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The impact of land use/land cover change on soil organic matter content/variation and composition

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SOM	Soil Organic Matter
SOC	Soil Organic Carbon
SIC	Soil Inorganic Carbon
OM	Organic Matter
GHG	Greenhouse Gas
DOC	Dissolved Organic Carbon
TMAH	Tetra Methyl Ammonium Hydroxide
POM	Particulate Organic Matter
AAOM	Aggregate Associated Organic Matter
NMR	Nuclear Magnetic Resonance
IR	Spectroscopy and Infrared
DRIFT	Diffuse Reflectance Infrared Fourier Transform
FTIR	Fourier-transform infrared
UV-VIS	Ultraviolet-Visible
ESR	Electron Spin Resonance
ATR	Attenuated Total Reflectance
JETF	Józsefmajor Experimental and Training Farm
L	Loosening
P	Moldboard Plowing+levelingDC Deep Tine Cultivation
SC	Shallow Tine Cultivation
D	Disking
NT	No-till
WRB	World Reference Base
MPAOM	Mineral Phase Associated with Stable Organic Matter
TPI	Topographic Position Index
TRI	Topographic Roughness Index
MRVBF	Multi-Resolution Valley Bottom Flatness
MRRTF	Multi-Resolution Ridge Top Flatness
TWI	Topographic Wetness Index
MAT	Mean Annual Temperature
MAP	Mean Annual precipitation
PCA	Principal Component Analysis

1. Introduction

1.1 Background

Soil organic matter (SOM) is a complex mixture of organic materials derived from plants, fungi, and animal residues, which undergo various stages of biogeochemical oxidation. It contains approximately twice as much carbon as the atmosphere (Loveland and Webb, 2003; Oelkers and Cole, 2008) and plays a crucial role in plant productivity, microbial distribution, and soil CO_2 emissions (Feng and Simpson, 2011). Soil carbon storage is an important ecosystem service that affects soil quality, water retention, flood mitigation, erosion prevention, nutrient availability, and food production (Grandy and Robertson, 2007). The quantity and quality of SOM serve as vital indicators of soil quality and functioning (Lal, 2004a; Brock *et al.*, 2012; Asabere *et al.*, 2018). However, soil organic carbon (SOC) stocks in agricultural ecosystems have been depleted due to human activities, erosion, and other degradation processes (Oldfield *et al.*, 2019). Climate change, rapid population growth, and challenges in natural resource exploitation threaten human survival. The demand for food is increasing while land and agricultural inputs face limitations (Turalija *et al.*, 2022). Therefore, achieving sustainable development, agriculture, and food production has become a global concern.

The world's soils contain the largest terrestrial carbon reservoir, consisting of SOC and soil inorganic carbon (SIC), and are integral to the global carbon cycle (Navarro-Pedreño *et al.*, 2021). Current estimates of the global SOC stock range from 1500 to 2400 PgC, but some concerns project climate change may destabilize these stocks, particularly in regions with permafrost (Lal *et al*., 2021).

The amount of SOC is determined by the balance between organic carbon input and output rates (Lal, 2001; Zuo *et al*., 2023). Carbon input to the soil includes various sources such as crop residues, root decay, manure, and organic waste. Increasing the amount of carbon stored in soils can contribute to climate change mitigation. Conversely, climate change affects soil systems, making it challenging to accurately predict the effects due to the complexity of soil interactions (Chabbi *et al.*, 2022). The urgent need to achieve sustainability in agricultural systems involves mitigating greenhouse gas emissions, which can be accomplished through practices such as carbon farming (Turalija *et al.*, 2022). Restoring soil carbon stocks through changes in land use and agricultural management practices, such as reducing tillage intensity and increasing residue inputs, can help mitigate atmospheric CO_2 increases (West and Post, 1997; Lal, 2004a, 2004b). By adopting sustainable land use and cautious soil/crop management practices, the capacity of the land-based carbon sink can be enhanced, as it already absorbs about one-third of all anthropogenic emissions (Lal *et al*., 2021). This not only contributes to climate change mitigation but also has the potential to improve food security by preserving soil fertility, enhancing crop productivity, and ensuring sustainable agricultural systems (FAO, IFAD, UNICEF, WFP, 2019).

In Summary, it is impossible to overstate the importance of soil carbon and organic matter (OM), as they are crucial for ecosystem health, climate change mitigation, and sustainable agriculture. To achieve global sustainability goals, it is necessary to implement sustainable land use/management techniques and have a deep understanding of SOM dynamics. This includes preserving soil carbon reserves through sequestration and storage in stable forms, which helps reduce carbon levels in the atmosphere and mitigate global warming (Smith *et al*., 2008). However, because of how human activities have affected soil systems, it is now necessary to create and implement sustainable land use/management techniques and plans to preserve or even increase SOC stocks. There are ongoing discussions regarding different land use patterns, soil management techniques, the influence of temperature and climate, and the potential impact of various factors on carbon sequestration and the preservation of carbon stocks in the future (Lal, 2004a; Feng *et al.*, 2022). More investigation and the implementation of efficient soil management techniques are required to address these issues.

1.2 Problem Statement and Justification

Land use is considered the primary factor that influences SOC concentration (Qin *et al.*, 2016). When compared to virgin soils, the overall release of organic carbon from crop fields is attributed to crop production and cultivation (Lal, 2004b). However, conservation agriculture techniques have generally been observed to increase SOC concentrations (Madarász *et al.*, 2021; Bohoussou *et al.*, 2022). Additionally, due to geographical factors such as erosion and the presence of sandy soil, even degraded crop fields may retain more SOC than the soils under permanent forests (Szatmári *et al.*, 2023). However, despite these theoretical limitations on SOC storage capacity, the ratios among different pools and the overall trend of changes in SOM composition resulting from land use patterns still largely remain obscure. Also, the complex nature of SOC regulating processes in the soil system is still not fully understood, which has kept it as a prominent research topic.

Despite its small size, Hungary's location at the intersection of three major temperate zones contains a wide variety of soil types and environmental factors, such as topography, pH, and texture. Moreover, agriculture covers two-thirds of the land area, while the presence of forests is also significant in proportion.

Numerous studies have been conducted in Hungary to identify the effect of land use and environmental covariates (climatic, topography) on SOM composition (Frank *et al.*, 2015; Kátai *et al.*, 2022; Szatmári *et al.*, 2023) but there is still a need to understand the drivers of SOM composition and whether land use changes or management practices are the primary factors influencing SOC sequestration in Hungary, or if environmental factors such as temperature and climate play a more significant role. The present study investigates the relationship between the current status of the SOM concentration and composition and its regulating environmental factors (land use/management, soil properties, climatic factors) and determines the most effective regulator of SOM concentrations and composition in four study areas.

1.3 Research objectives

The main objective of this study was to characterize the relative differences in SOM composition across four study areas with seven types of land use/management to show the effect of land use/management change on the quality and quantity of SOM. To achieve this aim, the following objectives were defined.

(I) assessing the impact of land use and land management practices on SOM composition and decomposition rate.

(II) Evaluate the effect of agro-technology and various tillage operations on SOM content in surface soil to determine the most suitable tillage system.

(III) Investigate the effect of afforestation on SOM quality and compare it to conservation and conventional tillage.

(IV) Investigate how organic matter composition varies across different soil fractions (focused on three tillage systems and the tree line soil samples)

(V) Investigate the relationship between organic matter composition and content.

(VI) Assessing the effect of environmental covariates (climatic and topographic factors) and soil properties on SOM composition

2. Literature review

2.1 Soil Organic Matter (SOM) dynamics

SOC is the primary component of SOM. The storage of SOC results from the dynamic ecological processes of photosynthesis, decomposition, and soil respiration (Ontl and Schulte, 2012). SOC serves as an indicator of soil health (Martín *et al*., 2019) and plays a vital role in food production, climate change mitigation, and adaptation (Purghaumi *et al.*, 2013; Chopin and Sierra, 2019; Luo *et al.*, 2019). High SOM content provides essential nutrients to plants (X. Zhao *et al.*, 2019) and enhances water availability and holding capacity (Jafarian and Kavian, 2013), thereby improving soil fertility (Jakab *et al.*, 2016; Szalai *et al.*, 2016), and ultimately enhancing food productivity and security (Lal, 2010). SOM has additional benefits such as enhancing structural stability, improving resistance to the impact of rainfall, increasing infiltration rate, and promoting faunal activities (Bationo *et al.*, 2007). It is known as an indicator of sustainable land use/management (Nandwa, 2001).

Soil can serve as a significant contributor to greenhouse gas (GHG) emissions into the atmosphere by accelerating the mineralization of SOC. On the other hand carbon sequestration in soil has been promoted as a method to mitigate CO_2 emissions (Smith *et al.*, 2008). Various projects are aimed at implementing soil management techniques that enhance the input of organic carbon and reduce the loss of SOC (Lal, 2004b). These techniques encompass practices such as the application of organic waste, minimizing tillage intensity, leaving crop residue in the field, implementing crop rotation and cover crops, and adopting proper irrigation management (Powlson *et al.*, 2011). The utilization of OM such as manure, sludge, crop residue, and compost has been employed since the early days of agriculture (Lehmann *et al.*, 2011), however, Organic waste can be expensive to acquire and apply. Soils enriched with OM tend to exhibit higher levels of SOC compared to those fertilized with synthetic fertilizers. Similarly, reducing tillage intensity and improving crop rotation have proven to be effective measures in increasing SOC levels (Martín *et al.*, 2019; West *et al.*, 1997), while they might cause increasing soil compaction and higher costs for crop management.

The formation of SOM is a gradual process that occurs over a long period, influenced by specific climatic and biological environmental conditions. As early as the nineteenth century, research on the characteristics of SOM components began (Zhai *et al.*, 2022). However, due to its complex and diverse composition, SOM's complex nature remains a significant challenge when defining OM processes within soils (Quideau *et al.*, 2001).

Understanding the composition of SOM is crucial because it directly impacts the processes of carbon accumulation and the overall potential for carbon storage in the soil (Matus *et al*., 2014). The stabilization of SOM occurs through biochemical processes, such as the stabilization of its chemical composition through recalcitrant compounds like lignin and polyphenols, as well as through chemical complexing processes like condensation reactions (Six *et al*., 2002). These processes contribute to soil stability. Labile organic matter consists of simple sugars, amino acids, microbial biomass, microbial metabolic composition, lipids, and alcohol, while recalcitrant organic matter includes lipids, esters, waxes, and alkenes (Wallenstein *et al*., 2013). This partitioning of OM types plays a role in influencing nutrient availability and emissions into the atmosphere. As it remains consistent in soils, the composition of OM can be used as an indicator of the quality of SOC and nitrogen (N) stocks (Franzluebbers, 2002).

During the process of transformation, including decomposition and mineralization of SOM, there are alterations observed in the compounds present in SOM (Ghani *et al*., 2023), such as aliphatic, aromatic, amide, phenol, carboxylate, and polysaccharide compounds (Margenot *et al*., 2015). This transformation process has a significant impact on the chemical and biochemical reactivity of SOM (Margenot *et al*., 2015). When soil management practices are modified, certain labile compounds, like carbohydrates, might change and reach a new stable state more rapidly (Campbell *et al*., 1998).

The composition of SOM is influenced by various factors, including the rate of decomposition, types of plant residues, soil texture, microbiological composition, chemical, and mineralogical composition, and climatic conditions such as temperature and moisture content (Lal *et al*., 2018). Furthermore, artificial effects like physical disturbance and land use practices can also impact SOM composition (Helfrich *et al*., 2006; Cao *et al*., 2011; Alam *et al*., 2014; Qin *et al*., 2016; Zhang *et al*., 2017). However, the relationship between land use and SOM properties is not well understood due to the relative stability and long turnover period of a significant portion of the organic fraction (Lei *et al*., 2023). Additionally, changes in OM content occur slowly and may not always provide sufficient information about future soil quality changes (Cardelli *et al*., 2012).

The composition of SOM under different land use/management systems is a current topic of interest as it plays a critical role in evaluating the chemical, biological, and physical properties of soil, as well as influencing the rate of SOM decomposition and stabilization *(*De Mastro *et al*., 2020; Poirier *et al*., 2005; Six *et al*., 2002). Another area of interest is the uncertainty surrounding the role of soils as sources or sinks in the global carbon cycle (Vilakazi *et al*., 2022), which has implications for the greenhouse effect and climate change (Disnar *et al*., 2003). However, the majority of studies have focused on forest and grassland ecosystems (Pisani *et al.*, 2016; Wang *et al*., 2016; Thai *et al.*, 2021), with limited research conducted on SOM composition in agricultural soils, particularly concerning tillage practices (Helfrich *et al.*, 2006; Moussadek *et al.*, 2014; Gao *et al.*, 2022). Changes in molecular-level SOM composition provide valuable insights into soil biogeochemical cycling in agroecosystems as different agricultural practices can alter SOM constituents by influencing crop productivity, litter, (Gurr *et al.*, 2016), microbial biomass, and enzyme activity (Hou *et al.*, 2016; Lupwayi *et al.*, 2019) and crop residue decomposition (Lupwayi et al., 2004). These alterations consequently affect SOC storage and dynamics (López-Garrido *et al.*, 2012).

The influence of climate change on SOC content can differ depending on the region, soil type, etc. However, it is expected that rising temperatures and more frequent extreme events will likely result in higher levels of SOC loss (Grosse *et al.*, 2011) due to the increase in the mineralization of the soil carbon (Zhang *et al.*, 2019). Additionally, the impact of climate change on land-use changes can indirectly affect soil carbon

2.2 Role of soil organic carbon in the carbon cycle

Soils play a critical role in the carbon cycle within terrestrial ecosystems, acting as both a supplier and storage site for carbon (Bade *et al.*, 2007). Soil organic carbon constitutes a substantial proportion of the global carbon reserves, with estimates suggesting that up to 3000 Pg (petagrams) of carbon is stored in the top meter of the soil profile (Scharlemann *et al.*, 2014; Heinze *et al.*, 2018). The organic carbon reservoir in soils is derived from various sources, such as plant residues, roots, decomposed OM, and microbial biomass (Bade *et al.*, 2007).

The stability of organic carbon can be significantly influenced by changes in land use and climate. Specifically, the upper layers of soil, especially those exposed to intensive land use practices or impacted by climate changes, are particularly susceptible to transitioning from carbon storage areas to carbon sources (Moritz *et al.*, 2009; Salomé *et al.*, 2010). These disruptions can accelerate the decomposition of SOM, resulting in the release of carbon dioxide (CO_2) into the atmosphere. Consequently, this exacerbates global warming and contributes to climate change (Moritz *et al.*, 2009).

Furthermore, hydrological occurrences like intense rainfall or floods can contribute to soil carbon loss. Such events, enable dissolved organic carbon (DOC) to migrate through the soil and enter streams and rivers (Wickland *et al.*, 2007).

Various management practices have been proposed to mitigate the potential loss of soil carbon and its subsequent environmental consequences. The implementation of sustainable land use/management approaches, such as conservation agriculture, afforestation, and agroforestry, can enhance soil carbon levels and promote its stability in agricultural and forested regions (Paustian et al, 1999; Lal, 2004a). Additionally, the restoration of degraded ecosystems and the adoption of methods that minimize soil disturbance, such as minimum tillage or no-till farming, can aid in the preservation of soil carbon reserves (Six *et al*., 2004).

Gaining a comprehensive understanding of the behavior of soil carbon and its interaction with land use and climate change is crucial for implementing sustainable land use/management practices and addressing climate change effectively (Smith, 2008).

2.3 Soil organic matter composition and cycle

SOM is a complex and diverse substance, consisting of different constituents like humic acid, fulvic acid, humin, and particulate organic matter (POM) (Guo *et al*., 2010). POM, which includes light organic debris, decomposes quickly and doesn't strongly bind to other soil particles, though some POM can be found within small soil aggregates (Guo *et al*., 2010).

There has been a significant increase in interest regarding the composition of SOM due to its crucial role in assessing the chemical, biological, and physical characteristics of soils (De Mastro *et al*., 2020; Helfrich *et al*., 2006; Six *et al*., 2002; Yao *et al.*, 2019). Furthermore, understanding the composition of SOM is essential for comprehending the rates at which it decomposes and stabilizes (Poirier *et al.*, 2005).

Variations in the composition of SOM can be explained by the interaction of four factors: the chemistry of inputs (such as the chemical makeup of plant litter), the type and abundance of decomposers (like soil organisms and external enzymes), the accessibility of the substrate (including both chemical and physical protection), and the energy levels within the system (which tend to be higher in tropical systems and those with high fertility inputs). Changes in any of these factors due to environmental influences will contribute to the variability in SOM composition (Grandy & Neff, 2008; Wang *et al.*, 2016; Yassir & Buurman, 2012).

On the other hand, the structural composition of SOM is closely associated with its cycling and preservation. Microbes show a preference for polysaccharides, a more readily degradable component of SOM, over SOM that contains lignin and alkyl C, which are considered more resistant to chemical breakdown (Smith *et al*., 2018).

The stability of SOM is influenced by various factors, including the input of OM, the characteristics of mineral surfaces, physical disturbance, and climate conditions (Yeasmin *et al.*, 2020). It is also affected by different functional pools involved in carbon stabilization processes (Demyan *et al.*, 2012). Transformations of SOM, such as decomposition and mineralization, lead to changes in the chemistry of functional groups, including an increase in the relative proportion of aromatic to aliphatic groups (Calderón *et al.*, 2011; Margenot *et al.*, 2015). Carbohydrates, proteins, cellulose, hemicellulose, and lignin are organic compounds found within SOM. Among these, carbohydrates, proteins, and cellulose are more easily decomposable, contributing to nutrient supply and soil structure. On the other hand, lignin is more resistant to decomposition (Calderón *et al.*, 2011; Moghiseh *et al*, 2013).

The stability of SOM is also influenced by its physical protection, which occurs through the formation of organic-mineral complexes. Various minerals, including phyllosilicates, iron, aluminum, manganese oxides, metals, and other clay-sized minerals, contribute to the relatively secure storage of SOM on their surfaces (Jakab *et al.*, 2019).

The chemical composition of SOM plays a crucial role in both the stabilization of soil carbon and its overall functions (Lei *et al.*, 2023). Aliphatic C-H groups are often associated with lighter fractions of soil organic carbon (SOC) and particulate organic matter (POM) (Rui *et al*., 2022; Six *et al*., 2004). Conversely, aromatic C groups, which are significantly linked to more stable organic carbon fractions, are indicative of stable components within SOM (Lei *et al.*, 2023). The chemical composition of SOM can also vary among soils in different regions due to various environmental conditions such as temperature, precipitation, and topography, as well as differences in soil age, origin, and potential management practices. Therefore, having a comprehensive understanding of the chemical compositions of SOM is crucial for evaluating soil formation processes and the factors that govern them. Based on the literature review, the changes in SOM's chemical composition and the mechanisms contributing to its stabilization have been extensively observed to be influenced by land use patterns (Bahadori *et al.*, 2021), clay size particle content (Czirbus *et al.*, 2016; Rakhsh *et al.*, 2020), SOC content *(Shahbaz et al*., 2017; Zhu *et al*., 2021), soil types (Fan *et al.*, 2020), particle composition (Zeng *et al.*, 2021) and soil pH (Jones *et al*., 2019). Several studies have emphasized that land use and organic modification have a significant impact on the chemical composition of SOM, thereby affecting soil carbon stabilization (Lei *et al.*, 2023).

Although the impact of agricultural practices on overall SOM has been documented, there is still limited knowledge regarding the specific changes in SOM composition and its stability in the soil (Paul *et al.*, 2003).

The complexity of SOM and its methods of stabilization presents challenges in examining its composition. Traditional methods involving separation based on density and size have been employed to isolate components with similar chemical or physical traits or decomposition rates. This allows the measurement of SOM in different quality fractions, distinguishing between easily degradable and more enduring carbon pools that are important for soil functions. For example, the carbon content in hot-water extractions has been linked to microbial biomass C, acting as a sensitive indicator of SOM quality and representing a less stable carbon pool (Demyan *et al.*, 2012).

Various modern methods are available to overcome the issues related to studying the composition of SOM, including chemolytic and thermochemolytic approaches, stable isotope and radiocarbon analysis, microbial markers, and spectroscopic techniques. Among these methods, nuclear magnetic resonance (NMR) spectroscopy and infrared (IR) spectroscopy are widely used due to their non-invasive nature, which allows the examination of samples without extensive pre-treatment or extraction. In particular, diffuse reflectance infrared Fourier transform (DRIFT) spectroscopy, a type of IR spectroscopy, is commonly employed to rapidly and reliably characterize functional groups and molecular structures within SOM under different management systems.(Calderón *et al.*, 2011; Demyan *et al.*, 2012; Yeasmin *et al.*, 2020). In the following, the most used OM characterization techniques have been reviewed.

2.3.1 Soil organic matter composition characterization techniques

Various techniques are used to characterize the structure of SOM, including both traditional and spectroscopy approaches. Traditional methods involve extracting SOM from the soil in a quantitative manner, while spectroscopy methodologies such as Fourier-transform infrared (FTIR), ultraviolet-visible (UV-VIS), and nuclear magnetic resonance (NMR) provide additional insights (Kögel-Knabner, 2000).

The majority of SOM exists in macromolecular structures that require a degradative step for molecular-level investigation. Typically, the analysis entails the reduction of macromolecules into smaller fragments via chemolytic and/or thermolytic (pyrolysis) activities. These fragments are then separated and analyzed using colorimetric or chromatographic methods. Researchers have studied humification and SOM using a variety of degradative and non-degradative techniques during the past century (Chen *et al.*, 1977).

FTIR and UV-VIS spectroscopy have been widely employed in the field of SOM analysis for both quantitative and qualitative characterization (Ellerbrock *et al.*, 1999; Zimmermann *et al.* 2007; Ludwig *et al.*, 2008; Calderón *et al.*, 2011; Demyan *et al.*, 2012; Nadi, Sedaghati and

Füleky, 2012; Margenot *et al.*, 2015; Szalai *et al.*, 2016; Vicente *et al.*, 2017; Nuzzo *et al.*, 2020; Yeasmin *et al.*, 2020). The main advantage of non-destructive analysis provided by these methods is that samples can be examined without requiring a lot of pre-treatment or extraction (Kögel-Knabner, 2000; Nocita *et al.*, 2014; Margenot *et al.*, 2015). In the pursuit of characterizing organic substances, I present here some common methodologies employed in the analysis of SOM.

2.3.1.1 Analytical pyrolysis

Analytical pyrolysis encompasses degraded methods used to characterize humic materials, with pyrolysis gas chromatograph mass spectrometry (Py-GC/MS) and pyrolysis field ionization mass spectrometry (Py-FIMS) being extensively applied for soil analysis (Nierop et al., 2001). The construction of two- and three-dimensional model structures greatly benefits from the utilization of Pyrolysis-GC/MS. This powerful method allows for the acquisition of molecular-level insights into SOM and humic substances (Chefetz *et al*., 2004; Nadi *et al*., 2012). Pyrolysis-GC/MS is a technique that involves chromatographic separation to separate the products of pyrolysis, allowing for the collection of mass spectral data on individual components. In contrast, Py-FIMS utilizes soft ionization, primarily generating molecular ions without separating the pyrolysis products. Pyrolysis is particularly useful for analyzing complex and heterogeneous high molecular weight molecules that are challenging to evaluate in their polymeric form. During pyrolysis, a sample is rapidly heated in an inert atmosphere, leading to the fragmentation of macromolecules. The volatile products are then separated and identified using GC/MS (Yassir and Buurman, 2012). Another method, which combines simultaneous pyrolysis and methylation of monomers with gaseous tetramethylammonium hydroxide (TMAH), has been introduced to address some of the issues associated with pyrolysis (Chefetz and Xing, 2009). This technique selectively hydrolyzes and methylates ester and ether bonds, facilitating the breakdown of ester and specific ether connections, promoting lignin methylation, and depolymerization.

2.3.1.2 Spectroscopic techniques

Alternative methods for assessing OM in complex macromolecular mixtures include non-invasive spectroscopic techniques such as electron spin resonance (ESR) spectroscopy, infrared (IR) spectroscopy, and NMR spectroscopy (Kögel-Knabner, 2000). One significant advantage of these methods is that they allow for the analysis of samples without extensive pre-treatment or extraction work. This reduces the likelihood of secondary reactions by examining the sample as a whole. However, these techniques often exhibit low sensitivity and resolution, making it challenging to identify specific chemicals. Spectroscopic techniques operate on the principle that different elements and molecules selectively absorb or reflect electromagnetic energy based on their wavelength (Simpson *et al.*, 2011). Reflectance spectroscopy is commonly used with opaque materials like soil, where the diffuse reflectance caused by the sample's surface roughness is measured. These methods provide a non-destructive approach to analysis and are easily standardized, fast, and reliable (Vohland *et al.*, 2011). However, material identification becomes more difficult due to overlapping signals in the visible light range (400–700 nm = Vis) and near-to shortwave infrared range (700–2500 nm = NIR) (Steffens *et al.*, 2021).

2.3.1.3 ^{13}C and ^{15}N NMR spectroscopy

NMR spectroscopy is an important method used for quality assurance and research purposes. It allows for the examination of the composition, purity, and molecular structure of various materials, including humic compounds (Margenot *et al.*, 2016). According to Baldock and Smernik (2002), this technique provides valuable data on the distribution of different organic carbon (OC) classes, such as carboxyl C, aromatic C, O-alkyl C, and alkyl C, as well as the chemical composition of complex organic compounds. Solid-state NMR spectroscopy, in particular, plays a crucial role in understanding the primary functional groups and molecular structure of humic compounds (Chefetz *et al.*, 2002). It offers a comprehensive explanation of the carbon-containing groups present in a sample and provides important new insights into the chemical structure of humic compounds.

To gain a better understanding of the relationship between the preservation of OM and its composition in different soil fractions, researchers have utilized solid-state ^{13}C NMR spectroscopy (Golchin *et al.*, 1995; Chenu and Plante, 2006; Carvalho *et al.*, 2009; Yeasmin *et al.*, 2020). This approach has revealed detailed information about the distribution of various OC classes (Oliver *et al.*, 2005). By analyzing the chemical changes in OC that occur during microbial decomposition, it becomes possible to determine the extent of SOM decomposition (Baldock *et al.*, 1992; Golchin *et al.*, 1995). ^{13}C and 15N NMR spectroscopy is widely used to characterize the composition of SOM. Quantitative analysis is made possible by the relationship between the intensity of an NMR signal and the concentration of the nuclei producing it (Kiem *et al.*, 2000). On the other hand, it requires an expensive infrastructure and a relatively high OM concentration.

2.3.1.4 UV VIS spectroscopy

Ultraviolet-visible spectroscopy, also referred to as UV-Vis or UV/Vis spectroscopy, is a scientific technique used to assess the absorption or reflectance of light within the ultraviolet-visible range, encompassing the visible, near-ultraviolet (UV), and near-infrared (NIR) regions. The UV-Vis-NIR spectra, covering wavelengths from 200 to 2,500 nm, provide comprehensive information about the composition of soil materials, and this method offers a straightforward and cost-effective means of measurement (Szalai *et al.*, 2016). This analytical approach holds significant value in the examination of electronic transitions occurring in molecules within this specific wavelength range. Additionally, it complements fluorescence spectroscopy, which primarily focuses on the analysis of transitions between excited and ground states of molecules (Nadi *et al*., 2012). UV-Vis spectroscopy is especially important for characterizing humic substances because they strongly absorb light in the UV-Vis range, due to the presence of aromatic chromophores and other chemical components (Li *et al.*, 2017). When examining the UV/Vis spectra of natural OM, it is common to observe decreasing absorption as wavelength increases (Birdwell and Engel, 2010).

To describe humic and fulvic acids in dilute, aqueous solutions, researchers have utilized the E_4/E_6 ratio, which measures the optical density or absorbance at 465 and 665 nm (Chen *et al*., 1977; McDonald *et al.*, 2004; John *et al.*, 2009; Yang and Xing, 2009). A lower E_4/E_6 ratio indicates a higher degree of aromatic ring condensation and a higher molecular weight. Fulvic acids typically have E_4/E_6 ratios ranging from 6.0 to 8.5, while humic acids, which indicate greater humification or age, often have lower ratios (Reddy, 2014). This ratio serves as a distinct metric for different fractions of OM matter or humic substances from various sources, irrespective of the amount of humic substances present. For humic acids, the E_4/E_6 ratio is typically less than 5.0 (Chen *et al*., 1977).

In conclusion, UV-Vis spectroscopy is a valuable tool for analyzing the absorption and reflectance characteristics of organic compounds, particularly in the study of humic substances. By measuring absorbance, researchers can gain insights into the molecular structure and aromatic content of these substances (Chen and Yu, 2021).

2.3.1.5 FTIR spectroscopy

FTIR spectroscopy has significantly contributed to the advancement of soil science by enhancing our understanding of the intricate composition of soil (Chen *et al*., 1977). It is a valuable tool for soil scientists due to its versatility, although analyzing and interpreting soil spectra can be challenging due to the inherent chemical diversity of soil samples (Laird *et al.*, 1994). Recent advancements in data acquisition methods, however, have helped overcome these challenges, allowing researchers to more comprehensively investigate the complex temporal dynamics and composition of the soil environment, as well as the chemical processes occurring within this intricate system.

FTIR spectroscopy is a specialized technology used for analyzing the organic and mineral components of soil samples (Laird *et al.*, 1994; Margenot *et al.*, 2016), due to its high sensitivity in characterizing these components. This helps clarify the underlying mechanisms and kinetics of interactions between minerals and SOM, which are crucial for biogeochemical processes. Additionally, FTIR spectroscopy's molecular-level resolution enables a deeper understanding of mineral and SOM structures, as well as the sorption of ions and organic molecules onto mineral surfaces (Laird *et al.*, 1994). Various techniques, such as attenuated total reflectance (ATR), transmission, and diffuse reflectance infrared Fourier transform spectroscopy (DRIFTS), are available for assessing soil samples using FTIR spectroscopy (Margenot *et al.*, 2016). Among these techniques, DRIFTS is the most commonly used and preferred (Demyan *et al.*, 2012; Margenot *et al.*, 2015; Yeasmin *et al.*, 2020).

FTIR spectroscopy has been applied to various materials, including peats, composts, separated fulvic and humic acids, and other pure organic compounds (Margenot *et al.*, 2015). DRIFTS has proven to be effective in studying complex materials like soils, even in the presence of overlapping peaks caused by mineral components (Jakab *et al.*, 2019). Changes in the chemistry of functional groups occur during SOM transformations, such as decomposition and mineralization. For example, the ratio of aromatic to aliphatic groups increases during decomposition. By quantifying these changes in functional groups, DRIFTS can provide insights into SOM transformations and stabilizing mechanisms (Chefetz and Xing, 2009). DRIFTS involves the analysis of bending and stretching vibrations of different functional groups within the mid-infrared range of 4000–400 cm^{-1}. These vibrations manifest as peaks on the mid-infrared spectrum and are associated with specific organic and inorganic functional groups.

Studies have suggested that identifying distinct mid-infrared peaks associated with specific functional group vibrations in organic molecules can aid in examining the dynamics and composition of SOM (Demyan *et al.*, 2012). For instance, Gerzabek *et al*. (2006) observed a correlation between the relative heights of peaks at 2920, 1630, and 1450 cm^{-1} in both bulk soil and silt-sized fractions of Eutric Cambisol, and their corresponding organic carbon concentrations (Gerzabek *et al.*, 2006). Various techniques have been used to assess short- and long-term changes in organic materials and analyze mid-infrared peaks. Grube *et al*. (2006) employed band intensity ratios, such as 1034:1384, 1384:2925, and 2925:1034 cm^{-1}, to monitor changes in OM in compost samples over 40 days. Another method utilized was relative peak area analysis, which involves dividing the area of a peak by the total area of all peaks under investigation (Grube *et al.*, 2006). Tatzber *et al*. (2009) applied this approach to study long-term changes in humic acids from bare fallow soils over 36 years (Tatzber *et al.*, 2009). Egli *et al*. (2010) employed the relative peak area method when investigating SOM in young glacial moraine soils. However, they did not consider the potential influence of various soil minerals, which could affect the visibility of organic vibrations (Egli *et al.*, 2010).

Although DRIFTS multivariate prediction models have proven effective in estimating the quantity of OM in different sizes and/or density fractions (Zimmermann et al., 2007; Janik et al., 2007), these models typically require a large number of samples for calibration and validation. Therefore, they may not be suitable when working with fewer than fifty samples, which is often the case in studies involving a single experiment. Additionally, there is a lack of clarity regarding the establishment and testing of a quantitative relationship between specific mid-infrared peaks and the composition of undiluted bulk SOM, particularly concerning different SOM fractions or grades. This uncertainty primarily arises from the prevalent use of dilution methods with KBr in most investigations (Demyan *et al.*, 2012).

DRIFTS proves to be a suitable technique for assessing the impact of management practices on SOM, as it demonstrates high sensitivity to even subtle changes in the quantity and quality of labile organic matter (Calderón *et al.*, 2011; Parikh *et al.*, 2014). This feature makes DRIFTS well-suited for evaluating SOM composition in on-farm contexts (Veum *et al.*, 2014; Margenot *et al.*, 2015; Nuzzo *et al.*, 2020).

To improve the characterization of SOM using DRIFTS, it is possible to correct the overlapping signals from minerals and organic materials by subtracting the mineral background from soil spectra (Cheshire *et al.*, 2000; Margenot *et al.*, 2015). This approach provides valuable insights into the molecular structures and functional groups of SOM under different management practices, as well as the changes in SOM composition resulting from these management adjustments (Ding *et al.*, 2002; Gerzabek *et al.*, 2006; Calderón *et al.*, 2011). For example, Capriel (1997) utilized this method to quantify the amount of aliphatic C–H units in soils subjected to various management strategies, revealing that the quantity of aliphatic C–H components in SOM decreased along with carbon content when management practices changed (Capriel, 1997).

Another study by Demyan *et al*. (2012) confirmed that specific peaks identified through DRIFTS analysis of bulk soils can be employed to investigate changes in OM composition within a Haplic Chernozem soil. This study demonstrated that the long-term application of organic and mineral fertilizers not only influenced the quantity of SOM but also its composition compared to an unfertilized control treatment (Demyan *et al.*, 2012). For DRIFTS analysis, it is essential to consistently and finely grind soil samples, with particle sizes smaller than 900 μm, to minimize the effects of light trapping and scattering variations on artifacts. Soil samples can be analyzed using DRIFTS either in their undiluted form ("neat") or diluted with KBr, typically at concentrations between 2% and 10% (Margenot *et al.*, 2016).

Comparing infrared techniques like FTIR to conventional quantitative soil extraction methods for assessing the physical-chemical properties of SOM, infrared methods are found to be faster, require fewer samples, and offer greater reproducibility. Therefore, infrared spectroscopy, including FTIR, has long been a reliable technique for studying the chemistry of SOM even before the adoption of modern FTIR devices. The semi-quantitative nature and high reproducibility of DRIFT spectroscopy are advantageous, and they simplify sample analysis by allowing easy mixing and grinding using a non-absorbing medium such as KBr (Nuzzo *et al.*, 2020). This eliminates the potential for changes in the characteristics of organic materials caused by pressing humic powders into KBr pellets (Nuzzo *et al.*, 2020).

In conclusion, various methods, including traditional quantitative extraction and spectroscopy techniques like FTIR, UV-VIS, and NMR, are employed to evaluate the structural features of SOM. FTIR spectroscopy is commonly used for both quantitative and qualitative characterization and enables non-destructive analysis. In addition to its user-friendly nature and minimal sample preparation requirements, DRIFTS spectroscopy is a valuable tool for assessing the quality of SOM due to its exceptional sensitivity to even minor changes in labile OM. These techniques contribute to our understanding of the characteristics, changes, and management implications of SOM in different agricultural scenarios (Demyan *et al.*, 2012; Margenot *et al.*, 2015; Nuzzo *et al.*, 2020).

2.4 Factors affecting soil organic matter

Understanding the factors that influence the soil carbon cycle and how they can be modified is crucial for effective soil carbon management. The environment plays a key role in regulating the inputs of SOM from plants and microorganisms, as well as the rate at which it is lost through microbial decomposition, fire, and the export of dissolved organic matter (DOM). These processes ultimately impact the abundance and composition of SOM (Feng, 2009).

The primary eco-environmental zones or biomes on Earth are determined by solar radiation, topography, and geology (Vancampenhout *et al.*, 2009). However, these zones may change due to global warming. While extensive research has been conducted on the effects of vegetation and climate on total carbon stocks, there is a lack of precise data linking SOM composition to biome-scale dynamics (Kögel-Knabner, 2000; Helfrich *et al.*, 2006; Nave *et al.*, 2024). As a result, it is challenging to identify trends and draw broad conclusions about how SOM chemistry responds to environmental changes (Kögel-Knabner *et al*., 2005; Lützow *et al*., 2006; Vancampenhout *et al*., 2009).

