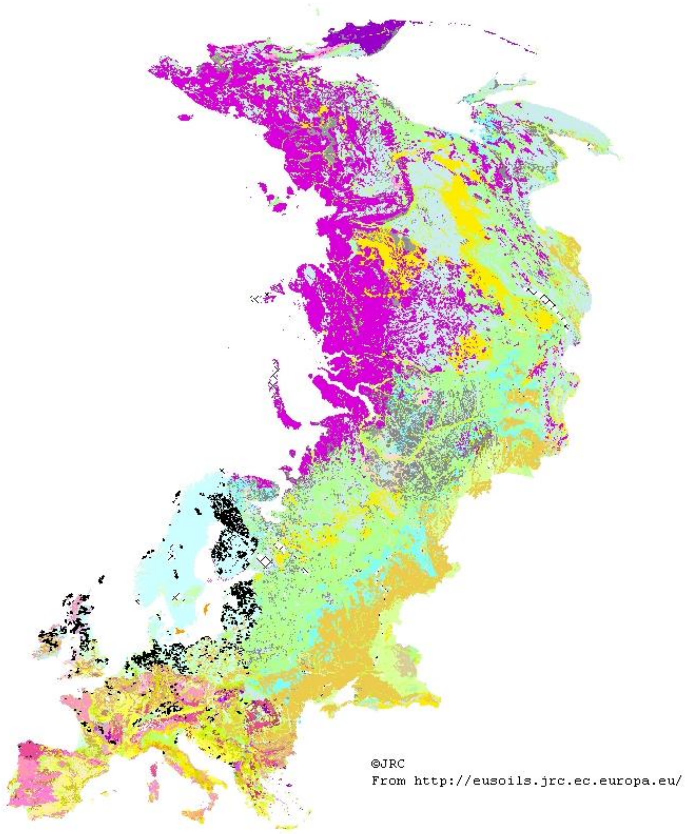
THE TOPOGRAPHICAL POSITION OF SOIL TYPES IN EUROPE

MSc Thesis



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Summary

Global warming and climate change are becoming important topics to deal with and of great concern to international bodies like the United Nations. Therefore, the research community increasingly uses environmental models to assess environmental impacts and environmental changes. These environmental models require soil maps, but they are hindered by the many complex mapping units in the available soil maps. The S-World (Soil of the World) solves this problem by disaggregating the complex mapping units using topography based on altitude. This study aims at a further refinement of the methodology through adding more topographical factors to the methodology using slope and relative altitude. The study focused on the European soil map to improve the methodology. The methodology aims to associate each soil type in the European soil map to their relative position on the landscape based on relative altitude and slope. Then, to examine the possible disaggregation of the complex mapping units in the European soil map. Different methods were evaluated: 1) Using the description of the soil types from soil classification to investigate what properties can be related to a topographical position for each soil and then relate each soil type to a relative position on the landscape. 2) Using the attributes of the European soil map that are related to altitude and slope to relate each soil type to a relative altitude and slope. 3) Using the homogeneous mapping units of the European soil map and digital elevation model to relate each represented soil type in the homogeneous mapping units to a range of relative altitude and slope. 4) Using soil profile data and digital elevation model to relate each soil type in the European soil map to a range of relative altitude and slope. 5) combining the results of the previous four methods all together. All the results of these methods have been tested on the complex mapping units to examine how many complex mapping units can be disaggregated.

The results show that we are able to disaggregate 42% of the complex mapping units of the European soil map when relying on method one, 32% when relying on method two, 93% when relying on method three, 15% when relying on method four, and 97% when combining the results from all first four methods.

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1. Introduction

Global ecosystems have been significantly affected by human activities over the last decades, resulting in environmental impacts like climate change and global deforestation which are becoming important topics to deal with (Stoorvogel et al., 2017a). Therefore, a set of international targets like sustainable development goals, and specific targets to combat poverty, climate change, and desertification have been set by many international bodies like the united nations and the Rio conventions. The research community is increasingly studying environmental changes and assessing environmental impacts (Stoorvogel et al., 2017b) using different environmental models like Integrated Model to Assess the Global Environment (IMAGE) (Stehfest et al., 2014), and the Lund-Potsdam-Jena Dynamic Global Model (LPJ) (Bondeau et al., 2007). Different processes such as soil erosion, soil conservation, soil restoration and crop growth have been estimated by these models that have specific requirements on soil data (Stoorvogel et al., 2017b). Some soil databases are provided by digital soil mapping (McBratney et al., 2003). Many soil maps are available and have been used for environmental modelling like the harmonized world soil database (HWSD) and the European soil map (ESM). The problem of these soil maps as they stand is that they include complex mapping units that are described by two or more soil types in one mapping unit. The relation between the soil types within one mapping unit is non-spatial resulting in undefined geographical location of the soil types in the complex mapping unit, only the areal percentage of the soil type is provided (Hiederer, 2013).

In many applications, the dominant soil type is used as a representative soil for the complex mapping unit or they take the weighted average of the soil properties for each soil type and consider it as representative for the whole complex mapping unit. These strategies are not appropriate when there are different soil types in a complex mapping unit, resulting in excluding other soil type/types in the first option or ending up with completely different soil properties in the second option, this will limit the quality of the environmental modelling in both options.

Based on "catena" concept which means a chain of soils linked to each other by one of the soil forming factors (Milne, 1936), Different soil types can be assigned to their most likely position along one hillslope due to these forming factors. In this study, different soils will be linked to each other based on the topography factor, relative altitude and slope.

Stoorvogel et al, (2017b) have developed a methodology to disaggregate complex mapping units of global soil map using a global toposequence based on altitude. However, the inclusion of other topographic factors like slope and curvature may improve the disaggregation of complex mapping units.

To improve the methodology of disaggregation of the complex mapping units, each soil type in the complex mapping units in the European soil map has to be linked to other soil types in one complex mapping unit based on relative altitude and slope (i.e. one soil type has higher altitude than the other or steeper slope). Different approaches have been applied in this study to link each soil type to their expected relative altitude and slope. Firstly, using the description of the soil types from soil classification to investigate what properties can be related to a topographical position for each soil and then relate each soil type to a relative position on the landscape. Secondly, using the attributes of the European soil map that are related to altitude and slope to relate each soil type to a relative altitude and slope. Thirdly, using the homogeneous mapping units of the European soil map and digital elevation model to relate each represented soil type in the homogeneous mapping units to a range of relative altitude and slope. Fourthly, using soil profile data and digital elevation model to relate each soil type in the European soil map to a range of relative altitude and slope. Finally, combining the results of the previous four methods all together. All the results of these methods have been tested on the complex mapping units to examine how many complex mapping units can be disaggregated.

Problem statement, and research questions:

The European soil map provides the majority of the mapping units as complex mapping units, where the geographical location of each soil type is not defined, only the areal percentage of each soil type is provided, whereas many environmental models require one soil type per mapping unit.

Research question:

- How can we link different soil types based on relative altitude and slope in one complex mapping unit from the available soil property database and geo-referenced soil databases to disaggregate these complex mapping units?
- Sub-questions:

1- Does soil classification provide information that can be used to link different soil types to each other in one complex mapping unit based on relative altitude and slope?

2- Do the Attributes of the European soil map provide information that can be used to link different soil types to each other in one complex mapping unit based on relative altitude and slope?

3- Is it possible to use homogeneous soil mapping units of the European soil map and digital elevation model (DEM) to link different soil types to each other in one complex mapping unit based on relative altitude and slope?

4- Is it possible to use soil-profile data and digital elevation model (DEM) to link different soil types to each other in one complex mapping unit based on relative altitude and slope?

2. Conceptual framework

2.1 Soil forming factors and soil mapping

Natural soil bodies are being described, classified and grouped in relation to the location of the soil that is being mapped. By doing this, soil properties information of a mapped soil can be interpreted to its spatial distribution on a map (Hudson, 1992). The soils and miscellaneous areas are associated with a specific kind of landform and placed in an ordered pattern that is related to one of the forming factors (time, living organisms, parent material, climate and topography) in a survey area of a soil map as the soil forming factors are the milestone of the soil distribution on the landscape. However, some boundaries are not clear, or the soils occur in an unpredictable pattern, that will result in a mapping unit with different soil types without boundaries between these soils. Also, some soils are integrated into one mapping unit even if they have clear boundaries or patterns because they have similar use or management.

In this study, we are aiming to disaggregate the soil mapping units that have more than one soil type based on one or more of the soil forming factors. 1) Time is a very long process that we cannot handle in our study, but we still can notice the effects of the time factor on the landscape due to the catena position. 2)Living organisms are usually represented by land cover digital data, which can include maps of vegetation, land use, and species distribution, or vegetation that represented by remotely sensed spectral data. Land cover and vegetation can give significant information about the soil types that can be suitable for certain plants, especially in the case of degraded lands, but different soil types may have the same vegetation when they have the same land use. 3) Parent material has a significant effect on the soil type but it's not efficient in terms of clarifying the boundaries between different soils as it's affected by toposequences and soil material movement especially along one hillslope. 4) climate cannot be used in terms to determine soil distribution on the landscape in a relatively short distance as we don't expect a significant climate change in the short distance and is very hard to determine precisely soil boundaries only based on climate. However, on one hillslope we may have climate differences, but it's influenced by the topographical position. 5) Topography seems to be the main appropriate factor that relates to all soil forming factors and can be used in terms to disaggregate complex soil mapping units based on the catena concept that explains the close relationships between a series of soils in different positions on the landscape.

Given the information from the European soil map, we believe that we can determine different soil types and disaggregate the complex soil mapping units based on the topography factor.

2.2 Soil Mapping Unit

A soil mapping unit is a collection of areas that have the same name of their soil components which can provide useful soil information to meet different users needs. Each mapping unit has different properties than the others in a survey area and has a description of its component (Soil Science Division Staff, 2017).

Four different types of mapping units are used in soil surveys: consociations, complexes, associations, and undifferentiated groups (Soil Science Division Staff, 2017).

