diversity index, as demonstrated in our study through a comparison of the absolute index calculated at the municipality scale versus the PD_H calculated at each raster cell, which yielded substantially different results between the two territories. PD_H allows for high-resolution mapping of soil taxonomic diversity by assigning a diversity index value to individual map units, potentially making it useful for inclusion in detailed spatial models.

Conclusions

1. Minor absolute differences were observed in STD between the two municipalities, with PD_H values generally being slightly higher in Taurene, a less intensively managed area, compared to Platone, which has relatively higher cropping intensity.
2. To enhance the accuracy of STD assessment in topographically complex terrains, higher-resolution soil mapping should be conducted to improve the representation of small-scale soil formations that are not detectable at larger mapping scales.
3. Temporary grasslands sown in arable land were related to high soil diversity areas while single-species grass swards fields were confined to areas with low soil diversity.

4. In both agricultural landscapes, the highest STD values were observed in areas of temporary grasslands sown in arable land. Other factors related to land use should be considered in future analyses to gain a deeper understanding of relationship between STD and cropping classes.

5. At municipal level, Taurene exhibited higher soil taxonomic diversity than Platone, consistent with its more heterogeneous upland landscape and previously documented complexity of soil formation processes. Platone showed a slightly higher Shannon Diversity Index values per cell than Taurene, which contradicts theoretical assumptions about soil taxonomic diversity in such landscapes.

6. Further research should focus on high-resolution modelling of the PD_H index, incorporating other environmental factors available at a detailed scale, such as topographic indicators or soil parent material.

Additionally, other diversity metrics, such as Simpson's Diversity Index or Patch Richness and Evenness, should be calculated using a similar approach to determine whether other indexes could reveal relationship between STD and cropping classes better.

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