The composition of SOM is influenced by numerous variables that interact in complex ways (Piccolo, 2002; Kelleher *et al.*, 2006; Vancampenhout *et al.*, 2009; Jones *et al.*, 2023). These factors include soil properties, land use/management practices, topography, geology, and climate (Paul, 2016). However, it is still not fully understood how significant each of these influencing factors is concerning soil carbon accumulation in different soil layers (Zhao *et al*., 2019). Below some of the main factors affecting SOM composition based on the literature review are summarized

2.4.1 Climate variables

The composition and amounts of OM added to the soil are strongly influenced by climatic conditions. Factors such as temperature, precipitation, and seasonal variations play a crucial role in determining the growth of vegetation, production of litter, and decomposition rates (Liu, *et al*., 2011). These climatic factors also have a significant influence on the spatial distribution of SOC, which in turn affects the composition of SOM (Davidson and Janssens, 2006; Jia *et al*., 2017). The interaction between the composition of SOM and climate factors occurs in various ways. Even small changes in the carbon reservoirs in the soil can have a substantial impact on the global carbon cycle and climate change, since soil SOM holds more carbon than both the atmosphere and all the plants on land combined, changes in SOM levels can affect how much carbon dioxide is in the atmosphere, which in turn can impact climate change (Islam, Singh and Dijkstra, 2022). Therefore, accurately understanding the effects of variable factors of SOM at different scales and locations is crucial for soil to act as a sink and reduce atmospheric CO_2 (Bai and Zhou, 2020). In this context, it is important to summarize the key climatic variables that influence the composition of SOM.

- Precipitation

Precipitation is a crucial climatic factor that directly influences soil moisture content, which in turn affects microbial activity and decomposition rates. Changes in precipitation patterns can directly affect soil moisture levels, subsequently influencing the decomposition of OM and microbial activity (Lei *et al.*, 2023). Increased precipitation can stimulate vegetation growth, leading to higher OM inputs and the subsequent accumulation of SOM (Alidoust *et al.*, 2018). Conversely, drought conditions may result in lower OM additions and even depletion of SOC due to reduced plant productivity (Chen *et al*., 2021; Lewis *et al.*, 2019).

Recent studies have highlighted the intricate connections between the composition of SOM and precipitation patterns (Davidson *et al*., 2006; Jia *et al*., 2017). Warmer and wetter climates, for example, have been found to promote higher decomposition rates, leading to decreased SOC concentration and alterations in the composition of SOM (Davidson and Janssens, 2006).

a- The amount and temporal resolution of precipitation:

The composition of SOM is greatly influenced by the amount and timing of precipitation. Increases in rainfall can enhance microbial activity, leading to accelerated decomposition of OM and a reduction in SOM reserves (Thomas *et al.*, 2020). Conversely, prolonged periods of drought followed by heavy rainstorms can result in nutrient leaching and erosion, which may affect the composition of SOM (Olson *et al.*, 2011; Smith *et al.*, 2008).

b- Water availability and oxygen levels:

The amount of rainfall impacts the availability of water in the soil, which in turn influences the activities of microorganisms involved in respiration and decomposition processes (Lal, 2004b; Smith *et al.*, 2018). Insufficiently drained soils that become waterlogged can create oxygen-deficient conditions, leading to the accumulation of OM in reduced forms and promoting the development of persistent fractions of SOM, Conversely, well-drained soils with adequate moisture content promote aerobic conditions, which support the breakdown of easily decomposable OM (Smith *et al*., 2022).

- Temperature

Temperature fluctuations can significantly influence the composition of SOM. Research by Ibáñez *et al*. (2023) indicates that higher temperatures often accelerate microbial activity, leading to enhanced decomposition of OM and increased release of carbon dioxide into the atmosphere (Ibáñez *et al*., 2023). This process can contribute to increased carbon losses from the soil, potentially exacerbating climate change (Feng *et al*., 2021).

Through several important mechanisms that affect SOM composition in terrestrial ecosystems, temperature affects SOM composition, in some ways that are summarized below:

a- Decomposition rates:

Microbial activity and the enzymatic activities that break down organic materials are directly impacted by temperature. Higher temperatures typically hasten the rates of decomposition, resulting in heightened organic carbon mineralization and a reduction in SOM reserves. On the other hand, lower temperatures might cause microbial activity and decomposition rates to slow down, which can lead to an accumulation of OM and possibly a greater SOM content (Davidson and Janssens, 2006; Melillo *et al.*, 2011; Schimel and Schaeffer, 2012; Jiménez-González *et al.*, 2020).

b- Microbial Community Composition:

The diversity and abundance of soil microbial communities, which are essential for the decomposition of SOM and nutrient cycling, can be influenced by temperature (Schimel and Schaeffer, 2012). Different microbial groups have distinct temperature preferences for their metabolic processes and temperature fluctuations can impact the functional diversity and composition of microbial communities, thus influencing the composition of SOM (Mateos-Rivera *et al.*, 2016).

c- Stabilization of SOM:

The stability of SOM fractions can be impacted by temperature. Higher temperatures have the potential to stimulate microbial activity, leading to the preferred breakdown of OM that is labile. More resistant and stable SOM fractions may accumulate as a result of this. On the other hand, lower temperatures may help to preserve labile OM and encourage the synthesis of stable SOM molecules (Jia *et al*., 2020).

d- Carbon Input and Allocation:

The temperature has an impact on plant production and growth, which in turn has an impact on the amount and composition of carbon that plants add to the soil. Increased temperatures have the potential to accelerate plant growth and improve subsurface carbon allocation, which will increase the amount of OM that is added to the soil (Melillo *et al.*, 2011). Temperature can also have an impact on the composition of carbon inputs such as plant litter and root exudates (Li *et al.*, 2022). The composition of SOM may then be changed by these modifications in carbon inputs (Schmidt *et al.*, 2011). According to Davidson and Janssens (2006), some plant species, for example, may create more resistant OM, which is less vulnerable to decomposition and increases the amount of SOC stabilization in the soil.

In summary, the way that climatic variables affect the composition of SOM is a complex and dynamic process that involves interactions between temperature, precipitation, vegetation, and microbial activity. Comprehending these associations is essential for forecasting the potential impact of climate shifts on SOM dynamics and the implications for global carbon cycling and climate change (Zhao *et al*., 2019).

2.4.2 Topography and Geology

Environmental factors, including elevation, slope, aspect, topography, geology, and other related factors play a significant role in shaping OM in soil. These variables might affect SOM formation, decomposition, and stabilization processes. They also affect temperature, moisture availability, vegetation patterns, water transport, and nutrient availability. To forecast soil carbon dynamics and create sustainable land management techniques, it is essential to comprehend the connections between environmental variables and SOM composition.

The composition of SOM is influenced by elevation and topographic position. Prior research has indicated the importance of topography and elevation in influencing differences in SOM features across a range of environments (Fellman *et al.*, 2010).

Elevation affects SOM composition by influencing temperature, precipitation, and vegetation patterns. Elevation gradients cause significant variations in temperature, precipitation patterns, and land cover in mountainous areas. Due to slower rates of decomposition, higher elevations typically have lower temperatures and better conditions for the retention of SOM. As a result, recalcitrant chemicals tend to be more abundant in SOM at higher elevations (Li *et al.*, 2017). So the distribution of OM and nutrient inputs into the soil might be significantly impacted by these differences (Liu *et al*., 2011).

The heterogeneity of SOM composition is further influenced by topographic position. The movement of water, soil moisture, and nutrient availability are influenced by many topographic characteristics, including ridges, slopes, and valley bottoms. These factors may have an impact on the composition of SOM too (Wang *et al*., 2020). Increased water flow and erosion on steep slopes frequently result in the loss of OM and topsoil (Smith *et al.*, 2008; Olson *et al.*, 2011). In contrast, soft slopes encourage water infiltration and retention, which leads to the buildup of

SOM (Liu *et al*., 2011). Water can carry dissolved organic matter (DOM) from SOM to neighboring aquatic systems as it flows downslope (Wu *et al.*, 2022). So the consequences of height and topographic gradients on SOM composition can be seen in downstream water quality and biogeochemical processes in aquatic ecosystems (Seifu *et al.*, 2021). SOM composition may also be indirectly impacted by slope gradient and aspect, which relate to the direction a slope faces. Water flow, soil drainage, and erosion are all impacted by slope, and these factors can change the composition of SOM (Zhu *et al*., 2014). Also, several studies have emphasized the effect of water erosion on SOC removal and resulting changes in C sequestration (Kimble *et al*., 2001; Cheng *et al.*, 2010; Olson *et al.*, 2011; Jakab *et al.*, 2016; Li *et al.*, 2019). The erosion processes change land unit SOC stock by transporting SOC-rich sediment off an agricultural land unit, oxidizing SOC stocks, and releasing carbon dioxide (CO_2) into the atmosphere, as well as causing loss of SOC through surface runoff. Thus, erosion, transport, and depositional processes redistribute landscape SOC, enhance oxidation, and create a SOC source and a sink (Olson *et al.*, 2016).

Understanding the relationships between elevation, topographic position, and SOM composition is essential for effective land use/management and conservation strategies. This is especially true in mountainous places where ecosystems are more susceptible to land-use disturbances and climate change. These variables interact dynamically, highlighting the intricacy of SOM dynamics and its significance for ecosystem sustainability and resilience.

2.4.3 Land use and management

Changes in land use and patterns have the potential to affect soil productivity and quality in various regions and periods. This impact is primarily due to alterations in carbon inputs, decomposition rates, ecosystem functioning, and biogeochemical cycles (Qin *et al.,* 2016; Zhang *et al.*, 2017). Since the chemical composition of SOM influences both its turnover time and accumulation in soils, it provides important information on the dynamics of SOC (Gao *et al.*, 2022). These concepts hold importance as they relate to the soil's capacity to maintain its structural and functional integrity during and after a disturbance, ensuring continuous functioning (resilience) (Pisani *et al.*, 2016). Land use patterns can impact the quality of SOM due to differences in artificial management techniques as well as the quantity and quality of litter (Liu *et al.*, 2014). For example, the level of aromatic increases with increasing management intensity, as previous studies reported less percentage of aromatic carbon in uncultivated areas and grassland compared with arable land and cultivation lands (Schnitzer *et al.*, 2006; Yao *et al.*, 2019). On the other hand, soils under forests have shown more intense aliphatic bands compared to cropland soils (Schnitzer *et al.*, 2006; Thai *et al.*, 2021). Additionally, Nierop *et al.* (2001) discovered that SOM in arable soil mostly consists of microbial proteinous material and highly humified plant litter, whereas SOM in permanent grasslands is primarily constituted of comparatively undecomposed material (Nierop *et al.,* 2001).

The relationship between land use and the characteristics of SOM is not yet fully understood. This is due, in part, to the presence of a considerable amount of OM with a long turnover time, sometimes lasting several thousand years, making it highly stable (Stevenson *et al*., 1996). Additionally, the concentration of OM varies gradually, which means it may not always serve as a reliable indicator of potential changes in soil quality (Cardelli *et al*., 2012). On the other hand, soil erosion, which can be intensified by land use change, is known as the most widespread form of soil degradation, which can affect SOM quality and quantity. The land area globally affected by erosion is 1094 million ha (M ha) by water erosion of which 751 M ha is severely affected. Therefore, land use/management and erosion control are important strategies to enhance soil quality and reduce the dangers of the greenhouse effect (Kimble *et al.*, 2001). Based on previous studies, land use affects the dynamic change processes of physical and chemical soil properties (Celik, 2005; Jafarian and Kavian, 2013) and soil carbon (Lettens *et al.*, 2005; Jafarian and Kavian, 2013) by changing the quantity and quality of SOM, causing changes in soil microbial activity and community structure and ultimately affecting the decomposition rate and stability of SOM (Bai and Zhou, 2020). According to the literature review, various studies have been conducted to assess the effect of land use changes and different tillage systems on soil physical and chemical properties (Post *et al.*, 2001; Guo and Gifford, 2002; Vesterdal and Leifeld, 2010; Wan *et al.*, 2011; Jafarian and Kavian, 2013; Tellen and Yerima, 2018; Yang *et al.*, 2018; Kazlauskaite-Jadzevice *et al.*, 2019). In most of the studies, croplands with different tillage systems, forestlands, and grazing lands are compared and results showed that SOC decreased in croplands as compared to forestlands. For example, Guo and Gifford (2002) reviewed the literature to survey the influence of land use change on soil carbon stock from 74 publications, their result showed that soil carbon stocks decline after land use change from pasture to plantation, native forest to plantation, native forest to crop, pasture to crop and also, C stock increased after land use change from native forest to pasture, crop to pasture, crop to plantation (Guo *et al*., 2002). In other studies, with a focus on different tillage systems (Halvorson *et al.*, 2002; Deen and Kataki, 2003; Dong *et al.,* 2009; Alam *et al.*, 2014), results showed, in most instances, increased levels of tillage or increased tillage periods lead to reductions of soil carbon. When conventional tillage is converted to conservation tillage, CO_2 emissions from the soil are reduced. For example, Holland (2004) in a review of conservation tillage in Europe highlighted significant reductions in CO_2 emissions through the adoption of conservation tillage methods. The majority of studies assessed in this review, showed soil CO_2 emissions under conservation tillage to be smaller than those under conventional tillage (Holland, 2004). In another study, Beare *et al.*, 1994 described the size and quality of biologically active pools of aggregate-associated SOM in long-term Conservation Tillage (CT) and No-Tillage (NT) soils of the southeastern USA, their results indicate that macro aggregates in NT soils provide an important mechanism for the protection of SOM that may otherwise be mineralized under CT practices (Beare *et al.*, 1994).

A study by Guo and Gifford (2002) found that land-use change from forests to croplands led to significant reductions in SOM content and changes in SOM composition (Guo *et al.*, 2002). Due to the significant effects that agriculture has on soils its effects can linger for years, even long after the farming has stopped (Falkengren-Grerup *et al*., 2006). For instance, compared to forests or natural grasslands, arable land often has less SOM because harvests reduce the quantity of SOM that is added to the soil (Paz-González *et al.*, 2000). Another study by Margenot *et al*. (2015) found that, in contrast to long-term experiments, on-farm management, which typically combines nutrient management, can vary annually and could influence labile SOM through reciprocal feedback of input diversity and soil microbial activity. Long-term experiments showed that organic management can increase labile C in the short term and total soil C in the longer term, though labile SOM responds more rapidly to management than total

SOC (Margenot *et al.*, 2015). Finally, it is clear that studies in this field are not scarce, but studies with a different perspective and considering different influencing factors on SC/SOC including land use, different tillage systems, and environmental covariates can help to establish a relationship between SOM quantity/composition and its influencing parameters, which can be very important to soil carbon management. Understanding this interrelation is fundamental for sustainable resource management and climate change mitigation and will help to develop and deliver a decision support toolbox (method) to support farmers, advisers, and policymakers.

3. Materials and Methods

This section provides an overview of the research area's physical location, climate trends, and conditions. The sampling design follows, outlining the procedures for gathering soil samples and preparation for the laboratory. The different soil properties and their laboratory analysis techniques are explained. Lastly, a discussion of the employed statistical and qualitative analysis follows.

3.1 Study areas

Hungary has a diverse landscape structure. The Great Plain is primarily utilized for croplands, while the mountainous regions are predominantly covered by forests. The remaining areas exhibit a mosaic pattern, where different land uses coexist nearby. This research is carried out in four distinct areas, each representing a unique environment. For instance, Józsefmajor focuses on a level region characterized by intensive agriculture based on crop fields. Szentendre Island exhibits a mosaic pattern, with small farms employing cutting-edge techniques such as agroforestry and biotechnology. Two other areas located in Zselic, as a steep area, were chosen due to their high erosion rates, abundant tree coverage, and eroded agricultural areas. The selection of these locations allows for a comprehensive analysis of Hungary's varied landscapes.

3.1.1 Józsefmajor Experimental and Training Farm (JETF) of Hungarian University of Agricultural and Life Science

The first study area is located in Józsefmajor Experimental and Training Farm (JETF) of the Hungarian University of Agricultural and Life Science (47° 41′ 18″ latitude N, - 19° 36′ 20″ longitude E; 110 m above sea level) (Figure 3.1). Based on the World Reference Base Classification system, the soil in this area is Endocalcic Chernozem (Loamic) with a clay loam texture (IUSS Working Group WRB, 2015). The climate is continental with an average annual temperature of 10.3 and 15 °C, during the vegetation period. The average temperature above 10 °C is usually 183 days annually, and it is usually between the 13th of April and the 13th of November. The annual average precipitation (for the 1961–90 period, based on a climate dataset of the Climatic Research Unit) is 560 mm, of which 395 mm falls in the vegetation period. The area of the Experimental Farm is below the average multi-annual rainfall in Hungary (Dekemati et al., 2019)

Briefly, the forested site is under open woodland (tree line) whereas the cropped area is under cultivation in all the tillage systems. The tree line was a compound of a few distributed trees, mostly dominated by *Robinia pseudoacacia* (Black Locust) in association with grass understory and had never been grazed.

Crop rotation was applied in the agricultural area, including mainly several cereal crops like rye (*Secale cereale L.*), maize (*Zea mays L.*), wheat (*Triticum aestivum L.*), oat (*Avena sativa L.*), barley (*Hordeum vulgar L.*), and some non-cereal plants such as mustard (*Sinapis alba L.*) or sunflower (*Helianthus anns L.*). In 2020, winter wheat was grown; before that sunflower was the cultivated crop. After harvest, plant residue was not removed from the site; in all experimental plots, around 80% of aboveground biomass was left on the site and incorporated into the soil (Tóth *et al.*, 2019).

The schedule of agricultural management for this study area is summarized in Table 3.1. In this trial, six different soil tillage treatments have been applied in 24 plots (13×180m) in four replicates from 2002. Before the tillage experiment was set up, the cropland had been under conventional tillage for over 50 years (Tóth *et al.*, 2018). Applied tillage treatments are including disking (D) [12–14 cm] (Väderstad Carrier 500); Shallow tine Cultivation (SC) [18–20 cm] (Kverneland CLC Pro); no-till (NT); Deep tine Cultivation (DC) [22–25 cm] (Kverneland CLC Pro); Loosening (L) [40–45 cm] (Vogel & Noot TerraDig XS; with five tines, equipped with the double spiked roller, total working width 2.5 m); conventional tillage–moldboard plowing +leveling (P) [28–30 cm] (Kverneland LM100). Details of tillage treatments (depth, plot size, and the used equipment) are shown in Table 3.2.

Table 3.1 Crop rotation in the study area, Józsefmajor Experimental Site, the Hungarian University of Agriculture and Life Sciences, Hungary (Dekemati *et al.*, 2019; Jakab *et al.*, 2023)

Year	**Culture**	**Management history**
2015/ 2016	Maise	Fertilizing (NPK 8-24-24), Primary soil tillage Seedbed preparation, Sowing, Fertilizing (N 24), Plant protection, Harvest
2016/ 2017	Winter oats	Primary soil, tillage, Seedbed, Preparation, Sowing, Fertilization Plant protection, Harvest
- +201 7/201 8	Soybeans (*Glycine max*)	Primary soil, Tillage, Seedbed preparation, Sowing, Fertilization Plant protection, Desiccation, Harvest
2018/ 2019	Winter wheat (*Triticum aestivum*)	Fertilization, Primary soil tillage Seedbed preparation Sowing, Fertilization, Plant protection, Harvest

Table 3.2. List of tillage treatments, applied equipment, working depths, widths, and plot dimensions in the experiment, Józsefmajor Experimental Site, Hungarian University of Agriculture and Life Sciences, Hungary (Dekemati *et al.*, 2019)

Tillage treatment	Working depth (cm)	Working width (cm)
Loosening (L)	40–45	250
Moldboard plowing+leveling (P)	28–30	160
Deep tine cultivation (DC)	22–25	300
Shallow tine cultivation (SC)	18–2	300
Disking (D)	12–14	500
No-till (NT)	3–5	300

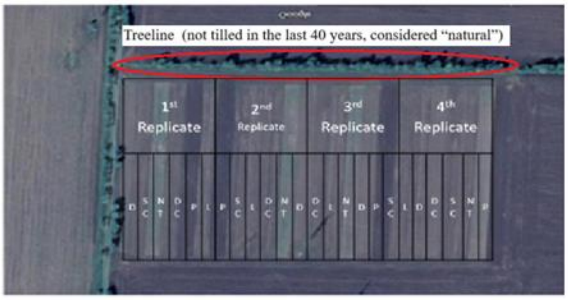


Figure 3.1. Location of study area in Józsefmajor (Hungary) and Soil samples repetitions:D – disking, SC – shallow tine cultivation, NT – no-till, DC – deep tine cultivation, P – plowing, L – loosening

Figure 3.1 shows the location of Józsefmajor in Hungary and the location of samples and their repetitions in the cropland for each tillage operation and tree line. In the following section, another study area on Szentendre Island will be described.

3.1.2 General Description of the Szentendre Island

Szentendre Island, situated in the middle stretch of the Danube River in Hungary, covers a vast area of 70 km^2, this island is an integral part of the Vác-Pest-Danube valley micro-region, which is bordered by the Pest Plain to the south, the Northern Mid-mountains to the north and east (47°43'14.2"N, 19°06'31.4"E). The Naszály, Börzsöny, and Visegrád Mountains encircle the island. It varies in width, spanning from 3.5 km^2 to 500 m. On average, the island stands at an elevation of 110 meters above sea level. According to the World Reference Base for Soil Resources (WRB, 2015), most farms on Szentendre Island predominantly feature Fluvisol as the soil type, characterized by a shallow humus layer (Table 3.3). The Peczely climate classification categorizes this region as moderately warm and moderately dry during mid-winter. The average annual temperature on the northern half of the island is 9.5 °C, while the southern half experiences a slightly higher average of 10.5 °C.

It is home to a permanent population of approximately 10,000 individuals, residing within four distinct communities (Nel and Masoudi, 2021). Moreover, the island encompasses several ecological sites within the Natura 2000 network and is partially located within the boundaries of the Danube-Ipoly National Park (Commission, 2011; Gergely, 2011).

Szentendre Island has served as a center for agricultural practices since the 17th century (Gergely, 2011). According to Orosz *et al*. (2020), the island's contemporary agricultural landscape predominantly features crops such as sunflower, corn, alfalfa, potatoes, orchards, vineyards, fruits, and cereals (Orosz, 2022). Five distinct locations on Szentendre Island, encompassing arable land, forests (Black locust), and farms practicing including conventional, organic, and permaculture horticulture, were selected for comparison. These sites were chosen due to their similar sizes ranging from 0.3 to 2 hectares, comparable agroecological characteristics, and horticultural production involving diverse crop rotations. Each of the three farms applies manure to their soil, and their fields are cultivated with a variety of crops. Notably, the conventional farm cultivates a minimum of ten different crop varieties. Conventional farming seeks to exclude or minimize natural influences on farming conditions with external inputs and infrastructure.

The Permaculture horticulture is in Tahitótfalu and operates as a Community Supported Agriculture (CSA) farm, specializing in the cultivation of fresh vegetables for a box system. Initially established in 2010, the farm focused on growing organic crops; however, over time, the proprietors became inspired by the principles of permaculture. On the other hand, the organic farm has obtained certification from Biokontroll Ltd., a recognized Hungarian certification authority. They employ soil cultivation techniques and implement ridge creation while primarily growing vegetables for the local fresh market on their conventional farm site (Szilágyi *et al.*, 2021). Permaculture, recognized as a systemic design approach, strives to establish sustainable and enduring agricultural practices and communities. By adopting a holistic perspective that emphasizes the interconnectedness of various components within a system, permaculture aims to develop designs that mimic the patterns observed in natural ecosystems (Hathaway, 2016). It is important to note that permaculture encompasses a comprehensive mindset regarding farming and its role within the ecosystem, extending beyond a mere assortment of methods or cropping strategies (Fiebrig *et al.*, 2020).

Organic farming, also known as biological or ecological farming, represents an advanced agricultural approach that enables the production of nutrient-rich food within carefully regulated and environmentally friendly environments. Organic farming emphasizes the utilization of natural processes instead of substituting them with external inputs (Kremen and

Miles, 2012; Szilágyi *et al.*, 2021). Conventional farming is a high-yield, profit-driven type of agriculture that mostly uses synthetic fertilizers and pesticides. It also frequently cultivates enormous areas in monoculture. A major priority for both large-scale farming systems is soil quality. While farmers in permaculture work to reduce soil disturbance, cover the surface with mulch, and use complex polycultures, and companion plants, organic farmers strive to maintain and improve soil quality through crop rotation and the addition of organic manure in place of fertilizers (de Tombeur *et al.*, 2018). The energy cycle is the key differentiating factor between organic and permaculture farming practices. A field or farm serves as an energy source, whereas permaculture aims to establish a closed-loop energy cycle. Moreover, the permaculture system may occasionally utilize seeds from non-native plant species or uncertified native resources (Turalija, 2022).As mentioned before, most farms on Szentendre Island feature Fluvisol soil. (Szilágyi *et al.*, 2021). The location of the study area and samples is shown in Figure 3.2.

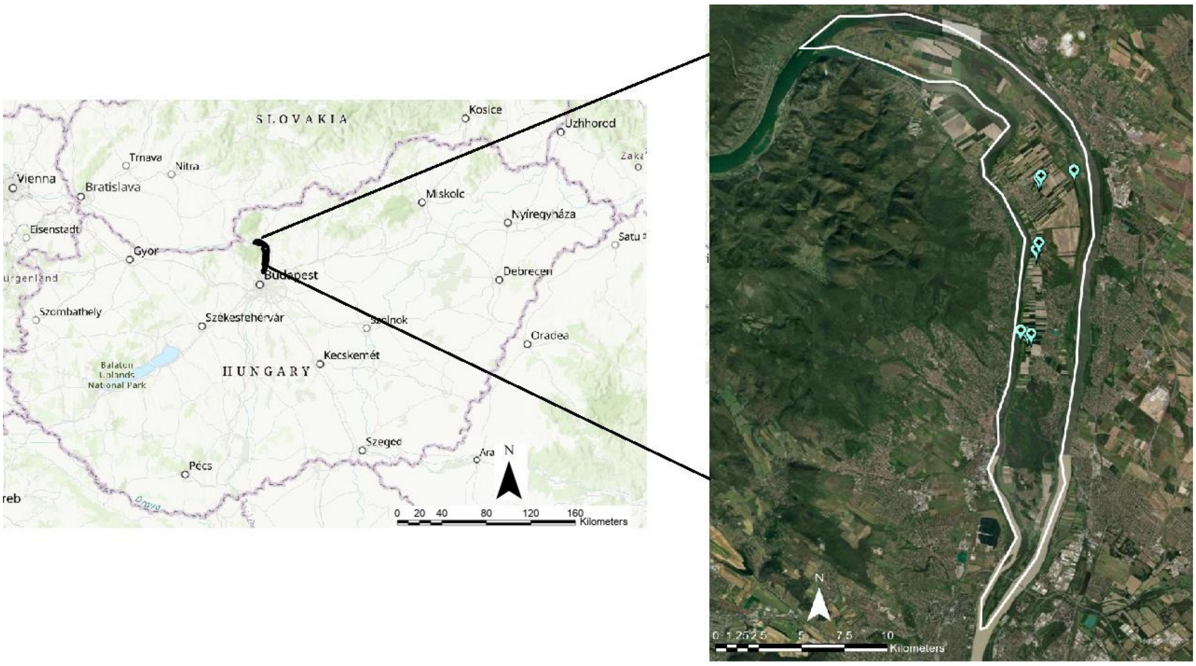


Figure 3.2. Location of the study area in Szentendre Island (Hungary)

Figure .3.3 shows the location of Szentendre Island in Hungary and also sampling points in this area. In the following two other study areas including Visnyeszéplak and Magyarlukafa in the Zselic area are described.

3.1.3 Zselic area (Visnyeszéplak and Magyarlukafa)

Zselic area, located in Hungary, is a hill range known for its diverse landscape and rich biodiversity. Situated at Latitude 46.2186° N and Longitude 17.8801° E, it is considered one of the most forested regions in South Transdanubia (figure 3.4). In this region, almost all of the soil types were Luvisols, or related to Luvisols. Zselic's climate falls under the moderately warm and moderately humid climate district (Csima and Horányi., 2008). The precipitation regime is sub-Mediterranean, with an average annual rainfall ranging from 730 to 760 mm, creating a humid environment. The yearly average temperatures, ranging between 9.8 and 10 °C, contribute to the distinctive climate conditions experienced in the region.

The dominant vegetation in Zselic consists of *Carpinus betulus-Quercus petraea and Tilia tomentosa (silver lime)–Fagus sylvatica* forests. Interestingly, around 77% of these forests have been designated for protective purposes, highlighting the region's commitment to nature conservation, which significantly influences forest management practices. In recent times, there has been a notable shift towards employing more natural methods in forest regeneration, accounting for approximately 40% of the area's forest management (Katona *et al.*, 2013).

Zselic's woodlands exhibit remarkable diversity, encompassing various types of dry, closed, and open woodland patches, as well as submountaneous mesophilous beech forests. Among the prevalent woody habitat types in the area are turkey oak-sessile oak woodlands, riverine ash-alder woodlands, sessile oak-hornbeam woodlands, hornbeam-beech woodlands, and alder and ash swamp woodlands, along with other hardwood forests and plantations (Keszthelyi, 2015).

The investigated land uses are located in two neighborhood villages named: Visnyeszéplak, and Magyarlukafa.

Magyarlukafa is a small village situated in the heart of the Zselic area, which is characterized by its diverse natural features, including deciduous forests, meadows, and wetlands. The village is surrounded by hills and is located 37 km from the Dráva River.

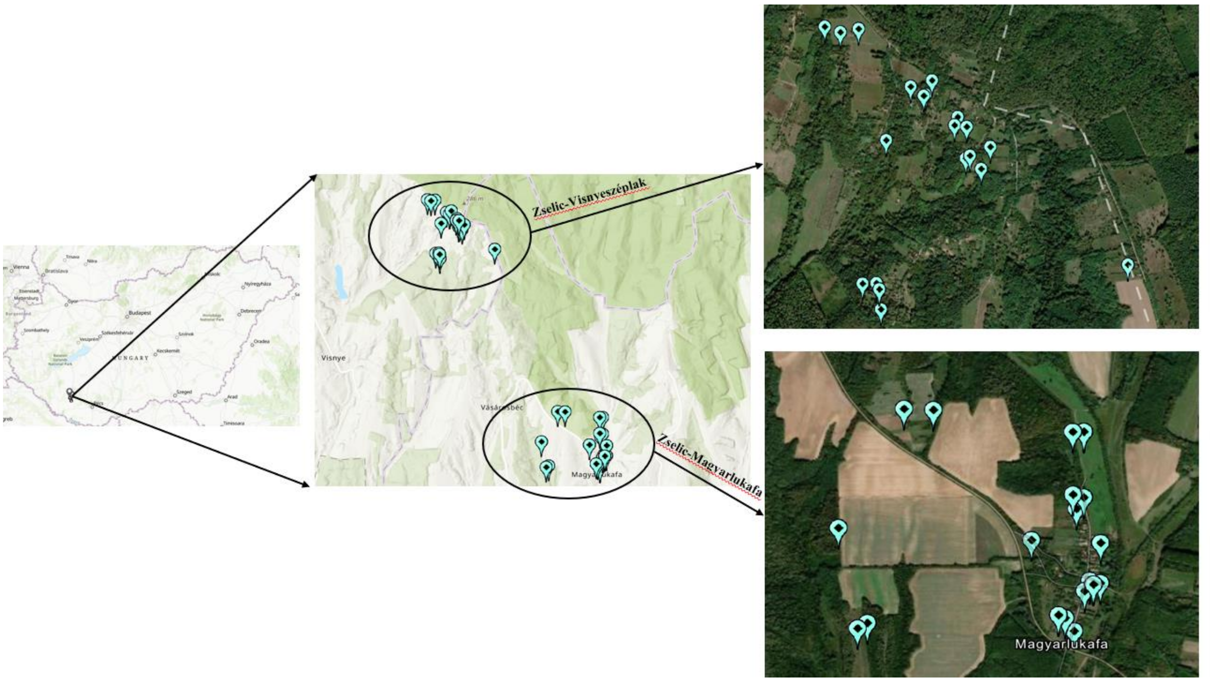


Figure 3.3. Location of study sites in the Zselic region (Hungary)

In Table 3.3 some environmental features of all study areas are summarized.

Table 3.3. The mean of climatic condition and topography in study areas (Józsefmajor, Zselic-Visnyeszéplak, and Magyarlukafa, Szentendre Island)

Area	Altitude (m)	Slope (%)	Precipitation (mm)	Temp (°C)	Evaporation (mm)
Józsefmajor	137.29	0.9109	543.65	10.82	590.17
Magyarlukafa	157.90	5.2803	712.76	10.44	694.57
Visnyeszéplak	235.43	4.5612	747.437	10.24	686.74
Szentendre Island	102.82	0.7368	566.287	11.47	544.63

Figure 3.3 shows the location of two study areas, Zselic-Visnyeszéplak, and Zselic-Magyarlukafa in Hungary, and, also the location of sampling points in the areas. Also, in Table 3.4, some environmental features of all study areas are summarized.

3.2 Sampling and data collection

3.2.1 Józsefmajor Experimental and Training Farm (JETF)

Surface bulk soil samples were collected randomly from five points at 0–10 cm depth within each plot and combined to make a composite sample based on the existing protocols. The samples were air-dried and grounded. A total of 24 samples were collected for all tillage operations (4 replicates per operation) at the time. We also collected 24 composite samples from the tree line area parallel to the cropland (because the tree cover density is different in the tree line area, parallel to each operation, soil samples were collected and then combined). Figures 3.4 and 3.5 show soil profile observation using a core sampler in the tree line and cropland respectively.

Figure 3.4. Treeline and Pürckhauer type soil core sampler at Józsefmajor (tree line) (28/05/2020)

Figure 3.5. Pürckhauer type soil core sampler in Józsefmajor (cropland) (26/08/2020)

3.2.2 Szentendre Island

Soil samples were collected from five land uses: arable land, forest, conventional horticulture, organic horticulture, and permaculture horticulture. Samples are from 0–30 cm depth with five repetitions for each land use (except arable land and forest, which have 15 repetitions each). With similar size (0.3–2 hectares) and agroecological features, horticultural production with diverse crop rotation and arable land with maize rotation.

3.2.3 Zselic Area

Soil samples were collected from four land uses (small areas, 100–200 m^2) including, arable land, and intensive farming in Magyarlukafa, orchard (grassed), forest (most of them natural but includes some black locust forests, with the age less than 30 years), grassland (mixed use of mowing and grazing). Samples are collected from a depth of 0–30 cm with 5 repetitions. Totally 41 soil samples were collected and after preparation (air-dried, and the roots were picked out of the soil by hand) were analyzed in a laboratory.

Table 3.4. Four study areas with sampling details

Study area		Land management		Sampling points	Sampling depth (cm)	Soil
Józsefmajor		Cropland	No-tillage	4	0-10	Chernozem soils
			Disking	4		
			Shallow cultivation	4		
			Deep cultivation	4		
			Loosening	4		
			Ploughing	4		
		Treeline		24		
		Total		48		
Zselic area	Magyarlukaf Visnyeszéplak	Arable land		11	0-30	Luvisol
		Orchard		10		
		Forest		10		
		Grassland		10		
		Total		41		
Szentendre Island		Permaculture horticulture		5	0-30	Fluvisol
		Arable land		15		
		Forest		15		
		Conventional horticulture		5		
		Organic horticulture		5		
		Total		45		

Table 3.4 shows our study areas and total samples from each study site and their reputations. In the following section, sample preparation and measurement methodologies are described.

3.3 Measurements Methodology

3.3.1 SOM Characterization

3.3.1.1 DRIFT measurements for SOM characterization of the bulk soil

The samples were finely ground <200 microns by hand using an agate mortar and pestle and then were kept overnight in an oven at 50 °C to minimize moisture. Mid-infrared spectra were recorded using a Bruker Vertex 70 Fourier transform infrared (FTIR) spectrometer (Vertex 70, Bruker Optics Ltd., Coventry, UK) in DRIFT mode with an RT-DLaTGS detector (figure 3.6). Spectra were collected in the 4000–600 cm^{-1} wavenumber range with a resolution of 4 cm^{-1} and three scans per sample separately to check the reproducibility of the analysis.

DRIFT spectra were corrected for background atmospheric CO_2 and water vapor. Rubber band correction employing fixed numerous data points in the spectral window was also used for baseline correction. Based on the prominent bands observed in spectra, five organic bands (Table 3.5) were selected and analyzed for band area integration. Briefly, the 2960–2840 cm^{-1} band area was assigned to aliphatic C (Lehmann and Solomon, 2010), and the 1680–1580 cm^{-1} band area to aromatic C (Demyan *et al.*, 2012). The band at 1465–1360 cm^{-1} was assigned to aliphatic C=H bending, phenolic lignin (Egli *et al.*, 2010; Lehmann and Solomon, 2010), 1547–1510 cm^{-1} was assigned to amide N (Zaccheo *et al.*, 2002; Lehmann and Solomon, 2010) and 1175–1148 cm^{-1} band was designated to polysaccharides (Spaccini and Piccolo, 2008; Egli *et al.*, 2010).