2.2.1 Consociations

A single soil is dominant in the consociation mapping unit and all soils in the mapping unit meet the criteria for the taxonomic class that has been used to name this mapping unit. Also, the soil types that don't meet the criteria -if exist- don't significantly affect the use of the mapping unit.

2.2.2 Complexes

Two or more different soil types are presented in a complex mapping unit and the soils occur in an unpredictable pattern or in a regular repeating pattern on the landscape. Soil complexes can't be presented separately and have different properties that can't be a consociation (Figure 1).

Figure 1. Areas meet the definition of a soil complex. Bottom photo; shows the distribution of the coppice dunes on the eroded phase of the Rotura series. Top photo shows a landscape of the Bluepoint-Rotur (Soil Science Division Staff, 2017).

2.2.3 Associations

Two or more different soil types are presented in an association mapping unit and the soils occur in a regular repeating pattern on the landscape. Soil associations can be presented separately at a scale of about 1:24,000 or larger, but these repeating patterns of the soil occurrence have been integrated due to land use or user needs. However, these soils have sufficiently different properties that can't be a consociation. Thus, the soil map only shows the characteristic landscapes of associated soils, not the individual soils (Figure 2).

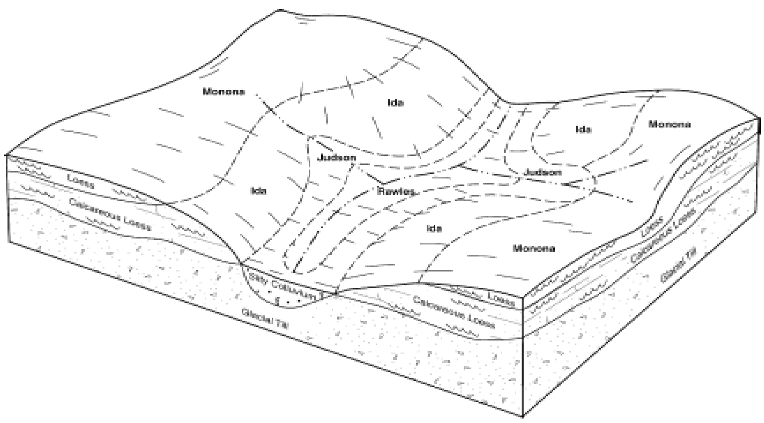


Figure 2. Block diagram describe the relationship between soils in the Monona-Ida-Judson association in the general soil map (published scale of 1:125,000) of Woodbury County, Iowa (USDA-NRCS, 2006).

2.2.4 Undifferentiated Groups

An undifferentiated group consists of different soil types that are not associated geographically. Thus, soil types do not always occur together in the same mapping unit delineation. However, they are included in the same mapping unit because they have similar use or management.

In this study, we are focusing on the European soil map. which includes soil mapping units with no specific type. Two types of mapping units have been distinguished from the European soil map. The first type is the consociation mapping units which are the mapping units that have just one soil type covers 100% of the mapping unit area. In this study, we will refer to the consociations as simple mapping units. The second type is the mapping units that include more than one soil type. These mapping units can be complexes, associations or undifferentiated groups. In this study, we will refer to these mapping units as complex mapping units.

3. Materials and methods

3.1 Materials

The materials that have been used in this study are expected to give information about the relative position (based on relative altitude and slope) of the soil types to link each soil type to the other soils in the complex mapping unit base on relative altitude and/or slope. These materials are:

- Soil classification that provides soil description, soil properties and the environment for each soil type.
- Soil map that has simple and complex mapping units, and provides geo-referenced soil database.
- Soil profile data that provides a spatial location for each soil type.
- A digital elevation model that provides topographical information in the study area.

3.1.1 Soil Classification

In this study, the world reference base for soil resources (WRB soil classification) has been used as it's comparable to the (WRB) soil classification that is provided in the European soil map. This soil classification includes two parts for each soil type: the reference soil group and the qualifier. The (WRB) provides description, properties and environment for each soil type. Different factors have been used from this information to link different soil types based on relative altitude and slope (E.g. a soil type with a high content of the organic matter expected to be in a lower altitude and plain slope than the other soil types. While a soil type with coarser texture and shallow profile expected to be in a higher relative altitude and a steeper slope than the other soil types).

3.1.2 European soil map

The European Soil map is an important source of data that is derived from many other datasets and services that are available in a public domain or after prior registration. The data as it stands allows expert users to use this data to run environmental models (Panagos et al., 2012) but still have a major limitation represented by the complex mapping units.

The European Soil map consists of several databases in this study the Soil Geographical Database of Eurasia (SGDBE4) version 4 beta have been used at scale 1:1,000,000 (1cm on the map equals 1km on the ground) (Panagos et al., 2012). The (SGDBE4) contains:

1- A table that includes soil mapping units, soil types within each mapping unit and indicates the areal percentage of each soil type from the total mapping unit area. However, the specific location and distribution for each soil type are not defined within the complex mapping units.
2- An attribute table that defines topographical values for each soil type. These values differ for the same soil type from one mapping unit to the other. These values are minimum and maximum elevation, and dominant slope.

3.1.3 Soil profile data

The World Soil Information Service (WoSIS) provides standardised soil profiles data to support digital soil mapping and environmental applications at broad scale levels. The present snapshot, referred to as 'WoSIS snapshot - September 2019' contains 196,498 geo-referenced soil profiles (Batjes et al., 2016), just (26,663) geo-referenced soil profiles have a WRB classification data. This soil profile data contains information on the soil classification system (the WRB soil classification), as well as the geographical coordinates.

3.1.4 Digital elevation model (DEM)

A digital elevation model has been used to extract data on relative altitude and slope. Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010) at a resolution of 30-arc-second (approximately 1 km which is comparable to the European soil map scale) has been used in this study to overlay on the European soil map and the soil profile data to extract the relative altitude and slope values for each soil type.

1- The mean altitude gives information on the elevation for each map cell which can be used to estimate the relative altitude for each soil type.
2- The standard deviation of altitude gives information on the variation of elevation for each map cell which can be used to estimate the slope for each soil type. The higher the mean of the output of the standard deviation of altitude, the more the expected slope.

3.2 Methods

The European soil map database consists of complex mapping units. An analysis of soil types within the mapping units has been done to indicates the percentage of the complex mapping units out of the whole mapping units. Based on S-World work that considered that different soil types occur in different altitude and used the altitude from digital elevation model to disaggregate the complex mapping units (Figure 3) (Stoorvogel et al, 2017b), this study is aiming to add slope factor to improve the methodology as the slope plays an important role in soil forming and may be useful, especially when there are different soil types in the same altitude range.
The derivation of the relationships applied in five different ways before it has been examined on the disaggregation of the complex mapping units:

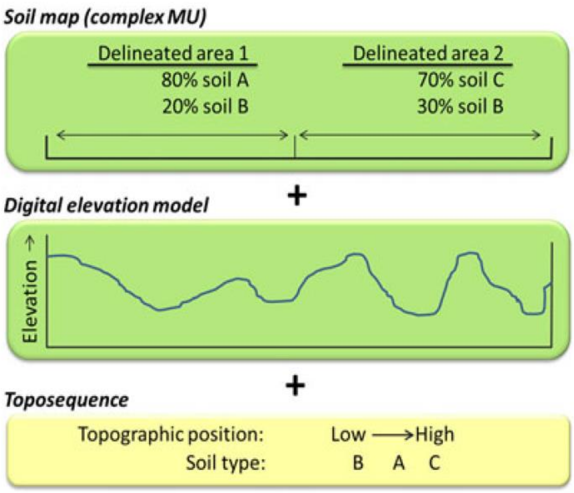


Figure 3. The process of disaggregation of complex mapping units in S-world (stoorvogel et al., 2017b).

1. Linking different soil types based on relative altitude and/or slope that are concluded from the diagnostic horizons and/or soil properties for each soil type from the (WRB soil classification).
2. Linking different soil types based on relative altitude and/or slope that are available in the attributes of the European soil map like, minimum elevation, maximum elevation, dominant slope class.
3. Using the digital elevation model and the homogenous soil mapping units of the European soil map to link different soil types based on relative altitude and/or slope.
4. Using digital elevation model and Soil-profile data to link different soil types based on relative altitude and/or slope. Using soil profile data may cover the whole soil types in the European soil map. while in the previous step we are relying just on the soil types that are found in the homogeneous mapping units to extract the relative altitude and slope values which may not cover the whole soil types in the European soil map.
5. Combining the results from the previous four steps to see to what extent can we disaggregate the complex mapping units in the European soil map if we use all available data that relates to altitude and slope.

3.2.1 The European soil map

The mapping units of the European soil map are described by the soil types and their areal percentages of the mapping unit. Many mapping units have soil types that cover 100% of the mapping unit area, in this case, we consider these mapping units as simple mapping units and there is no need to be disaggregated. Whereas, the other mapping units have been considered as complex mapping units. However, many of these complex mapping units have duplicates of one soil type in the same mapping unit but each soil type assigned to an areal percentage of the mapping unit and different soil attributes such as altitude and slope. In this study, we are interested in the relative altitude and the slope for each soil type apart to relate it to the other soil types and we are not interested to separate the duplicate soil types in a complex mapping unit. To reach this aim, the duplicates of the soil types in one soil mapping unit have been combined with each other as each soil type has to be assigned to the

same range of relative altitude and slope values. If a complex mapping unit has duplicate soil types (the same Reference Soil Group (RSG) and the same qualifier) they will be combined and the sum of areal percentages of the duplicates will be considered as an areal percentage of the same soil type in this mapping unit.
Also, the number of unique soil combinations in all soil mapping units have been counted to get an overview of what are the soil types that we are interested in to separate.