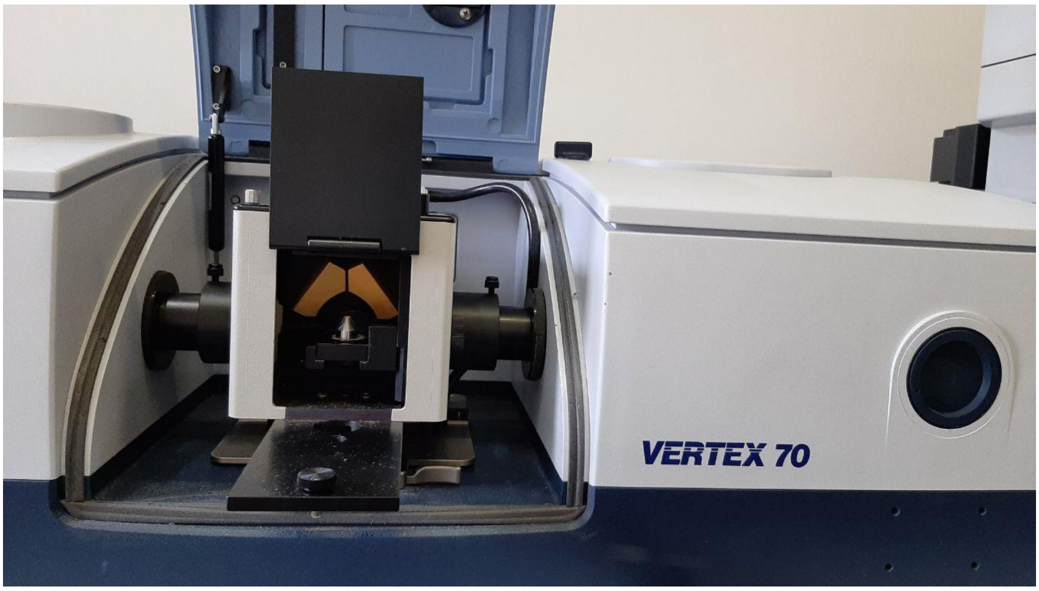


Figure 3.6. Bruker Vertex 70 Fourier transform infrared (FTIR) spectrometer (Vertex 70, Bruker Optics Ltd., Coventry, UK) used for DRIFT measurement

All spectral processing and band integration was done using the OPUS software (version OPUS 8.1). For band area integration, at an identified band position, the integration limit (upper-lower wavenumbers) was fixed and a local baseline was drawn between the two endpoints.

Table 3.5. Investigated DRIFT bands and their probable assignments

Band number	Band region (cm^{-1})	Probable assignments
1	2960–2840	Aliphatic C-H stretching of CH_3 and CH_2
3	1680–1580	Aromatic C=C and/or –COO- stretching
4	1547–1510	N-H and C=N of amide bond
5	1465–1360	Aliphatic C-H bending of CH_3 and CH_2, phenolic lignin
6	1175–1148	polysaccharides

Figure 3.7 shows an example of the upper-lower wavenumbers bound area calculation.

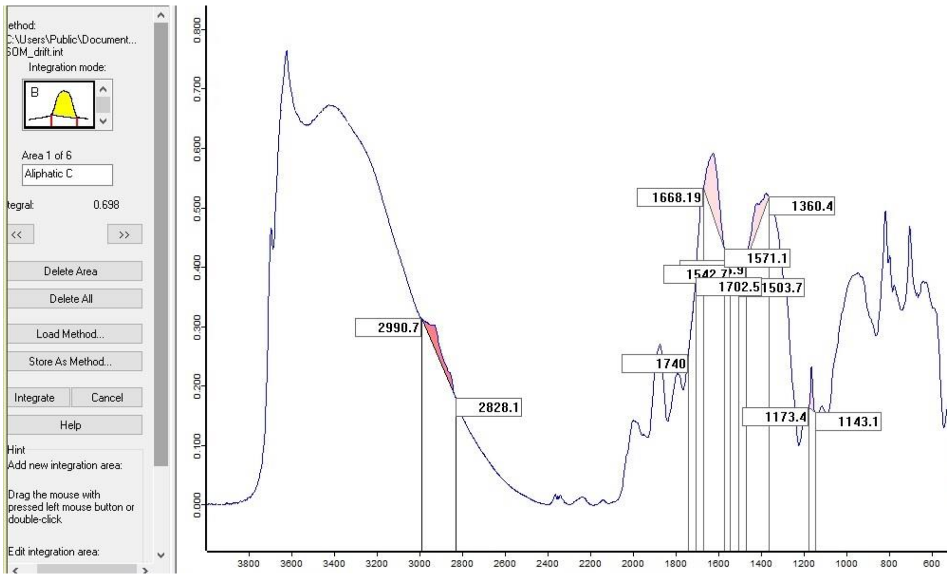


Figure 3.7. Upper-lower wavenumbers band area calculation for the selected bands in OPUS software

The relative band area (RBA) for the selected bands was calculated as follows (Demyan *et al.*, 2012; Yeasmin *et al.*, 2020) (eq. 3.1): $RBA = \frac{\text{The area of a particular band}}{Sum\ area\ of\ all\ bands} \times 100$ (1)

Two indices were calculated to relate the differences in functional groups with SOM composition (Margenot *et al.*, 2015; Yeasmin *et al.*, 2020) as given below:

Aromaticity (Ratio Aromatic: Aliphatic C) = $\frac{\text{RBA}(1680-1580)}{\text{RBA}(2960-2840)+\text{RBA}(1465-1360)}$ (2)

The ratio of C to O functional groups =

$$\frac{RBA(2960-2840)+(1680-158)+(1547-1510)+(1465-1360)}{(1175-1148)} \qquad (3)$$

The degree of decomposition and maturity of OM has been proven to increase aromaticity (Veum *et al.*, 2014; Margenot *et al.*, 2015). Also, an increase in the ratio of C-rich compounds (e.g., aliphatic, aromatic) to O-rich functional groups (e.g., carboxyl, polysaccharides) is likely to be associated with decreased biological reactivity, and recalcitrance of OM (Ding *et al.*, 2002; Veum *et al.*, 2014; Margenot *et al.*, 2015; Yeasmin *et al.*, 2020).

3.3.1.2 Soil OM pool fractionation

In this study, we applied an approach of SOM pool fraction for DRIFT measurement (figure 3.9). However, we just applied this experiment for three of the tillage operations and tree lines in the Józsefmajor case study (because of the time and finance limitations). In this regard, bulk samples were fractionated to provide labile and stable C pools. For the fractionation, the Zimmermann method (Zimmermann *et al.*, 2007) modified by Poeplau *et al.* (2013) was applied. Firstly the aggregate fraction (>63µm) is separated by wet sieving. The aggregate fraction is then divided into mineral aggregates and sand (>1.0 g cm^{-3}) and particulate organic matter (POM <1.0 g cm^{-3}) using separation by specific weight. SOM occluded by the aggregates and POM together represent the labile OM fraction. Fraction <63 µm represents the mineral associated with stable organic matter (MAOM) *(Zimmermann et al.*, 2007). Besides, the aggregates are also built up by separate mineral particles directly holding the stable OM (Figure 3.8, 3.9).

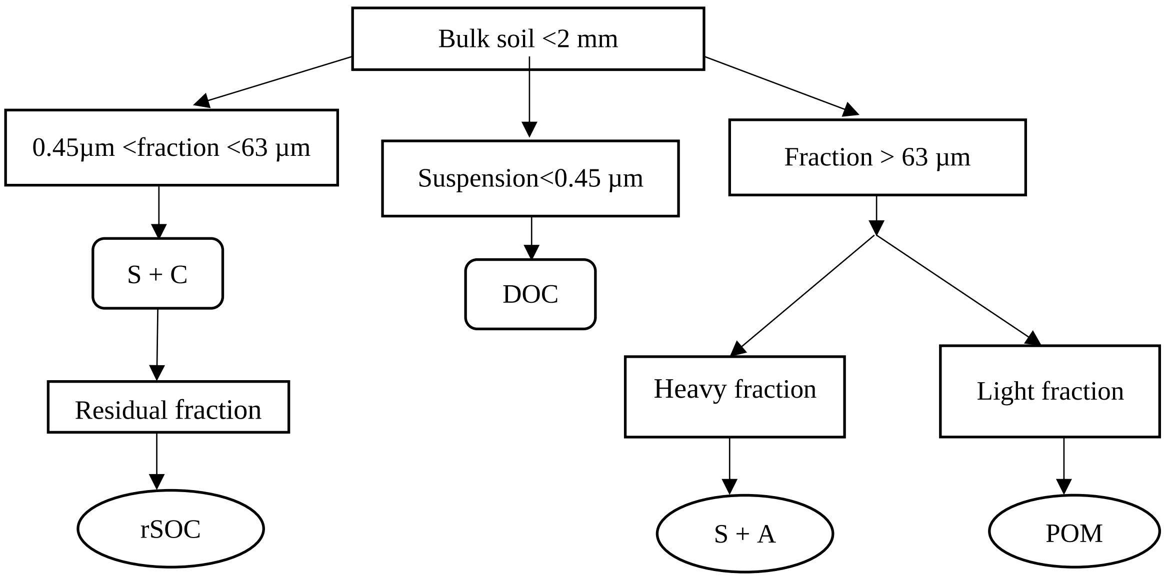
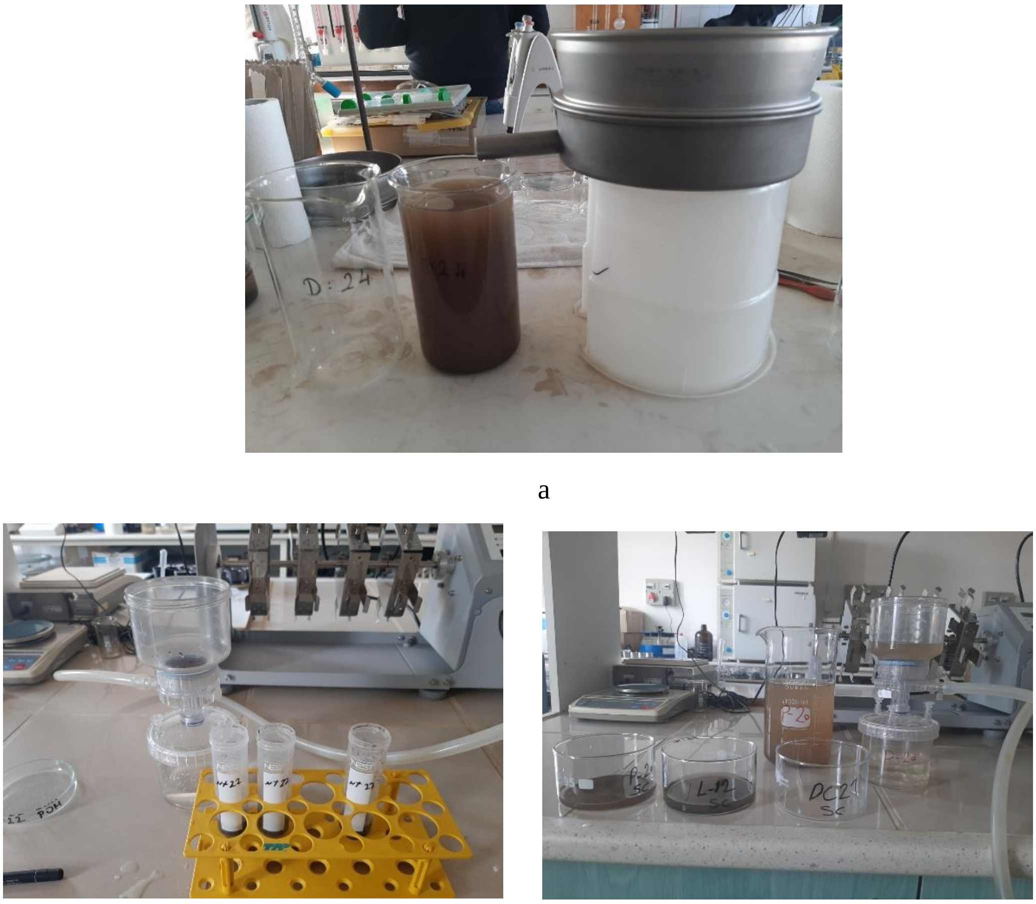


Figure 3.8. Diagram of the fractionation procedure; S + C: Silt and clay, rSOC: resistant soil organic carbon, DOC: dissolved organic carbon, S + A: sand and stable aggregates, and POM: particulate organic matter (based on Zimmermann *et al. (2007)*



a

b c

Figure 3.9. Fractionation procedure; a: dissolved organic carbon, S + A = sand and stable aggregates, b and c POM = particulate organic matter and s + c= Silt and clay fraction

Only the additionally occluded SOM belongs to the labile pool (aggregate associated organic matter; AAOM). Figure 3.9 shows the fractionation procedure of samples (tree line) located in Józsefmajor. The following section explains other soil properties measured for the study areas.

3.3.2 Soil properties and Soil Organic Matter content measurement

In this research, soil samples were gathered from the study area and later transported to the laboratory for a thorough examination. The objective of this laboratory analysis was to assess different important characteristics of the soil that have a significant impact on comprehending the overall health, productivity, and state of the soil. One of the main factors examined was the soil pH. pH is a measurement of how acidic or alkaline the soil is, and it has a direct impact on the availability of nutrients for plants.

Another significant characteristic investigated was the soil texture. Soil texture refers to the relative amounts of sand, silt, and clay particles present in the soil. It plays a crucial role in determining the soil's capacity to retain water, its drainage properties, and its ability to hold nutrients. Analyzing the soil texture allows us to comprehend its physical attributes and provide suitable suggestions for land utilization and maintenance. As part of the laboratory examination, the percentage of salinity (m/m) was also assessed. Salinity refers to the concentration of soluble salts found in the soil. Elevated levels of salinity can disturb plant growth and overall productivity. Furthermore, the laboratory analysis encompassed the determination of the percentage of calcium carbonate ($CaCO_3$) (m/m). The presence of $CaCO_3$ provides insights into the soil's calcium status and the existence of carbonates. This parameter holds particular significance in regions with calcareous soils, as it can affect nutrient availability and soil structure. The laboratory analysis also involved the assessment of the SOM percentage (m/m). SOM refers to the organic material present in the soil, resulting from the decomposition of plant and animal residues. It should be noted that the amount of Humus (soil organic content) performed by the Hungarian Standard MSZ-08-0210-1977 (Tóth *et al.*, 2018). Additionally, the laboratory analysis encompassed the measurement of nitrite and nitrate levels (mg/kg) in the soil. Nitrite (NO_2^-) and nitrate (NO_3^-) are forms of inorganic nitrogen that play a crucial role in supporting plant nutrition. Lastly, the laboratory analysis included the determination of P_2O_5, which represents the available phosphorus content in the soil. Phosphorus is an essential nutrient required for various biological processes in plants. All samples were sent to the laboratory for soil properties measurement (Table 3.7). Figure 3.10 shows $CaCO_3$ measurement (a) using Scheibler methodology and also pH using the multi-parameter analyzer.

a b

Figure 3.10. Laboratory measurement, a: $CaCO_3$ content measurements of samples using Scheibler method b: pH measurement of samples using the multi-parameter analyzer

Table 3.6. Soil properties measurement methodology in study areas (Józsefmajor, Zselic-Visnyeszéplak, and Magyarlukafa, Szentendre Island)

Soil properties	Method	Device
pH (KCl 1:2,5)	MSZ-08-0206-2:1978 2	WTW inolab pH7310 pH-mérő
Texture-related parameters used only in Hungary [KA] KA-ST	MSZ-08-0205:19785.	VOS PB S40 Electric mixer
Salinity % (m/m)	MSZ-08-0206-2:1978 2.4.	WTW Cond 7110 conductometer TetraCon 325/S electrode
$CaCO_3$ % (m/m)	MSZ-08-0206-2:1978 2.2.	K-10 calcimeter
SOM content % (m/m)	MSZ 08-0210:1977 MSZ-08-0452: 1980	Thermo Scientific Evolution 60s UV-Visible spectrometer
NO_2 + NO_3 (KCl soluble) (mg/kg)	MSZ 20135:1999. 4.2.2. EPA 353.1:1978	Thermo Scientific Gallery discrete analyzer
Mg (mg/kg)	MSZ 20135:1999 4.2.2., 5.1.	Thermo Scientific iCAP 6300 Radial View ICP-OES spectrometer
KCl (mg/kg)	MSZ 20135:1999 4.2.2., 5.1.	
K_2O (mg/kg)	MSZ 20135:1999 4.2.1., 5.1.	
Na (mg/kg)	MSZ 20135:1999. 4.2.1., 5.1.	
P_2O_5 (mg/kg)	MSZ 20135:1999. 4.2.1., 5.1.	
Cu (mg/kg)	MSZ 20135:1999 4.2.3., 5.1.	
Mn (mg/kg)	MSZ 20135:1999 4.2.3., 5.1.	
Zn (mg/kg)	MSZ 20135:1999 4.2.3., 5.1.	

Table 3.6 shows all measured soil properties and the methodology used in the laboratory. Soil properties measured in all study areas are presented in Appendix A, table A1, A2, A3, and A4.

3.3.3 Determination of the applied environmental factors

For each sampling point, various topography-related environmental covariates were computed by utilizing a digital elevation model with a resolution of 100 m. These covariates encompassed a range of geomorphometric properties that play a significant role in shaping the local environment (Table 3.7).

To capture the prevailing climatic conditions, several parameters including mean annual precipitation, temperature, evapotranspiration, and evaporation values were extracted (Table 3.8). These climatic indicators were derived from reliable data sources, allowing for a comprehensive understanding of the prevailing weather patterns in the study areas.

Appendix B Table B1 represents all environmental factors derived for each sampling point in our study areas.

Table 3.7. The source of environmental covariates used in the study (Szatmári *et al.*, 2023)

Factors	Covariates	Unit	Reference/Source
Topography	Elevation	[m]	DEM
	Slope	[%]	DEM
	Profile curvature	[-]	DEM
	Total curvature	[-]	DEM
	Topographic position index	[m]	DEM
	Topographic roughness index	[-]	DEM
	Surface area	[m^2]	DEM
	MRVBF	[-]	DEM
	MRRTF	[-]	DEM
	LS factor	[-]	DEM
	Topographic wetness index	[-]	DEM
	SAGA wetness index	[-]	DEM
	Vertical distance to channel network	[m]	DEM
	Horizontal distance to channel network	[m]	DEM
	Channel network base level	[m]	DEM
	Diurnal anisotropic heating	[-]	DEM
	Mass balance index	[-]	DEM
	Stream power index	[-]	DEM
Climate	Mean annual precipitation	[mm]	Szentimrey and Bihari (2007)
	Mean annual temperature	[°C]	Szentimrey and Bihari (2007)
	Mean annual evapotranspiration	[mm]	Szentimrey and Bihari (2007)
	Mean annual evaporation	[mm]	Szentimrey and Bihari (2007)

DEM: digital elevation model, LS factor: slope length-gradient factor of the USLE equation, MRVBF: multiresolution valley bottom flatness, MRRTF: multiresolution ridge top flatness

3.3.4 Data Analysis

The analyzed variables were described using the mean and standard deviation and graphically presented as box and whisker plots. The skewness, kurtosis, and Shapiro-Wilk test, based on comparing the quantiles of the fitted normal distribution to those of the data, was used to check the normal distribution of the variables. Several variables displayed a non-normal distribution, namely SOM content, pH, $CaCO_3$, Aliphatic C, Aliphatic C-H phenolic lignin, and aromaticity. A nonparametric Kruskal–Wallis test, which tests the null hypothesis that the SOM medians within each of the seven land use types are the same, was used for the non-normally distributed variables. One-way analysis of variance (ANOVA) was also used to detect the significance of different land use/management practices on the variables considered normally distributed. For multiple comparisons, a post hoc test of Tukey of $p<0.05$ was applied (95% family-wise confidence level). All analysis was performed using R software (version R4.0.3).

Correlation analysis was performed using a nonparametric procedure (Spearman rank correlation coefficient because the data did not always show a normal distribution. Spearman correlation coefficients were used to determine the strength of possible relationships between SOM composition and environmental variables, soil property, and SOM content. The significance of the findings was determined through the chi-square test, with a significance level (α) of 0.05.

3.3.4.1 Principal Components Analysis

Multivariate analysis procedure including Factor Analysis (FA) was used to determine discriminant variables. These kinds of methods are also referred to as 'dimension reduction' or 'data-reduction' techniques (Pacini *et al.*, 2014) because they have the advantage of capturing the complexity of factors/data by taking into account numerous environmental dimensions and highlighting a few more explanatory dimensions. PCA analysis is useful in estimating a priori the number of homogenous groups in the data sets (Tittonell et al., 2010; Dossa *et al.*, 2011). The ideal number of components was determined by applying both the Cronbach's alpha threshold and the eigenvalue rule (>1).

All soil, climatic, and other environmental properties that were investigated were standardized based on their standard deviations, and the resulting Z-scores were further subjected to analysis. To achieve dimensional reduction, principal component analysis (PCA) was conducted, followed by varimax rotation with Kaiser's normalization.

Before implementing PCA, relationships among soil properties and environmental covariates tested and all dependent variables are represented by the most relevant factors. So in the end, eight soil properties including Na (mg/kg), Cu (mg/kg), Humus %, Mg (mg/kg), NO_2 + NO_3 (KCl soluble) (mg/kg), P_2O_5 (mg/kg), pH-KCl, $CaCO_3$ % (m/m) and four environmental covariates including precipitation, slope, temperature, and TPI were selected. Then factors for soil characteristics were extracted using PCA and Varimax rotation with Kaiser Normalization. The eigenvalue threshold (>1), the Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy (>0.5) and Bartlett's test of sphericity significance (<0.00001) were applied (Hair et al., 2010). The data was standardized for analysis automatically using the PCA procedure before analysis. Outliers in the data were examined and revised accordingly. Loadings that were greater or equal to 0.4 were considered for interpretation purposes (Samuels, 2017).

Finally, to identify the most relevant and effective environmental covariates and soil properties on OM compound, spearman correlation analysis was applied among the environmental covariates and the OM-dependent varimax rotated principal components (rPCs) to discover the most relevant and effective environmental covariates on SOM composition.

4. Results and discussion

4.1 Primary soil property variations under different land uses

4.1.1 Soil property variation in Józsefmajor

A significantly ($p < 0.05$) higher SOM percentage was observed in the tree line (surface layer: 0-10cm) compared to the tillage practices (Table 1). A comparison of the types of tillage demonstrated that conservation practices, such as disking and no-tillage, resulted in higher SOM levels, and intensive practices, such as plowing, showed a lower percentage. Nonetheless, a significant difference between tillage operations was observed, as follows ($p<0.05$): disking>deep cultivation/shallow cultivation/loosening/no-tillage>plowing. Thus, the no-tillage value was between disking and loosening and differed from that of plowing. Similarly, the proportion of $CaCO_3$ was significantly higher in plowing than under other land use/management types. A significant difference between the tree line and the other land uses was observed in terms of pH (Table 4.1).

Table 4.1. Mean and SD of SOM, pH and $CaCO_3$ in Józsefmajor (n=48, 24 samples from the treeline and four samples from each tillage operations). Different letters indicate significant differences at the p=0.05 level.

Land management	SOM (%)		pH_{dw}		$CaCO_3$ (%)	
	Mean	SD	Mean	SD	Mean	SD
Treeline	9.32 [a]	1.54	5.49 [c]	0.63	0 [a]	0.00
No-tillage	3.44 [b]	0.25	4.70 [a]	0.15	0.03 [a]	0.10
Disking	3.83 [c]	0.32	4.88 [a]	0.11	0.25 [a]	0.30
Shallow cultivation	2.98 [d]	0.16	4.90 [b]	0.11	0.25 [a]	0.50
Deep cultivation	3.12 [e]	0.19	5.00 [b]	0.22	0.12 [a]	0.30
Loosening	2.95 [d]	0.23	5.12 [b]	0.13	0 [a]	0.00
Ploughing	2.39 [f]	0.14	5.42 [c]	0.19	1.01 [b]	1.10

The analyzed data indicate a higher SOM quantity in the tree line. The presence of black locusts (for at least 40 years) increased and/or preserved SOM content. Additionally, we observed an inverse relationship between tillage intensity and SOM content. Conservation tillage, such as disking and no-tillage, resulted in a significantly higher SOM content than more intensive tillage (Table 1). Most studies indicated a decrease in the uppermost layer due to tillage intensity but also indicated an increase in the below layers (Cardelli *et al.*, 2012; Martín *et al.*, 2019; Krauss *et al.*, 2020; Slepetiene *et al.*, 2022; Jakab *et al.*, 2023). In this study area, different soil tillage treatments have been applied since 2002; thus, there was sufficient time for differences to develop among the systems.

4.1.2 Soil property variation in Szentendre Island

A significantly higher SOM percentage (Tukey p-value<0.05) was observed in the permaculture horticulture topsoil (0-30 cm) followed by forest, organic horticulture, and arable land, and the lowest value belonged to conventional horticulture (permaculture horticulture >forest>organic horticulture>arable land>conventional horticulture).

De Tombeur *et al*. (2018) in their study indicated that permaculture/bio/intensive micro-gardening practices enhance SOM storage and modify the distribution of SOM in soil and suggest that these practices strongly affect soil properties compared to conventional farms (de Tombeur *et al.*, 2018). Another study also showed the improvement of the physical properties and soil organic matter of the soil by applying this kind of treatment in an agricultural field (Vovk and Korže, 2018).

In addition, pH in arable land showed a significantly lower value compared to permaculture and forest (table 4.2).

Table 4.2. Mean and SD of SOM, pH and $CaCO_3$ in Szentendre Island n=45. Different letters indicate significant differences at the p=0.05 level.

Land use	SOM (%)		pH		$CaCO_3$ (%)	
	Mean	SD	Mean	SD	Mean	SD
Permaculture horticulture	3.0 [b]	0.37	7.63 [a]	0.02	9.7 [a]	0.69
Arable land	1.77 [a]	0.32	7.28 [b]	0.3	12.37 [a]	4.78
Forest	2.7 [b]	0.42	7.6 [a]	0.08	8.0 [a]	4.37
Conventional horticulture	1.48 [a]	0.22	7.5 [ab]	0.09	9.9 [a]	2.27
Organic horticulture	2.11[a]	0.24	7.59 [ab]	0.039	13.32 [a]	1.94

4.1.3 Soil property variation in the Zselic area

A significantly higher SOM percentage was observed in the grassland samples compared to arable land and orchards in the depth of 0–30 cm. Nonetheless, a significant difference between different land uses was observed, as follows (p<0.05): grassland>arable land/orchard>forest. There are a lot of studies showed higher soil organic matter under forests comparing grassland (Evrendilek *et al*., 2004; Keen *et al.*, 2011) and cropland (Evrendilek *et al.*, 2004; Slepetiene *et al.*, 2022). However, their findings contrasted with this study where results showed that grassland had higher SOM compared to forest. This might be because animals that contribute organic carbon from their droppings graze the grassland of this study. Kamp *et al*. (2009) also found a higher carbon stock under Imperata grassland (about 37.3 ton ha^{-1} in the first 40 cm) than under primary forest (33.19 ton C ha^{-1}), which is consistent with our result. Forests in this area showed a lower amount of SOM compared to cultivated areas (arable land and orchards). The higher SOM in the cropland as compared to the forest in this study might be due to the C application of other organic manures (Keen *et al.*, 2011).

The measured pH also showed a significantly higher value in arable land compared to forest and grassland. However, we could not find differences between different land uses for $CaCO_3$ (Table 4.3).

Table 4.3. Mean and SD of SOM, pH, and $CaCO_3$ in Zselic area (0–30 cm) (n=41). Different letters indicate significant differences at the p=0.05 level.

Land management	SOM (%)		pH		$CaCO_3$	
	Mean	SD	Mean	SD	Mean	SD
Arable land	2.5^{b}	0.708	7.25^{b}	0.47	2.96^{a}	3.36
Orchard	2.5^{b}	0.408	6.5^{ab}	1.02	2.2^{a}	3.56
Forest	2.4^{b}	0.730	5.85^{a}	1.27	0.46^{a}	0.98
Grassland	2.8^{a}	0.73	6.30^{a}	0.917	1.34^{a}	2.64

As the results show, in all three study areas, practices focused on conservation and land use types that are more natural (forest, grassland) or have less intensive management styles tended to have higher levels of SOM, and because in cultivated area harvests cause to decrease its input to soil (Malo *et al.*, 2005; Zajícová and Chuman, 2019). Instance in Józsefmajor, the higher SOM under the tree line than that in cropland (Table 4.1) was observed and it is generally attributed to higher OM inputs and the lack of physical disturbance associated with tillage (Yao *et al.*, 2019). Aeration during tillage accelerates the rate at which organic matter decomposes into minerals. Erosion also contributes to the easier removal of SOC (McLauchlan, 2006; Zajícová and Chuman, 2019; Assefa *et al.*, 2020). These findings imply that land use/management strategies aimed at soil preservation and the accumulation of organic matter are beneficial for enhancing SOC content (Yao *et al.*, 2019).

De Kovel *et al*. (2000) and Arrouays *et al*. (2001) have similarly demonstrated that SOC content is significantly influenced by vegetation and land usage (De Kovel *et al.*, 2000; Arrouays *et al*., 2001). However, SOC content tends to encompass a broad range of values within soil types, depending on their inherent properties (Martin *et al.*, 2011).

The pH levels displayed variations across the study areas, with arable land generally presenting lower pH values in Józsefmajor and Szentendre Island compared to other land use types. This lower pH is commonly observed in cultivated and more intensively managed lands, as also confirmed in various studies (Chemeda *et al.*, 2017; Assefa *et al.*, 2020). E.g Muche *et al*.

(2015) found that natural forests exhibited significantly higher soil pH compared to cultivated land, plantation forests, and grazing areas, potentially leading to increased toxicity of manganese and aluminum and a slower microbial conversion of NH_4^+ to nitrate (Muche *et al.*, 2015), which is also indicated by Assefa *et al*. (2020).

Nonetheless, in the Zselic area, higher pH levels were observed in arable land compared to other land uses. This may be influenced by factors such as agricultural practices (liming, fertilizers) and soil management. Regarding $CaCO_3$ levels, we couldn't find any meaningful pattern, however, in Józsefmajor, plowing had a notable impact on increasing $CaCO_3$ in the soil. This suggests that intensive tillage practices can lead to higher $CaCO_3$ levels.

Consequently, we recommend the implementation of land conservation practices that involve minimizing tillage and introducing crop rotation.

4.2 Chemical composition of the SOM under different land use management

4.2.1 Chemical composition of SOM in Józsefmajor bulk soil

Wave number ranges related to organic moieties revealed relevant variations among the land use/management types (Table 4.4). Aromatic C (1680–1580 cm^{-1}) and aliphatic C-H (2960–2840 cm^{-1} and 1465–1360 cm^{-1}) had the highest ratio C groups in each land use/management system, with a few exceptions. Overall, plowing had higher aromatic C and lower aliphatic C-H, and the tree line had larger aliphatic C-H bands.

Almost all management types showed significant differences in values for aliphatic C-H. The highest value was observed at the tree line, followed by disking and no-tillage, which differed from the other tillage systems. Moderate values were observed in deep cultivation and shallow cultivation, and the lowest values were measured under loosening and plowing, which did not differ. In addition, in Aromatic C compounds, the significantly highest value was observed under plowing, followed by, loosening, deep cultivation, and shallow cultivation. The significantly lowest value was measured under the tree line, no-tillage, and disking.

The highest value for phenolic lignin was observed under the tree line, followed by plowing, disking, deep cultivation, loosening, and shallow cultivation tillage groups. Finally, the lowest value was observed under no-tillage. However, the differences were not significant. Amide values were significantly higher under no-tillage, tree line, and disking and lowered under plowing, loosening, and shallow cultivation. In addition, higher polysaccharide levels were observed under the tree line, no-tillage, and disking, which differed significantly from the lower levels observed under plowing, shallow cultivation, and loosening (Table 4.4, fig 4.1).

Table 4.4. Mean, and SD of the relative band area (RBA) (%) of different organic functional groups (compound) in the soil (0–10 cm) DRIFT spectra from the tree line and six tillage operations. Different letters indicate significant differences at the p=0.05 level.

		Disking	Deep cultivation	Loosening	No-tillage	Plowing	Shallow cultivation	Treeline
Aliphatic C-H	SD	1.10	2.60	1.85	1.21	1.71	1.34	3.60
	RBA	24.96^{d}	21.23^{bc}	19.12^{ab}	23.58^{cd}	15.99^{a}	21.17^{bc}	35.73^{e}
Amide N	SD	0.33	0.46	0.25	0.26	0.311	0.26	0.27
	RBA	2.87^{cd}	2.15^{ac}	2.72^{ac}	3.27^{d}	2.51^{a}	2.78^{ac}	3.00^{b}
Aromatic C	SD	1.00	1.60	2.28	1.94	1.93	2.21	2.67
	RBA	44.31^{b}	46.40^{bc}	48.27^{c}	45.13^{b}	51.62^{d}	45.49^{bc}	32.86^{a}
Polysaccharides	SD	0.17	0.38	0.34	0.37	0.49	0.64	0.42
	RBA	6.45^{b}	6.68^{b}	6.78^{b}	6.69^{b}	6.63^{b}	6.96^{b}	5.80^{a}
Phenolic lignin	SD	1.00	1.68	1.21	1.29	1.67	1.33	1.83
	RBA	21.26^{a}	22.80^{ab}	23.08^{ab}	21.30^{a}	23.22^{ab}	23.57^{b}	23.44^{b}

Regarding the indices, aromaticity differences were observed between most land use/management types. The average aromaticity values ranged from 0.55 to 1.3 in the 48 soil samples from all land use/management systems (Fig 4.2 b). The highest value was observed under plowing, followed by loosening and deep cultivation; however, these were not significantly different. Moderate values were observed under shallow cultivation, no-tillage, and disking; however, these did not differ. Finally, the lowest value was measured under the tree line. Disregarding the tree line, the aromaticity of the tillage operation soils increased significantly in the order P>L>DC>SC>NT>D. The C/O ratios varied (13–16) among the land use/management systems (Fig 4.2 a). Overall, a significantly higher value was observed under the tree line, followed by the tillage groups, namely disking, plowing, deep cultivation, no-tillage, loosening, and shallow cultivation, where no differences were observed (table 4.4).

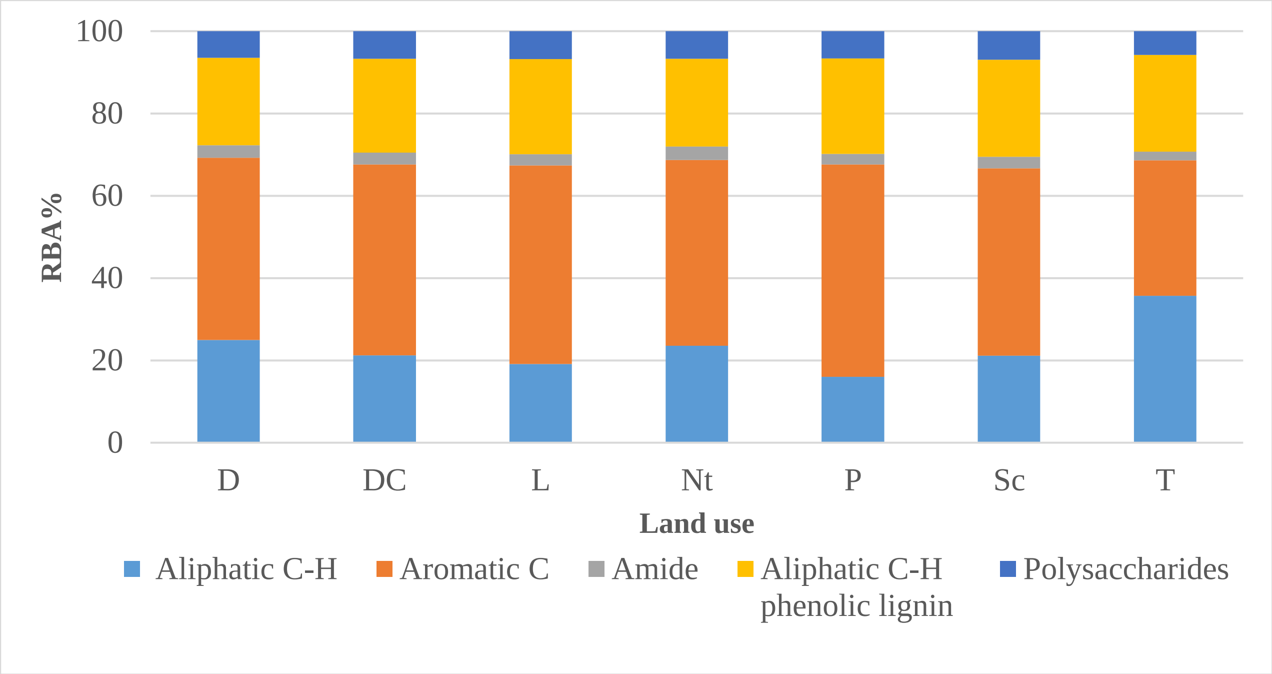


Figure 4.1. The bar graph compares the mean values of relative band area (RBA) of different organic functional groups (compound) for the seven different levels of land use/management in Józsefmajor

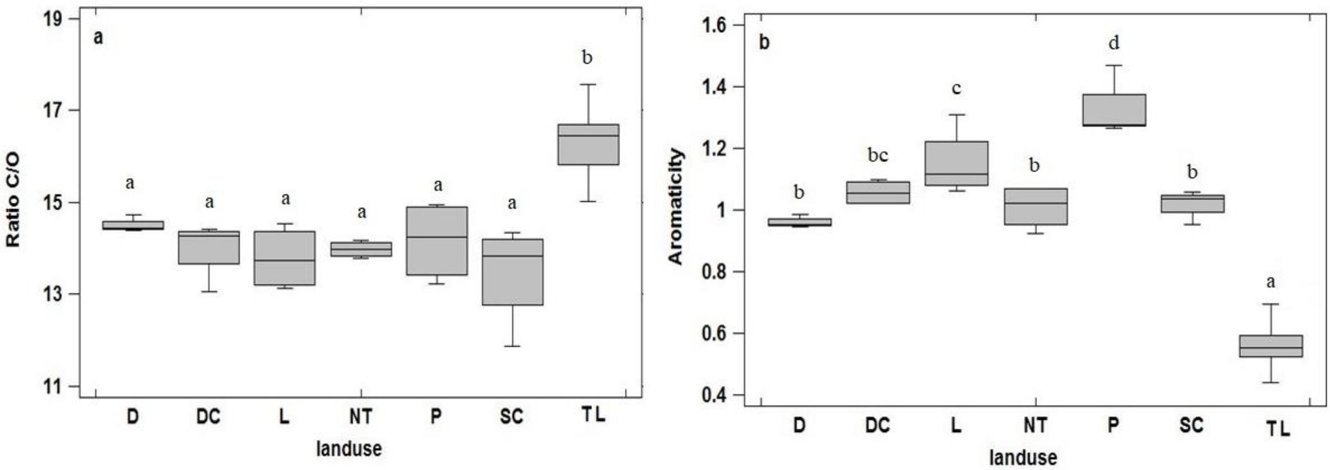


Figure 4.2. Data distribution for C/O functional group ratio (a) and aromaticity (b) for the seven land use/management types. D: Disking, DC: Deep cultivation, L: Loosening, NT: No tillage, P: Ploughing, SC: Shallow cultivation, TL: Treeline. Different letters indicate significant differences at the p=0.05 level.

4.2.1.1 Chemical composition of SOM in Józsefmajor separate carbon pools

In Table 4.5, each cell represents the value of the corresponding SOM composition for a specific land use/management plan considering fractionate soil (e.g. DC fine means fine fractioned soil, S+C, (0.45 µm<fraction< 63µm) under deep cultivation land management, and DC agg means aggregate fraction, S+A, (fraction>63µm under deep cultivation land management))

Here are some observations based on the mean values of the RBA (%) for each SOM composition:

Aliphatic C-H: The highest RBA is observed in the "T - Agg", followed by the "Nt - Agg" and "T - Agg". The lowest RBA is observed in the "P - Fine" (T-agg> Nt- agg> T-fine> DC-agg> Dc-agg> P-agg> Dc-F> P-fine).

Amides: The highest RBA is observed in the "P - Agg", followed by "Dc - Agg" and "Nt - Agg", and the lowest RBA (%) is observed in the "T - Agg" plan. (P-Agg> Dc-Agg> Nt Agg> P-fine> Dc-fine> Nt-fine> T-fine> T-Agg). The output of pairwise comparisons between the average ranks using the Bonferroni procedure shows, that 6 of the comparisons are statistically significant at the 95.0% confidence level (Table 4.5).

Aromatic C: The highest RBA is observed in the "P - fine", followed by "P - Agg" and "Dc - fine". The lowest RBA is observed in the "T-Agg" (P-fine> P-Agg> Dc-fine> Dc-Agg> Nt-fine> Nt-Agg> T-fine> T-Agg). Based on multiple comparisons (Table 4.5) five homogenous groups are identified within which there are no statistically significant differences.

Polysaccharides: The highest RBA is observed in the "P- Agg", followed by the "Dc - Agg" and "Nt - Agg". The lowest RBA is observed in the "T - Agg" (P-Agg> Dc-Agg> Nt-Agg> Dc-fine> Nt-fine> P-fine> T-fine> T-Agg).
Aliphatic C-H phenolic lignin: The highest RBA is observed in the "T-Agg", followed by "T - fine" and "Dc-fine". The lowest RBA is observed in the "DC - Agg". (T-Agg> T-fine> Dc-fine=Nt-fine> P-fine> P-Agg> Nt-Agg> Dc-Agg). The output of pairwise comparisons between the average ranks of the eight groups using the Bonferroni procedure, shows 4 of the comparisons are statistically significant at the 95.0% confidence level (Table 4.5).

Aromaticity: The highest RBA is observed in the "P - fine", followed by "P - Agg" and "Dc - fine". The lowest RBA (%) is observed in the "T-Agg" plan (P-fine> P-Agg> Dc-fine> Dc-Agg> Nt-fine> Nt-Agg> T-fine> T-Agg). The output of pairwise comparisons between the average ranks of the eight groups using the Bonferroni procedure shows that six of the comparisons are statistically significant at the 95.0% confidence level (Table 4.5). C/O ratio: The highest mean value is observed in the "T - Agg", followed by the "T-fine" and "P-fine". The lowest mean value is observed in the "P-agg" plan (T-Agg> T-fine> P-fine> Nt-fine> Dc-fine> Nt-Agg> Dc-Agg> P-Agg). Based on multiple comparisons differences were observed between treeline (both carbon pools) and other plans (Table 4.5 and Fig 3). For aromatic-C, aliphatic C-H, and C/O ratios, we used ANOVA (Tukey's honestly significant difference (HSD) procedure) but for other compositions, we used the Kruskal Wallis test (due to lack of normality of data) to test differences. However, in all land use/management and both soil fractions, there is a significant difference between tree lines and other plants. In addition, we can see differences between different land use/management for Aliphatic C-H, Amide N, and Aromatic C (Table 4.5 and Fig 4.3).

Table 4.5. Mean, and SD of the relative band area (RBA) (%) of different organic functional groups (compound) in 2 fractions of soil (0–10 cm) DRIFT spectra from treeline and three tillage operations (n=24). Different letters indicate significant differences at the p=0.05 level.

		DC Fine	**DC Agg**	**Nt Fine**	**Nt Agg**	**P fine**	**P Agg**	**T fine**	**T Agg**
Aliphatic C-H	SD	0.71	1.9	1.68	1.21	1.01	2.04	1.83	2.83
	RBA	16.05 [ab]	23.97 [c]	20.1 [bc]	30.7 [d]	13.9 [a]	17.5 [abc]	29.58 [d]	49.29 [e]
Amides	SD	0.20	1.18	0.20	0.50	0.45	0.53	0.32	0.3
	RBA	5.10 [a]	7.33 [a]	5.00 [ab]	6.27 [a]	5.28 [a]	7.57 [a]	4.13 [a]	2.66 [b]
Aromatic C	SD	0.93	2.48	1.15	0.57	1.28	2.50	1.56	2.61
	RBA	54.96 [df]	51.97 [d]	51.39 [d]	45.98 [c]	59.66 [f]	55.79 [df]	41.13 [b]	29.01[a]
Polysaccharides	SD	0.24	0.77	0.19	0.46	0.15	0.58	0.19	0.83
	RBA	7.31[a]	8.86 [a]	6.83 [ab]	7.69 [a]	6.82 [ab]	9.09 [a]	5.74 [ab]	5.33 [b]
Aliphatic C-H phenolic lignin	SD	0.25	3.56	0.81	1.07	0.88	1.59	0.98	1.39
	RBA	16.56[ab]	8.86 [a]	16.56 [ab]	9.32 [a]	14.93 [a]	10.02 [a]	19.40 [ab]	20.94 [b]
Aromaticity	SD	0.077	0.31	0.08	0.03	0.18	0.33	0.06	0.05
	Mean	1.68 [a]	1.66 [a]	1.40 [a]	1.14 [ab]	2.12 [a]	2.05 [a]	0.84 [a]	0.46 [b]
C/O ratio	SD	0.47	0.99	0.40	0.77	0.34	0.73	0.58	2.43
	Mean	12.68 [bc]	10.33 [ab]	13.62 [c]	12.02 [abc]	13.66 [c]	10.03 [a]	16.42 [d]	18.11 [e]

Dc-Fine: fine fraction of soil under deep cultivation, Dc-Agg: Aggregate fraction of soil under deep cultivation, Nt-fine: fine fraction of soil under No-tillage, Nt- Agg: Aggregate fraction of soil under No-tillage, P-fine: fine fraction of soil under plowing, P-Agg: Aggregate fraction of soil under plowing, T-fine: fine fraction of soil under the tree line, T-Agg: aggregate fraction of soil under the tree line.

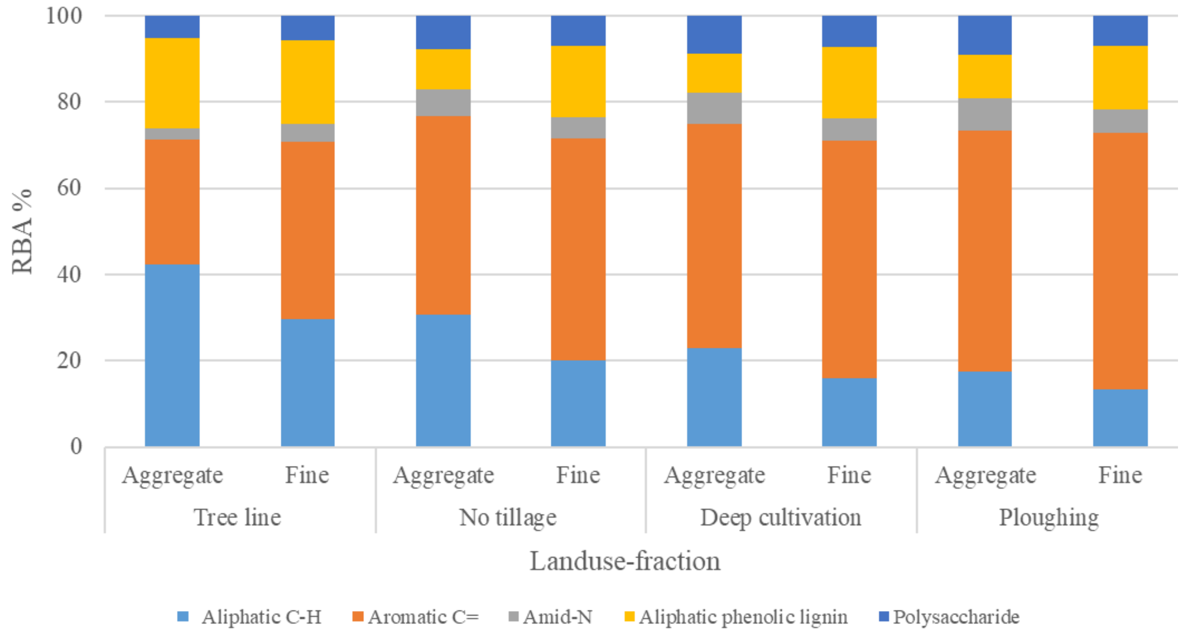


Figure 4.3. The bar graph compares the mean values of relative band area (RBA) of different organic functional groups (compound) for the soil size fraction under three tillage operations and tree line in Józsefmajor

In summary, the result showed a significant difference between most of the groups for aliphatic C-H and aromatic C, however for the ratio of C/O there are differences under the tree line with an aggregate fraction of soil and three of tillage operation (within aggregate fraction) and also between both fine and aggregate fractions under the tree line. However, aromaticity shows just a significant difference between tree line (within aggregate fraction) and plowing and deep cultivation (within aggregate fraction). For three compositions of Amid-N, polysaccharide, and aliphatic phenolic lignin, it shows significant differences between the aggregate fraction of soil under tree line and other tillage operations (plowing, deep cultivation, and no-tillage).

The result suggests that plow-based management, results in increased aromatic C content, and tree line (T) and no-tillage (Nt) land management practices promote higher aliphatic C-H content compared to plow-based (P) practices, especially in the fine soil fraction. For aromaticity and C/O ratio, plowing in fine fraction stands out with the highest values, while the tree line (T) in aggregate fraction has the lowest ratio. These results indicate that plow-based management in fine soil fractions may lead to higher aromaticity and C/O ratio. This could be associated with differences in carbon sequestration and decomposition rates across land use/management practices. There are three reasons for this difference: Firstly, the soil particle size distribution largely represents the degrees of SOM decomposition (Lützow et al., 2007). Consequently, it's logical that the resistant compounds were retained relatively and selectively in the aggregate fractions due to their short-term persistence (Kleber, 2010); Secondly, the

micro aggregate fraction of soil also can retain aromatics and lignin (Totsche *et al.*, 2018; Wang *et al.*, 2021; Wang *et al.*, 2017). Thirdly, N-containing compounds, mainly derived from microbial metabolites and necromass (Simpson *et al.*, 2007; Kopittke *et al.*, 2020), can easily and firmly attach to minerals (especially Fe and Al oxy-hydroxides) (Kopittke *et al.*, 2020), hence persisting for a long time in the fine fraction due to organo-mineral associations (Chen *et al.*, 2023; Kleber *et al.*, 2021; Kögel-Knabner and Amelung, 2021; Possinger *et al*., 2020).
Despite cultivation, it has been observed that the aggregate fraction of soil exhibits a composition that is less aromatic and more labile (Ndzelu *et al.*, 2021; Jakab *et al.*, 2023), compared to the mineral-associated organic matter (MAOM) (Ding *et al.*, 2002; Yeasmin *et al.*, 2020). This observation is also supported by the distribution of aromaticity and phenolic lignin. The difference might be due to variations between the compositions of plant residues above the ground (shoots and leaves) and below the ground (roots) and their distinct manners of decomposition (Abiven *et al.*, 2005). Tillage typically diminishes aggregation and the content of POM. We propose that the faster turnover of large aggregates in conventional tillage, such as plowing, compared to conservative tillage like no-tillage (NT), leads to a swift formation of micro aggregates or fine particles within the large aggregates and contributes to greater stability. Analyzing the data demonstrates that both tillage and aggregates have a significant impact on the composition of SOM. This confirms the findings of Ndzelu *et al*. (2021) in their investigation of various tillage methods in acidic Cambisols, as well as the discoveries of Malou *et al*. (2020) when studying SOM composition in Arenosols. In the case of acidic soil conditions and the absence of a fine soil fraction in these studies, the influence of unprotected, fresh OM on SOM composition was likely heightened (Malou *et al.*, 2020; Ndzelu *et al.*, 2021). Consequently, this might have led to alterations in the compounds of SOM (Neufeldt *et al.*, 2002). The primary aim of tillage is to improve the structure of soil by creating strong and retaining soil aggregates. Although plowing has been a traditional practice throughout history, recent studies highlight its detrimental impact when not performed correctly. Therefore, we believe that when plowing is carried out appropriately in suitable environmental conditions, it could, at least temporarily, enhance the stability of soil aggregates (Álvaro-Fuentes *et al.*, 2008; Szatmári *et al.*, 2023).
We also tested three tillage operations disregard the tree line for more detailed information.
Based on the results aromatic C and aliphatic C-H were the most abundant C groups in all analysis groups and land use/management (Table 4.6). Overall, the aliphatic phenolic lignin group shows a higher range in the fine fraction of soil (0-10 cm) in all tillage operations.

Also, aggregate soil fractions show a higher range of aliphatic C-H in all three tillage operations. About other functional groups (Amide and polysaccharide), we cannot see any pattern. The fine soil fraction had a higher ratio of C/O functional group for all tillage than the aggregate fraction (Table 4.6). Regarding aromaticity, fine and aggregate fractions of soil under plowing had a higher range, followed by the fine fraction of soil under deep cultivation.

Table 4.6. Mean, and SD of the relative band area (RBA) (%) of different organic functional groups (compound) in two fractions of soil (0–10 cm) DRIFT spectra from three tillage operations in Józsefmajor. Different letters indicate significant differences at the p=0.05 level.

		Dc fine	DC Agg	Nt fine	Nt Agg	P fine	P Agg
Aliphatic C-H	SD	0.71	1.91	1.68	1.21	1.01	2.04
	RBA	16.05 [b]	22.95 [d]	20.18 [c]	30.71 [e]	13.29 [a]	17.50 [bc]
Amides	SD	0.20[a]	1.83[dc]	0.20[a]	0.50[bc]	0.45[ab]	0.53[d]
	RBA	5.10	7.33	5.00	6.27	5.28	7.57
Aromatic C	SD	0.93[c]	2.48[b]	1.15[b]	0.57[a]	1.28[d]	2.50[c]
	RBA	54.96	51.97	51.39	45.98	59.66	55.79
Polysaccharides	SD	0.24[ab]	0.77[c]	0.19[a]	0.46[b]	0.15[a]	0.58[c]
	RBA	7.31	8.86	6.83	7.69	6.82	9.09
Aliphatic C-H phenolic lignin	SD	0.25[b]	3.56[a]	0.81[b]	1.07[a]	0.88[b]	1.59[a]
	RBA	16.56	8.86	16.56	9.32	14.93	10.02
Aromaticity	SD	0.07[bc]	0.31[b]	0.08[ab]	0.03[a]	0.18[d]	0.33[cd]
	Mean	1.68	1.66	1.40	1.14	2.12	2.05
C/O ratio	SD	0.47[bc]	0.99[a]	0.40[c]	0.77[b]	0.34[c]	0.73[a]
	Mean	12.68	10.33	13.62	12.02	13.66	10.03

We used the ANOVA test and multiple comparisons of Tukey to find significant differences between this land use/management. The results show differences between all groups for aliphatic C-H and aromatic C, furthermore, it shows the difference between fine and aggregate fractions of soil samples under the same land use for Amid-N and aliphatic phenolic lignin and polysaccharide and different land uses showed no differences. For aromaticity, we can see differences between plowing (both aggregate and fine fraction) and no tillage and deep cultivation (both aggregate and fine fraction). C/O ratio also showed differences between no tillage (aggregate fraction) and deep cultivation and plowing (aggregate) and also between fine and aggregate fraction in each land use (Tables 4.6, appendix C Table C1 and C2).

The differences between two-soil size fractions (fine: Mineral associated OM or stable OM , aggregate: aggregates occluded OM or liable OM) are also compared disregarding land use/management (Table 4.7), however, we cannot see a specific trend for different SOM compositions. For example, aliphatic and C/O ratios showed higher value in aggregate fraction but aromatic C, aromaticity, and amide N showed higher range in the fine fraction.

Table 4.7. Mean, and SD of the relative band area (RBA) (%) of different organic functional groups (compound) in two fractions of soils of Józsefmajor based on all data (tree line + tillage operations (0–10 cm). Different letters indicate significant differences at the p=0.05 level.

		Fine	Aggregate
Aliphatic C-H	SD	6.69	9.78
	RBA	25.22 [a]	36.10 [b]
Amide N	SD	0.57	2.1
	RBA	4.46 [a]	4.13 [b]
Aromatic C	SD	7.42	11.19
	RBA	45.86 [a]	36.42 [b]
Polysaccharides	SD	0.64[a]	1.70[a]
	RBA	6.16	6.40
Phenolic lignin	SD	1.89[a]	5.77[a]
	RBA	18.27	17.09
Aromaticity	SD	0.47[b]	0.61[a]
	Mean	1.13	0.84
C/O ratio	SD	1.59[a]	4.00
	Mean	15.39	15.67

In summary, our findings in Józsefmajor demonstrate that alterations in soil aggregation induced by tillage practices could potentially regulate changes in soil organic matter (SOM) dynamics. The results indicate that the particle size of the soil primarily influences the molecular composition of SOM, with selective retention of components in both fine particle and aggregate fractions. Aliphatic-containing compounds are enriched in aggregate fractions, while aromatic compounds are prevalent in fine fractions due to their respective abilities to adsorb soil minerals (Chen *et al.*, 2023; Matus *et al.*, 2014; Steffens *et al.*, 2021).

4.2.2 Chemical composition of SOM in Szentendre Island bulk soil

Wave number ranges related to organic moieties revealed relevant variations among the land use/management types (Table 4.8). Aromatic C and aliphatic C-H had the highest ratio C groups in each land use/management system (same as Józsefmajor and Zselic area). Overall, arable land and organic farming had the highest and lowest aromatic C respectively, and organic horticulture and permaculture horticulture had the highest and lowest aliphatic C, which differ significantly. However, Aromatic C compounds, showed the significantly highest value under permaculture, followed by arable land and conventional. The significantly lowest value also was measured under organic farming (permaculture horticulture> arable land> conventional horticulture> organic horticulture). Additionally, for phenolic lignin, the significantly highest value was observed under permaculture horticulture, followed by forest, and the significantly lowest value was observed under conventional (permaculture horticulture >forest>arable land>organic horticulture >conventional horticulture). Higher polysaccharide values were observed under the forest, which differed significantly from the lower values, under organic farming (Table 4.8 and Fig 4.4) (forest> permaculture horticulture> arable land> conventional horticulture> organic horticulture). We also found the highest aromaticity under permaculture horticulture and arable land and the lowest values under organic farming (permaculture horticulture> arable land> conventional horticulture> forest> organic horticulture). Regarding the ratio of C/O, the highest values were observed under organic, which differed from the estimated lowest values under permaculture horticulture (organic horticulture> conventional horticulture> arable land> forest> permaculture horticulture).

Table 4.8. Mean, and SD of the relative band area (RBA) (%) of different organic functional groups (compound) in the uppermost soil layer (0–30 cm) DRIFT spectra from different land use/management (Szentendre Island 0-30cm).

		Arable land	Forest	Permaculture horticulture	Conventional horticulture	Organic horticulture
Aliphatic C-H	SD	6.68	9.41	2.97	2.65	1.61
	RBA (%)	46.39 [a]	47.91 [a]	43.38 [a]	51.84 [b]	52.19 [b]
Aromatic C	SD	3.62	6.11	2.006	1.50	1.19
	RBA (%)	32.38 [a]	29.01 [b]	32.96 [a]	30.58 [ab]	27.61 [b]
Polysaccharides	SD	0.95	2.07	0.45	0.49	0.33
	RBA (%)	3.24 [a]	4.14 [a]	4.084 [a]	2.93 [ab]	2.33 [b]
phenolic lignin	SD	2.62	4.88	1.29	1.07	1.40
	RBA (%)	17.99 [a]	18.93 [a]	19.57 [a]	14.65 [b]	17.86 [a]
Aromaticity	SD	0.09	0.12	0.052	0.03	0.02
	Mean	0.51 [a]	0.44 [ab]	0.52 [a]	0.46 [ab]	0.39 [b]
C/O	SD	9.40	13.72	2.66	5.25	6.49
	Mean	32.52 [a]	28.21 [a]	23.76 [a]	33.91 [ab]	42.83 [b]

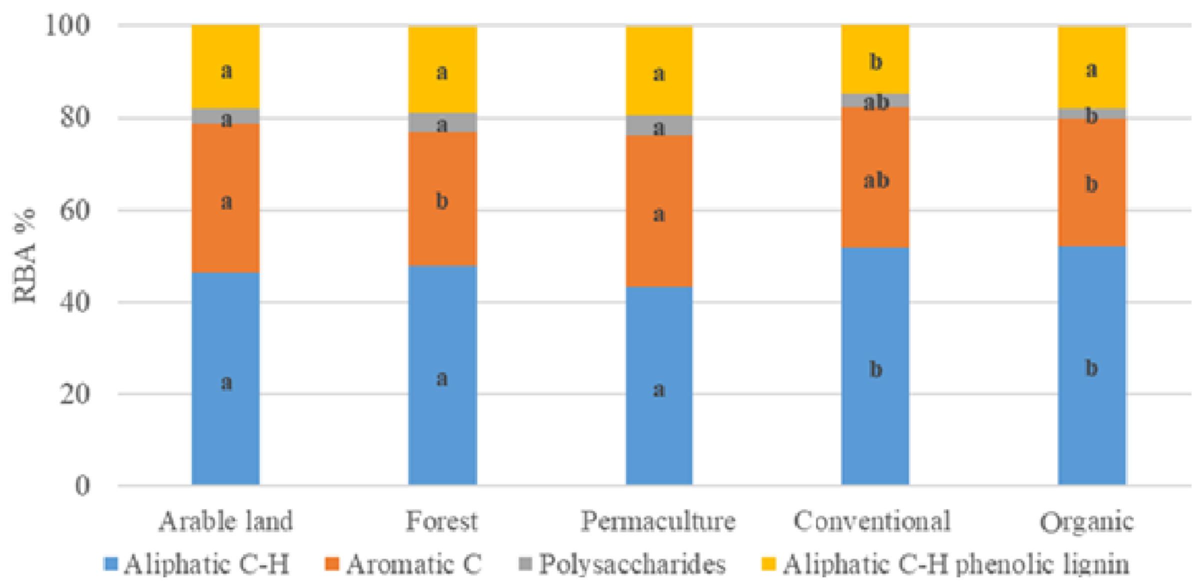


Figure 4.4. The bar graph compares the mean values of relative band area (RBA) of different organic functional groups (compound) of different land use/management in Szentendre Island

4.2.3 Chemical composition of SOM in Zselic area topsoil 0–30 cm (Magyarlukafa, Visnyeszéplak)

Wave number ranges related to organic moieties revealed relevant variations among the land use/management types (Table 4.9). Aromatic C and aliphatic C-H had the highest ratio C groups in each land-use management system (same as Józsefmajor and Szentendre Island). Overall, forest and arable land had the highest and lowest aromatic C ratio, and arable land and grassland had the highest and lowest aliphatic C-H (Fig 4.5). However, there was not any significant difference between different land uses for this component. Aromatic-C compounds, showed the significantly highest value under forest, followed by, grassland and orchard. The significantly lowest value was measured under the arable land (forest> grassland> orchard> arable land).

Additionally, for phenolic lignin, the significantly highest value was observed under the arable land, followed by orchard and grassland, and the lowest value was observed under forest (arable land> orchard> grassland> forest). Amide values were significantly higher under forest, followed by grassland and orchard, and lowered under arable land (forest> grassland> orchard> arable land). In addition, higher polysaccharide levels were observed under the forest, which differed significantly from the lower levels, observed under arable land. However, its level was significantly higher than grassland and orchard too (forest> grassland> orchard> arable land) (Table 4.9).

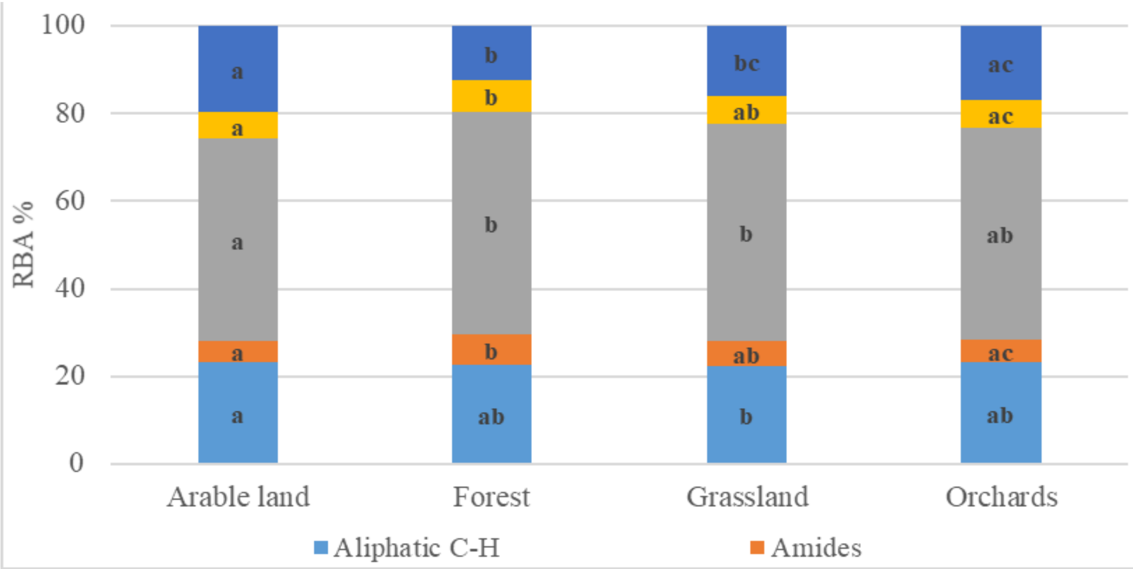


Figure 4.5. The bar graph compares the mean values of relative band area (RBA) of different organic functional groups (compound) of different land use/management in the Zselic area

Regarding the indices, aromaticity differences were observed between land use types. The average aromaticity values ranged from 1.1 to 1.51 in the soil samples from all land use/management systems. The highest value was observed under forest, followed by grassland, and orchards and the significantly lowest value was estimated under arable land (forest> grassland> orchard> arable land).

Table 4.9. Mean, and SD of the relative band area (RBA) (%) of different organic functional groups (compound) in the soil density (0–30 cm) DRIFT spectra for different land uses (Zselic area: Magyarlukafa, Visnyeszéplak).

		Arable land	Forest	Grassland	Orchards
Aliphatic C-H	SD	3.29	3.85	5.54	4.16
	mean	23.28^{a}	22.68^{a}	22.32^{a}	23.26^{a}
Amides	SD	1.41	1.68	1.78	2.02
	RBA (%)	4.73^{a}	6.85^{b}	5.91^{bc}	5.23^{ac}
Aromatic C	SD	4.21	4.53	8.22	5.65
	RBA (%)	46.27^{a}	50.86^{b}	49.29^{ab}	48.35^{ab}
Polysaccharides	SD	0.73	0.66	1.00	1.00
	RBA (%)	5.98^{a}	7.18^{b}	6.45^{ab}	6.18^{a}
Phenolic lignin	SD	4.56	4.34	5.65	4.71
	RBA (%)	19.73^{b}	12.41^{a}	16.08^{ac}	16.96^{bc}
Aromaticity	SD	0.25	0.40	0.55	0.42
	Mean	1.10^{a}	1.51^{b}	1.42^{ab}	1.28^{ab}
C/O	SD	2.38	1.44	2.81	3.44
	Mean	16.00^{b}	13.04^{a}	14.91^{ab}	15.72^{b}

4.2.4 Comparison of SOM chemical composition across different land uses in the study areas

The DRIFT spectra results revealed relevant concentrations of aromatic C and aliphatic C-H in soil samples across various land use/management types.

Our findings indicate that in cultivated lands (such as permaculture horticulture and arable land in Szentendre Island, and across six different tillage operations in Józsefmajor), the presence of aromatic C is significantly higher compared to other land uses. These results are consistence with Gonzales-Perez *et al*. (2007) who also reported less percentage of aromatic carbon in uncultivated areas and grassland compared with arable land and cultivation lands (González-Pérez *et al.*, 2007). In another study it also observed that aromatic C groups were higher in the SOMs of the three cultivated lands than in native grasslands (Yao *et al.*, 2019).

However, the situation is different in the Zselic area, where a higher aromatic C ratio is observed in forests. A higher aromatic C ratio in the forest area might be due to the relative accumulation or the higher incidence of forest fires (which is not the case in Hungary) however, other factors like climate, topography, soil properties, and vegetation type can affect the concentration of soil organic matter composition. Additionally, in Józsefmajor and between different tillage systems, we noted higher aromatic C under conventional tillage compared to conservation tillage. Schnitzer *et al.* (2006) similarly reported an increase in aromatic C with higher cultivation intensity. Nevertheless, Man *et al.* (2021) reported higher aromatic content under conservation tillage compared to conventional tillage in their study (Man *et al.*, 2021). They suggested that conservation tillage might preserve lignin in the soil, as aromatic carbon can be derived from lignin. However, it's essential to note that aromatic C can also originate from proteins (such as toluene), tannins, and other polyphenols, including charcoal (Vancampenhout *et al.*, 2009). This implies that crop rotation in the study area might influence the results and lead to these different outcomes.

Regarding aliphatic C-H, it is more concentrated in natural ecosystems (such as the tree line in Józsefmajor and organic farming in Szentendre Island) compared to more intensive land management (e.g. all tillage operations in Józsefmajor and arable land in Szentendre Island). Moreover, as we examine the connection between tillage operations and the aliphatic component, it appears that the latter likely decreases with increasing management intensity. This finding is supported by Thai *et al.* (2021), who found that the soils under the forest have more intense aliphatic bands compared to cropland soils (Thai *et al.*, 2021). Schnitzer *et al.* (2006) also reported a decrease in aliphatic C-H in SOM with increased cultivation. These results are attributed to aliphatic predominance in biodegradation and aromatics' high biodegradation resistance (Schnitzer *et al.*, 2006). However, in our other study areas (such as the Zselic area), arable land and orchards showed higher aliphatic C-H than the grassland and forest sites. Similarly, in Szentendre Island, conventional farming exhibited high values for aliphatic C-H. Aliphatic originates from plant waxes and suberin found in tree roots and bark (Kögel-Knabner *et al.*, 1992; Augris *et al.*, 1998; Lorenz *et al.*, 2007). In forests, tree branches and bark contribute significantly, making up to 40% of the material above the ground because litter doesn't integrate much into the soil due to bioturbation, root material plays a substantial role (Van Bergen *et al.*, 1998; Vancampenhout *et al.*, 2009).

Changes in the SOM, such as decomposition and mineralization, involve alterations in functional group chemistry. For instance, the relative increase in aromatic to aliphatic groups during decomposition (Hsu and Lo, 1999). In our case studies, particularly in more natural ecosystems like the tree line in Józsefmajor, SOM decomposition seems to be in an early stage, because of the higher proportion of aliphatic C-H compounds to aromatic C observed in forest, tree line, and other natural land use/management (except in the Zselic area). This could be the consequence of the much higher OC input than the reduced decomposition due to the lack of cultivation and soil turnover. Furthermore, the ratio of aromatics is assumed to increase as the degree of SOM humification increases (Mahieu *et al*., 1999), for example, by the aromatization of simple sugars or lipids (González Pérez *et al.*, 2004; Certini *et al.*, 2011). Land-use effects were particularly pronounced for the amides and polysaccharides in Józsefmajor, and also in the Zselic area. Significantly higher amide N ratios in the tree line and conservation tillage (NT and D) in Józsefmajor, and forest in the Zselic area compared to more intensified tillage systems and agriculture may probably be the result of a slower turnover of the tree line and forest's leave litter (and also conservation farm cover residue) (Gill and Jackson, 2000). Also, significantly lower polysaccharide concentrations were observed in the soil of tree line compared to in the soil of arable land in Józsefmajor. However, in two other study areas, we observed different results, as forests in both provide results with the highest polysaccharide and lowest values in organic farming (in Szentendre Island) and arable land (in Zselic area) respectively. In earlier studies, (Martens *et al*., 2004; Baumann *et al.*, 2016) reported a higher content of polysaccharides in a natural ecosystem (grassland) compared to forest soils. The results of the two indices, i.e., aromaticity and ratio of C-containing to O-containing functional groups, are consistent with the concept of a relatively more advanced stage of decomposition of SOM in the cropland. The calculated aromaticity in Józsefmajor was much greater in the cropped land (27%) than in the tree line soil samples (15%). Also, in Szentendre Island, arable land, permaculture horticulture, and conventional horticulture showed higher aromaticity compared to other land management. However, the Zselic area, shows different results and arable land presents the lowest aromaticity compared to others (it suggests that other factors might affect SOM decomposing in this hilly slope landscape).

Aromaticity is estimated to be higher in microbial more processed OM (Helfrich *et al.*, 2006). Baldock *et al*. (1997) also proposed aromaticity as a decomposition index; however, they indicated that the index's utility is limited to a soil profile or a set of organic materials derived from the same parent material (Jagadamma, 2009). We suggest that afforestation might increase the SOM compound concentration (SOMcc) and even the aliphatic compounds due to both higher OM input and lower decomposition even in the investigated period. This causes a high content of easily available carbohydrates in the organic matter inputs (Helfrich *et al.*, 2006). Gregorich *et al*. (1996) analyzed the transformation of plant residues into SOM in a maize field and a nearby mixed hardwood forest. They also found higher aromaticity of the SOM in the arable soil (31%) compared to the forest soil (23%). The highest ratio of the C to O functional group appears in the tree line (Józsefmajor) and Organic farm (Szentendre Island). It also shows less variation between different tillage operations in Józsefmajor. These results are consistent with Yeasmin *et al*. (2020) who reported the ratio of C/O group depletion after cropping (Yeasmin *et al.*, 2020). However, in two other study areas, permaculture horticulture and forest also showed the lowest value for the C/O ratio.

As the final result, we've observed that soil disturbance affects the dynamics of SOM as also reported in prevoues study (Paustian *et al.*, 1999). Nevertheless, Puget and Lal (2005) found that soil organic matter became more intricate under no-tillage and simpler under plowing in the surface soil of a Mollisol due to decreased tillage intensity (Puget and Lal, 2005).

In conclusion, the interaction between tillage methods and soil fractions can have intricate impacts on SOM composition. These factors play a significant role in the influence of fresh organic matter and the stability of SOM compounds, ultimately shaping the composition and alterations in soil organic matter in various agricultural settings and land use/management practices. Furthermore, in addition to the well-known benefits of conservation agriculture, such as reducing greenhouse gas emissions, preventing soil erosion, and boosting crop yields (as noted by (Lal *et al*., 2018). Our study reveals that employing long-term conservation tillage is more effective in preserving soil organic matter compared to traditional tillage methods.

It should be noted that, the composition of soil organic matter is affected by different factors such as the type of plant litter and land use/management, soil organisms, and the degree of degradation and preservation of these primary and secondary sources of soil organic matter (Helfrich *et al.*, 2006).

4.3. Connection between SOM concentration and composition

We observed a significant positive correlation (r=0.95, p< 0.0ii5) between Aliphatic C-H (RBA) and SOMin Józsefmajor (Table 4.10). The correlation analysis conducted in Józsefmajor also indicated that the increase in SOM was more favorable for reducing aromatic C RBA in the soil. Zheng *et al*. (2021) and Lei *et al*. (2023) also reported a significant negative correlation (P<0.01) between the total SOC content and aromatic C (Zheng *et al.*, 2021; Lei *et al.*, 2023). In another study, Margenot *et al*., 2015, also confirmed that SOC had positive and strongest correlations with aliphatic C-H ratio and negative correlations with other functional groups such as aromatic C (Margenot *et al.*, 2015).