3.2.2 Soil classification

The reference soil groups (RSGs) and soil qualifiers description of each soil type that is included in the European soil map provide information of one or more of the soil properties that are considered as topographical related properties in this study. These properties have been grouped in main four groups: 1) Soil texture: Coarse texture is linked to a higher altitude and steeper slope due to the erosion of the finer sizes. 2) Soil fertility: the high soil organic matter content has been linked to a relatively lower altitude and plain slope as relatively higher altitude and steeper slope may result in topsoil removal including the organic matter. 3) Soil profile depth: A shallow soil profile might be a result of the erosion of the soils that are in higher altitude or in steeper slope. While the increase of the soil depth might be a result of accumulation activities in the lower altitude or plain slope. 4) Water retention: The saturation conditions, waterlogged deposit and periodic flood are linked to a lower altitude and plain slope as there are drainage problems in these soils. These properties have been linked to a topographical position on the landscape (e.g. coarser texture is linked to a higher altitude and steeper slope while saturation conditions are related to a lower altitude and a plain slope). Assign different soil types to different topographical position on the landscape can be used to link different soil types in a complex soil mapping unit based on relative altitude and/or slope. First, the reference soil groups (RSGs) have been used to relate each soil type to its probable altitude and slope. If the soil group has a property that relates it to a relative altitude and/or slope, the qualifier will not be used for this soil type. Then, the soil types that haven't been linked to an altitude and/or slope based on their (RSGs), the qualifiers have been used for these soils. The European soil map includes 25 (RSGs) and 48 soil qualifiers (table 1).

Table 1. Reference Soil Groups (RSGs) and soil qualifiers in the European soil map.

Reference Soil Groups (RSGs)				**Soil qualifiers**					
1.	AB Albeluvisol	17	LV Luvisol	1	ab Albic	17	fr Ferric	33	pl Plinthic
2.	AC Acrisol	18	PH Phaeozem	2	ad Aridic	18	ga Garbic	34	pr Protic
3.	AL Alisol	19	PL Planosol	3	an Andic	19	ge Gelic	35	rs Rustic
4.	AN Andosol	20	PZ Podzol	4	ao Acroxic	20	gl Gleyic	36	rz Rendzic
5.	AR Arenosol	21	RG Regosol	5	ar Arenic	21	gs Glossic	37	sa Sapric
6.	AT Anthrosol	22	SC Solonchak	6	ca Calcaric	22	ha Haplic	38	so Sodic
7.	CH Chernozem	23	SN Solonetz	7	cb Carbic	23	hi Histic	39	st Stagnic
8.	CL Calcisol	24	UM Umbrisol	8	cc Calcic	24	hu Humic	40	sz Salic
9.	CM Cambisol	25	VR Vertisol	9	ch Chernic	25	lv Luvic	41	th Thaptic
10.	CR Cryosol			10	cr Chromic	26	le Leptic	42	ti Thionic
11.	FL Fluvisol			11	cy Cryic	27	li Lithic	43	tu Turbic
12.	GL Gleysol			12	dy Dystric	28	mo Mollic	44	ty Takyric
13.	GY Gypsisol			13	et Entic	29	oa Oxyaquic	45	um Umbric
14.	HS Histosol			14	eu Eutric	30	pa Plaggic	46	vi Vitric
15.	KS Kastanozem			15	eun Endoeutric	31	pe Pellic	47	vr Vertic
16.	LP Leptosol			16	fi Fibric	32	pi Placic	48	ye Yermic

If two soil types have the same relative position on the landscape, they will be considered as soil types that can't be separated within a complex mapping unit in the European soil map. Otherwise, they will be considered as soil types that can be separated within a complex mapping unit in the European soil map.

3.2.3 Attributes of the European soil map

The European soil map includes many attributes per soil type in each mapping unit, such as maximum and minimum altitude from sea level, dominant and secondary limitation to agricultural use, dominant parent material, land use, and dominant slope. In this study, we are interested just in the topographical variables that related to slope and altitude. These variables are dominant slope, maximum and minimum altitude.

To examine the relative positions on the landscape for each soil type, the maximum altitude, the minimum altitude and the dominant slope values with confidence intervals of 95% have been considered for each soil type. The mean of the maximum altitude plus the confidence intervals of 95% has been considered as the highest altitude value for each soil type, the mean of the minimum altitude minus the confidence intervals of 95% has been considered as the lowest altitude value for each soil type, the mean of the dominant slope plus the confidence intervals of 95% has been considered as the highest slope value for each soil type and the mean of the dominant slope minus the confidence intervals of 95% has been considered as the lowest slope value for each soil type.

If two soil types don't have overlapping values of altitude and/or slope they will be considered as soil types that can be separated within a complex mapping unit in the European soil map. while, if they have overlapping values in both variables (altitude and slope) they will be considered as soil types that can't be separated within a complex mapping unit in the European soil map.

3.2.4 The homogenous mapping units of the European soil map and DEM

Slope and relative altitude values have been extracted from the digital elevation model for the homogeneous soil mapping units to relate these values for each soil type in the European soil map. Subsequently, plotting the soil types of the homogeneous mapping units due to their relative altitude and slope will give an overview of the relative position on the landscape for each soil type.

3.2.4.1 Extracting relative altitude and slope for the homogeneous mapping units

Extracting the relative altitude and slope have been applied for the homogeneous mapping units (simple mapping units) that have one soil type covers 100% of the mapping unit area. But the number of the included mapping units (soil types) was too few compared to the full count of the mapping units in the European soil maps. Also, many soil types have been represented by just one mapping unit. To be sure about the results, there was a need to include more soil mapping units. For that, soil mapping units that have soil types covering 90% or more of the areal percentage of the mapping units have been considered as homogeneous mapping units as a first option. The second option was to consider all soil mapping units that have soil types covering 75% or more of the areal percentage of the mapping units as homogeneous mapping units. Finally, we compared the results of the previous options to see which one has the better results of soil separation.

3.2.4.2 Overlaying the digital elevation model on the European soil map

The Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010) has been used to extract the altitude and slope values for each mapping unit that is included in the European soil map. Just the homogeneous mapping units are considered in this step because we will use these values to relate each soil type to a range of altitude and slope values.

3.2.4.3 Calculating the relative Altitude of the soil types of the European soil map

To explore the relative position based on the altitude of the soil types (in this case the homogeneous mapping units) the relative altitude has been calculated. The relative altitude has been calculated in two steps: 1) the neighbourhood focal statistics (annulus) have been applied (Figure 4) to give each homogeneous mapping unite a mean altitude value of the neighbour mapping units. 2) these neighbourhood values of the homogeneous mapping units from the previous step have been subtracted from the mean altitude values for the same mapping units. This results in, each mapping unit has a value. If the value is (> 0) then this mapping unit is in relatively higher altitude than the neighbour mapping units. Whereas, if the value (< 0) then this mapping unit is in relatively lower altitude than the neighbour mapping units.

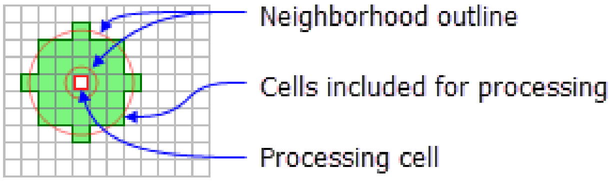


Figure 4. Annulus neighbourhood example for the Focal Statistics function (inner radius 1 cell, outer radius 3 cells) https://pro.arcgis.com/en/pro-app/arcpy/spatial-analyst/nbrannulus-class.html

Different values of outer radios have been used to estimate what is the better value to use in this study. Neighbourhood focal statistics (annulus) when inner radius 1 cell, outer radius 5, 10 and 20 cells have been applied on the mean altitude of the DEM and just including the mapping units that have soil types with 75% of the areal percentage or more (which are considered as homogeneous mapping units) to examine the best value to use.

3.2.4.4 Relative position of the soils on the landscape

Plotting the Extracted relative altitude and slope values of the soils with confidence intervals of 95% will give insight into the relative position of the soil types. Examine the higher and the lower values of the relative altitude and slope when confidence intervals of 95% have been used to link different soil types to each other based on relative altitude and/or slope (e.g. If soil type has lower relative altitude values than the other and there are no overlapping values, it will be liked to the other soil type as it has always a lower position on the landscape than the other soil type). In that term, if the higher and lower values of the relative altitude or slope of two soil types don't overlap, they will be considered as soil types that are able to be separated. If the two values overlapping, they will be considered as soil types that are not able to be separated. The calculation of the higher and lower values of the relative altitude and slope has been done as the following: the mean of the relative altitude plus the confidence intervals of 95% has been considered as the highest relative altitude value for each soil type, the mean of the relative altitude minus the confidence intervals of 95% has been considered as the lowest relative altitude value for each soil type. The same has been done to calculate the highest and the lowest slope values.

3.2.5 Soil profile data and DEM

The World Soil Information Service (WoSIS) represents for each soil type the reference soil group name, the names of the prefix (primary) qualifiers, and the suffix (supplementary) qualifiers. To extract the relative altitude and slope values for each soil type in the European soil map from soil profile data there was a need first to make the soil types of the soil profile data comparable to the soil types in the European soil map. then, relative altitude and slope values have been extracted from the digital elevation model for the soil profiles data. Subsequently, plotting the soil types from the soil profile data due to their slope and relative altitude will give an overview of the relative position on the landscape for each soil type.

3.2.5.1 Standardization of the soil types of the soil profile data to be comparable to the soil types of the European soil map

To make the soil types of the soil profile data comparable to the soil types of the European soil map, the reference soil group names and the name of the prefix qualifiers have been combined with neglecting the suffix qualifiers, as the prefix qualifiers are the only qualifiers that are taken into consideration in the European soil map. After that, just soil types that are included in the European soil map have been considered from the soil profile data.

3.2.5.2 Overlaying the digital elevation model on the soil types of soil profile data

The relative altitude and slope values have been extracted from the digital elevation model and the soil profile data for each soil type that included in the European soil map. Because we will use these values to relate each soil type in the European soil map to a range of altitude and slope values.

3.2.5.3 Calculating the relative Altitude of the soil profile data

To calculate the relative altitude of the soil types of the soil profile data, we have done the same as in the previous step of calculating the relative altitude of the European soil map. We just used the soil types of the soil profile data instead of the homogeneous mapping units. Also, in this step, we have just used neighbourhood focal statistics (annulus) when inner radius 1 cell and outer radius 20 cells.