The aromatic-C groups are primarily considered recalcitrant carbon components, signifying the stabilization of SOM (Lei *et al.,* 2023). Thus aliphatic C-H bands mark the presence of labile C and were considered to be more readily accessible and actively used by microorganisms compared to aromatic-C (Calderón *et al.*, 2011). The correlation analysis also aligned with soils having lower SOC levels, indicated by higher relative amounts of aromatic-C and lower levels of aliphatic C-H. This suggests that soils with lower SOC levels might have been less favored for SOM decomposition than soils with higher SOC. This also suggests that soils tended to become more resistant, marked by increased levels of aromatic-C and a higher degree of humification during the decomposition of SOM. These findings are consistent with those of Lei *et al*. (2023). Previous research has indicated that the observed increase in aliphatic functional groups compared to aromatic functional groups as SOC levels rise may be attributed to several mechanisms. Aliphatic enrichment has been noted during the decomposition of organic residues (Hsu and Lo, 1999; Baddi *et al.*, 2004). It is considered a measure of the biological quality of SOM (Veum *et al.*, 2014) and is linked to higher levels of labile and total soil carbon (Gerzabek *et al.*, 2006; Demyan *et al.*, 2012). It was also identified as a substance that could bind between macro aggregates. This role was crucial in the stabilization of SOC within aggregates, particularly for the long-term storage of carbon (Tivet *et al.*, 2013; Lei *et al.*, 2023). This phenomenon has been suggested to result from increased inputs of aliphatic-rich organic matter, such as plant residues from cover crops, and the deposition of aliphatic compounds due to increased microbial biomass (Aranda *et al.*, 2011).

The inverse relationship between the degree of soil organic matter decomposition (aromaticity) and soil organic matter in Józsefmajor (r=-0.9, p<0.05) might suggest the accumulation of less decomposed organic matter when soil organic C is higher, previous studies also confirmed this fact (Six *et al.*, 2002; Margenot *et al.*, 2015).

The C/O ratio also exhibited a strong positive relationship with increasing soil organic matter ($r=0.8$, $p<0.5$) in Józsefmajor, possibly due to definitions of decomposition and recalcitrance focused on chemistry (Schmidt *et al.*, 2011) or bulk SOM characterization (Margenot et al., 2015). It indicates that an increase in the C/O ratio is thought to be associated with greater recalcitrance of SOM and decomposition as the ratio of aromatic to aliphatic functional groups. When observing the variations in SOC content among the different groups, the most significant distinction was the tendency towards the accumulation of aromatic structures in soils having relatively lower SOC content. This tendency is often linked to the recalcitrance of SOM (Higher C/O ratio) since the aromaticity of SOM frequently serves as an indicator of its chemical stability and ability to resist degradation (Tinoco *et al.*, 2015).

Amid N and polysaccharides also showed significant negative relationships with SOM content in Józsefmajor (Table 4.10). Prior studies have reported that amides and polysaccharides can be influenced by factors beyond SOM content, such as geographic location (Baumann *et al.*, 2016) and soil nitrogen (Sinsabaugh *et al.*, 2004). According to Laudicina *et al*. (2015), the number of amide groups increases as aggregate size decreases (Laudicina *et al.*, 2015). Sinsabaugh *et al*. (2005) also proposed that nitrogen availability plays a fundamental role in polysaccharide composition. However, in the Zselic area and Szentendre and Szentendre Island, neither aliphatic components of the OM nor other functional groups showed strong correlations with SOM across fields. The correlation coefficients were relatively weak (e.g. $r=-0.35$, $pp=0.024$ in the Zselic area and $r=-0.25$, $p= 0.08$ in Szentendre Island for aliphatic C-H). One possible explanation for these different relationships between study areas is that SOM concentration is significantly lower in Szentendre Island (mean=2.23%) and Zselic area (mean= 2.48%) compared to Józsefmajor (mean=6.22%). As we mentioned before SOM decomposition rate is less when SOM is lower, so consequently it can affect the SOM dynamic and its composition. Finally, soil organic carbon content is significantly influenced by the soil-forming factors, possibly due to their impact on the chemical composition of SOM. The results suggest that soils with notably higher carbon contents also possess SOM with distinctly varied molecular compositions. It is irrespective of whether these molecular differences cause or result from its stability or resistance to decomposition.

Table 4.10. Linear correlation (Pearson) model of the SOM concentration versus composition in 3 study areas (Józsefmajor, Szentendre Island, Zselic area)

			Aliphatic C-H	Aromatic C	Amides	Polysaccharides	Phenolic lignin	Aromaticity	Ratio C/O
SOM concentration	Józsefmajor	Correlation Coefficient	0.95	-0.94	-0.7	-0.82	0.07	-0.9	0.8
		P-Value	0.00	0.00	0.49	0.000	0.00	0.00	0.00
	Szentendre Island	Correlation Coefficient	-0.25	0.06	-	0.22	0.28	0.10	-0.20
		P-Value	0.08	0.67	-	0.13	0.055	0.49	0.17
	Zselic area	Correlation Coefficient	0.35	-0.2	0.07	0.075	-0.05	-0.13	-0.05
		P-Value	0.02	0.14	0.62	0.65	0.75	0.39	0.75

This particular aspect is significant because soils with high SOM do not necessarily guarantee that the SOC is more stable or resistant to decomposition (Jiménez-González *et al.*, 2020), which is evident in the composition exhibited in the Józsefmajor.

To get more accurate insight into SOM composition differences between different land uses, we compared the same land uses in different case studies (for example tree line in Józsefmajor, forests in Szentendre, and forest in Zselic-Magyarlukafa and Zselic-Visnyeszéplak), based on the normality of data, we applied ANOVA test (just aliphatic C-H in the forests and tree line), also in cases the data did not show normal distribution, the Kruskal-Wallis test was applied (table 4.11 and 4.12).

Comparing forest and tree lines in our four case studies shows that the aliphatic components of the SOM are significantly lower in the Zselic forested area; whereas Szentendre Island forests showed the highest value compared to other study areas (Szentendre Island> Józsefmajor> Zselic-Visnyeszéplak> Magyarlukafa). We could see the same order for phenolic lignin accordingly. The ratio of aromatic C also showed a significantly highest value in Zselic-Magyarlukafa and Zselic-Visnyeszéplak and the lowest value was observed in Szentendre Island (Zselic-Visnyeszéplak> Zselic-Magyarlukafa> Józsefmajor> Szentendre Island). For

Polysaccharide, we could observe the lower values in Szentendre Island and Józsefmajor, which were different from the observed higher values in Zselic-Magyarlukafa and Zselic-Visnyeszéplak (Zselic-Magyarlukafa> Zselic-Visnyeszéplak> Józsefma-jor> Szentendre Island). However, aromaticity showed a significantly higher value in Zselic-Magyarlukafa and Zselic-Visnyeszéplak compared to two other areas of Szentendre Island and Józsefmajor. The C/O ratio however showed a higher value in Józsefmajor and Szentendre Island compared to two other study areas of Zselic-Magyarlukafa and Zselic-Visnyeszéplak (Table 14).

Table 4.11. Comparison SOM composition under forest and tree line (natural ecosystems) in the study areas (Józsefmajor, Szentendre, Zselic-Magyarlukafa, Zselic-Visnyeszéplak). Different letters next to the means indicate significant ($p<0.05$) differences among the study sites.

		Józsefmajor	**Szentendre**	**Magyarlukafa**	**Visnyeszéplak**
Aliphatic C-H	SD	3.40	4.92	4.50	2.32
	RBA	35.73[b]	46.73[a]	24.49[c]	20.87[c]
Amides	SD	0.20	-	1.04	1.73
	RBA	2.15[b]	-	7.188[a]	6.51[a]
Aromatic C	SD	2.35	4.13	5.31	3.27
	RBA	32.86[b]	29.75[b]	49.24[a]	52.47[a]
Polysaccharides	SD	0.24	1.95	0.48	0.79
	RBA	5.80[b]	4.22[b]	7.19[a]	7.17[a]
Phenolic lignin	SD	1.71	3.81	4.95	4.12
	RBA	23.44[a]	19.28[b]	11.87[b]	12.96[b]
Aromaticity	SD	0.063	0.099	0.47	0.34
	Mean	0.56[b]	0.46[b]	1.42[a]	1.59[a]
C/O	SD	0.72	13.68	0.88	1.81
	Mean	16.26[ac]	28.11[a]	12.94[b]	13.10[cb]

When we compare arable land in our study areas (table 4.12), we could see fewer differences between Józsefmajor, Magyarlukafa, and Zselic-Visnyeszéplak for all soil organic matter compositions except for the amide N ratio, however, Szentendre Island showed a significantly lower value for all compounds except aliphatic C-H and C/O ratio compare other study areas. Based on these observations we can conclude land use can be effective on soil organic matter (SOM) composition but as it is clear there might be other factors that can affect soil organic matter composition and derive different compounds in different areas.

Here we consider environmental covariates and test different environmental factors (such as climatic and topographic covariates) and soil properties.

Table 4.12. Comparison SOM composition under arable lands in the study areas (Józsefmajor, Szentendre, Magyarlukafa, Zselic-Visnyeszéplak). Different letters next to the means indicate significant (p<0.05) differences among the study sites.

		Józsefmajor	Szentendre	Magyarlukafa	Visnyeszéplak
Aliphatic C-H	SD	3.23	5.97	2.14	2.62
	RBA(%)	21.01[b]	48.67[a]	21.02[bc]	25.42[ba]
Amides	SD	0.35		1.30	1.80
	RBA(%)	2.86[a]		4.67[b]	5.12[b]
Aromatic C	SD	2.81	3.43	3.85	4.58
	RBA(%)	46.87[a]	31.04[b]	47.53[a]	45.31[a]
Polysaccharides	SD	0.33	0.84	0.62	1.02
	RBA(%)	6.70[a]	2.98[b]	6.12[a]	6.03[a]
Phenolic lignin	SD	1.39	2.47	4.32	4.81
	RBA(%)	22.54[a]	17.28[b]	20.64[ab]	18.11[ab]
Aromaticity	SD	0.13	0.08	0.26	0.24
	Mean	1.08[a]	0.47[b]	1.17[a]	1.07[a]
C/O	SD	0.70	8.68	1.54	3.35
	Mean	13.95[b]	34.73[a]	15.46[b]	16.03[b]

4.4 Correlation between the chemical composition of the SOM and environmental covariates

Here we evaluated the contribution of the environmental variables (topographic and climatic covariates) and soil properties to soil organic matter composition. For this purpose, after analyzing the scatter plot of SOM composition for each factor, we decided to focus on variables that mostly show a trend with each organic carbon component. Table 4.13 provides correlations (r) and corresponding p-values (p) between different soil organic matter compositions and various environmental covariates..

The first row represents different soil organic matter compositions, while the first column shows the environmental covariates being examined

Table 4.13. Pearson correlation coefficient between SOM compound and environmental covariates in the study areas (Józsefmajor, Szentendre, Magyarlukafa, Zselic-Visnyeszéplak)

Covariates	Aliphatic		Aromatic		Amide-N		Phenolic lignin		Polysaccharide		Aromaticity		C/O Ratio	
	r	p	r	p	r	p	r	p	r	p	r	p	r	p
Altitude	-0.74	0.001	0.80	0.0003	0.66	0.02	0.50	0.04	0.70	0.001	0.80	0.0003	-0.70	0.006
Slope	-0,72	0.002	0.75	0.001	0.68	0.02	-0.30	0.1	0.60	0.01	0.75	0.001	-0.60	0.02
Topographic position index	-0.20	0.40	0.30	0.2	0.60	0.04	-0.54	0.03	0.30	0.20	0.47	0.07	-0.40	0.10
Topographic roughness index	-0.69	0.004	0.76	0.0009	0.80	0.002	-0.50	0.03	0.64	0.009	0.78	0.0005	-0.60	0.01
Surface area	0.60	0.01	-0.64	0.009	-0.58	0.05	0.34	0.20	-0.54	0.03	-0.65	0.008	0.60	0.02
MRVBF	0.73	0.001	-0.80	0.0003	-0.78	0.004	0.50	0.054	-0.60	0.01	-0.80	0.0003	0.60	0.02
MRRTF	0.40	0.09	-0.55	0.03	-0.76	0.006	0.51	0.04	-0.33	0.20	-0.59	0.01	0.47	0.07
LS factor	-0.67	0.005	0.63	0.01	0.32	0.30	-0.10	0.50	0.53		0.55	0.03	-0.40	0.09
Topographic wetness index	0.67	0.005	-0.65	0.008	-0.20	0.40	0.20	0.40	-0.70	0.003	-0.58	0.02	0.53	0.04
MAP	-0.75	0.001	0.84	0.0001	0.80	0.002	-0.50	0.02	0.60	0.004	0.84	0.0001	-0.50	0.02
MAT	0.80	0.00	-0.80	0.00	0.32	0.20	0.32	0.20	-0.79	0.0004	-0.80	0.0001	0.73	0.006
Mean annual evapotranspiration	0.88	0.00	-0.60	0.01	0.30	0.20	0.30	0.20		0.0006	-0.80	0.0001	0.75	0.004
Mean annual evaporation	-0.88	0.00	0.90	0	0.75	0.007	-0.40	0.10	0.80	0.0002	0.87	0.00	-0.60	0.009

DEM: digital elevation model, LS factor: slope length-gradient factor, MRVBF: multiresolution valley bottom flatness, MRRTF: multiresolution ridge top flatness, MAP: Mean annual precipitation, MAT: Mean annual temperature
*Red cells show a significant correlation (p<0.05)

In addition, the correlation maps between different factors are exhibited 4.6.

-1 1

	Aliphatic C	Aromatic C=	Polysaccharide	Aliphatic Phenolic Lignin	Amide-N	Altitude	Evaporation	Evapotranspiration	LS factor	MRRTF	MRVBF	Precipitation
Aliphatic C		-0.95	-0.92	0.22	-0.61	-0.75	-0.89	0.88	-0.67	0.44	0.73	-0.76
Aromatic C=	-0.95		0.92	-0.5	0.85	0.81	0.9	-0.86	0.64	-0.56	-0.8	0.85
Polysaccharide	-0.92	0.92		-0.39	0.76	0.75	0.81	-0.78	0.54	-0.33	-0.62	0.69
Aliphatic Phenolic Lignin	0.22	-0.5	-0.39		-0.95	-0.53	-0.41	0.3	-0.16	0.52	0.51	-0.58
Amide-N	-0.61	0.85	0.76	-0.95		0.67	0.75	-0.78	0.33	-0.76	-0.79	0.81
Altitude	-0.75	0.81	0.75	-0.53	0.67							
Evaporation	-0.89	0.9	0.81	-0.41	0.75							
Evapotranspiration	0.88	-0.86	-0.78	0.3	-0.78							
LS factor	-0.67	0.64	0.54	-0.16	0.33							
MRRTF	0.44	-0.56	-0.33	0.52	-0.76							
MRVBF	0.73	-0.8	-0.62	0.51	-0.79							
Precipitation	-0.76	0.85	0.69	-0.58	0.81							

-1 1

	Aliphatic C	Aromatic C=	Polysaccharide	Aliphatic Phenolic Lignin	Amide-N	Slope	Surface Area	Temperature	TPI	TRI	TWI
Aliphatic C		-0.95	-0.92	0.22	-0.61	-0.73	0.62	0.88	-0.21	-0.69	0.68
Aromatic C=	-0.95		0.92	-0.5	0.85	0.76	-0.64	-0.86	0.34	0.76	-0.65
Polysaccharide	-0.92	0.92		-0.39	0.76	0.64	-0.54	-0.8	0.31	0.65	-0.7
Aliphatic Phenolic Lignin	0.22	-0.5	-0.39		-0.95	-0.4	0.34	0.32	-0.55	-0.54	0.21
Amide-N	-0.61	0.85	0.76	-0.95		0.68	-0.59	-0.76	0.61	0.81	-0.23
Slope	-0.73	0.76	0.64	-0.4	0.68						
Surface Area	0.62	-0.64	-0.54	0.34	-0.59						
Temperature	0.88	-0.86	-0.8	0.32	-0.76						
TPI	-0.21	0.34	0.31	-0.55	0.61						
TRI	-0.69	0.76	0.65	-0.54	0.81						
TWI	0.68	-0.65	-0.7	0.21	-0.23						

Figure 4.6. Pearson correlation maps of SOM composition and environmental covariates

Taking into account the information presented in Table 4.13 and Figure 4.6, we can present the correlation for each organic component as follows. (As we have included individual samples, and when it comes to the environmental covariate, samples with identical values have led to an unusual data distribution, employing graphical linkage through x-y plots would be useful for illustrating this phenomenon (appendix D figure D1).

- **Aliphatic-C compounds and environmental covariates**

Surface area, MRVBF, TWI, MAT, and Mean annual evapotranspiration demonstrate a positive correlation with aliphatic compounds, implying their potential role in increasing the presence of these compounds within the soil. This does not imply that these factors directly cause higher aliphatic compound content, but the correlation suggests that areas with higher values for these covariates may tend to also have higher aliphatic compound levels. For instance, temperature and evapotranspiration may reflect conditions conducive to SOM stabilization in these forms, but further experimental validation would be necessary to establish causality.

Conversely, negative correlations were observed with altitude, slope, mean annual evaporation, and precipitation (MAP), implying these factors tend to occur in conjunction with lower levels of aliphatic compounds. Again, this relationship should not be interpreted as these factors constraining aliphatic compound formation, but rather that higher elevations or precipitation may be associated with conditions that favor different SOM composition

- **Aromatic-C and environmental covariates**

Aromatic compounds showed positive correlations with altitude, slope, MAP, and evaporation, potentially indicating that these factors are associated with environments where aromatic SOM components are more prevalent.

On the other hand, MRVBF and MAT exhibited negative correlations, which could suggest that conditions of higher temperature or flatter landscapes might coincide with lower aromatic levels, In contrast, surface area, TWI, and mean annual evapotranspiration showed milder relation to the abundance of these compounds.

- **Amide-N and environmental covariates**

Amide-N showed strong positive correlations with TRI, MAP, and mean evaporation, indicating these factors might promote the presence of nitrogen in the form of amides within the soil. Conversely, altitude, slope, and TPI exhibited weaker positive correlations. Factors like MRVBF and MRRTF, however, were negatively correlated with Amide-N.

- **Phenolic Lignin and environmental covariates**

Phenolic lignin had very weak correlations with environmental covariates, with a slight positive association with altitude and MRVBF, and a minor negative correlation with TPI, TRI, and precipitation. This suggests that environmental factors may not have a significant effect on phenolic lignin levels in the soil.

- **Polysaccharide and environmental covariates**

Altitude and mean annual evaporation had strong positive correlations with polysaccharides, highlighting their role in enhancing the presence of these compounds. However, other factors like slope, TRI, LS factor, and precipitation showed weaker correlations. Negative correlations were observed with TWI, temperature, and evapotranspiration, indicating these factors might limit polysaccharide levels. Regarding the polysaccharides, a clear influence of climate can be seen. Samples taken in colder climate regions show a high abundance of relatively less-decomposed cellulose- and other plant-material-derived sugars (Vancampenhout *et al.*, 2009).

- **Aromaticity and environmental covariates**

Factors like altitude, slope, TRI, MAP, and mean annual evaporation were positively correlated with aromaticity, implying they play a significant role in increasing the presence of aromatic compounds. On the other hand, MRVBF, precipitation, and evapotranspiration showed strong negative correlations, suggesting higher values for these variables could reduce aromaticity.

- **C/O Ratio and environmental covariates**

Mean annual temperature and evapotranspiration were positively correlated with the C/O ratio, suggesting they could influence the ratio of carbon to oxygen in the soil. Altitude showed a moderately strong negative correlation, and slope, TRI, and evaporation also had weaker negative correlations, implying a milder effect on the C/O ratio.

The comparison of results indicates that environmental variables, particularly climate-related factors and topographical features like slope and elevation, show the strongest and most consistent correlations with the composition of soil organic matter. This is particularly evident in specific molecular components such as aliphatic C-H, aromatic carbon, and polysaccharides. Several studies have already confirmed the significant influence of climatic factors especially MAT and MAP on SOM composition, both at regional and global scales (Amelung *et al*., 1997; Melillo *et al.*, 2011; Jiménez-González *et al.*, 2020; Lei *et al.*, 2023). Szatmári *et al*. (2023)

have proven the role of mean annual temperature and evapotranspiration on potential SOC saturation in Hungary (Szatmári *et al.*, 2023).

In our research, we discovered a negative correlation between Mean Annual Temperature (MAT) and aromatic C ($r = -0.8$, $p = 0$), polysaccharides ($r = -0.74$, $p < 0.005$), and the decomposition index of aromaticity ($r = -0.8$, $p < 0.005$). This association could be attributed to lower temperatures restraining soil respiration (Wang *et al.*, 2016). Additionally, Jiménez-González *et al*. (2020) found that in warmer climatic conditions, there's a reduced tendency for the accumulation of aromatic and polycyclic aromatic hydrocarbons in SOM, potentially due to increased occurrences of wildfires (Jiménez-González *et al.*, 2020).

Melillo *et al.* (2002) also reported rising temperatures increase both plant productivity and the decomposition rate of plant residues, which leads to more carbon inputs into the soil. However, higher temperatures also stimulate microbial activity and soil respiration, which in turn accelerates SOM decomposition (Wang *et al.*, 2017).

In a different investigation, Feng *et al.* (2021) highlighted that regions with higher temperatures tended to have lower SOC. This was attributed to the acceleration of soil microbial activities and SOC mineralization in warmer conditions. However, our study revealed a contrasting result where MAT and aromaticity, considered as decomposition indicators, showed a negative relationship.

Our research also revealed strong positive correlations between precipitation and several components, including the ratios of aromatic carbon ($r = 0.86$, $p < 0.005$), polysaccharides ($r = 0.6$, $p < 0.005$), amide nitrogen ($r = 0.8$, $p < 0.005$), and aromaticity ($r = 0.84$, $p < 0.005$). In contrast, we found negative correlations for the aliphatic C-H ratio ($r = -0.76$, $p < 0.005$) and aliphatic phenolic lignin ($r = -0.5$, $p < 0.005$). Previous study suggested that decomposition processes are faster in moist environments compared to dry ones, which could explain why polysaccharides and aromatics might diminish rather than accumulate in areas with higher precipitation (Amelung *et al*., 1997).

However, diverse findings have been presented in several studies. For instance, according to Lal (2004 b), increased precipitation or the existence of surface water might hinder the soil decomposition processes of SOM and result in the accumulation of SOM stock. In contrast, Lei *et al*. (2023) suggested that MAP could accelerate SOM decomposition by activating soil microbial processes (Lei *et al.*, 2023). Precipitation affects soil moisture levels, which in turn regulate the decomposition of SOM. In areas with insufficient precipitation, low soil moisture and elevated salinity can reduce plant productivity, ultimately limiting SOM accumulation (Osland *et al.*, 2018). Additionally, low soil moisture increases soil aeration, thereby enhancing aerobic microbial activity and carbon decomposition (Thomas *et al.*, 2020). Consequently, precipitation often displays a positive correlation with soil organic matter concentration (Wang *et al.*, 2017; Wu *et al.*, 2022). Some studies present different findings regarding aromaticity. For example, Arshad and Schnitzer (1989) proposed a potential negative correlation between the aromaticity of humic acids in Kenyan soils and mean annual precipitation (Arshad and Schnitzer, 1989). Similarly, Zech *et al*. (1989) reported a decline in SOM aromaticity in various forest subsoils as the precipitation-to-temperature ratio increased (Zech *et al*., 1989).

We observed a negative correlation between the C/O ratio and MAP ($r= -0.5$, $p < 0.005$) and a positive correlation with MAT ($r= 0.73$, $p < 0.005$). This correlation can potentially explain the higher microbial activity in areas with higher temperatures and lower precipitation, which is consistent with previous studies (Melillo *et al.*, 2011; Wu *et al.*, 2022; Lei *et al.*, 2023). Moreover, our findings revealed a positive correlation between MAP and polysaccharide content ($C= 0.6$, $p<0.005$) and a negative correlation with MAT. These results align with the research of Amelung *et al*. (1997), who also observed an increase in polysaccharide content with rising precipitation. Adequate moisture promotes the production of polysaccharides by both plants and microbes, aiding in their stabilization.

Topographical factors, such as elevation, slope, and related characteristics, also significantly influence SOM composition. The influence of topographical factors on soil organic matter relies on land use (because vegetation cover moderates the effects of soil erosion and deposition on slopes) Zhu *et al.* (2014). They also can affect soil organic matter content and composition indirectly for example when elevation increases, temperature generally decreases, influencing microbial activity and decomposition rates (Sowerby *et al.*, 2005). Higher elevations and slopes may experience greater precipitation, affecting leaching and nutrient cycling, and erosion which lead to an effect on soil organic carbon content and composition, especially topsoil (Cheng *et al*., 2010; Jakab *et al*., 2016; Wu *et al*., 2022). In regions with steep slopes, erosion may lead to the removal of topsoil, while deeper soil minerals are incorporated into the surface layer through agricultural tillage practices (Berhe and Kleber, 2013). The subsoil generally contains lower levels of SOC, and the interaction between subsoil minerals and topsoil organic matter can form mineral-organic associations that reduce OM decomposition (Ellerbrock *et al*., 2016). This might be the reason that arable land in the Zselic area showed lower aromaticity and so lower decomposition compared to other land use, which was contrary to two other study areas. These arable lands are located in eroded crop fields. Zselic area has a steeper slope (S= 4.92%) and higher altitude (E=196 m) compared to Józsefmajor (S= 0.91%, E=102.82 m) and Szentendre Island (S=0.73%, E=102.82 m). Consequently, this hillslope landscape is affected by higher precipitation which according to some previous studies can increase SOM decomposition (Osland *et al.*, 2018; Chen and Yu, 2021; Lei *et al.*, 2023).

4.5 Correlation between the chemical composition of the SOM and the soil properties

Here we evaluated the contribution of the soil properties to soil organic matter compound. For this purpose, after analyzing the scatter plot of SOM composition for each factor, we applied the Pearson correlation between variables. The results are presented in Table 4.14. This table shows Pearson product-moment correlations between each pair of variables. The table provides correlations (r) and corresponding p-values (p) between different soil organic matter compositions and various soil properties.

The first row represents different soil organic matter compositions, while the first column shows the soil properties being examined.

Table 4.14. Pearson correlation coefficient between SOM compound and soil properties in study areas (Józsefmajor, Szentendre, Magyarlukafa, Zselic-Visnyeszéplak)

Soil properties (content)	Aliphatic C-H		Aromatic		Amide-N		Phenolic lignin		Polysaccharide		Aromaticity		C/O Ratio	
	r	p	r	p	r	p	r	p	r	p	r	p	r	p
pH	0.60	0.002	-0.40	0.04	0.40	0.60	-0.30	0.08	-0.70	0.0001	-0.30	0.90	0.60	0.0002
$CaCO_3$	0.80	0.00	-0.60	0.001	0.30	0.10	-0.20	0.10	-0.90	0.00	0.58	0.003	0.90	0.00
Salinity	-0.30	0.10	0.20	0.20	-0.30	0.20	0.39	0.06	0.20	0.20	0.05	0.80	-0.30	0.10
NO_2+NO_3	-0.03	0.80	-0.07	0.70	-0.30	0.20	0.28	0.20	0.09	0.60	-0.10	0.30	-0.17	0.40
P_2O_5	0.06	0.70	-0.10	0.60	-0.05	0.80	0.09	0.60	-0.10	0.50	-0.10	0.50	0.03	0.80
Mg	0.16	0.40	-0.30	0.70	-0.50	0.01	0.48	0.02	0.01	0.90	-0.30	0.07	-0.10	0.70
Zn	0.30	0.09	-0.57	0.005	-0.48	0.04	0.40	0.04	0.10	0.60	-0.56	0.006	-0.01	0.90
Cu	0.30	0.10	-0.20	0.10	0.09	0.70	-0.10	0.50	-0.20	0.30	-0.20	0.30	0.20	0.30
Mn	-0.40	0.04	0.10	0.30	-0.80	0.00	0.70	0.0003	0.50	0.005	0.01	0.90	-0.58	0.004
Na	0.60	0.001	-0.78	0.00	-0.70	0.0003	0.47	0.02	-0.50	0.01	-0.70	0.00	0.30	0.07

*Red cells show the significant correlation ($p < 0.05$)

➢ Aliphatic-C and soil properties correlation

In our analysis, we observed correlations between pH, Mn, Na, and $CaCO_3$ with aliphatic C-H. Among these properties, $CaCO_3$ exhibited a particularly robust relationship with aliphatic C-H. These findings underscore the significance of soil pH and mineral composition, specifically calcium carbonate, in influencing the levels of aliphatic C-H.

- **Aromatic C and soil properties correlation**

We observed a weak correlation between pH and $CaCO_3$ with aromatic-C in our analysis. Interestingly, Na displayed a strong negative correlation with aromatic C.

- **Amide N and soil properties correlation**

In our analysis, we observed a negative correlation between both zinc (Zn) and sodium (Na) with Amide-N. Interestingly, this negative correlation was notably stronger for sodium (Na).

- **Phenolic lignin and soil properties correlation**

We found a very weak positive correlation between sodium (Na) and zinc (Zn) with aliphatic phenolic lignin in our analysis.

- **Polysaccharide and Soil properties correlation**

In our analysis, we observed robust negative correlations between both pH and $CaCO_3$ and polysaccharides, while sodium (Na) exhibited a milder negative correlation. On the other side, manganese (Mn) displayed a weak positive correlation with polysaccharides.

- **Aromaticity and soil properties correlation**

Regarding aromaticity, the analysis revealed a weak positive correlation with calcium carbonate ($CaCO_3$). Conversely, we observed both weak and strong negative correlations with sodium (Na) and zinc (Zn) respectively.

- **C/O ratio and soil properties correlation**

Concerning the C/O ratio, the analysis shows a weak positive correlation with calcium carbonate ($CaCO_3$) and a notably stronger positive correlation with pH. Conversely, there was a weak negative correlation observed with manganese (Mn). These findings suggest that the presence of calcium carbonate and higher pH levels may contribute to an increase in the C/O ratio, while manganese appears to have a subtle limiting effect. Among soil properties, soil pH typically stands out as a significant factor influencing SOM composition (Andersson and Nilsson, 2001; Vancampenhout *et al.*, 2009; Tonon *et al.*, 2010; Wang, Camps-Arbestain and Hedley, 2016). The outcomes of our study demonstrate that pH significantly influences soil organic matter composition, particularly in terms of aliphatic C-H, aromatic-C, polysaccharides, and the C/O ratio. This influence might be attributed to its impact on microbial activity (Aciego Pietri and Brookes, 2008; Tonon *et al.*, 2010) hydrolysis, and protonation processes. Specifically, protonation regulates several soil processes, including solubilization and complexation, which impact soil organic matter stability by controlling the sorption and desorption of organic carbon on mineral surfaces (Tonon *et al.*, 2010). Tonon *et al.* (2010)

affirmed that soil pH significantly regulates the decomposition of fresh organic matter, particularly the light fractions while showing a relatively weaker impact on the chemical and structural composition of organic matter linked with soil minerals. In our study, we identified the carbonate content as another factor that significantly influences soil organic matter composition. We observed a positive correlation between $CaCO_3$ and C/O ratio ($r = 0.9$, $p < 0.00$) and also a positive correlation with aliphatic C-H ($r=0.8$, $p<0.00$) and aromaticity ($r = 0.5$, $p < 0.003$) Its increase significantly affects the aliphatic C-H and C/O ratio and moderately impacts aromaticity. It also showed a negative correlation with aromatic C ($r = -0.6$, $p < 0.003$) and polysaccharide ($r = -0.9$, $p < 0.00$).

The influence of $CaCO_3$ on soil organic matter composition can be attributed to its impact on soil pH and mineralization processes (Rowley *et al.*, 2018). According to their findings, the presence of $CaCO_3$ in the soil leads to a series of changes in soil biogeochemistry. These changes include an increase in pH, significantly higher levels of extractable calcium (Ca), and twice as much soil organic carbon (SOC). In a separate study, Rowley *et al.* (2018) confirmed that $CaCO_3$ can affect the stability of occluded SOC by playing a role in aggregate stabilization (Rowley *et al*., 2018). Dou *et al.* (2023) also support this observation (Dou *et al.*, 2023). They demonstrated that an increase in $CaCO_3$ content resulted in a decrease in the proportion of aromatic carbon (C) and alkyl C in SOC. Conversely, there was an increase in the proportion of O-alkyl C. In summary, $CaCO_3$'s influence on soil organic matter composition can be linked to its effects on soil pH, mineralization, and aggregate stabilization.

4.6 The results of the applied principal component analysis for dimension reduction

We also applied PCA to reduce the number of input variables and to identify the grouped soil and environment-related properties. These kinds of methods are referred to as ‘dimension reduction’ or ‘data-reduction’ techniques because they have the advantage of capturing the complexity of data by considering numerous data dimensions and highlighting a few dimensions that are more explanatory of the data set. The aim of the reduction was to explain the chemical composition of the SOM.

4.6.1 Principal component analysis for environmental covariates and soil properties

Describing the environmental conditions, 13 properties, including climate and topography, and ten soil properties were summarized as three PCs, explaining 63.45% of the total variance (KMO=0.663) (Table 4.15). The loading values higher than 0.6 are considered the effective properties in each category (rPC). The rPC1 represents the slope steepness, precipitation, and temperature properties (29% variance), whereas rPC2 is about the soil properties mainly pH and CaCO3 content (21.63%). Organic matter content also loads moderately on both rPC1 and rPC2. rPC3 represents P2O5 and $NO_2 + NO_3$ (12% variance) (Table 4.16).

Table 4.15. Principal Components Analysis (Varimax Rotation) for environmental and soil factors in the study areas (Józsefmajor, Szentendre, Magyarlukafa, Zselic-Visnyeszéplak)

Factor Number	Eigenvalue	Percent of Variance	Cumulative Percentage
1	3.53	29.44	29.448
2	2.59	21.63	51.078
3	1.48	12.376	63.454

Figure 4.7 also shows the PCA biplot of soil properties and environmental covariates indicating the highest loading values in rPC1 and rPC2.

Table 4.16. Factor loading PCA matrix after varimax rotation

	rPC 1	*rPC 2*	*rPC 3*
Na content (mg/kg)	0.815	0.051	0.323
OM content %	0.591	-0.557	0.324
$NO_2 + NO_3$ (mg/kg)	0.081	-0.218	0.614
P_2O_5 (mg/kg)	-0.194	0.250	0.796
pH-KCl	-0.087	0.891	0.169
$CaCO_3$ % (m/m)	0.251	0.890	-0.071
Precipitation	-0.885	0.041	0.127
Slope	-0.844	-0.012	0.256
Temperature	0.738	0.525	-0.173

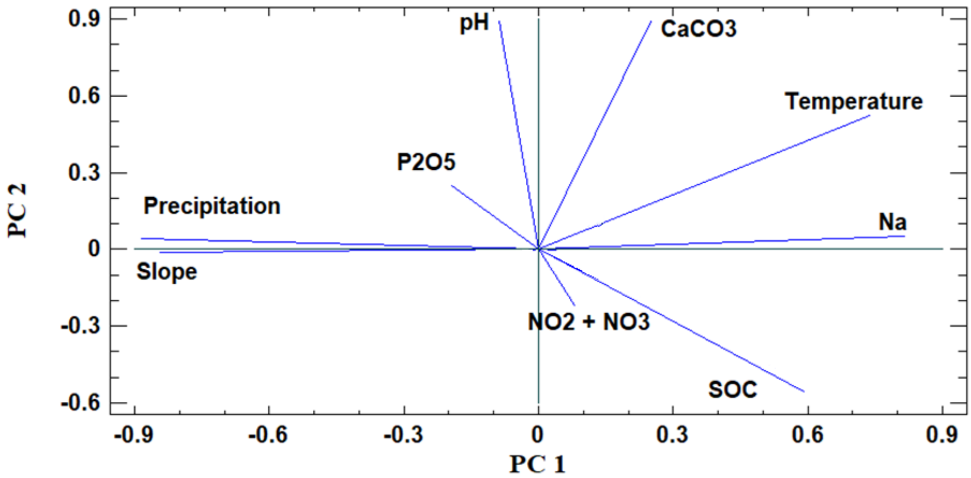


Figure 4.7 The loading vectors of principal component analysis (PCA)

The first principal component (PC1), which explains the largest variation in the data, is primarily driven by environmental variables. On the positive side, it shows a strong influence of temperature and sodium (Na), while on the negative side, it is linked to slope and precipitation. This suggests a clear pattern: areas with higher temperatures and sodium levels are typically flat and experience lower precipitation, indicating drier conditions. The second principal component (PC2) emphasizes the role of soil pH. It has a strong positive association with calcium carbonate ($CaCO_3$) content, which is known as a regulator of soil pH. Finally, the third principal component appears to be related to nutrient availability, particularly nitrogen ions ($NO_2 + NO_3$) and phosphorus (P_2O_5). These nutrients are critical for soil fertility and reflect the biological and chemical processes in the soil. Table 4.17 presents Spearman rank correlations between each pair of variables (SOM compositions and principal components extracted from environmental covariates).