3.2.5.4 Relative position of the soils on the landscape

Plotting and examining the Extracted relative altitude and slope values of the soils with confidence intervals of 95% have been done for the soil profile data in the same way as the previous step of the homogeneous mapping units of the European soil map.

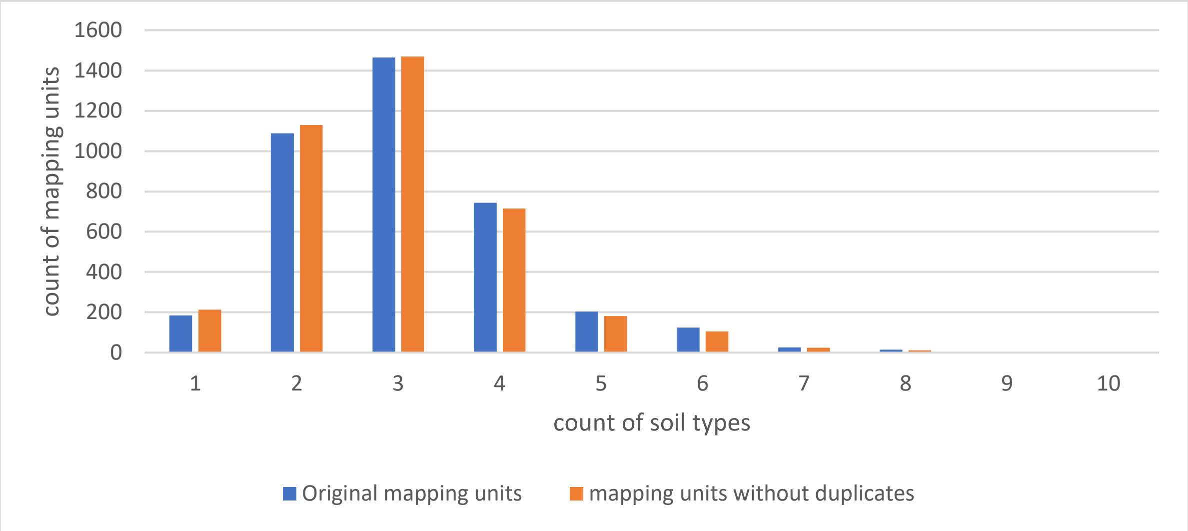
3.2.6 Combining the results of the previous four methods

Combining the results of the soil classification, the attributes of the European soil map, the homogeneous mapping units of the European soil map and the DEM, and the soil profile data and the DEM has been done by combining the results of the unique soil combinations separation of these methods together to include the maximum number of possible separations from all the data that we use in this study. The results of these soil separation have been tested on the complex mapping units of the European soil map to examine the disaggregation possibilities.

4. Results

4.1 The European Soil Map

As a starting point to reach the goal of this study the duplicate soil types in the same complex mapping unit have been combined with each other in the European soil map. The effect of the combining is shown in Figure 5.



Figuer 5. Original mapping units and mapping units without duplicates and its related count of Soil types.

The results of removing the soil duplicates in the complex mapping units have shown less soil mapping units that have 4, 5, and 6 soil types. While more soil mapping units that have 1 and 2 soil types. However, the difference is minimal, but combining the same soil types within a complex mapping unit makes the data more concise in terms of soil area percentage especially when extracting soil properties based on homogenous soil mapping units. Moreover, we are not interested in disaggregating the soil duplicates in a complex mapping unit.

Also, the number of unique soil combinations in all complex mapping units have been counted to get an overview of what are the soil types that we are interested in to separate. The unique soil combinations are shown in figure 6.

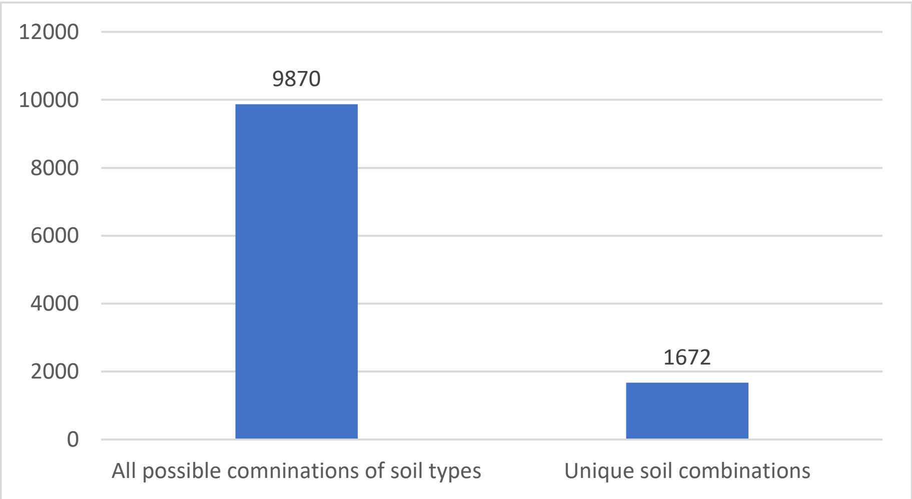


Figure 6. All possible soil combinations and the unique soil combinations in the complex mapping units of the European soil map.

The results show that there are 1672 unique soil combinations from 9870 possible combinations. These unique soil combinations are the soil types that we are interested in to separate in this study because the aim of the study is to disaggregate just the complex mapping units.

4.2 Soil classification

The first step was to use the reference soil groups (RSGs) that have properties that can be related to a relative position on the landscape. These (RSGs) are shown in table 2. Just 12 soil groups out of 25 soil groups have been used to relate different soil types to their relative position. One soil group was related to a higher altitude and steeper slope. Whereas, the other 11 soil groups were related to a lower altitude and plain slope.

Table 2. WRB soil groups that have been assigned to topographical related properties and their expected position.

	Soil groups	Topographical related properties	Expected position on the landscape
1	LP Leptosol	Shallow depth of the soil profile. Extremely gravelly and/or stony. Common in mountainous regions.	Higher altitude and steeper slope
2	AB Albeluvisol	Flat to undulating plains with drainage problems.	Lower altitude and plain slope
3	CH Chernozem	Rich in organic matter.	
4	FL Fluvisol	Alluvial deposits.	
5	GL Gleysol	Saturated with groundwater for long periods.	
6	HS Histosol	Rich in organic matter. The vast majority occurs in lowlands.	
7	KS Kastanozem	Rich in organic matter.	
8	LV Luvisol	High clay content. Most common in flat or gently sloping land.	
9	PH Phaeozem	Rich in organic matter.	
10	PL Planosol	Clayey alluvial and colluvial deposits. Typically, in seasonally waterlogged flat lands.	
11	SN Solonetz	Dense, strongly structured and clayey subsurface horizon. Normally associated with flat lands.	
12	VR Vertisol	Heavy clay soils with a high proportion of swelling clays.	

The second step was to use the soil qualifiers when the RSG of the soil type doesn't have topographical related properties. These qualifiers are shown in table 3. Just 22 qualifiers out of 48 qualifiers have been used to relate different soil types to their relative position. 6 qualifiers are related to a higher altitude and steeper slope. Whereas, the other 16 qualifiers are related to a lower altitude and plain slope.

Table 3. WRB soil qualifiers that have been assigned to topographical related properties and their expected position.

	Qualifier	Topographical-related properties	Expected position on the landscape
1	ab Albic	Coarser texture with removed clay and free iron.	Higher altitude and steeper slope
2	hi Histic	Shallow depth of the soil profile.	
3	le Leptic	Shallow depth of the soil profile.	
4	li Lithic	Shallow depth of the soil profile.	
5	st Stagnic	Coarser texture and wet conditions with removed clay and free iron.	
6	oa Oxyaquic	Saturation conditions.	
7	pe Pellic	Sedimentations with high proportion of swelling clay.	Lower altitude and plain slope
8	ti Thionic	Waterlogged deposit.	
9	ty Takyric	Occur in periodically flooded soils.	
10	vr Vertic	Contains 30 percent or more clay and linked to the lowest position in the landscape.	
11	ad Aridic	Accumulation at the soil surface by aeolian or alluvial activity.	
12	lv Luvic	Illuvial accumulation of clay.	
13	an Andic	Rich in organic matter.	
14	cb Carbic	Illuvial materials and high-water retention	
15	et Entic	Illuvial materials and high-water retention.	
16	fi Fibric	Rich in organic matter. and the vast majority occurs in lowlands.	
17	ga Garbic	Rich in organic matter.	
18	gl Gleyic	Saturated with groundwater for a period that allows reducing conditions to occur.	
19	pa Plaggic	Rich in organic matter.	
20	rs Rustic	Illuvial materials and high-water retention.	
21	sa Sapric	Rich in organic matter. and the vast majority occurs in lowlands.	
22	um Umbric	Rich in organic matter.	

If two soil types from the European soil map occur in a complex mapping unit and have been both related to the same expected position on the landscape, or both have no topographical related properties they have been considered as soil types that are not able to be separated. Whereas, all other combinations have been considered as soil types that are able to be separated.

The results are shown in figure 7. Almost 56% of the unique soil combinations were able to be separated in the European soil map based on the soil types properties and its topographical related positions.

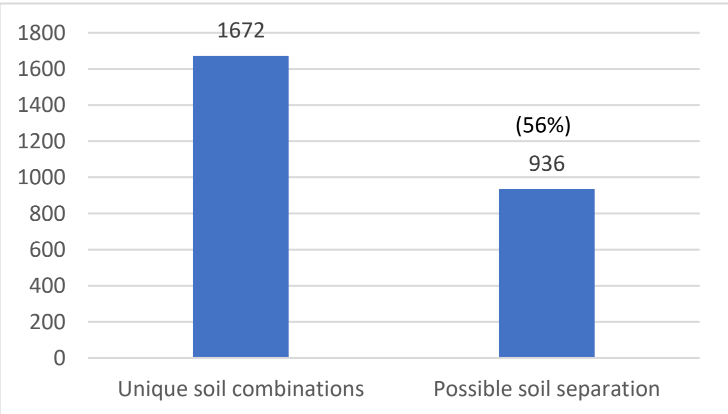


Figure 7. Possible unique soils separation due to soil properties and all unique soil combinations in the European soil map.

These soil separations have been applied to the complex mapping units of the European soil map to explore the disaggregation possibilities of these mapping units. The results are shown in figure 8.

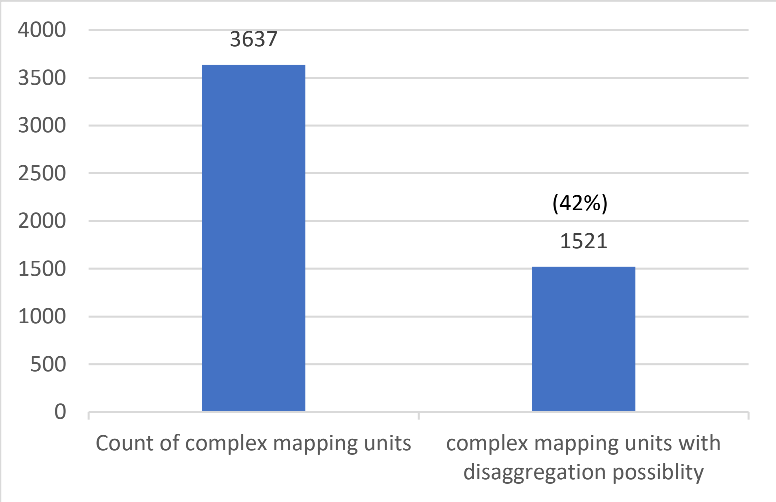


Figure 8. Possible disaggregation of the complex mapping units due to soil properties in the European soil map.

The results show that almost 48% of the complex mapping units in the European soil map were able to be disaggregated based on the soil types properties and their topographical related positions.

4.3 Attributes of the European soil map

The attributes of the European soil map has some missing values of the interested variables, these missing values are; 181 dominant slope values, and 134 minimum and maximum altitude values from 5247 values. These missing values cannot be extracted from other sources as the specific location for each soil type is not defined within the mapping units.

After calculating the values of the maximum and the minimum altitude, and the maximum and the minimum dominant slope for each soil type when confidence intervals are 95%. We have considered the soils that have no overlapping values of altitude and/or dominant slope as soil types that can be separated. Otherwise, they will be considered as soil types that can't be separated. The results are shown in figure 9.

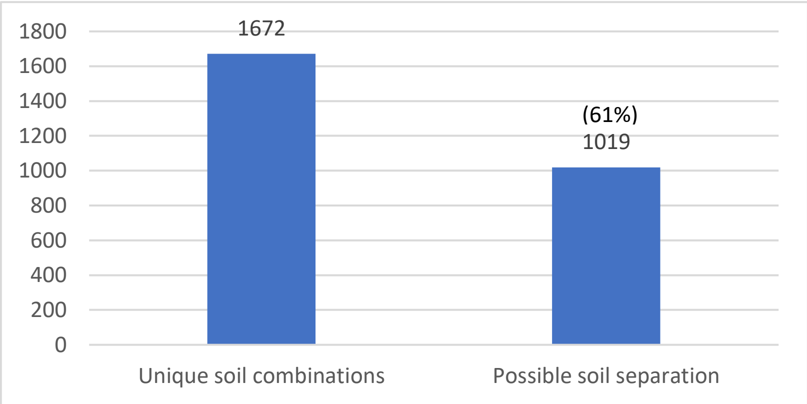


Figure 9. Possible unique soils separation due to the attributes of the European soil map in the European soil map.

The results show that almost 61% of the unique soil combinations were able to be separated in the European soil map based on the attributes of the European soil map.

These soil separations have been applied to the complex mapping units of the European soil map to explore the disaggregation possibilities of these mapping units. The results are shown in figure 10.

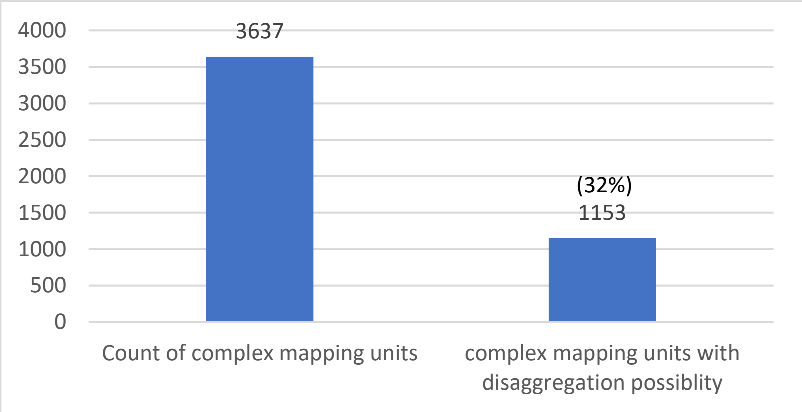


Figure 10. Possible disaggregation of the complex mapping units due to the attributes of the European soil map.

The results show that almost 32% of the complex mapping units in the European soil map were able to be disaggregated based on the attributes of the European soil map.

4.4 European soil map and DEM

4.4.1 Relative altitude

plotting the extracted slope and relative altitude when the soil mapping units have 75% and more of the soil type and when using neighbourhood statistics to calculate the relative altitude when the outer radius is 5, 10 and 20 show the effect of the different neighbourhood statistic values. Comparing the three outcomes we have considered the annulus outer radius of 20 as the most appropriate value for the calculation as the different soil types have better distribution (separation) than the others, see Figures 11, 12 and 13.

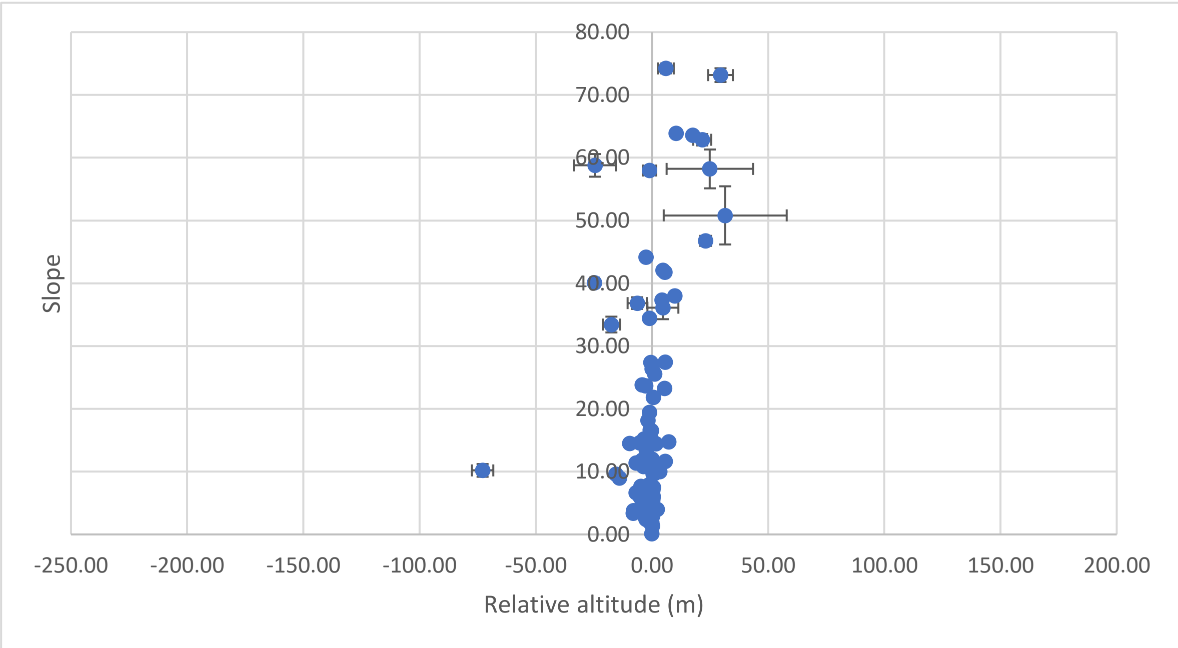


Figure 11. Soil types slope and relative altitude when one soil type has 75% and more of the mapping unit area is considered as homogeneous mapping unit and 5 cells outer radius of the neighbourhood statistics.

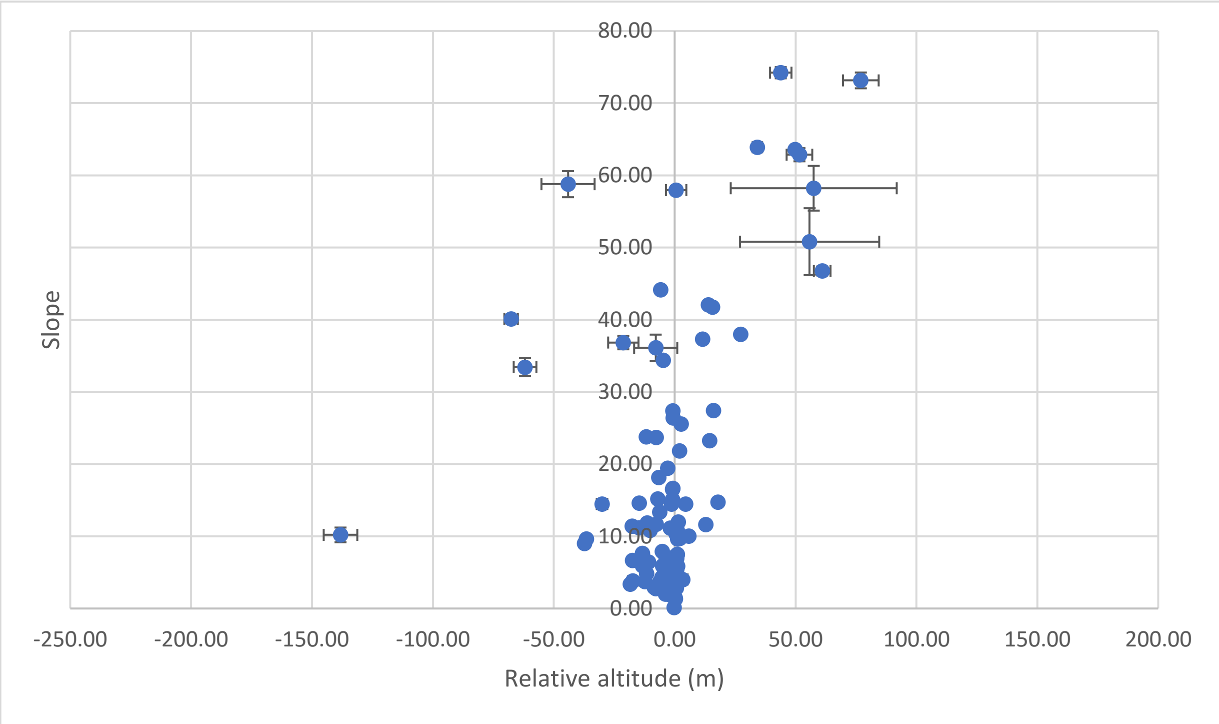


Figure 12. Soil types slope and relative altitude when one soil type has 75% and more of the mapping unit area is considered as homogeneous mapping unit and 10 cells outer radius of the neighbourhood statistics.