Table 4.17 Spearman rank correlations between SOM composition and the three rotated principal components extracted from environmental and soil covariates for all the study areas ()

		rPC1	rPC2	rPC3
Aliphatic C-Ratio	r	0.64	0.29	0.08
	p	0.00	0.01	0.35
Amide	r	-0.79	0.38	-0.36
	p	0.00	0.00	0.00
Aromatic C=	r	-0.72	-0.21	-0.13
	p	0.00	0.02	0.13
Polysaccharide	rt	-0.51	-0.46	-0.03
	p	0.00	0.00	0.70
Phenolic lignin	r	0.40	-0.24	0.30
	p	0.00	0.0007	0.001
Aromaticity	r	-0.73	-0.26	-0.09
	p	0.00	0.005	0.32
C/O ratio	r	0.51	0.46	0.03
	p	0.00	0.00	0.70

* Red cells show a significant correlation at a p<0.05 level

rPC1, is closely linked to slope steepness, and precipitation, shows weak to medium correlations with most SOM composition components. Notably, aromaticity exhibits a strong negative correlation ($r = -0.73$, $p < 0.05$), while the C/O ratio has a moderate positive correlation ($r = 0.51$, $p < 0.05$), consistent with our earlier findings in section 4.2. This suggests that steep slopes and highly humid areas are associated with reduced aromaticity, (likely due to limited fresh or microbial organic matter in these environments). rPC2, which reflects soil chemical properties, particularly pH and $CaCO_3$ content, also shows weak to medium correlations with SOM components including amide, polysaccharide, and, C/O ratio. There is a positive relationship between amide ($r = 0.38$, $p < 0.05$) and C/O ratio ($r = 0.46$, $p < 0.05$), suggesting that higher pH and carbonate content enhance the amide fraction of SOM. rPC3, which primarily represents temperature, highlights its influence on SOM components. It shows strong positive correlations with aliphatic C-H ($r = 0.64$, $p < 0.05$) and the C/O ratio ($r = 0.51$, $p < 0.05$), indicating that warmer conditions may promote these components. Conversely, temperature negatively correlates with polysaccharides ($r = -0.51$, $p < 0.05$) and aromaticity ($r = -0.73$, $p < 0.05$), suggesting that higher temperatures might accelerate SOM decomposition, reducing these fractions. The inverse relationship between amide and aromatic compounds and rPC_1 implies a scarcity of fresh/microbial organic matter on steep slopes and in the most humid sites. Furthermore, the influence of pH and $CaCO_3$ appears to increase the amide ratio of SOM. In conclusion, while the PCA results provide valuable insights, they only explain two-thirds of the variance. So It is important to note that the first three principal components collectively explain 63.4% of the variance, which, leaves a substantial portion of variability unexplained. It indicates that factors not included in our analysis, like the type of minerals present and the land use, may be important determinants of the composition of SOM. This highlights the need for further exploration of additional factors, particularly land use and mineralogy, to gain a more comprehensive understanding of SOM composition across varying landscapes. Figure 4.8 illustrates how different land-use types and locations contribute to the distribution of SOM composition in the study areas, based on principal component analysis. Each point represents a sample, and the different shapes and colors show how the samples are grouped by land-use types (such as Conventional, Arable, Forest, etc.), based on this scatter plot, tree line, and tillage operations differ significantly along rPC_1, and also rPc2, as this area is almost flat and there is no significant difference in temperature we can conclude that land use/land management along with soil properties (pH and $CaCO_3$) is the most important driver of SOM composition in Jozsefmajor. Forest and arable land also show differences along PC_2, but in opposite directions, which suggests there are no clear overall conclusions from this separation. This implies that other underlying environmental factors (possibly related to pH, precipitation, or microclimate) are contributing to the variability in these land uses, which aligns with the idea that land use alone does not fully explain SOM composition distribution. The Zselic area crop fields and the Szentendre Island crop fields also vary along PC_1; however, both are arable land. This difference is likely due to location-specific factors (Zselic is a hilly and wet area and Szentendre Island is a flat and relatively dry area). Overall, these findings highlight the significant impact of local environmental conditions (such as climate and specific soil properties) on SOM composition distribution, often more so than general land-use types. This is a critical insight, suggesting that localized management practices and environmental variables must be considered when studying or attempting to manage SOM dynamics in different landscapes.

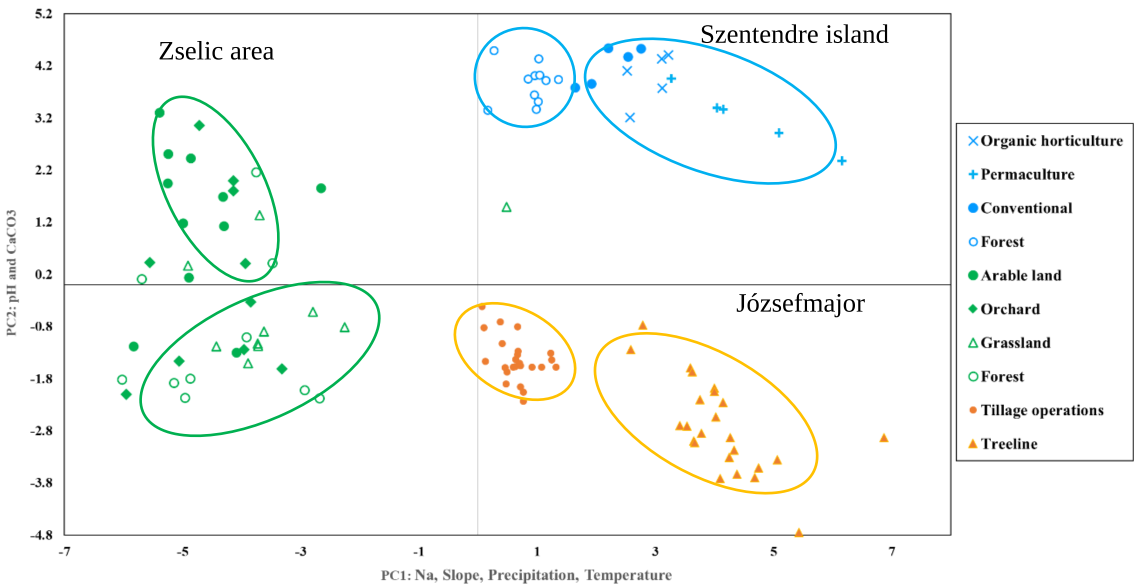


Figure 4.8 Principal Component Analysis (PCA) of different land-use Management based on soil and environmental parameters

5. Conclusions and suggestions

5.1 Conclusions

In this chapter, we present the conclusions based on the results obtained for the following specific objectives:

(I) Assessing the impact of land use and land management practices on SOM composition and decomposition:
This objective was addressed in three study areas in Hungary, including eight land use types; tree line, arable land, permaculture horticulture, organic horticulture, conventional horticulture, forest, grassland, and orchard.
The examination of different land use/management practices showed higher concentrations of aromatic C and aliphatic C-H compounds across the soil samples compared to other OM compositions. The findings indicate that cultivated lands (such as permaculture horticulture, Conventional horticulture, and arable land) have significantly higher levels of aromatic C compared to other land use types. On the other hand, less intensively managed systems (such as the tree line and organic farming) exhibited higher concentrations of aliphatic C-H, except for the Conventional horticulture in Szentendre Island. Therefore, it can be inferred that cultivated areas have a more resistant composition of organic carbon compared to other land use types.
However, different results were observed in two other study areas. Comparing land use effects of SOM composition in three study areas revealed that land use can be one driver of OM compound but not the only one. In total natural land uses such as tree line, forest, and grassland, notably, different dynamics are observed in the study areas for polysaccharide and amide, these variations underscore the complexity of soil composition influenced by different land management practices across diverse environments. We discovered that forests lead to an increase in the polysaccharide ratio when compared to crop fields. However, a tree line aged 40 years does not seem sufficient to bring about a change in this soil organic matter compound The results of two indices of aromaticity and the ratio of C/O functional groups support the concept of a relatively advanced stage of SOM decomposition in croplands. The calculated aromaticity in Józsefmajor was significantly higher in cropped land (27%) than in tree line soil samples (15%). Similarly, in Szentendre Island, arable land, permaculture horticulture, and conventional horticulture displayed higher aromaticity compared to other land use/management practices. However, in the Zselic area, different results were observed, with arable land exhibiting the lowest aromaticity compared to other land use types.

Overall, it is evident that different land uses can influence the composition of SOM. However, exceptions, such as the aromaticity in the Zselic area's arable land, suggest that it is not the sole determinant of SOM composition.

(II) Evaluate the effect of agrotechnical and various tillage operations on SOM content in surface soil to determine the most suitable tillage system.

The conclusion for this objective is based on Józsefmajor Experimental and Training Farm (JETF). we conclude conventional tillage (Plowing, loosening) has more resistance compounds of organic matter than conservation tillage (no-tillage, disking, shallow cultivation). This also leads to higher aromaticity under conventional tillage.

Because the entire field had been plowed for an extensive period (50 years) and the conservation tillage techniques had been applied since 2002, we can conclude that SOM increased owing to the less intensive tillage associated with the conservation practices. In addition, the greater decomposition under plowing and loosening was the result of tillage-induced oxygen abundance in the subsoil stimulating microbiological activity. These results suggest that decomposition increases with increasing tillage intensity, whereas SOM increases under conservation practices owing to less intensive tillage.

(III) Investigate the effect of afforestation on SOM quality and comparing to conservation and conventional tillage

Here we compared the small woodland (tree line) in Józsefmajor to JETF. This study found that the natural ecosystem (tree line) and adapted conservation tillage, namely no-tillage and disking, produced similar results for most SOM compounds.

Moreover, the results of the two indices, aromaticity and C/O ratio, indicate that SOM has a higher degree of decomposition in cropland. The DRIFTS results revealed that tree line soil had the lowest aromaticity (15%) and, therefore, a lower decomposition rate and higher SOM recalcitrance compared to the cropland soil (27%). This study demonstrates that land use change and afforestation can alter the structure and stability of SOM compounds.

Finally, we conclude that afforestation is similar to conservation tillage, mostly no-tillage and disking, which is indicative of fast (<40 years) regeneration; accordingly, regeneration agriculture and the development of conservation tillage represent the superior solution for increasing SOM and food security in the present soil and climate conditions.

(IV) Varying OM composition in different soil fractions in three tillage systems and a tree line

Comparing three land use/management (Treeline, No-tillage, and plowing) revealed that plowing-based management leads to an increase in the content of aromatic C, while tree line (T) and no-tillage (Nt) land use/management practices promote higher levels of aliphatic C-H, particularly in the fine soil (S+C) fraction. Thus, it can be concluded that plowing-based management in the fine soil fraction may result in higher aromaticity and C/O ratio, indicating lower decomposition and higher stability of soil organic matter. Despite cultivation, the composition of the soil's aggregate fraction (S+A) is observed to be less aromatic and more labile which suggests that the process of cultivation seems to affect the soil making it less rich in aromatic substances and more susceptible to alteration.

The results from Józsefmajor demonstrate that changes in soil aggregation caused by tillage practices have the potential to influence soil organic matter dynamics. So, we conclude that the size of soil particles influenced by tillage primarily affects the molecular composition of soil organic matter, with specific components being retained in both mineral-associated organic matter and aggregate-associated organic matter. Aliphatic-containing compounds tend to be enriched in aggregate fractions, whereas aromatic compounds are more prevalent in fine fractions due to their ability to adsorb soil minerals.

(V) The connection between OM composition and content

The findings indicate that soils with significantly higher organic carbon levels also contain SOM with noticeably diverse molecular compositions. It is important to note that these molecular differences do not necessarily cause or result in the stability or resistance of SOM to decomposition. This aspect is noteworthy because soils with a high content of SOC (soil organic carbon) do not necessarily guarantee that the SOC is more stable or resistant to decomposition. This observation is evident in the composition displayed in the Józsefmajor.

(VI) Assessing the effect of environmental covariates (climatic and topographic factors) and soil properties on SOM composition

The results indicate that certain environmental factors, particularly climatic conditions and topographical characteristics like slope and elevation, are significantly correlated with the composition of soil organic matter. Specifically, there is a notable correlation between these factors and the presence of aliphatic C-H, aromatic C, and polysaccharides in the soil. In our study, we observed a negative correlation between the Mean Annual Temperature (MAT) and aromatic C, polysaccharides, as well as aromaticity. However, since there was not a wide range of temperatures (ranging from 10.24°C to 11.47°C) among the study areas, we can conclude that temperature is not a significant driver of soil organic matter composition in these particular regions. On the other hand, other topographic factors, such as altitude/elevation (ranging from 102.82 to 235.43 meters) and slope steepness (ranging from 0.73% to 5.28%) varied more widely. This difference was particularly noticeable between two smaller areas within the Zselic area, and two other study areas of the Józsefmajor and Szentendre Island. Based on the correlation results, we can identify these topographic factors as influential factors that contribute to the different soil organic matter compositions, especially regarding aromaticity in cultivated land within the Zselic area compared to the Józsefmajor and Szentendre Islands.

Additionally, according to the Principal Component Analysis (PCA), it is confirmed that factors related to slope steepness, represented as rotated Principal Component 1 (rPC1), affect soil organic matter composition in different areas. We also observed significant variation in precipitation values (ranging from 543.65 to 747.43 mm) between the Zselic area and the other two study areas (Józsefmajor and Szentendre Island). As precipitation is a known influential factor on soil organic matter composition, we can consider it as another reason for the differences in soil organic matter composition among the Zselic area, Józsefmajor, and Szentendre Island. The combination of steep slopes and higher precipitation in the Zselic area may intensify erosion, which can impact soil organic matter composition and decomposition.

Among soil properties, we conclude that soil pH and calcium carbonate ($CaCO_3$) are the primary properties that might influence SOM composition. However, based on the PCA analysis, rPC1 (which represents slope, precipitation, and temperature) and rPC2 (which represents pH, and $CaCO_3$) showed correlations with soil organic matter composition, indicating that the interaction between pH and mineral content in the soil can affect soil organic matter composition. Comparing these results to the impact of land management on SOM composition emphasizes the importance of environmental variables (like soil properties, temperature, and pH) in determining SOM composition, which means local conditions have a stronger influence on SOM than land use alone.

5.2 Recommendation

Based on the findings of the study, the following recommendations are suggested:

- Promoting conservation tillage practices

Considering the research indicating that conservation tillage methods, such as no-tillage and disking, contribute to increased levels of aliphatic C-H and have the potential to improve the stability of soil organic matter (SOM), it is advisable to actively promote and advocate for these practices in agricultural environments. It is important to educate farmers and land managers about the advantages of conservation tillage, emphasizing its positive influence on the composition of SOM and the rate at which it decomposes.

- Afforestation initiatives for soil health

It has been recognized that afforestation, like conservation tillage, has a beneficial impact on the quality of soil organic matter (SOM). Consequently, the promotion of afforestation initiatives, particularly in regions where soil degradation or low SOM levels are evident, is highly recommended. This suggestion aligns with the concept that afforestation is a rapid regeneration process, making it an applicable approach to enhance SOM and improve food security, especially considering the prevailing soil and climate conditions.

- Importance of monitoring soil aggregation

The study highlights the importance of monitoring soil aggregation induced by tillage practices, as it can potentially regulate changes in SOM dynamics. Understanding the relationship between soil aggregation and SOM composition is crucial for implementing effective land use/ management strategies.

- Monitoring and adjusting land use/management based on environmental factors and soil properties

The research highlights the strong relationship between environmental factors, particularly topographic elements and climate conditions, and the composition of soil organic matter (SOM). It shows these factors can be the main driver of SOM composition and affect its dynamic, especially in hilly and steep environments. As a result, it is advisable to monitor and adapt land use/management approaches according to the specific environmental characteristics of a given area. This may require considering factors such as the steepness of slopes, elevation, precipitation, and pH when designing land utilization and tillage strategies, to align them more effectively with the desired SOM composition.

- Considering sustainable agricultural practices

Considering the findings of the study, it is highly recommended that natural agricultural methods, such as permaculture horticulture, be implemented within the farming community. The research indicates that permaculture techniques have a similar effect on the dynamics and composition of SOM as those observed in natural ecosystems like forests. Embracing the principles of permaculture in agricultural practices can yield multiple advantages, supporting environmental sustainability and ensuring soil health.

KEY SCIENTIFIC FINDINGS

1- Afforestation can affect SOM composition and dynamics due to higher organic matter input in a short period (40< years).

2- The study emphasizes the importance of soil particle size (two-size fraction of soil) in determining the molecular composition of SOM. It highlights that aliphatic compounds, tend to be enriched in aggregate-associated OM fractions, while aromatic compounds are more prevalent in fine fraction OM. This can be attributed to their respective abilities to be stabilized by soil minerals. Also, the higher ratio of aromaticity in the fine fraction compared to aggregate fraction and the higher C/O ratio in the fine fraction compared to the aggerate fraction suggest that lower decomposition rate and biological reactivity in the fine fraction, which led to recalcitrant OM in the fine fraction of soil.

3- The findings highlight a similarity between the effects of organic farming and natural ecosystems on SOM decomposition rate (both help OM stability). This similarity suggests that organic farming practices can be considered sustainable land use, as they exhibit comparable impacts on soil composition and organic matter decomposition, similar to those seen in undisturbed natural ecosystems.

4- In the Zselic area, regional differences in SOM composition seem strongly influenced by local environmental factors, particularly topography and climate. Forests in Zselic show higher aromatic C ratios and increased aromaticity, suggesting slower SOM decomposition compared to arable lands, which exhibit lower aromatic C levels. This contrasts with the trends observed in other study areas. The hillslope landscape, with its higher precipitation, steeper slopes, and greater altitude, likely contributes to these differences by promoting reduced decomposition rates in arable lands due to the higher moisture and drainage conditions

5- Spatial variability in climatic and topographical factors contributes to variations in SOM composition. The findings highlight the complex interplay between environmental conditions, topography, and land use in shaping SOM dynamics and composition. Local environmental conditions may overwrite land use determined variations in SOM composition.

SUMMARY

Among different factors affecting SOM content and composition, there is a broad agreement that land-use change is a major altering force of SOC through altering soil carbon turnovers, decomposition, and soil erosion Land use shifts prompt immediate soil disturbance (e.g. tillage, cropping) and ambient environmental changes that can fundamentally alter both carbon inputs and decomposition rates and eventually affect soil carbon content. This is an essential issue in Hungary because the area of the country is 9.3 million hectares and 6.4 million hectares are turned into agricultural land with different tillage systems.

Therefore, land use/management is an important strategy to enhance soil quality and reduce the dangers of the greenhouse effect.

The overall goal of this study was to provide quantitative information on the effects of land use change and land use/management on soil organic matter content and composition. To achieve this aim of the study, five specific objectives were pursued. For the first objective, the effect of agrotechnical and various tillage operations on SOM composition in surface soil is evaluated to determine the most suitable tillage system. In the second objective, the effect of afforestation on SOM quality was assessed, and its results were compared to the conservation and conventional tillage The third objective determined the variation of OM composition in different particle fractions of the soil in three tillage systems and a tree line.

In the fourth objective, the connection between OM composition and content was evaluated. The last objective assessed the impact of environmental covariates (climatic and topographic factors) and soil properties on SOM composition.

The study conducted in Hungary has a rather diverse landscape structure where the mountain parts are mainly forested, the great plain is mainly covered with croplands but the rest has a mosaic pattern with several land uses next to each other. The research investigation was conducted via four case studies. The four sites represent various conditions. The first area is Józsefmajor, a flat area with intensive agriculture based on crop fields, with a mean precipitation of 543.65 mm per annum and an average annual temperature of 10.82°C. The soils of the site are mainly Endocalcic Chernozems (Loamic) with a clay loam texture. These are good agricultural soils that are deep and moderately well-drained. 48 samples are collected from 6 tillage operations (disking (D); Shallow tine Cultivation (SC), no-till (NT); Deep tine Cultivation (DC), Loosening (L); conventional tillage-moldboard plowing (P)) and a semi-natural tree line. The second area is Szentendre Island, which shows a mosaic pattern of

different land uses and small farms with mainly innovative bio farms, agroforestry conventional farm arable land, and forest. Mean precipitation is 566.287 mm per annum, and average annual temperature is 11.47 °C. Soils of the site are mainly Luvisols which, are characterized by a shallow humus layer.

A total of 45 samples were collected from five land uses including arable land, forests, conventional horticulture, organic horticulture, and permaculture horticulture.

Another study area contains two sub-areas where located in the Zselic area named Visnyeszéplak and Magyarlukafa which are hilly and steep with relevant erosion and the dominance of forest and eroded crop fields. The mean precipitation and mean annual temperature in Zselic-Magyarlukafa are 712.76 mm per annum and 10.44°C. Also, in Zselic-Visnyeszéplak mean annual precipitation is 747.437 mm, and the average annual temperature is 10.24°C. In this region, almost all of the soil types are Luvisols, or related to Luvisols. Soil samples were collected from four land uses (small areas, 100-–200 m^2) including arable land in Zselic-Visnyeszéplak, and intensive farming in Magyarlukafa) orchard (grassed), forest (most of them natural but including some black locust forests, with a minimum of 10 years of age and not older than 30 years), grassland (mixed use of mowing and grazing). Totally 41 soil samples were collected from area. The main reason for site selection beyond their diversity was based on former experiences related to the sites.

Mid-infrared spectra were recorded using a Bruker Vertex 70 Fourier transform infrared (FTIR) spectrometer (Vertex 70, Bruker Optics Ltd., Coventry, UK) in DRIFT mode with an RT-DLaTGS detector. DRIFT spectra were corrected for background atmospheric CO2 and water vapor. Rubber band correction employing fixed numerous data points in the spectral window was also used for baseline correction. Based on the prominent bands observed in spectra, five organic bands were selected and analyzed for band area integration. including, aliphatic C-H, aromatic C, phenolic lignin, amide N, and polysaccharides.

Two indices of aromaticity and C/O ratio were calculated to relate the differences in functional groups with SOM quality composition.

To investigate the effect of SOM pool fraction on SOM composition we chose three tillage systems in Józsefmajor and the tree line, bulk samples were fractionated to provide labile and stable C pools. For the fractionation, the Zimmermann method improved by Poeplau (Poeplau *et al.*, 2013) was applied. To investigate the effect of environmental covariates on OM composition, various topography-related environmental covariates were computed (For each sampling point) by utilizing a digital elevation model with a resolution of 100 m. These covariates encompassed a range of geomorphometric properties that play a significant role in shaping the local environment.

One-way analysis of variance (ANOVA) was used to detect the significance of different land use/management practices on the variables considered (normally distributed variables). For multiple comparisons, a post hoc test of Tukey of $p<0.05$ was applied (95% family-wise confidence level). A nonparametric Kruskal–Wallis's test, was used for non-normally distributed variables. Correlation analysis was performed using a nonparametric procedure (Spearman rank correlation coefficient; Sachs, 1992) and Pearson was used to determine the strength of possible relationships between SOM composition and environmental variables, soil properties, and OM content.

The analysis was performed using R software (version R4.0.3) and Stratigraphic.

The results of bulk soil characterization revealed that cultivated lands, in Szentendre Island and Józsefmajor, exhibited significantly higher concentrations of aromatic C compared to other land uses. Conversely, aliphatic C-H was found to be more concentrated in natural ecosystems, including the tree line in Józsefmajor and organic farming in Szentendre Island, based on this result we suggest that in natural ecosystems like tree lines and forests, the decomposition of SOM is in an early stage, as evidenced by a higher proportion of aliphatic C-H compounds to aromatic C. The aromaticity and the ratio of C to O functional groups reflected a more advanced stage of SOM decomposition in croplands, while different results were observed in the Zselic area. Furthermore, afforestation was found to increase SOM compound concentration and aliphatic compounds due to higher organic matter input and lower decomposition rates.

When comparing different tillage systems for their impact on the composition of organic matter (OM), we found that conventional tillage resulted in higher levels of aromatic C and lower levels of the aliphatic component compared to conservation tillage. This also led to higher aromaticity in fields where conventional tillage was employed. Based on these findings, we suggest that conventional tillage methods, such as plowing and loosening, exhibit greater resistance to changes in SOM composition compared to conservation tillage techniques like no-tillage, disking, and shallow cultivation. Since the entire field had been plowed for a long period of 50 years, and conservation tillage practices were implemented for the same duration, we can conclude that the increase in SOM is a result of the less intensive tillage associated with conservation practices. These results indicate that decomposition rates tend to increase with higher tillage intensity, while SOM levels increase under conservation practices due to the less intensive tillage methods employed. Pearson correlation revealed a significant correlation between OM composition and content just in Józsefmajor. The increase in SOC content was found to be more favorable for reducing aromatic C and increasing Aliphatic C-H in the soil. We suggest that soils with lower SOC levels tended to have higher levels of aromatic-C and lower levels of aliphatic C-H, suggesting that these soils were less favored for decomposition of soil organic matter (SOM) and tended to become more resistant.

Assessing the relationship between environmental covariates and OM composition performed by Spearman and PCA revealed that precipitation is the most important driver of OM compound between topographic factors, slope steepness, and climatic factors. We also find the relationship between other factors like temperature and altitude with different components of SOM. However, considering the variation of these factors between study areas suggests that they cannot play an important role in this regard. Precipitation showed positive correlations with various components of SOM, such as the ratios of aromatic C ($r=0.86$, $p<0.005$), polysaccharides ($r=0.6$, $p<0.005$), amide N ($r=0.8$, $p<0.005$), and aromaticity ($r=0.84$, $p<0.005$), suggest that decomposition occurs faster in moist sites compared to dry ones. Arable land in the Zselic area, characterized by eroded crop fields and steep slopes, shows lower decomposition compared to cultivated areas in two other study areas, likely due to the association between organic matter and minerals in the topsoil resulting from subsoil mineral interactions. This landscape is influenced by higher precipitation, which can further increase soil organic matter decomposition, according to previous studies. The results emphasize the intricate relationship between environmental conditions, topography, and land use in influencing the dynamics and composition of SOM. According to the findings, we can suggest the main drivers of SOM composition in the study area are local conditions (especially precipitation and slope) and land use.

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Appendices

Appendix A: Results of soil properties in Józsefmajor, Szentendre Island, and Szelic area

Table A. 1. Results of soil properties in Józsefmajor (a=arable land, T= tree line)

Samples	Land use/ management	pH (KCl)	texture (KA)	Salinity % (m/m)	$CaCO_3$ % (m/m)	Humus % (m/m)	$NO_2 + NO_3$ (mg/kg)	P_2O_5 (mg/kg)	K_2O (mg/kg)	Mg (mg/kg)	Na (mg/kg)	Zn (mg/kg)	Cu (mg/kg)	Mn (mg/kg)
a1	P	5.66	46.15	0.050	<0,1	2.20	17.26	215.54	214.64	260.5	28.76	1.35	3.239	346.3
a2	Nt	4.88	51.77	0.073	<0,1	3.28	42.36	415.66	300.27	282.5	25.97	1.86	3.405	392.6
a3	Sc	5.09	47.61	0.072	<0,1	2.89	40.33	314.74	299.01	283.7	60.15	1.52	3.046	320.7
a4	DC	5.12	46.87	0.078	<0,1	2.86	43.34	285.06	271.45	265.3	41.02	1.46	3.024	334.7
a5	D	5.01	50.84	0.051	<0,1	4.10	36.19	447.84	359.00	289.0	25.43	2.05	2.998	368.4
a6	L	5.32	47.61	0.059	<0,1	2.65	27.43	247.80	218.35	308.4	25.49	1.36	2.933	326.4
a7	Sc	4.99	47.61	0.079	<0,1	2.84	46.24	293.36	286.66	294.5	31.94	1.64	3.146	348.8
a8	P	5.28	45.45	0.043	<0,1	2.40	16.15	122.66	196.67	269.1	24.10	1.09	3.275	340.7
a9	D	4.91	48.38	0.094	<0,1	3.37	>50	329.67	348.13	304.9	17.46	1.70	3.006	345.1
a10	Nt	4.62	50.84	0.074	<0,1	3.26	>50	347.01	343.27	333.1	20.25	1.89	9.075	355.4
a11	L	5.02	46.15	0.037	<0,1	3.17	21.23	222.83	284.31	327.6	50.73	1.35	3.264	339.1
a12	DC	4.81	48.38	0.043	<0,1	3.11	29.62	253.25	327.27	304.8	47.42	1.65	3.504	359.1
a13	D	4.74	48.38	0.08	<0,1	3.99	>50	376.45	424.03	291.8	26.80	2.09	3.304	361.8
a14	Nt	4.71	49.18	0.05	<0,1	3.81	40.45	270.00	305.30	303.5	25.28	2.03	3.35	357.6
a15	DC	5.29	47.61	0.06	<0,1	3.22	32.99	288.37	284.23	314.0	29.21	1.63	3.259	353.7
a16	L	5.06	47.61	0.05	<0,1	2.89	24.66	155.66	209.38	321.3	28.26	1.37	3.445	354.1
a17	Sc	5.06	50	0.07	<0,1	2.99	32.17	201.96	272.54	316.1	30.20	1.46	3.428	356.7
a18	P	5.45	46.15	0.02	<0,1	2.52	8.07	109.32	196.87	291.0	31.01	1.23	3.859	359.2
a19	L	5.14	46.87	0.08	<0,1	3.09	38.05	242.50	307.90	321.8	28.50	1.46	3.554	369.5

a20	P	5.24	44.77	0.02	<0,1	2.46	7.32	109.31	213.02	284.7	44.72	1.10	3.333	337.9
a21	DC	4.86	47.61	0.04	<0,1	3.31	22.64	184.15	303.08	318.6	53.12	1.99	3.62	390.8
a22	Nt	4.95	50	0.06	<0,1	3.42	38.92	424.41	492.22	314.1	20.01	2.12	3.02	346.2
a23	Sc	4.84	47.61	0.06	<0,1	3.20	32.76	291.04	380.58	298.1	41.78	1.57	3.221	346.8
a24	D	4.86	49.18	0.09	<0,1	3.86	>50	685.62	621.54	221.1	22.07	2.61	3.615	381.9
T1	T	4.85	>60	<0.02	<0.5	9.68	4.57	346	472	466.1	191	7.55	4.89	425
T2	T	5.07	>60	<0.02	<0.5	9.7	5.87	623	748	486.3	83.6	6.26	6.95	397
T3	T	4.97	59	<0.02	<0.5	9.81	16.1	560	483	552.2	85	7.31	4.74	400
T4	T	4.92	57	0.03	<0.5	7.95	26.4	271	499	523.2	81.2	5.47	4.64	387
T5	T	5.10	58	0.02	<0.5	8.94	18.7	394	513	515.1	81.5	7.79	5	379
T6	T	5.25	>60	<0.02	<0.5	10.56	57.1	1000	644	532.4	79.6	6.98	4.38	332
T7	T	4.39	>60	<0.02	<0.5	11.21	27.4	370	444	384.0	89.9	7.36	4.98	384
T8	T	4.82	>60	<0.02	<0.5	9.92	29.9	286	382	295.1	81.5	7.88	4.55	379
T9	T	5.8	>60	0.03	<0.5	9.41	24.4	463	871	201.1	78.5	6.76	6.64	382
T10	T	5.21	>60	0.02	<0.5	10.88	34.3	383	669	315.0	75.2	9.49	4.73	381
T11	T	4.99	>60	0.02	<0.5	11.86	24.6	386	661	325.2	70.7	8.29	5.02	378
T12	T	5.13	>60	<0.02	<0.5	10.84	27.1	500	703	363.1	77.3	8.23	4.99	360
T13	T	5.4	>60	0.04	<0.5	10.86	51	517	778	512.0	52.5	7.86	5.19	362
T14	T	5.15	>60	0.06	<0.5	11.22	77	399	455	600.1	76.7	6.72	4.58	277
T15	T	6.21	>60	<0.02	<0.5	10.16	53.5	580	646	602.2	80.7	7.46	4.55	271
T16	T	6.35	>60	0.06	<0.5	8.08	18.6	552	618	437.3	82.5	5.34	4.41	317
T17	T	6.2	>60	0.04	<0.5	6.95	26.5	420	724	507.1	88.6	6.17	4.72	301
T18	T	6.22	>60	0.06	<0.5	8.33	29.3	483	856	467.2	86.8	5.16	4.33	325
T19	T	6.61	58	0.03	<0.5	5.82	14	579	550	412.3	76.2	4.09	4.7	284
T20	T	6.5	>60	0.04	<0.5	7.54	29.6	521	688	464.2	79.9	4.68	4.57	264
T21	T	5.72	>60	0.04	<0.5	7.42	27.7	534	640	464.3	84.3	5.91	4.91	358
T22	T	5.62	58	0.03	<0.5	8.14	25.4	459	486	487.0	83	5.91	4.83	361
T23	T	5.36	>60	0.06	<0.5	9	65.6	549	847	408.2	71.6	7.57	5.29	372
T24	T	6.48	>60	0.05	<0.5	9.4	24.2	790	484	543.1	71.6	9.83	5.65	251

Table A. 2. Results of soil properties in Szentendre Island

Samples	Land use	pH-KCl	texture (KA)	Salinity % (m/m)	$CaCO_3$ % (m/m)	Humus %	$NO_2 + NO_3$ (KCl soluble) (mg/kg)	P_2O_5 (mg/kg)	K_2O (mg/kg)	Mg (mg/kg)	Na (mg/kg)	Zn (mg/kg)	Cu (mg/kg)	Mn (mg/kg)
S1	Permaculture	7.67	48	0.075	10.00	2.88	43.7	190	>600	429	118	1.3	2.7	19
S2	Permaculture	7.60	47	0.035	10.80	2.91	28.3	324	>600	398	89	1.4	2.7	17
S3	Permaculture	7.65	51	0.153	8.96	3.71	>50,0	>700	>600	489	148	2	3	23
S4	Permaculture	7.65	47	0.054	9.39	2.79	20.1	169	>600	360	97	1.1	2.9	19
S5	Permaculture	7.61	44	<0,020	9.71	2.99	21.6	413	>600	258	89	1.6	3.5	27
S6	Arable land	7.47	N/A	N/A	10.43	2.07	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
S7	Arable land	7.58	N/A	N/A	10.08	1.92	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
S8	Arable land	7.63	N/A	N/A	10.98	1.98	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
S9	Arable land	7.64	N/A	N/A	6.79	2.13	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
S10	Arable land	7.60	N/A	N/A	2.53	2.15	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
S11	Forest	7.73	47	<0,020	10.30	2.27	4.71	64.1	179	134	20	1.5	1.4	14
S12	Forest	7.61	38	<0,020	8.86	3.08	9.42	95	371	219	26	2.1	2.8	44
S13	Forest	7.68	48	<0,020	9.01	2.81	5.11	79.2	249	171	33	1.4	2.1	25
S14	Forest	7.67	50	<0,020	8.76	3.39	4.1	72.8	323	198	27	2	2	35
S15	Forest	7.52	52	<0,020	8.29	3.04	12.1	104	281	208	28	2.1	2.5	41
S16	conventional	7.43	38	<0,020	12.50	1.55	32	531	224	271	65	2	5.1	22
S17	conventional	7.42	38	0.027	11.30	1.54	32.8	557	200	218	57	2.3	5.7	22
S18	conventional	7.50	33	<0,020	10.70	1.64	21.8	576	219	271	62	2.2	4.8	21
S19	conventional	7.55	29	0.086	7.49	1.08	>50,0	479	252	193	47	1.7	5.5	29
S20	conventional	7.64	33	<0,020	7.54	1.59	23.2	375	218	250	47	1.5	3.7	32
S21	Arable land	7.11	32.4	N/A	9.39	1.48	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
S22	Arable land	6.57	70	N/A	7.94	1.46	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
S23	Arable land	6.79	33	N/A	10.77	1.27	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
S24	Arable land	7.39	32	N/A	16.05	1.23	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
S25	Arable land	7.31	32	N/A	13.10	1.31	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
S26	Forest	7.62	39	<0,020	3.30	2.57	12.2	138	216	113	<15	3.2	>20	35

S27	Forest	7.64	34	<0,020	2.00	1.93	14.4	191	239	130	<15	3.5	>20	85
S28	Forest	7.67	38	<0,020	3.32	3.01	13.8	163	229	111	<15	4.2	>20	42
S29	Forest	7.67	34	<0,020	2.37	2.57	17.5	212	211	136	<15	4.5	>20	40
S30	Forest	7.72	25	<0,020	1.62	2.09	10.7	196	173	113	16	3.5	18	84
S31	organic	7.55	45	0.027	10.50	2.47	31.5	466	389	311	69	2.1	3.9	30
S32	organic	7.63	43	0.027	12.80	2.07	21.5	484	405	276	76	2.1	3.3	24
S33	organic	7.57	45	<0,020	14.90	2.05	8.77	350	296	328	84	1.6	3.5	21
S34	organic	7.58	43	0.027	13.00	2.18	23.4	466	319	337	84	2	3.8	21
S35	organic	7.64	45	<0,020	15.40	1.78	11.8	252	244	339	86	1.5	3	18
S36	Arable land	7.21	44.4	N/A	18.76	1.95	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
S37	Arable land	7.26	44.2	N/A	16.84	1.83	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
S38	Arable land	7.22	46	N/A	17.93	1.89	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
S39	Arable land	7.36	43	N/A	18.00	2.01	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
S40	Arable land	7.07	44.2	N/A	16.05	1.91	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
S41	Forest	7.47	>60	<0,020	12.20	2.98	14.60	193	197	206	36	>10	7.0	26
S42	Forest	7.50	60	<0,020	12.90	3.26	17.40	151	167	213	38	8.8	7.0	24
S43	Forest	7.52	60	<0,020	12.40	2.65	12.6	172	137	216	29	9.1	6.6	22
S44	Forest	7.52	58	<0,020	12.60	2.48	9.39	162	124	237	29	8.6	6.5	23
S45	Forest	7.50	>60	<0,020	13.10	2.42	8.82	175	130	197	37	8.8	6.7	24

Table A. 3. Results of soil properties in Zselic area (Vis: Zselic-Visnyeszéplak 0-30cm)