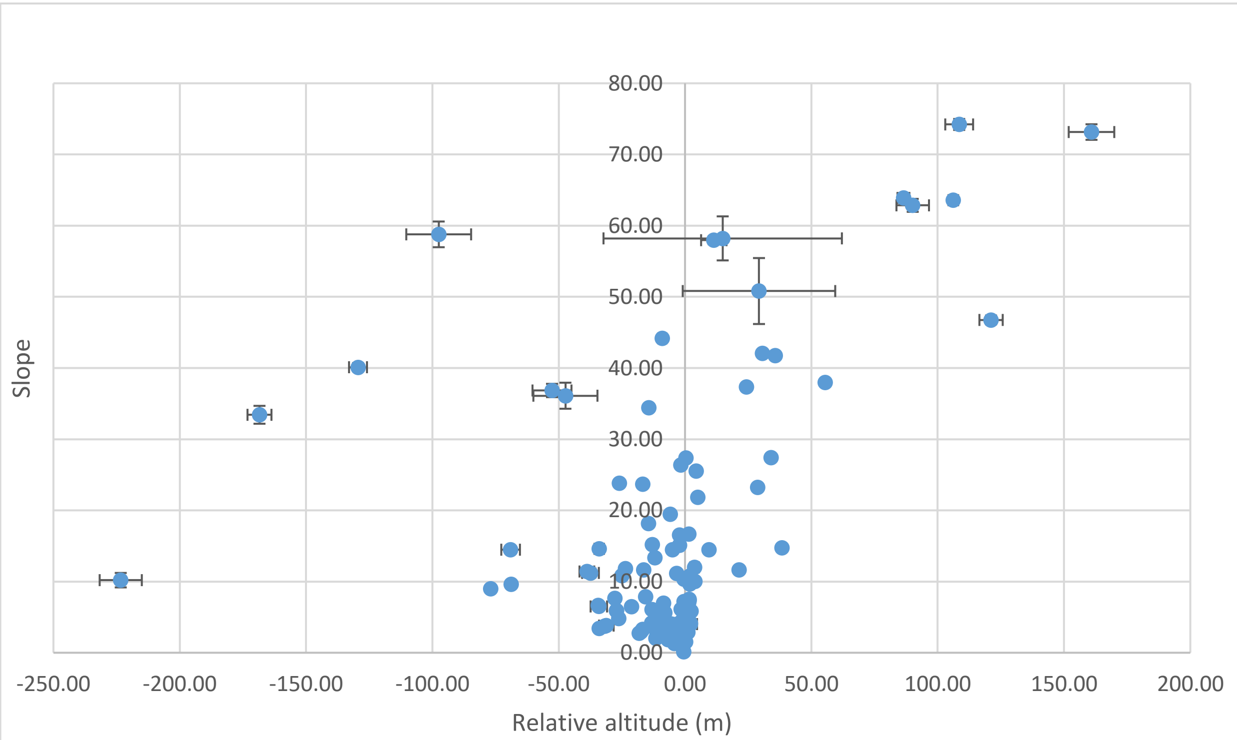


Figure 13. Soil types slope and relative altitude when one soil type has 75% and more of the mapping unit area is considered as homogeneous mapping unit and 20 cells outer radius of the neighbourhood statistics.

4.4.2 *Relative position of the soils on the land* landscape

Table 4 shows the number of the related inputs of each approach of considering the homogeneous mapping units. Including mapping units that have Soil types with 75% and more of the area is more reliable than the others, as it includes more soil types, mapping units, as well as more map cells. Thus, soil types that have 75% and more of the mapping unit area have been considered as a representative for the whole mapping unit are and these mapping units have been considered as homogeneous mapping units.

Table 4. Soil mapping units that have soil types cover 100%, 90%, 75% and more of the mapping units area and its related inputs in the calculations.

Soil type percentage	Count of included soil type	Count of included mapping units	Count of included map cells
100 %	105	218	11875414
90 % and more	110	1091	25336883
75% and more	116	2188	36570772

Plotting the soil types that have 75% and more of the mapping units area, due to its relative altitude and slope when annulus neighbour statistics outer radius of 20 cells and 95% confidence intervals give figure 14. From the figure, different soil types have been associated with different slope and altitude ranges. For example, if there are eutric Leptosol (LPeu) and calcaric Leptosol (LPca) in the same mapping unit we can consider the (LPeu) in the lower position. While, if there are dystric Leptosol (LPdy) and haplic Leptosol (LPha) in the same mapping unit we can consider the (LPha) in the steeper slope.

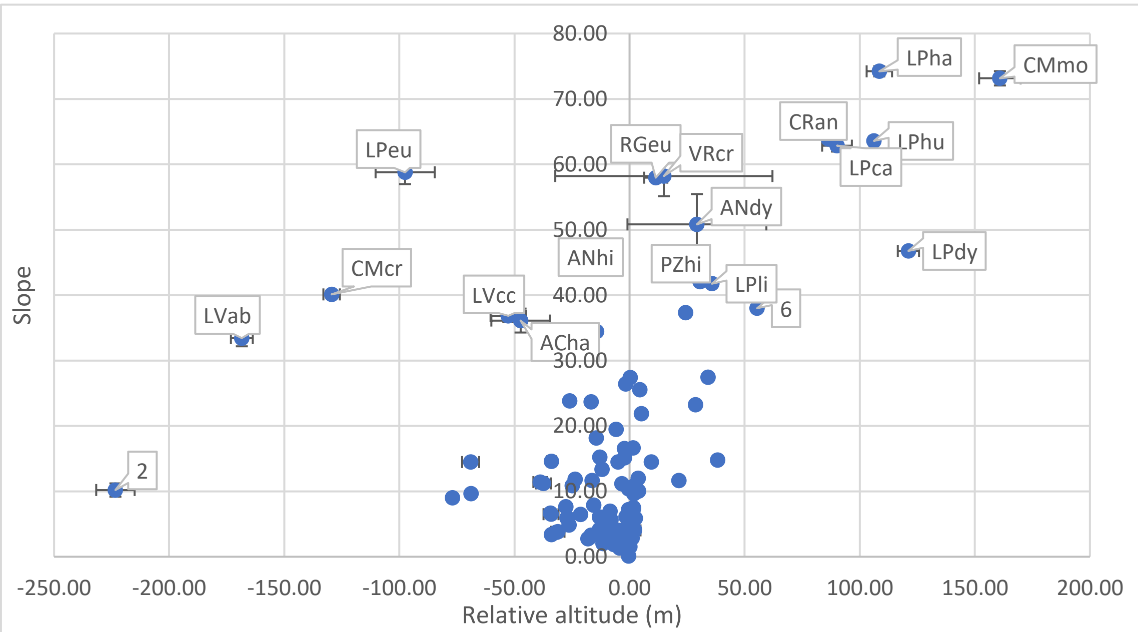


Figure 14. Soil types slope and relative altitude when one soil type has 75% and more of the mapping unit area is considered as homogeneous mapping unit and 20 cells outer radius of the neighbourhood statistics.

After calculating the values of the maximum and the minimum altitude, and the maximum and the minimum slope for each soil type when confidence intervals are 95%. We have considered the soils that have no overlapping values of the relative altitude and/or the slope as soil types that can be separated from each other. Otherwise, they will be considered as soil types that can't be separated. The results are shown in figure 15.

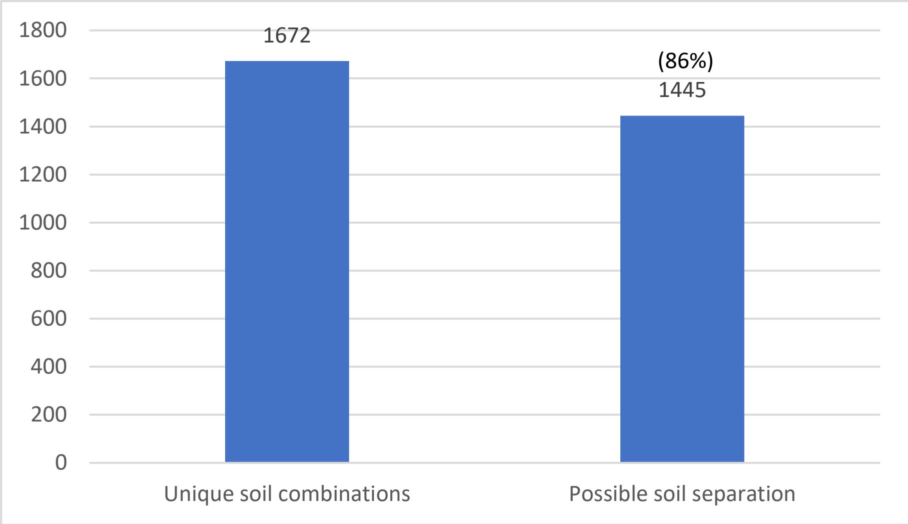


Figure 15. Possible soil separation due to the homogeneous mapping units of the European soil map and DEM, and all unique soil combinations in the European soil map.