Samples	Land use	Depth [cm]	pH (KCl 1:2,5) [-	texture [KA]	Salinity% [m/m]	$CaCO_3$% [m/m]	Humus %[m/m]	$NO_2 + NO_3$ (KCl soluble) (mg/kg)	P_2O_5 (mg/kg)	K_2O (mg/kg)	Mg (mg/kg)	Na (mg/kg)	Zn (mg/kg)	Cu (mg/kg)	Mn (mg/kg)
Vis1	Orchard	0-30	4.49	45.45	<0,02	<0,1	2.095	10.36	36.95	115.62	279	14.27	0.64	1.78	128
Vis2	Arable	0-30	7.4	44.11	0.03	2.91	2.195	22.19	284.95	168.05	180.7	18.790	1.423	6.60	111.3
Vis3	Grass	0-30	7.23	49.18	<0.02	1.13	2.197	6.80	39.86	109.17	271.5	14.66	0.60	4.89	114.7
Vis4	Orchard	0-30	7.48	41.66	<0.02	9.52	1.32	3.38	133.66	119.20	149.2	40.42	0.54	7.31	34.09
vis5	Forest	0-30	7.19	51.72	0.02	<0,1	3.45	29.34	41.25	108.66	411.8	14.20	1.05	3.6	127
vis6	Forest	0-30	4.87	52.63	0.04	<0,1	3.28	42.79	42.77	127.04	249.7	9.79	1.50	5.20	198.2
vis7	Grass	0-30	5.38	44.11	<0.02	<0,1	1.60	4.06	32.07	97.30	279.9	13.29	<0,5	2.36	116
vis8	Arable	0-30	7.02	46.15	0.05	<0,1	2.76	42.48	782.50	698.72	194.3	12.39	4.50	3.51	151.2
vis9	Arable	0-30	6.56	46.15	0.09	<0,1	2.97	61.38	474.44	357.87	281.9	12.39	2.20	3.35	143.7
vis10	Orchard	0-30	5.94	55.00	0.03	<0,1	2.58	23.54	140.30	136.78	363	12.12	1.87	25.48	132.8
vis11	Arable	0-30	7.29	51.72	0.07	11.14	3.58	54.62	1050.53	938.78	274.6	47.29	4.45	3.016	22.84
vis12	Forest	0-30	7.23	52.00	0.04	2.43	2.42	30.24	83.77	138.45	236	15.00	1.01	4.14	124.3
vis13	Grass	0-30	5.69	44.77	<0,02	<0,1	1.72	16.16	62.83	98.00	282.4	14.04	1.28	4.59	158.4
vis14	Arable	0-30	6.98	58.82	0.13	<0,1	3.43	82.99	377.54	697.64	301.5	27.09	2.37	2.92	137.7
vis15	Grass	0-30	5.32	43.47	<0,02	<0,1	2.34	3.49	78.99	147.28	261.6	7.93	0.99	2.79	140.2
vis16	Orchard	0-30	5.14	47.61	<0,02	<0,1	2.04	3.45	44.32	122.67	279.7	9.87	0.98	2.69	164.2
vis17	Forest	0-30	4.44	46.87	<0,02	<0,1	1.88	15.51	36.91	132.77	236.8	9.68	0.75	2.18	136.1
vis18	Forest	0-30	4.99	46.87	<0,02	<0,1	2.66	14.13	143.29	194.73	273.1	7.01	1.27	8.60	127.9
vis19	Grass	0-30	5.17	48.38	<0,02	<0,1	2.32	16.84	44.61	109.86	257.3	10.08	0.74	4.96	124.6
vis20	Orchard	0-30	6.34	50.00	0.05	<0,1	2.78	49.13	190.70	421.51	268	10.73	2.04	1.77	131.6
Vis1	Orchard	30-60	4.49	45.45	<0,02	<0,1	2.09	10.36	36.95	115.62	279	14.27	0.64	1.78	128
Vis2	Arable	30-60	5.69	45.45	<0,02	2.76	1.36	6.82	39.54	110.29	326.4	16.76	0.56	1.964	125.2
Vis3	Grass	30-60	6.95	42.86	<0,02	0.00	1.08	6.63	120.23	118.00	170.5	19.39	0.82	4.849	101.6
Vis4	Orchard	30-60	6.93	41.10	<0,02	10.38	1.36	0.95	37.21	101.97	207.5	12.24	0.52	4.198	104.4
vis5	Forest	30-60	7.41	43.48	<0,02	3.81	1.08	3.57	119.93	121.64	203.1	38.66	0.54	7.617	38.4
vis6	Forest	30-60	7.24	46.15	<0,02	0.00	1.73	7.11	40.06	100.41	321	18.79	0.49	3.199	85.41
vis7	Grass	30-60	6.26	45.45	<0,02	0.00	0.95	1.98	48.12	98.69	299.8	13.60	<0,5	2.286	109.3
vis8	Arable	30-60	4.73	45.45	0.030	0.00	1.85	25.75	35.56	103.36	227.6	9.20	0.93	3.867	153.2
vis9	Arable	30-60	6.98	42.86	<0,02	0.00	1.55	1.07	678.18	509.68	241.9	15.96	3.85	2.426	133.3
vis10	Orchard	30-60	6.28	46.15	0.043	0.00	1.68	26.70	148.16	147.70	255.3	13.53	1.17	2.9	134.1

vis11	Arable	30-60	6.7	44.78	<0,02	12.16	1.02	2.45	165.45	116.37	323.7	12.08	0.81	7.861	108.2
vis12	Forest	30-60	7.44	46.00	0.023	1.42	1.71	19.45	503.11	271.70	197.5	47.90	2.42	1.947	17.5
vis13	Grass	30-60	7.08	45.45	<0,02	0.00	1.21	14.92	47.50	102.67	206.2	12.15	0.65	3.846	116.5
vis14	Arable	30-60	6.3	42.25	<0,02	0.00	1.28	4.32	74.76	100.87	327.8	10.68	0.77	3.252	143.1
vis15	Grass	30-60	6.52	36.00	0.049	1.22	1.08	22.64	78.24	132.97	307	26.27	0.89	2.33	130.1
vis16	Orchard	30-60	6.93	40.00	<0,02	0.00	1.32	1.28	53.88	121.92	270.7	11.74	0.70	3.609	103.9
vis17	Forest	30-60	5.26	47.62	<0,02	0.00	1.04	5.46	30.62	105.36	269.8	15.96	0.67	2.627	160.1
vis18	Forest	30-60	5.58	42.86	<0,02	0.00	0.90	1.13	58.65	111.13	277.1	12.08	0.50	1.877	127.4
vis19	Grass	30-60	6.33	40.00	<0,02	0.00	1.08	1.89	64.91	107.67	298.9	11.65	0.83	15.55	128.7
vis20	Orchard	30-60	5.5	42.86	<0,02	0.00	1.08	4.66	50.48	90.07	252.9	9.72	<0,5	3.25	106.9

Table A. 4. Results of soil properties in Zselic area (M1: Magyarlukafa, 0-30cm and 30-60 cm)

Samples	Land use	Land use	Depth [cm]	pH (KCl)	texture (KA)	Salinity% (m/m)	$CaCO_3$% (m/m)	Humus % (m/m)	NO_2 + NO_3 (KCl soluble) (mg/kg)	P_2O_5 (mg/kg)	K2O (mg/kg)	Mg (mg/kg)	Na (mg/kg)	Zn (mg/kg)	Cu (mg/kg)
M1	Arable	0-30	7.34	48.38	<0,02	3.04	2.03	17.55	1163.66	457.78	166.4	17.55	3.50	2.79	125.50
M2	Arable	0-30	8.46	37.50	0.07	5.06	1.59	36.55	2596.16	1883.62	227.6	42.60	5.35	2.50	45.59
M3	Forest	0-30	6.76	50.84	0.04	<0.1	2.17	26.52	804.23	328.43	258.6	8.73	3.28	2.44	149.40
M4	Arable	0-30	6.93	43.47	0.03	1.58	2.10	23.47	2979.51	647.51	250.6	24.25	7.27	3.76	148.00
M5	Arable	0-30	7.36	41.09	0.05	<0.1	1.57	19.41	1044.17	495.11	220.8	14.21	4.40	2.63	162.50
M6	Orchard	0-30	7.10	50.00	0.03	<0.1	1.96	19.21	613.50	290.33	275.4	8.45	3.74	2.44	158.90
M7	Arable	0-30	7.12	44.77	0.06	4.86	2.28	54.13	3809.83	734.81	214.0	27.79	8.29	3.71	65.48
M8	Orchard	0-30	6.63	52.63	0.04	0.64	2.37	12.31	479.47	180.62	330.2	13.89	2.28	19.63	105.00
M9	Forest	0-30	4.76	50.00	<0,02	<0.1	3.47	32.25	300.60	255.68	227.6	9.76	1.28	2.04	128.50
M10	Grass	0-30	6.47	46.87	<0,02	<0.1	2.18	5.64	50.415	106.00	331.3	9.02	0.80	2.91	155.40
M11	Orchard	0-30	7.39	47.62	0.05	6.89	2.38	47.86	1246.68	745.84	234.5	31.31	4.48	2.79	44.18
M12	Arable	0-30	7.36	40.54	0.04	4.05	1.91	36.89	3039.05	525.16	232.8	36.98	5.74	5.37	91.34
M13	Grass	0-30	7.64	63.82	0.06	7.49	3.23	32.61	273.67	180.49	352.9	86.56	1.22	2.86	61.87
M14	Orchard	0-30	7.29	53.57	0.03	<0.1	2.50	23.21	412.92	375.52	234.5	8.130	1.67	2.08	142.50
M15	Orchard	0-30	7.18	52.63	0.03	4.94	2.32	21.28	623.87	181.89	176.0	19.72	1.53	1.62	82.29
M16	Grass	0-30	7.14	58.82	0.05	<0.1	4.01	27.06	59.55	102.21	388.0	39.74	0.99	3.57	207.50
M17	Forest	0-30	4.98	53.57	<0,02	<0.1	3.64	23.49	36.85	127.71	319.4	6.35	1.09	2.16	127.00
M18	Grass	0-30	7.03	56.60	0.03	4.86	2.92	26.02	232.46	163.41	179.5	19.83	1.41	1.88	81.24
M19	Forest	0-30	5.39	54.54	0.03	<0.1	3.77	26.40	86.70	159.05	357.5	7.99	1.25	9.66	151.20
M20	Grass	0-30	5.93	50.00	<0,02	<0.1	2.12	8.66	17.99	99.70	323.0	10.03	0.47	1.32	114.40
M21	Forest	0-30	7.89	41.09	0.05	2.246	1.50	21.40	1977.90	1417.18	251.2	31.65	7.85	2.33	113.00

Appendix B: Environmental covariates in the study area (S: Szentendre Island, M: Magyarlukafa, V: Zselic-Visnyeszéplak and Józsefmajor)

Table B. 1. Environmental covariates in the study area (S: Szentendre Island, M: Magyarlukafa, V: Visnyeszéplak and Józsefmajor)

ID	Altitude	Slope	TPI	TRI	surface_area	MRVBF	MRRTF	LS_factor	TWI	Precipitation	Temperature	Evapotranspiration	Evaporation
S1	102.45	0.69	0.24	0.48	1.00	4.99	1.82	0.01	13.07	569.40	11.65	1170.55	544.70
S2	102.45	0.69	0.24	0.48	1.00	4.99	1.82	0.01	13.07	569.40	11.65	1170.55	544.70
S3	102.45	0.69	0.24	0.48	1.00	4.99	1.82	0.01	13.07	569.40	11.65	1170.55	544.70
S4	102.45	0.69	0.24	0.48	1.00	4.99	1.82	0.01	13.07	569.40	11.65	1170.55	544.70
S5	102.45	0.69	0.24	0.48	1.00	4.99	1.82	0.01	13.07	569.40	11.65	1170.55	544.70
S6	102.39	1.33	-0.04	0.58	1.00	4.99	2.97	0.06	12.15	569.07	11.61	1168.02	543.94
S7	102.39	1.33	-0.04	0.58	1.00	4.99	2.97	0.06	12.15	569.07	11.61	1168.02	543.94
S8	102.39	1.33	-0.04	0.58	1.00	4.99	2.97	0.06	12.15	569.07	11.61	1168.02	543.94
S9	102.39	1.33	-0.04	0.58	1.00	4.99	2.97	0.06	12.15	569.07	11.61	1168.02	543.94
S10	102.39	1.33	-0.04	0.58	1.00	4.99	2.97	0.06	12.15	569.07	11.61	1168.02	543.94
S11	105.08	0.66	0.23	0.58	1.00	5.99	3.99	0.09	11.63	567.12	11.34	1156.70	552.98
S12	105.08	0.66	0.23	0.58	1.00	5.99	3.99	0.09	11.63	567.12	11.34	1156.70	552.98
S13	105.08	0.66	0.23	0.58	1.00	5.99	3.99	0.09	11.63	567.12	11.34	1156.70	552.98
S14	105.08	0.66	0.23	0.58	1.00	5.99	3.99	0.09	11.63	567.12	11.34	1156.70	552.98
S15	105.08	0.66	0.23	0.58	1.00	5.99	3.99	0.09	11.63	567.12	11.34	1156.70	552.98
S16	101.86	0.90	-0.33	0.76	1.00	4.78	0.51	0.36	11.93	568.90	11.71	1166.70	549.35
S17	101.86	0.90	-0.33	0.76	1.00	4.78	0.51	0.36	11.93	568.90	11.71	1166.70	549.35
S18	101.86	0.90	-0.33	0.76	1.00	4.78	0.51	0.36	11.93	568.90	11.71	1166.70	549.35
S19	101.86	0.90	-0.33	0.76	1.00	4.78	0.51	0.36	11.93	568.90	11.71	1166.70	549.35
S20	101.86	0.90	-0.33	0.76	1.00	4.78	0.51	0.36	11.93	568.90	11.71	1166.70	549.35
S21	101.86	0.90	-0.33	0.76	1.00	4.78	0.51	0.36	11.93	568.90	11.71	1166.70	549.35
S22	101.86	0.90	-0.33	0.76	1.00	4.78	0.51	0.36	11.93	568.90	11.71	1166.70	549.35
S23	101.86	0.90	-0.33	0.76	1.00	4.78	0.51	0.36	11.93	568.90	11.71	1166.70	549.35
S24	101.86	0.90	-0.33	0.76	1.00	4.78	0.51	0.36	11.93	568.90	11.71	1166.70	549.35
S25	101.86	0.90	-0.33	0.76	1.00	4.78	0.51	0.36	11.93	568.90	11.71	1166.70	549.35
S26	106.48	1.06	0.99	1.32	1.00	4.86	3.25	0.17	10.87	568.32	11.71	1171.93	548.98
S27	106.48	1.06	0.99	1.32	1.00	4.86	3.25	0.17	10.87	568.32	11.71	1171.93	548.98
S28	106.48	1.06	0.99	1.32	1.00	4.86	3.25	0.17	10.87	568.32	11.71	1171.93	548.98
S29	106.48	1.06	0.99	1.32	1.00	4.86	3.25	0.17	10.87	568.32	11.71	1171.93	548.98
S30	106.48	1.06	0.99	1.32	1.00	4.86	3.25	0.17	10.87	568.32	11.71	1171.93	548.98
S31	101.47	0.06	0.09	0.17	1.00	3.96	2.84	0.00	13.87	561.51	11.19	1083.84	535.20
S32	101.47	0.06	0.09	0.17	1.00	3.96	2.84	0.00	13.87	561.51	11.19	1083.84	535.20

S33	101.47	0.06	0.09	0.17	1.00	3.96	2.84	0.00	13.87	561.51	11.19	1083.84	535.20
S34	101.47	0.06	0.09	0.17	1.00	3.96	2.84	0.00	13.87	561.51	11.19	1083.84	535.20
S35	101.47	0.06	0.09	0.17	1.00	3.96	2.84	0.00	13.87	561.51	11.19	1083.84	535.20
S36	101.41	0.39	0.23	0.42	1.00	4.90	2.44	0.00	14.05	561.32	11.19	1084.71	532.34
S37	101.41	0.39	0.23	0.42	1.00	4.90	2.44	0.00	14.05	561.32	11.19	1084.71	532.34
S38	101.41	0.39	0.23	0.42	1.00	4.90	2.44	0.00	14.05	561.32	11.19	1084.71	532.34
S39	101.41	0.39	0.23	0.42	1.00	4.90	2.44	0.00	14.05	561.32	11.19	1084.71	532.34
S40	101.41	0.39	0.23	0.42	1.00	4.90	2.44	0.00	14.05	561.32	11.19	1084.71	532.34
S41	102.42	0.64	0.95	1.78	1.00	3.96	2.04	0.08	11.73	562.01	11.20	1080.84	544.87
S42	102.42	0.64	0.95	1.78	1.00	3.96	2.04	0.08	11.73	562.01	11.20	1080.84	544.87
S43	102.42	0.64	0.95	1.78	1.00	3.96	2.04	0.08	11.73	562.01	11.20	1080.84	544.87
S44	102.42	0.64	0.95	1.78	1.00	3.96	2.04	0.08	11.73	562.01	11.20	1080.84	544.87
S45	102.42	0.64	0.95	1.78	1.00	3.96	2.04	0.08	11.73	562.01	11.20	1080.84	544.87

id	Altitude	Slope	TPI	TRI	surface_area	MRVBF	MRRTF	LS_factor	TWI	Precipitation	Temperature	Evapotranspiration	Evaporation
M1	142.74	6.82	-0.35	5.17	0.99	0.42	0.15	2.47	10.88	706.18	10.47	967.90	694.65
M2	146.47	8.09	1.60	6.03	0.99	0.17	0.14	2.92	10.38	706.16	10.45	967.02	693.57
M3	156.71	8.86	0.41	6.17	0.99	0.10	0.13	3.60	9.34	706.31	10.44	967.01	693.92
M4	137.96	4.71	-2.19	4.40	1.00	1.28	0.06	3.02	11.53	705.88	10.46	967.53	694.45
M5	145.10	3.68	0.80	3.07	1.00	0.23	1.49	1.07	10.20	707.81	10.47	968.13	692.86
M6	145.50	4.03	-0.23	2.63	1.00	1.02	0.28	1.62	10.98	707.96	10.46	967.81	693.00
M7	142.74	6.82	-0.35	5.17	0.99	0.42	0.15	2.47	10.88	706.18	10.47	967.90	694.65
M8	215.74	3.89	4.14	7.03	1.00	0.09	1.27	0.67	10.35	731.20	10.41	964.67	694.12
M9	198.48	7.49	-1.47	6.58	0.99	0.27	0.09	3.32	10.22	726.69	10.40	964.95	694.90
M10	174.27	1.56	1.58	2.82	1.00	0.07	2.61	0.37	10.34	707.93	10.44	966.87	695.13
M11	142.74	6.82	-0.35	5.17	0.99	0.42	0.15	2.47	10.88	706.18	10.47	967.90	694.65
M12	142.74	6.82	-0.35	5.17	0.99	0.42	0.15	2.47	10.88	706.18	10.47	967.90	694.65
M13	136.29	0.58	-0.94	1.58	1.00	3.91	0.02	3.14	12.70	706.79	10.48	968.21	694.57
M14	146.47	8.09	1.60	6.03	0.99	0.17	0.14	2.92	10.38	706.16	10.45	967.02	693.57
M15	155.01	4.83	-0.50	5.47	1.00	0.53	0.28	2.76	11.50	706.12	10.44	967.07	694.11
M16	137.89	5.41	-1.86	4.10	1.00	1.03	0.10	3.52	10.95	706.24	10.42	966.49	695.09
M17	150.61	9.35	0.43	7.57	0.99	0.04	0.07	3.72	10.19	706.01	10.41	966.43	696.02
M18	140.90	4.16	0.78	3.09	1.00	0.35	0.91	1.10	10.34	708.96	10.48	968.47	691.49
M19	178.64	3.69	0.02	3.25	1.00	1.11	0.13	0.98	11.61	734.22	10.43	964.82	697.52
M20	178.64	3.69	0.02	3.25	1.00	1.11	0.13	0.98	11.61	734.22	10.43	964.82	697.52
M21	200.46	1.52	2.96	4.13	1.00	0.00	2.67	0.30	10.43	734.76	10.44	964.06	695.67

id	Altitude	Slope	TPI	TRI	Surface area	MRVBF	MRRTF	LS_factor	TWI	Precipitation	Temperature	Evapotranspiration	Evaporation
V1	224.37	8.61	2.96	8.81	0.99	0.15	0.07	1.30	11.31	740.69	10.26	952.72	693.13
V2	235.10	4.83	-0.23	4.90	1.00	0.70	0.15	1.89	11.55	754.40	10.24	951.00	683.41
V3	242.00	5.72	-1.32	5.06	1.00	0.71	0.08	1.72	11.05	754.10	10.22	951.07	682.50
V4	242.00	5.72	-1.32	5.06	1.00	0.71	0.08	1.72	11.05	754.10	10.22	951.07	682.50
V5	210.04	6.68	-2.29	5.90	0.99	0.75	0.02	2.66	12.05	748.94	10.28	951.11	685.75
V6	236.43	0.59	-0.74	1.23	1.00	2.02	2.88	1.94	13.10	735.49	10.28	950.79	689.77
V7	238.57	2.34	-0.12	2.57	1.00	0.53	1.43	1.63	10.78	740.36	10.27	950.87	688.94
V8	241.61	4.56	-0.81	4.07	1.00	0.56	0.27	2.32	10.79	744.64	10.26	950.98	688.14
V9	224.37	8.61	2.96	8.81	0.99	0.15	0.07	1.30	11.31	740.69	10.26	952.72	693.13
V10	242.21	3.05	0.24	3.09	1.00	0.69	0.81	0.72	11.89	753.17	10.21	951.01	683.57
V11	242.21	3.05	0.24	3.09	1.00	0.69	0.81	0.72	11.89	753.17	10.21	951.01	683.57
V12	246.19	1.07	-0.02	1.68	1.00	1.45	2.92	0.42	12.08	751.81	10.19	951.13	682.82
V13	248.63	1.59	0.92	2.04	1.00	0.32	2.97	0.29	11.14	752.40	10.20	951.14	682.06
V14	234.92	5.30	1.84	5.69	1.00	0.20	0.58	1.35	10.84	753.63	10.26	951.05	684.38
V15	228.25	4.09	-1.07	4.04	1.00	1.20	0.26	1.70	12.44	751.65	10.27	951.09	685.57
V16	234.92	5.30	1.84	5.69	1.00	0.20	0.58	1.35	10.84	753.63	10.26	951.05	684.38
V17	237.40	5.49	0.37	4.51	1.00	0.55	0.21	1.37	12.56	753.44	10.26	951.11	684.63
V18	224.37	8.61	2.96	8.81	0.99	0.15	0.07	1.30	11.31	740.69	10.26	952.72	693.13
V19	229.15	2.88	-0.08	4.40	1.00	1.48	0.16	1.39	10.94	740.11	10.26	952.80	694.59
V20	246.04	3.12	0.39	2.42	1.00	0.57	2.80	0.70	10.45	731.65	10.15	952.90	689.00
V1	224.37	8.61	2.96	8.81	0.99	0.15	0.07	1.30	11.31	740.69	10.26	952.72	693.13
Józsefmajor	137.29	0.91	0.21	0.81	1.00	5.91	4.95	0.16	11.33	543.65	10.82	1042.65	590.17

Appendix C: Significance tests of the relationship between tillage operation practices and soil organic matter composition

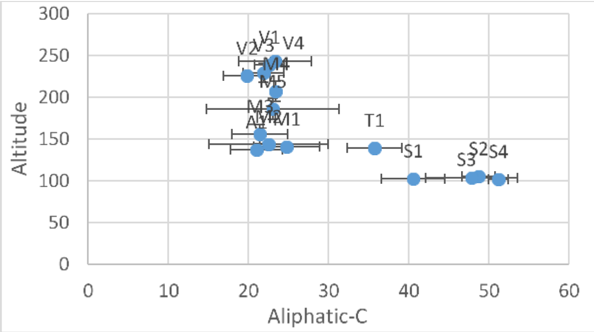
Table C1 multiple comparisons to find which land use/management is different from which based on soil size fraction and SOM composition

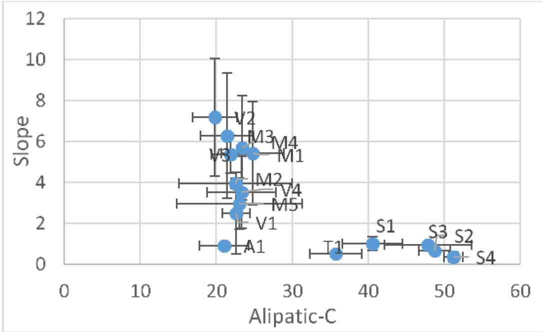
Contrast	Aliphatic-C-H	Amid	Aromatic-C	Aliphatic C-H phenolic lignin	polysaccharide	Aromaticity	C/O
contrast	sig	sig	sig	sig	sig	sig	sig
Dc F – Dc agg	*						
Dc F – Nt F							
Dc F – PF							
Dc F – TF	*		*				*
Dc agg – Nt agg	*		*				
Dc agg – P agg							
Dc agg – T agg	*	*	*	*	*	*	*
Nt F-Nt agg	*		*				
NtF – PF	*		*				
Nt F – T F	*		*				
Nt agg – P agg	*		*				
Nt agg – T agg	*	*	*	*	*		*
P F-P agg							
P F – T F	*		*				
P agg – T agg	*	*	*	*	*	*	*
T F – T agg	*	*	*			*	*

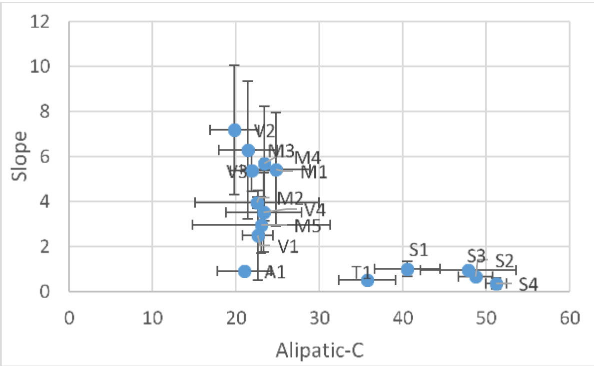
Table C2- Multiple comparisons to find which land use/management is different from which based on SOM composition in various pools

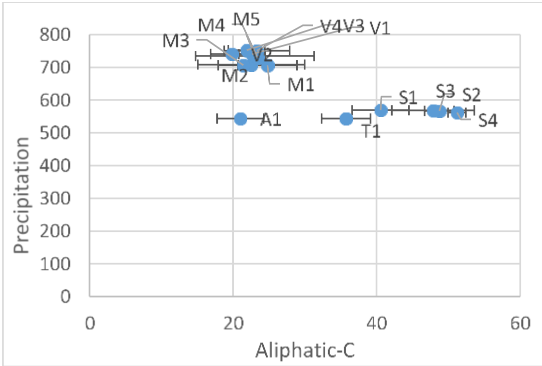
	Aliphatic C-H	Amid-N	Aromatic-C	lignin	polysaccharide	Aromaticity	C/O
Contrast	Sig.					sig	
Dc Agg – Dc F	*	*	*	*	*		*
Dc agg – Nt agg	*		*		*	*	*
Dc agg – P agg	*		*			*	
Dc F – Nt F	*		*				
Dc F – P F	*		*			*	
Nt agg – Nt F	*	*	*	*	*		*
Nt agg – P agg	*	*	*		*	*	*
Nt F – P F	*		*			*	
P F – P agg	*	*	*	*	*		*

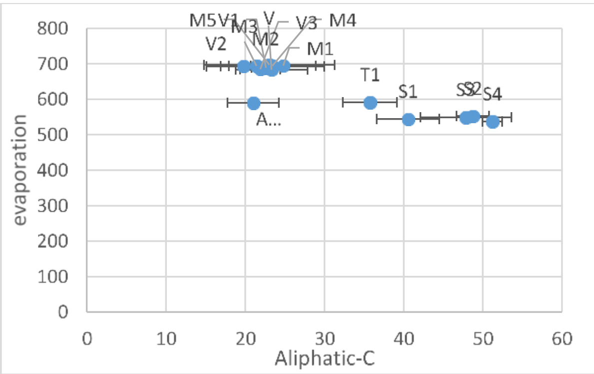
Appendix D: distribution plot of SOM composition based on environmental covariate

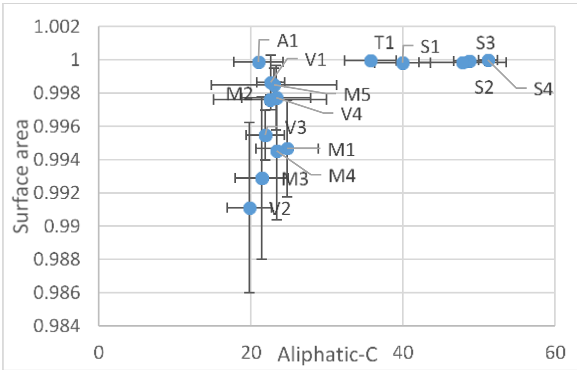


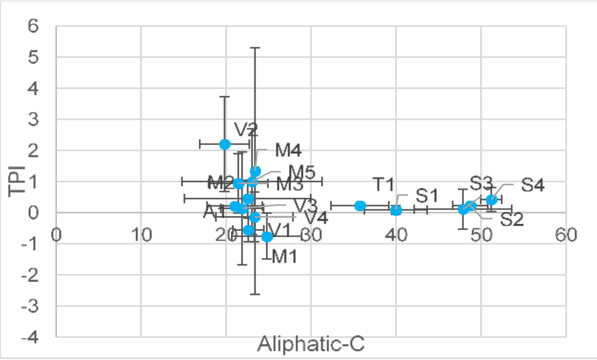


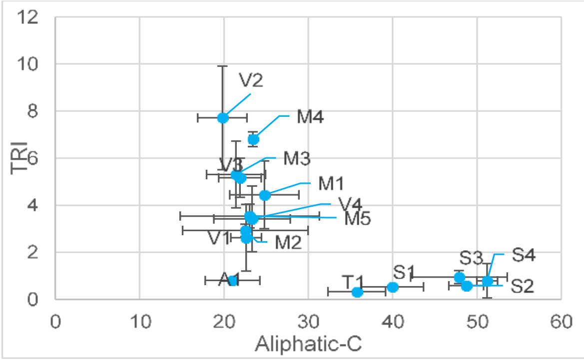









TPI
Aliphatic-C
V2
M4
M5
M2
M3
T1
S1
S3
S4
A1
V3
V4
S2
V1
M1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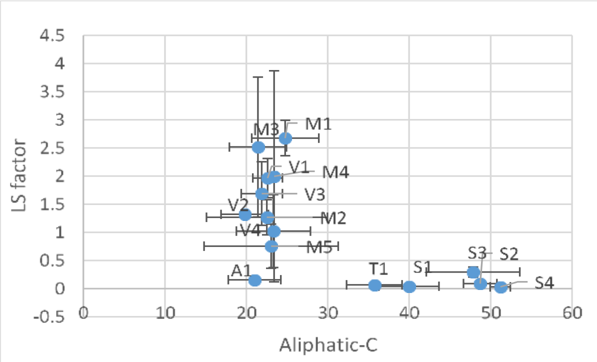
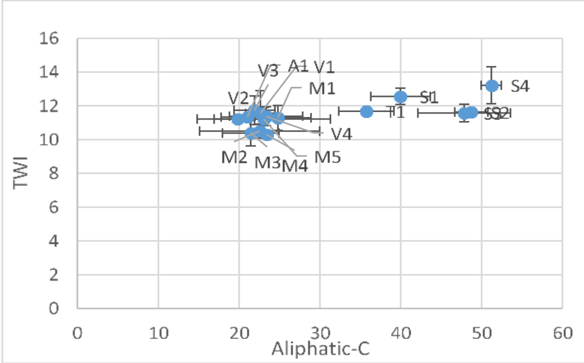
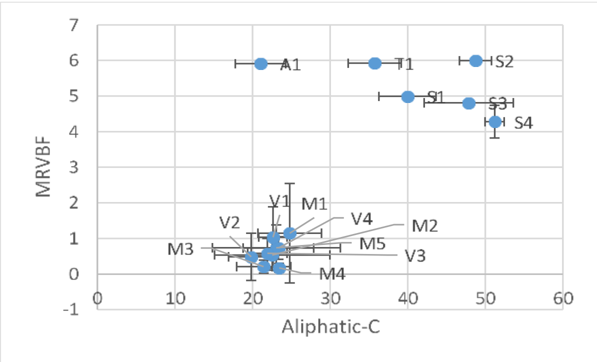
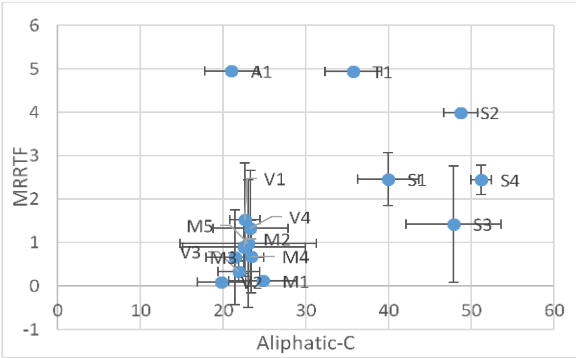
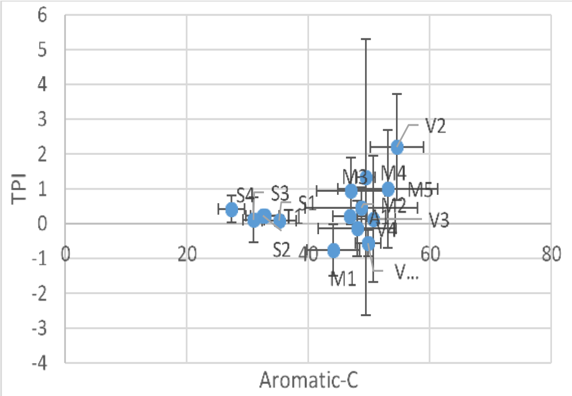
Aliphatic-C
V2
M4
M3
V3
M1
V4
M5
V1
M2
S3
S4
S1
T1
A1
S2

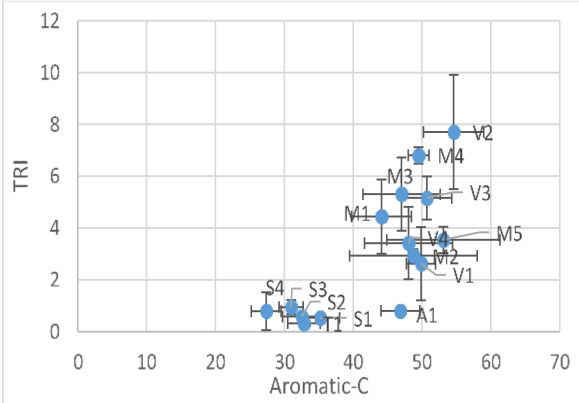

LS factor
Aliphatic-C
M3
M1
V1
M4
V3
V2
M2
V4
M5
A1
T1
S1
S3
S2
S4

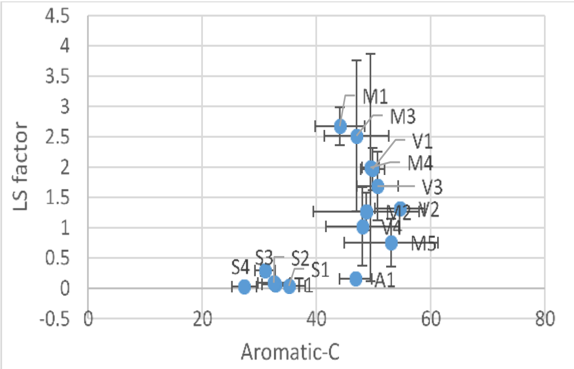

TWI
Aliphatic-C
V3
A1
V1
M1
V2
S1
S4
T1
S2
V4
M2
M3
M4
M5

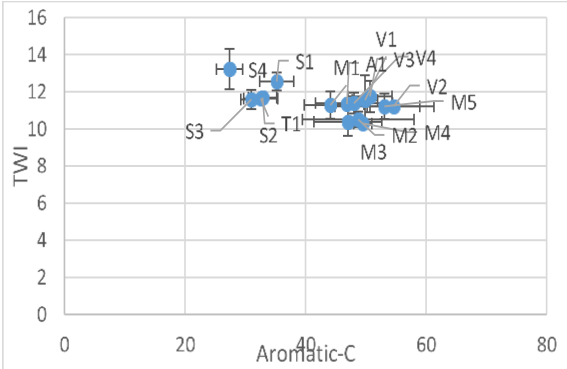

MRVBF
Aliphatic-C
A1
T1
S2
S1
S3
S4
V1
M1
V2
V4
M2
M3
M5
V3
M4

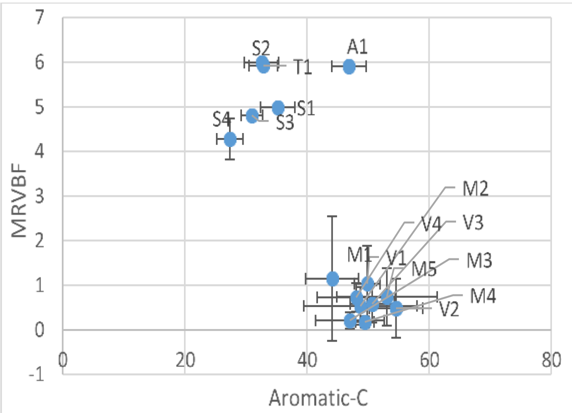

MRRTF
Aliphatic-C
A1
T1
S2
V1
S1
S4
M5
V4
S3
M2
V3
M3
M4
M1

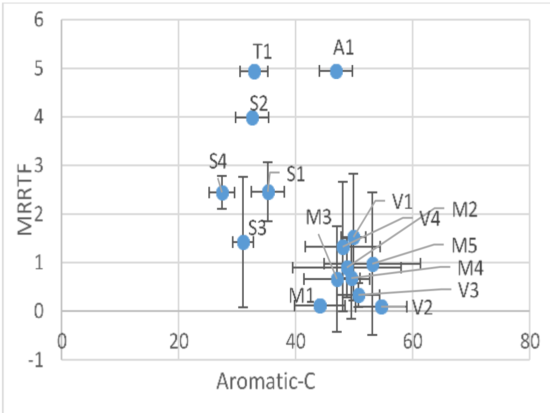

TPI
Aromatic-C
V2
M3
M4
M5
S4
S3
S1
T1
M2
A1
V3
V4
S2
M1
V...

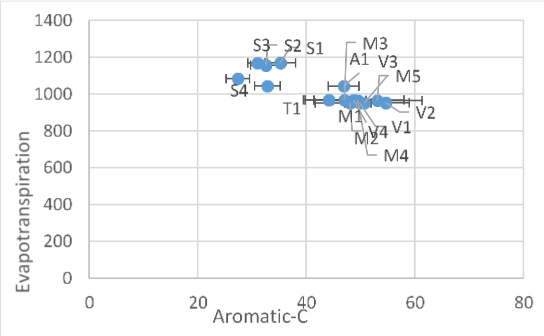

TRI
Aromatic-C
V2
M4
M3
V3
M1
M5
V4
M2
V1
S4
S3
S2
S1
T1
A1

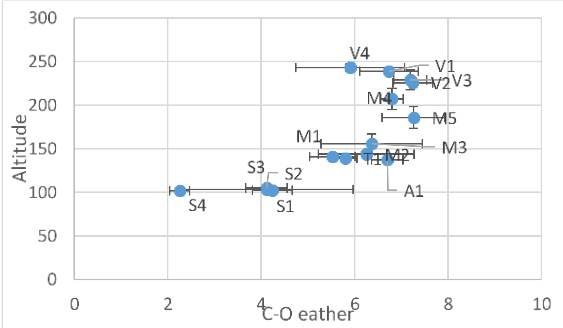

LS factor
Aromatic-C
M1
M3
V1
M4
V3
M2
V2
V4
M5
S4
S3
S2
S1
T1
A1

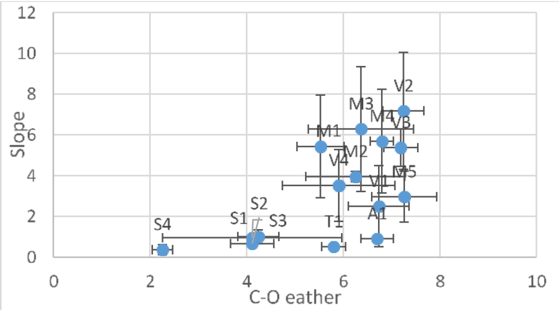

TWI
Aromatic-C
V1
S4
S1
M1
A1
V3V4
V2
M5
S3
S2
T1
M2
M4
M3

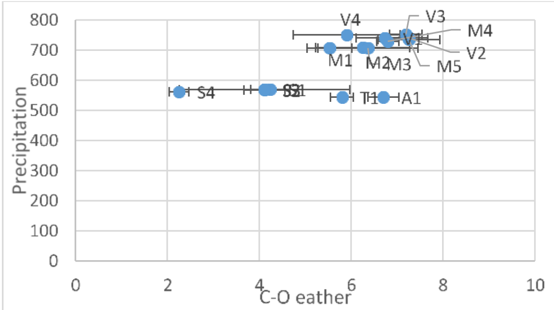

MRVBF
Aromatic-C
S2
A1
T1
S1
S4
S3
M2
V4
V3
M1
V1
M5
M3
M4
V2

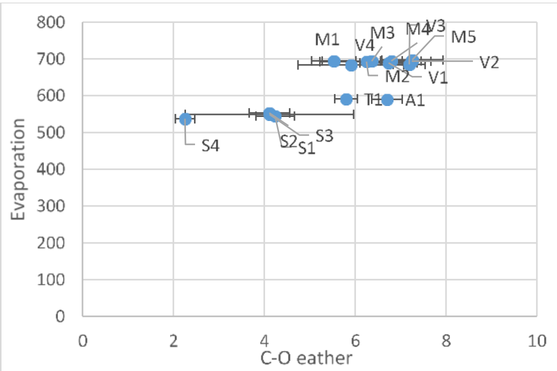

MRRTF
Aromatic-C
T1
A1
S2
S4
S1
S3
M3
V1
V4
M2
M5
M4
V3
M1
V2

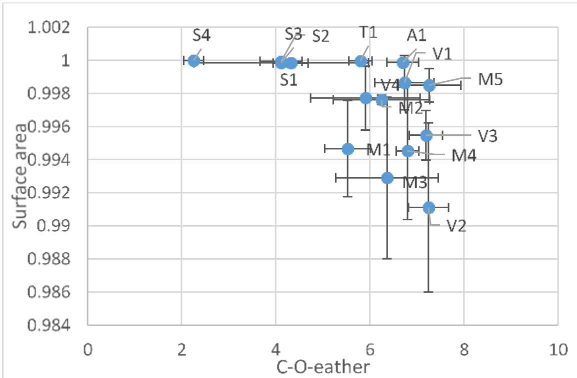

Evapotranspiration
Aromatic-C
S3 S2 S1 M3 A1 V3 M5 S4 T1 M1 V2 V4 V1 M2 M4

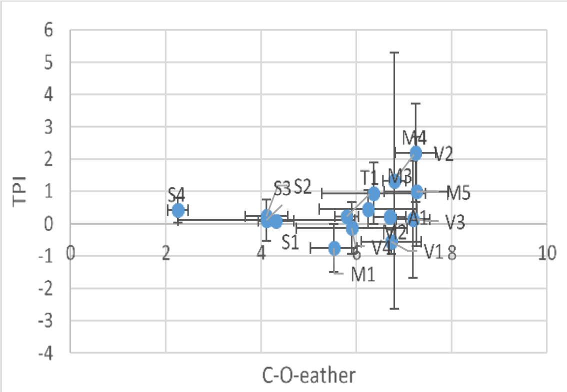

Altitude
C-O eather
V4 V1 V2 V3 M4 M5 M1 M3 M2 T1 S3 S2 A1 S4 S1

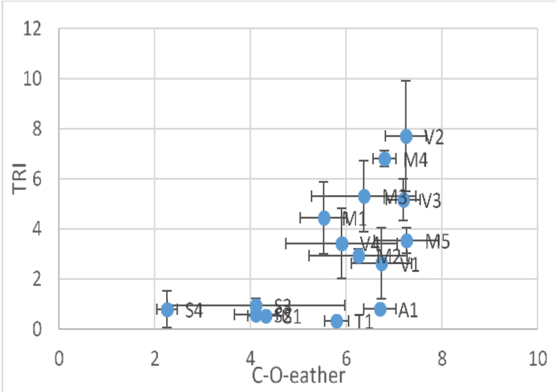

Slope
C-O eather
V2 M3 M4 V3 M1 M2 V4 M5 V1 S2 S1 S3 T1 A1 S4

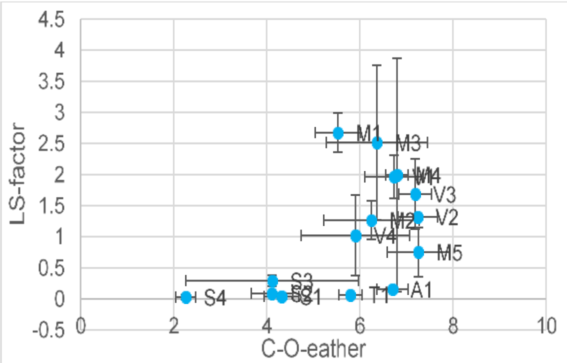

Precipitation
C-O eather
V4 V3 M4 V1 V2 M1 M2 M3 M5 S4 S2 S1 T1 A1

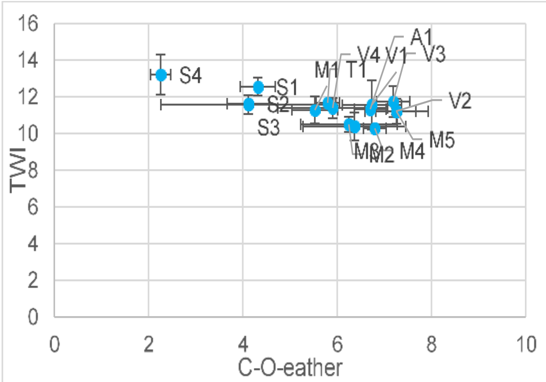

Evaporation
C-O eather
M1 V4 M3 M4 V3 M5 V2 M2 V1 T1 A1 S4 S3 S2 S1

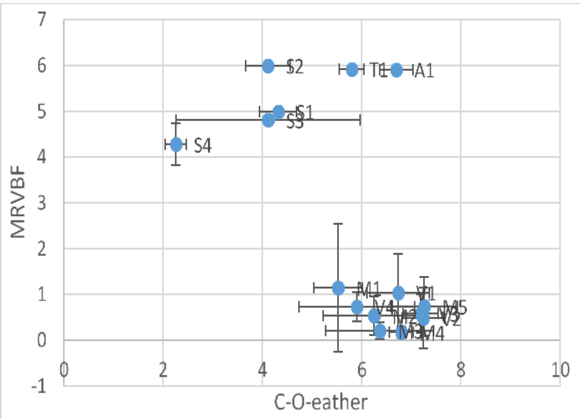

Surface area
C-O-eather
S4 S3 S2 T1 A1 V1 S1 V4 M5 M2 V3 M1 M4 M3 V2

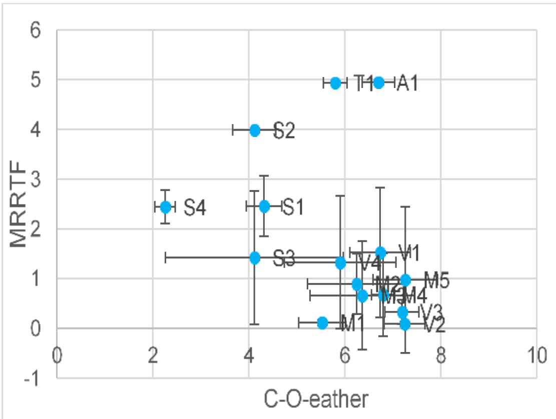

TPI
C-O-eather
S4
S3 S2
S1
T1 M3
M4
V2
M5
A1
V3
M2
V4
V1
M1

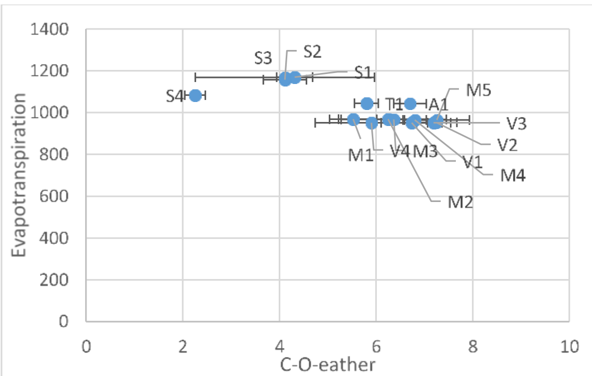

TRI
C-O-eather
V2
M4
M3
V3
M1
V4
M5
M2
V1
S4
S3
S1
A1
T1

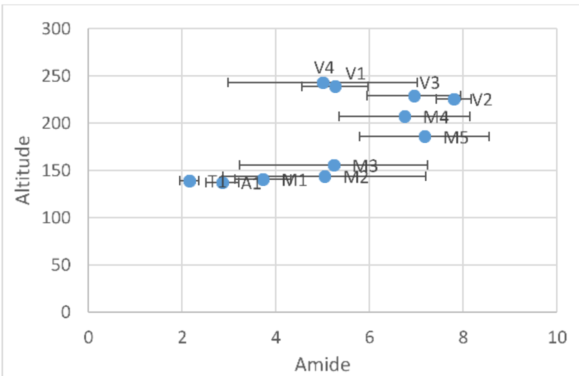

LS-factor
C-O-eather
M1
M3
M4
V3
M2
V2
V4
M5
S3
S4
S1
T1
A1

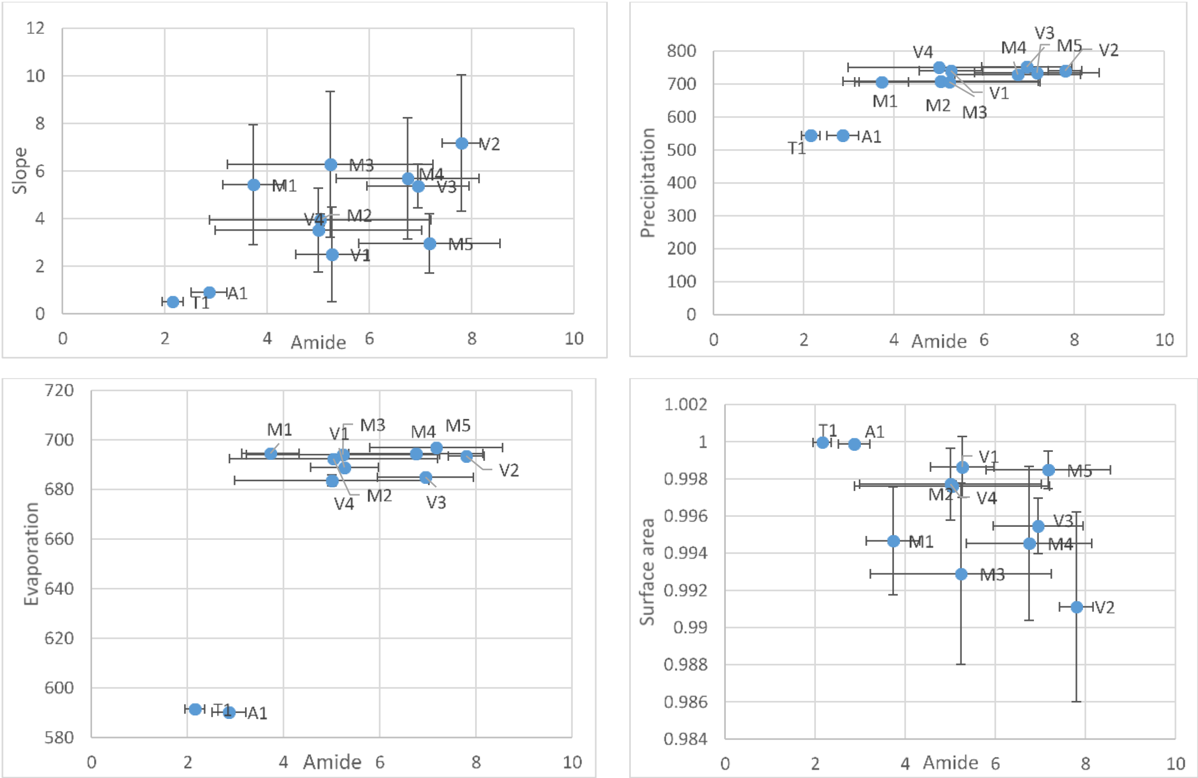

TWI
C-O-eather
S4
S1
S2
S3
M1 T1
V4 V1
A1
V3
V2
M5
M2 M4

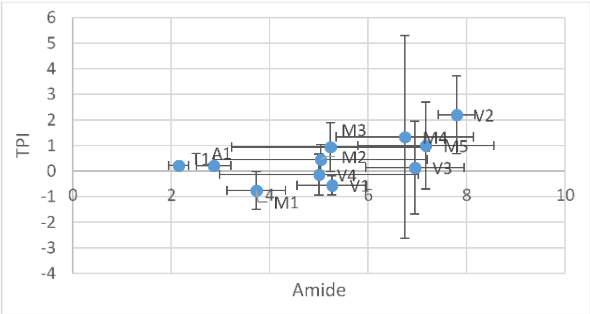

MRVBF
C-O-eather
S2
T1
A1
S1
S3
S4
M1
V1
V4
M5
V2
M4

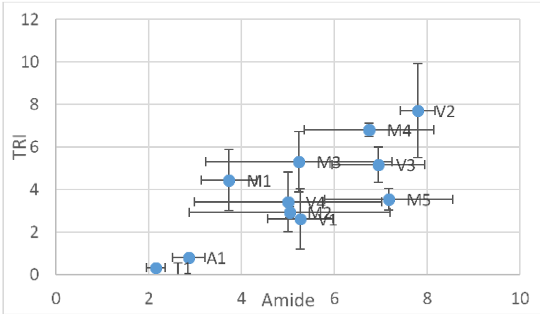

MRRTF
C-O-eather
T1
A1
S2
S4
S1
S3
V1
V4
M5
M4
V3
M1
V2

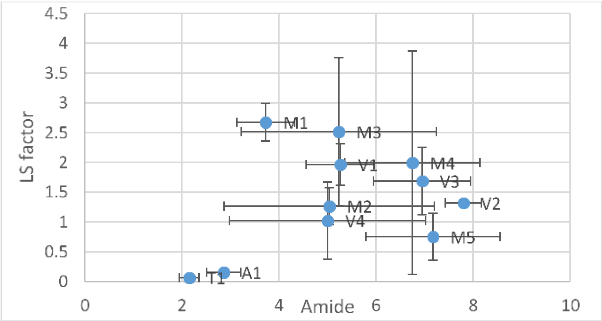

Evapotranspiration
C-O-eather
S3
S2
S1
S4
M5
T1
A1
V3
V2
M1
V4
M3
V1
M4
M2

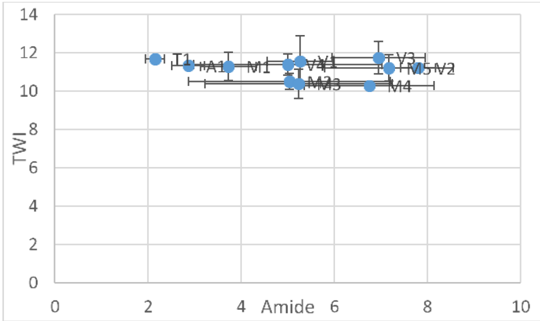

Altitude
Amide
V4
V1
V3
V2
M4
M5
M3
M2
M1
A1

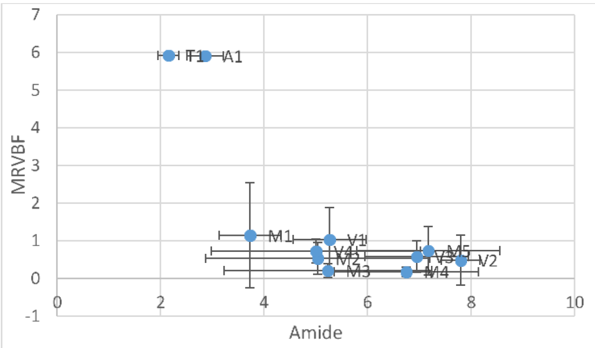

Slope
Amide
T1
A1
M1
M2
M3
M4
M5
V1
V2
V3
V4
Precipitation
Amide
T1
A1
M1
M2
M3
M4
M5
V1
V2
V3
V4
Evaporation
Amide
T1
A1
M1
M2
M3
M4
M5
V1
V2
V3
V4
Surface area
Amide
T1
A1
M1
M2
M3
M4
M5
V1
V2
V3
V4

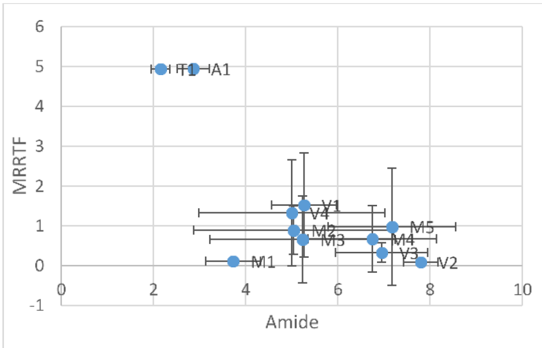

TPI
Amide
T1
A1
M1
M2
M3
M4
M5
V1
V2
V3
V4

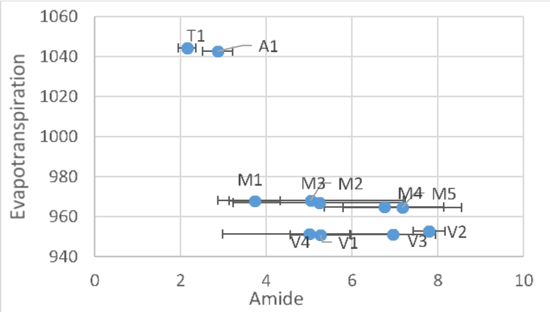

TRI
Amide
T1
A1
M1
M3
M4
M5
V1
V2
V3
V4

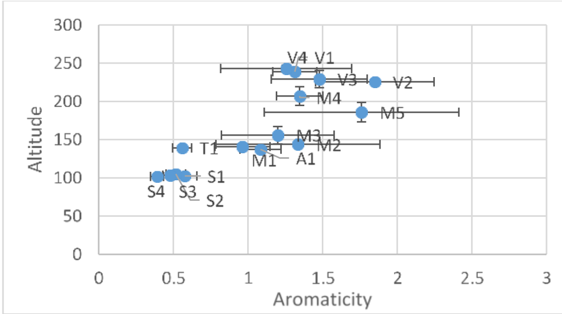

LS factor
Amide
T1
A1
M1
M2
M3
M4
M5
V1
V2
V3
V4

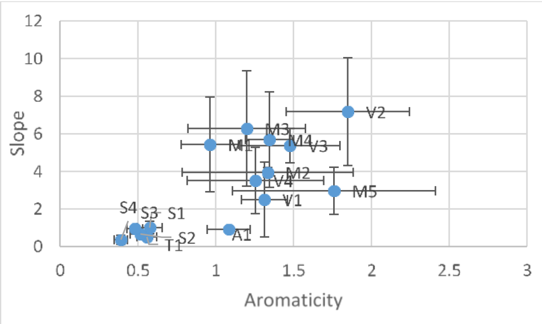

TWI
Amide
T1
M1
M4
V3

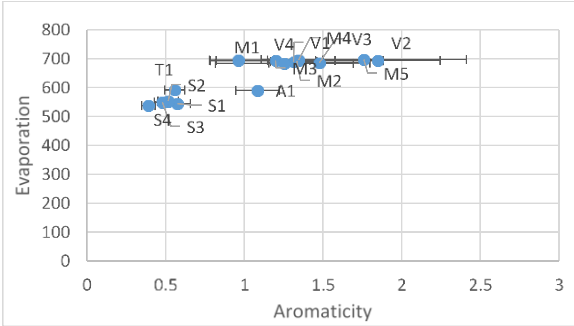

MRVBF
Amide
A1
M1
M2
M3
M5
V1
V2

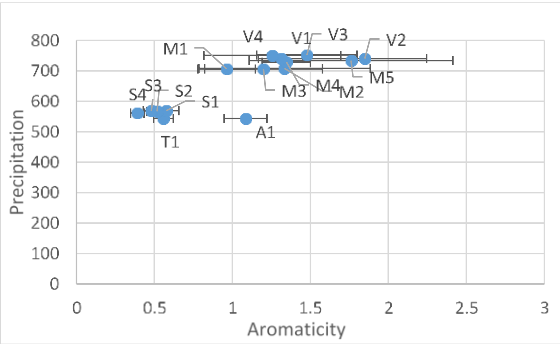

MRRTF
Amide
A1
M1
M2
M3
M4
M5
V1
V2
V3
V4

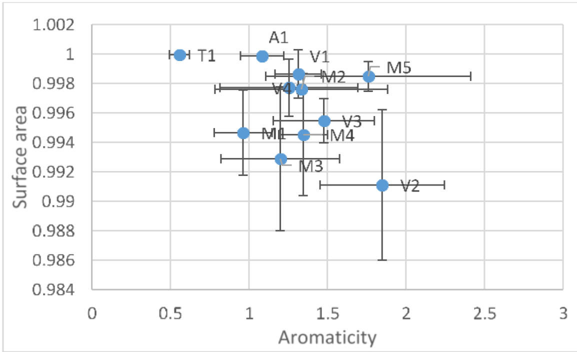

Evapotranspiration
Amide
T1
A1
M1
M3
M2
M4
M5
V4
V1
V3
V2

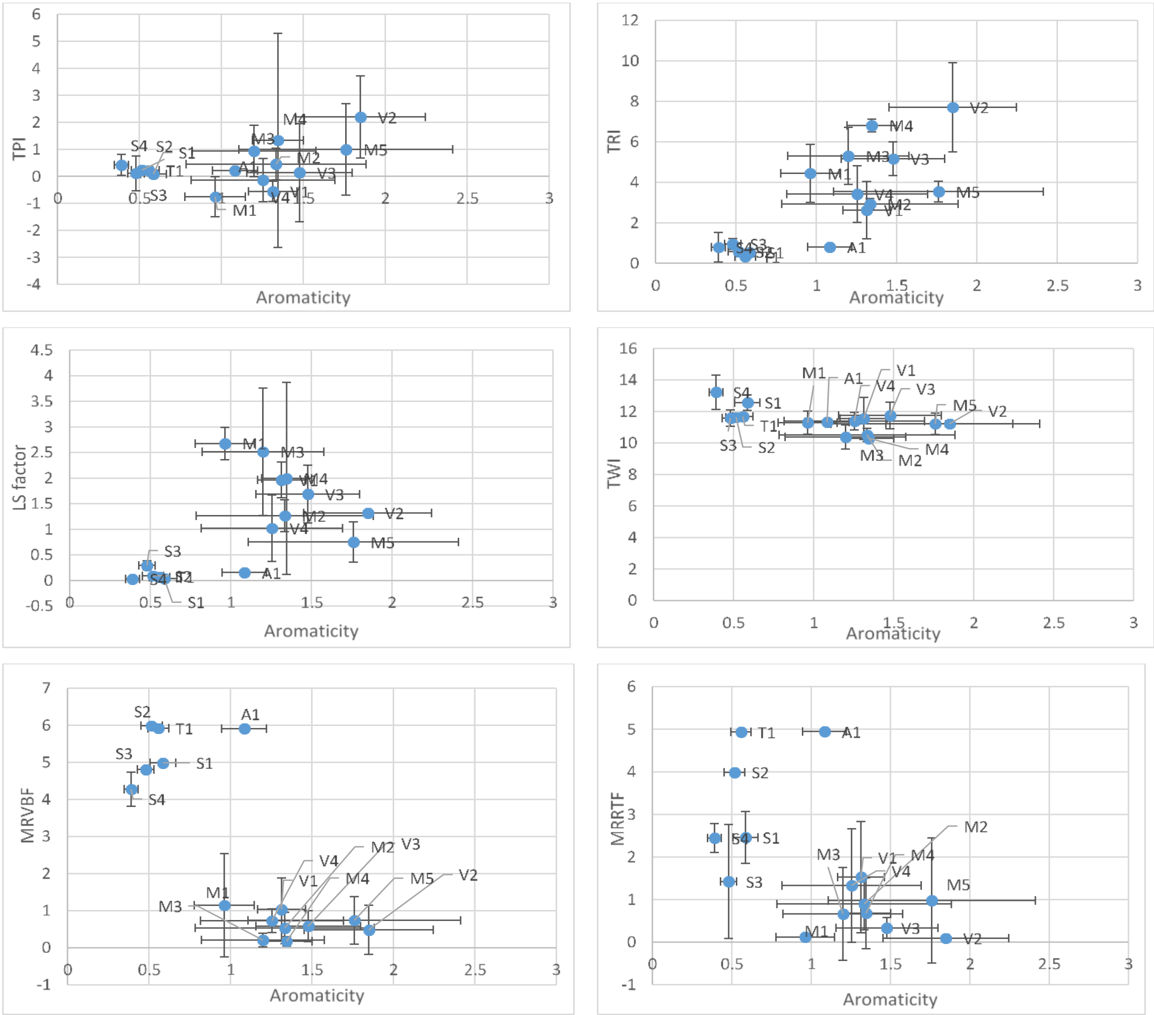

Altitude
Aromaticity
V4
V1
V3
V2
M4
M5
M3
M2
T1
M1
A1
S4
S3
S2
S1

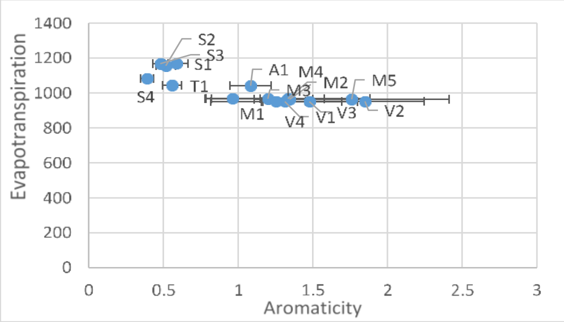

Slope
Aromaticity
V2
M3
M4
V3
M1
M2
V4
M5
V1
S4
S3
S1
S2
T1
A1

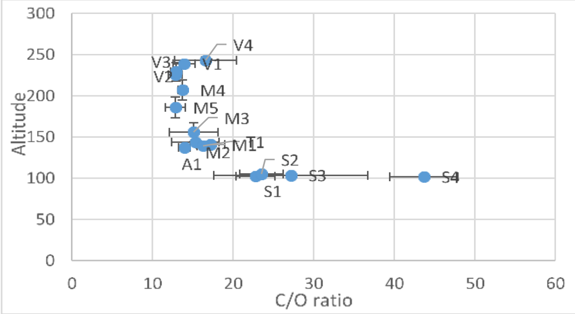

Evaporation
Aromaticity
M1
V4
V1
M4
V3
V2
M3
M2
M5
T1
S2
A1
S1
S4
S3

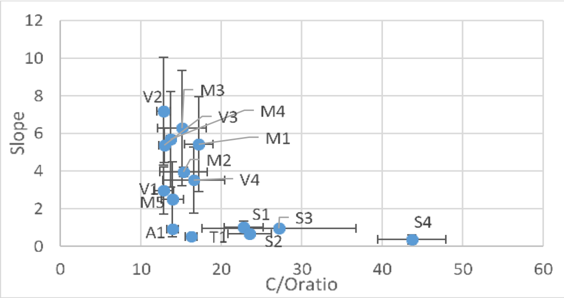

Precipitation
Aromaticity
V4
V1
V3
V2
M1
M5
M3
M4
M2
S4
S3
S2
S1
T1
A1

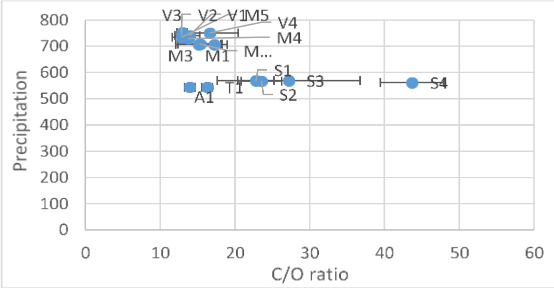

Surface area
Aromaticity
A1
T1
V1
M5
M2
V4
V3
M1
M4
M3
V2

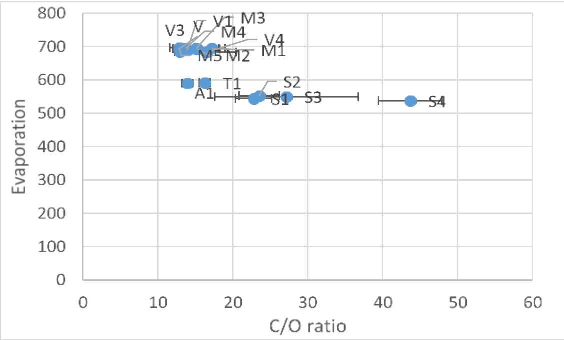

TPI
Aromaticity
TRI
Aromaticity
LS factor
Aromaticity
TWI
Aromaticity
MRVBF
Aromaticity
MRRTF
Aromaticity

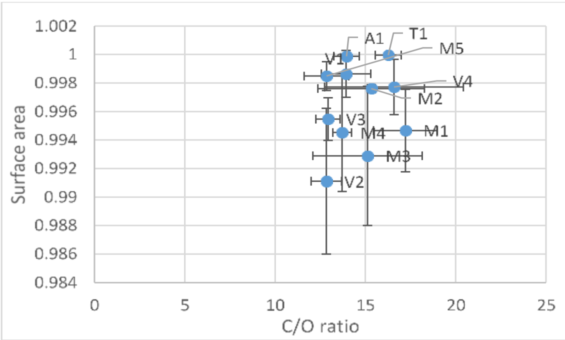

Evapotranspiration
Aromaticity
S2
S3
S1
S4
T1
A1
M4
M3
M2
M5
M1
V4
V1
V3
V2

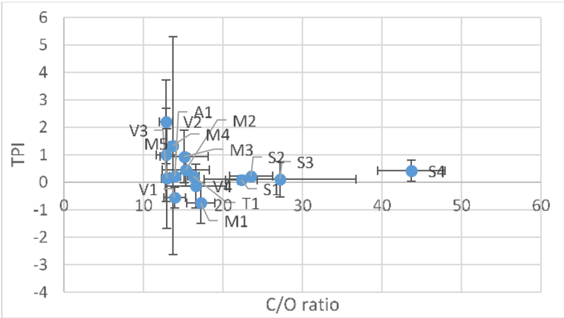

Altitude
C/O ratio
V4
V3
V1
V2
M4
M5
M3
T1
M1
M2
A1
S2
S3
S4
S1

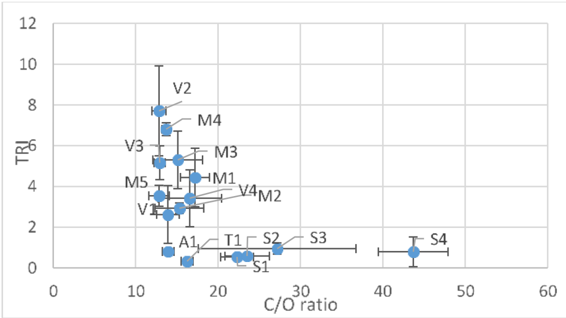

Slope
C/Oratio
V2
M3
V3
M4
M1
M2
V4
V1
M5
A1
T1
S1
S2
S3
S4

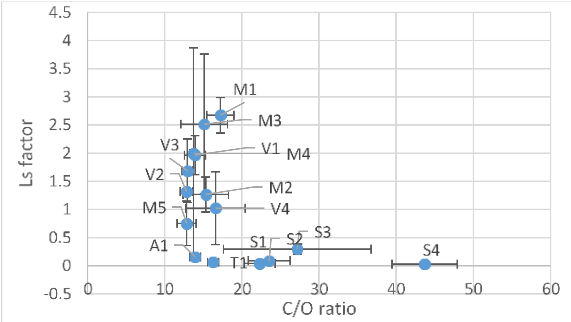

Precipitation
C/O ratio
V3
V2
V1
M5
V4
M4
M3
M1
M...
S1
S3
S4
T1
A1
S2

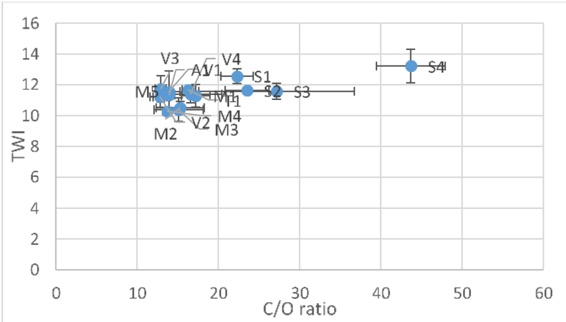

Evaporation
C/O ratio
V3
V1
M3
M4
V4
M5
M2
M1
T1
A1
S2
S1
S3
S4

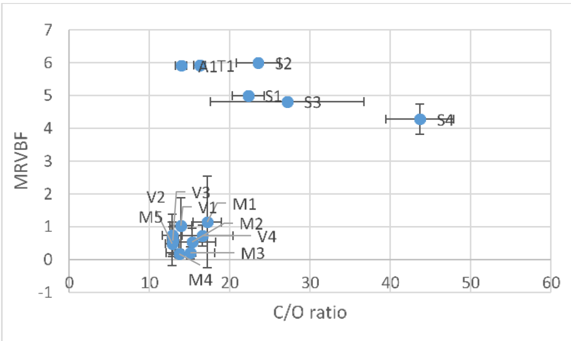

Surface area
C/O ratio
A1
T1
M5
V1
V4
M2
V3
M4
M1
M3
V2

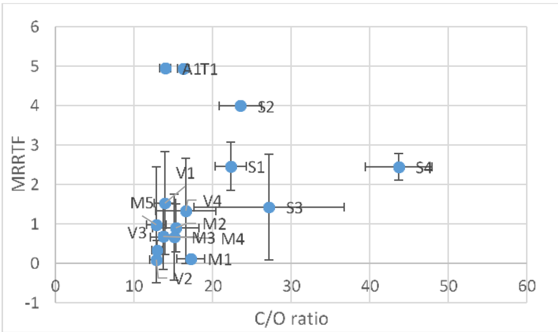

TPI
C/O ratio

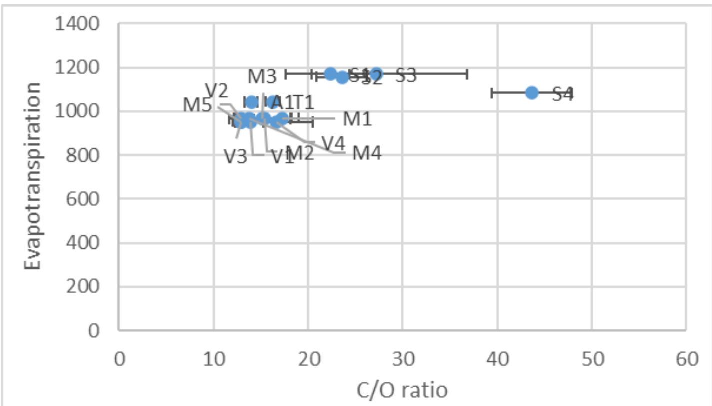

TRI
C/O ratio


Ls factor
C/O ratio


TWI
C/O ratio


MRVBF
C/O ratio


MRRTF
C/O ratio


Evapotranspiration
C/O ratio