The results show that almost 86% of the unique soil combinations are able to be separated in the European soil map due to the homogeneous mapping units of the European soil map and the digital elevation model.

These soil separations have been applied to the mapping units of the European soil map to explore the disaggregation possibilities of these mapping units. The results are shown in figure 16.

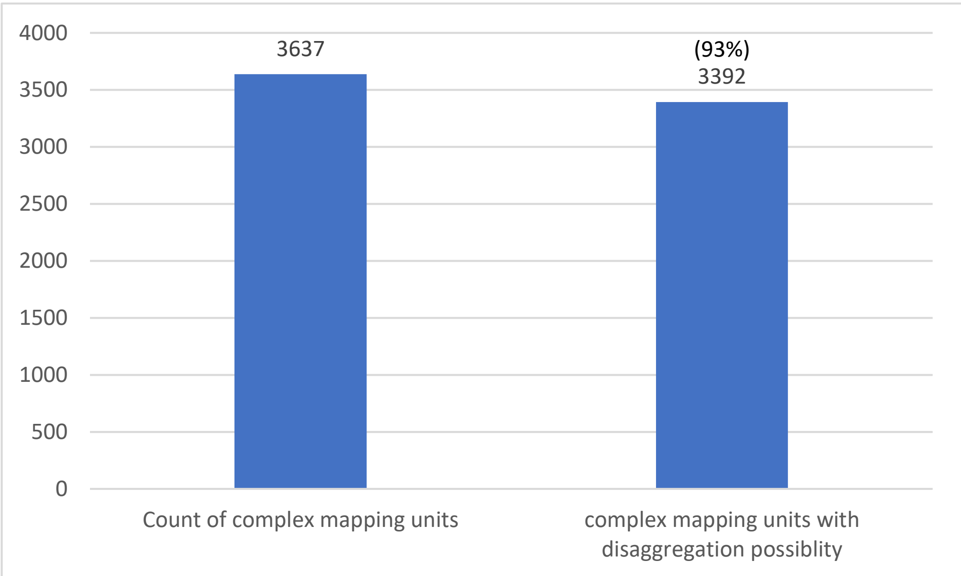


Figure 16. Possible complex mapping units separation due to due to the homogeneous mapping units of the European soil map and DEM, and all complex mapping units in the European soil map.

The results show that almost 93% of the complex mapping units in the European soil map are able to be disaggregated based on the homogeneous mapping units of the European soil map and the digital elevation model.

4.5 Soil profile data and DEM

4.5.1 Standardization of the WRB classification of the soil profile data to be comparable to European soil map database

After standardizing the WRB classification of the soil profiles data, we ended up with 108 soil types from 2073 soil profiles, these soil types were representative for 108 soil types from 143 soil types of the European soil map.

4.5.2 *Relative position of the soils on the land* landscape

Plotting the Extracted relative altitude and slope values of the soil profiles points with confidence intervals of 95% will give an insight about the relative position for each soil type in the European soil map on the landscape, see figure 17.

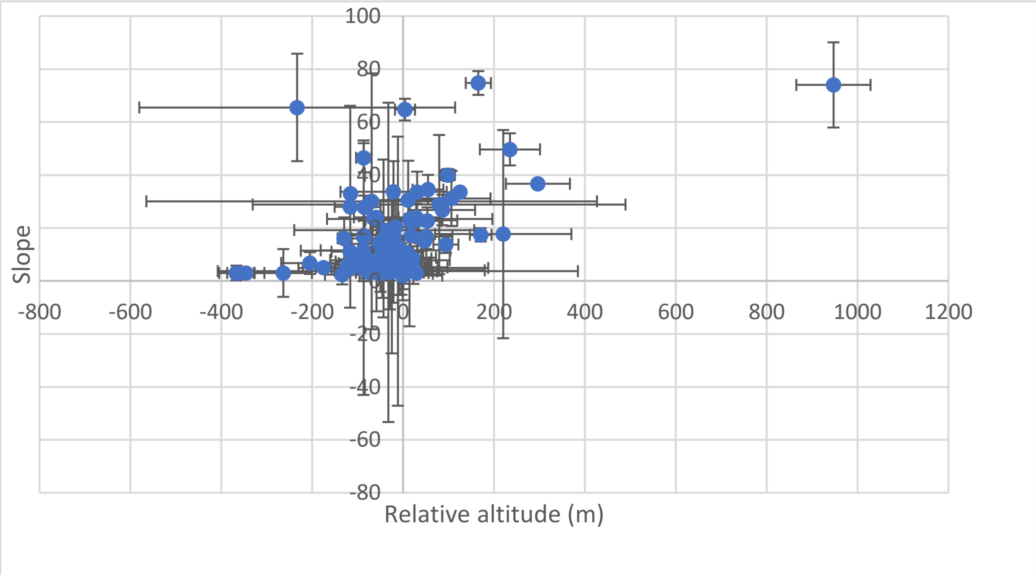


Figure 17. Soil types slope and relative altitude of the Soil profile data when confidence intervals of 95%

To examine the separation possibilities of the unique soil combinations in the European soil map, the maximum and the minimum values of the relative altitude and slope when confidence intervals of 95% have been considered as a representative value for each soil type. If two soil types have no overlapping values of the relative altitude or the slope, they will be considered as soil types that are able to be separated from each other. Otherwise, they will be considered as soil types that can't be separated. The results are shown in figure 18.

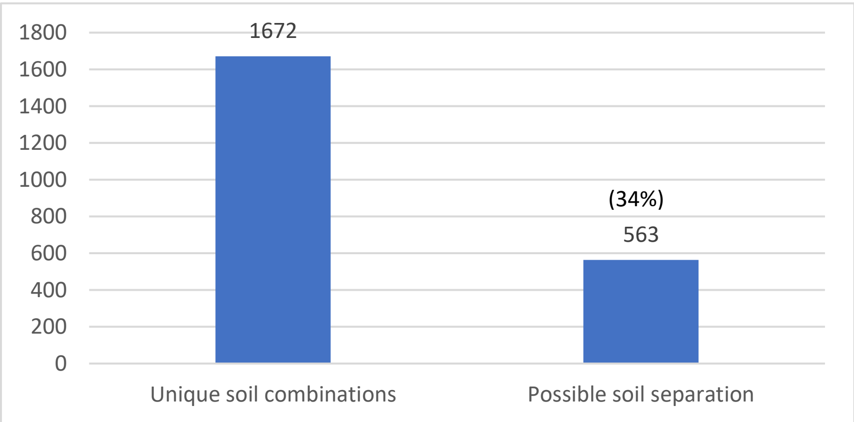


Figure 18. Possible soil separation due to soil profile data and DEM, and all unique soil combinations in the European soil map.

The results show that almost 34% of the unique soil combinations are able to be separated in the European soil map due to soil profile data and the digital elevation model.

These soil separations have been applied to the complex mapping units of the European soil map to explore the disaggregation possibilities of these mapping units. The results are shown in figure 19.

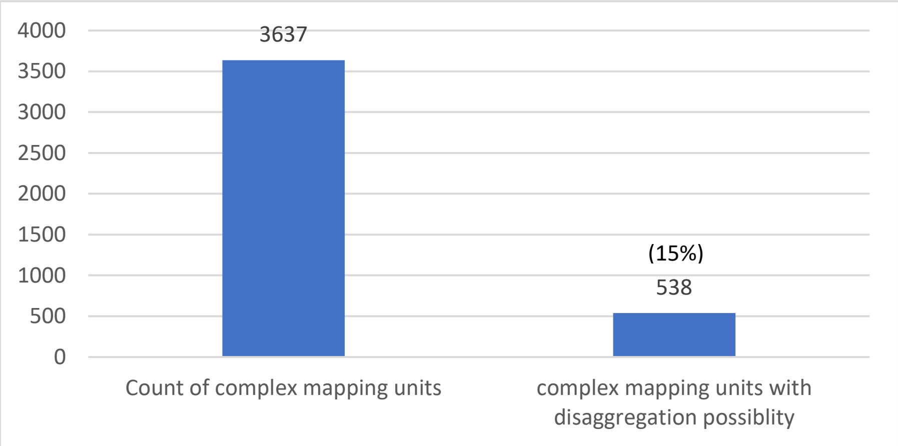


Figure 19. Possible complex mapping units separation due to soil profile data and DEM, and all complex mapping units in the European soil map.

The results show that almost 15% of the complex mapping units in the European soil map are able to be disaggregated based on soil profile data and the digital elevation model.

The number of the disaggregation of complex mapping units due to the soil profile data and the DEM were relatively low comparing to the results of the other methods. To increase the number of possible disaggregation, we have examined the overlapping percentages of the soil types that are considered as not able to be separated. Figure 20 shows an example of four soil types, two are completely separated and the other two have overlapping values.

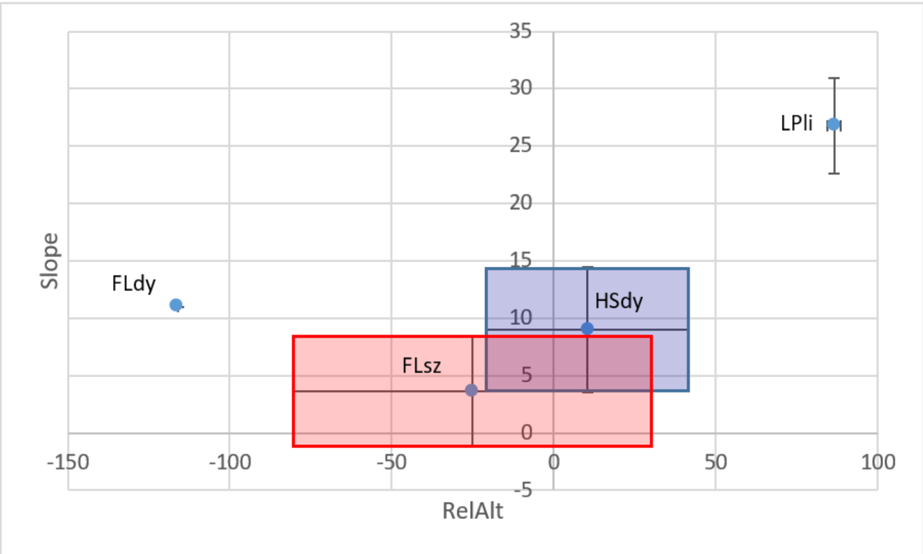


Figure 20. Example of overlapping and clear separation values between four (WRB) soil types from soil profiles data.

Soil types FLdy and LPli are clearly separated when confidence intervals 95% and soil type LPli has higher altitude and a steeper slope than the other. While soil types FLsz and HSdy have no clear separation when confidence intervals 95% due to the overlapping of their values. However, it's reasonable to say that soil type HSdy has a higher altitude and a steeper slope than the FLsz. Also, other soil types that are not able to separate have different percentages of overlapping.

The results of the overlapping percentages of the soil types that do not have a clear separation in the soil profile data are represented in table 5.

Table 5. Percentages of the soil types when overlapping percentages are ≤25, 26-50%, 51-75% and ≥75

Overlap percentages	Count of occurrence	Soil types Percentage %
≤ 25 %	2284	83.21
26_50 %	442	16.10
51_75 %	11	0.40
≥ 75 %	8	0.29

The results show that in the soil types that have been considered as soils that are not able to be separated there are around 83% of these soils that have overlapping percentages equal or less than 25%, 16% have overlapping percentages between 26 and 50%, and the rest less than 1% have overlapping percentages between 51 and 99%. Due to this overlapping percentages, we can assign these soils to different altitudes and/or slopes. However, including these soils will affect the quality of the results as we considered 0% overlapping when 95% confidence intervals as a requirement for separation.

4.6 Combining the results of the previous four methods

The results of the unique soil combinations separation of the soil classification, the attributes of the European soil map, the homogeneous mapping units of the European soil map and the DEM, and the soil profile data and the DEM are shown in figure 21.

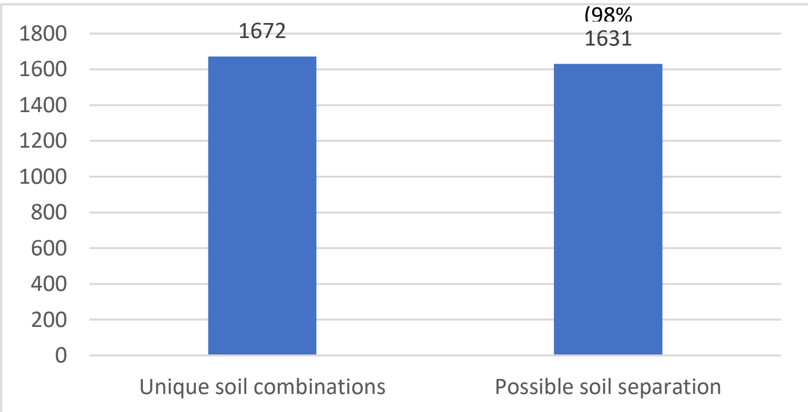


Figure 21. Possible soil separation due to the combined methods, and all unique soil combinations in the European soil map.

The results show that almost 98% of the unique soil combinations are able to be separated in the European soil map due to combining the results of the four methods together.

These soil separations have been applied to the complex mapping units of the European soil map to explore the disaggregation possibilities of these mapping units. The results are shown in figure 22.

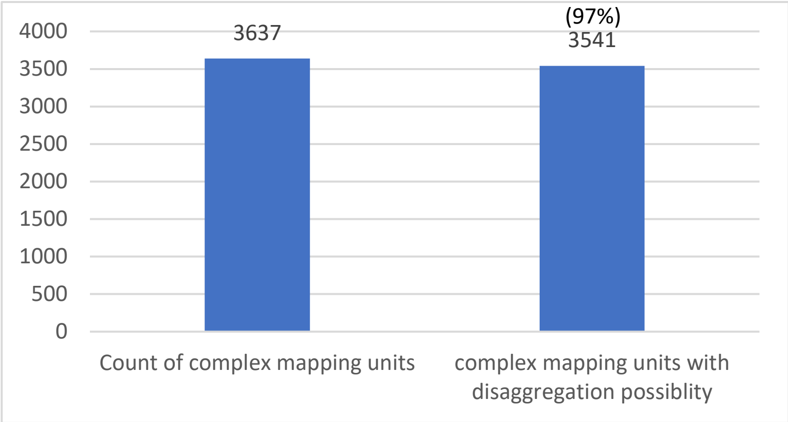


Figure 22. Possible complex mapping units separation due to combined all methods, and all complex mapping units in the European soil map.

The results show that almost 97% of the complex mapping units in the European soil map are able to be disaggregated based on combining the results of the four methods together.

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5. Discussion and Conclusion

This study uses soil property database and the geo-referenced soil databases to link each soil type to the others due to their expected position on the landscape based on altitude and slope. The results have been tested on the complex mapping units of the European soil map to estimate the disaggregation possibilities. The improved methodology has added the slope factor to the altitude factor that has been in the previous stud of Stoorvogel et al.,2017b. the results of the methods that have been used in this study are represented in figure 23.

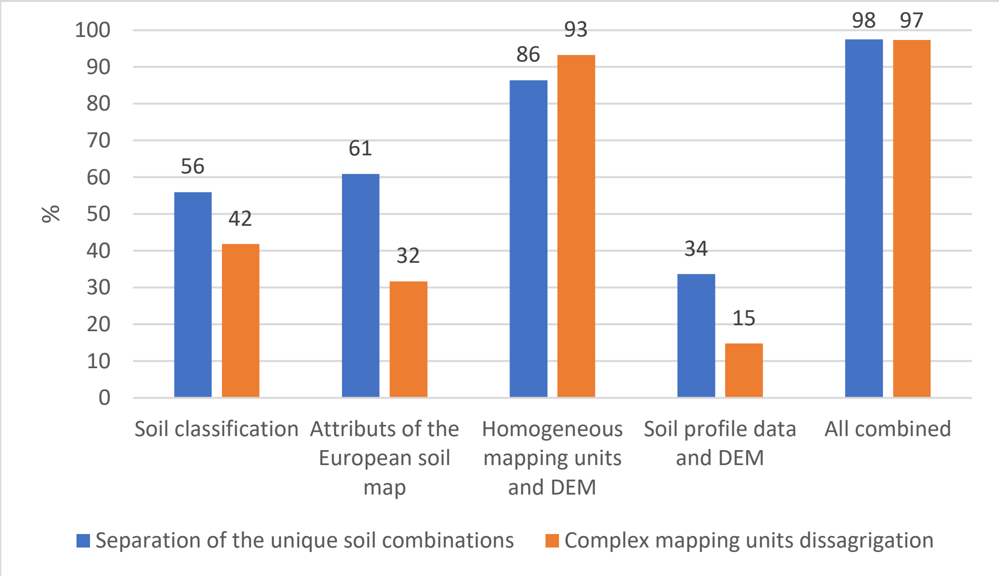

Figure 23. Comparison of separation of the unique soil combinations and complex mapping units disaggregation of all methods in the European soil map.

The results show that we are able to disaggregate 97% of the complex mapping units of the European soil map when we are relying on the all four methods together, but this result is obviously linked to the third method which used the homogeneous mapping units of the European soil map and the DEM. The other three methods were not promising to disaggregate the complex mapping units as this method. However, each methodology that has used in this study has one or more major limitations which may affect the results; 1) Soil classification has qualitative data and the inputs that have been used in this step were very hard to give different topographical properties for different soil types. Moreover, the altitude and slope were combined together in this step as we were not able to group the soil types in more than two groups based on the soil types properties, one is related to a higher altitude and steeper slope and the other is related to a lower slope and plain slope. In this case, we can say that we just rely on one factor: slope or altitude. 2) Attributes of the European soil map has many missing values of altitude and slope, the slope was defined as a class which declines the differentiation between different soil types, and the altitude was represented just as a maximum and minimum values while the real values were not provided which allow the most extreme values to take place in the calculations. 3) The homogeneous mapping units of the European soil map have been considered when there is a dominant soil type that covers 75% or more of a mapping unit which may not representative of the whole mapping unit. Although we did not consider all the dominant soil types, we still used some dominant soil types to reach these results. Even though, we wanted to decline using dominant soil types in the first place. That might be the reason behind the high disaggregation results of this method. 4) Soil profile data provides points of the soil types that we have used to extract the relative altitude and slope values. These values of the soil points might be not representative of the whole soil type area. Moreover, the soil points that we have used were distributed all around the world and not just in Europe (the study area) which makes the relative altitude and the slope values not representative values for the same soils in Europe due to the high climate differentiation.

These results are based just on 0% overlapping of the slope and relative altitude values of the unique soil combinations for the qualitative methods (Methods 2,3 and 4) to keep the quality of the results as much as possible. Otherwise, different overlapping percentages of relative altitude and slope can be included to have different results.

In general, even when we have combined all the results of the methods together, we were not able to disaggregate 100% of the complex mapping units. That was expected from the beginning as we were not expecting to disaggregate the soil complexes. From the definition, soil complexes can't be presented separately and have different properties that can't be a consociation. whereas, soil associations and undifferentiated soil groups can be presented separately, in this study due to relative altitude and slope.

The soil type distribution is explained by the soil forming factors. The topography factor has been already used to disaggregate complex mapping units based on altitude. While the methodology of this study is suitable to use as a base of disaggregation of the complex mapping units using the topography based on relative altitude and slope. Although, there is a need to apply and validate the results in the future the results show that using more than one factor can be used to link each soil type to a relative position on the landscape to use it for complex mapping units disaggregation. The community of the soil science seeks for suitable soil maps that represent each soil type in one mapping unit. The results of this study can be improved in the future due to the increase of the available legacy and auxiliary data which can be examined to the methodology of this study to improve the results. Resulting in an appropriate soil map that can increase the quality of the results of the environmental models which may help to achieve the sustainable development goals and the Rio conventions.

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