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Soil dynamics within Icelandic birch woodland chronosequences

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Soil dynamics within Icelandic birch woodland chronosequences

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a doctoral degree in Restoration Ecology

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Clarification of contribution

I hereby declare that this project is based on my own observations, is written by me, and that it has not been previously submitted to a higher degree, neither in part nor in whole. The three accompanying papers are my own work, done under the supervision and with the assistance of my PhD committee: Ólafur Arnalds (Agricultural University of Iceland), Jóhann Þórsson (Land and Forest), Randy Dahlgren (University of California, Davis), and Ása L. Aradóttir (Agricultural University of Iceland).

My contributions to the three papers were as follows:

Paper I: I conceptualized the research and developed the methodology with Ólafur Arnalds, Jóhann Þórsson, Kristín Svavarsdóttir (Land and Forest), Ása L. Aradóttir, and Anna M. Behrend (PhD student, Agricultural University of Iceland). I collected all the soil samples, with the help of field assistants, and performed the laboratory analysis on the samples at the soil laboratory at the Agricultural University of Iceland. I conducted data analysis and interpretation with the help of my supervisors. I wrote the manuscript, which was reviewed and supervised by all co-authors. I corresponded with the scientific journal to which the paper was submitted.

Paper II: I conceptualized the research and developed the methodology with Ólafur Arnalds, Jóhann Þórsson, Kristín Svavarsdóttir, and Ása L. Aradóttir. I collected the soil samples (same samples as for paper I) and performed the laboratory analysis, with the help of laboratory assistants. Sample analysis was carried out at the Agricultural University of Iceland, and part of the samples were sent to the chemistry lab Efnagreiningar for further analysis. I conducted the data analysis and interpretation with the help of Ólafur Arnalds and Randy Dahlgren. I wrote the manuscript, which all co-authors reviewed. I also handled correspondence with the journal for publication.

Paper III: I conceptualized the research and developed the methodology with Jóhann Þórsson, Ólafur Arnalds, and Ása L. Aradóttir. I collected the soil samples (same as for papers I and II) and performed the laboratory analysis, with the help of laboratory assistants. Sample analysis was carried out at the Agricultural University of Iceland. In addition, I carried out measurements in the field with field assistants. I analyzed and interpreted the data with the help of my supervisors. I wrote the original manuscript, which was revised and approved by all co-authors.

Sólveig Sanchez

Abstract

The reduction of natural woodland cover in the world has led to a significant deterioration in soil fertility and disruption of soil nutrient cycles. In Iceland, land degradation increased vastly after the erasure of mountain birch woodlands, the country's only native forest-forming tree species. The Icelandic government aims to restore part of these lost woodlands. This thesis seeks to fill important knowledge gaps regarding birch woodland soils in relation to woodland restoration. Ten birch woodland chronosequences (non-forested to 60+ years old woodlands) across the country were investigated, with a focus on soil organic carbon (SOC), soil chemical and colloidal constituents, and hydrological processes. The soils are typical Andisols with a colloidal fraction dominated by allophane, ferrihydrite, and mineral-organic complexes (MOCs). The research revealed that allophane in the soils had extremely variable Al/Si ratios, which were related to influences of soil age, dust accumulation rates, and soil pH. The results showed significant SOC sequestration in old birch woodland soils, with carbon stocks of 7.4 kg/m^2 in the top 30 cm (significantly higher than non-forested sites: 5.0 kg/m^2), and a yearly SOC accumulation of 0.04-0.07 kg/m^2/yr. The rapid increase was mostly attributed to andic soil properties and bonds with soil colloids, including MOCs, which enhanced SOC stability. Ferrihydrite was more abundant in the soils than was expected and had an influence on carbon dynamics. The restoration of birch woodlands to 5% of the land cover would lead to a SOC sequestration totaling 7% of the country's current greenhouse gas emissions. The water retention capacities of the old woodlands were also the highest in this study (FC 63.5%, WP 45.6% on average), with excessively rapid infiltration rates (>586 mm/h in summer). This can be explained by the site's porous soils and rich vegetation cover, which assisted the water inflow and prevented ice blockage during winter (a key factor for hydrological soil health). Dust emerged as an influential factor on soil properties, such as carbon dynamics and Al/Si ratios of allophane, and by buffering the soil pH. Dust deposition buries carbon (up to 0.026 kg/m^2/yr in the highest dust categories), contributing to SOC accumulation. In general, natural birch woodlands in Iceland positively impact soil quality, as their soils are carbon-rich, fertile systems, with optimal hydrological properties. Their conservation and restoration are of fundamental environmental value in Iceland today and for Iceland of tomorrow.

Keywords: Andisols, *Betula pubescens*, soil carbon, soil pH, allophane, soil water retention, infiltration, dust deposition.

Ágrip

[Mótun jarðvegsþátta við þróun skóglendis frá skóglausu landi til birkiskógar].

Eyðing náttúrulegs skóglendis hefur leitt til hnignunar á frjósemi jarðvegs og röskunar á næringarefnahringrásum víða um heim. Á Íslandi jókst landhnignun til muna eftir eyðingu birkiskóganna, en birki er eina innlenda trjátegundin sem myndar skóga. Íslensk stjórnvöld stefna á að endurheimta hluta birkiskóganna. Markmið þessarar rannsóknar er að fylla upp í mikilvæg þekkingargöt er lúta að jarðvegi birkiskóganna, m.a. í tengslum við endurheimt náttúrulegs skóglendis á Íslandi. Til rannsóknar voru valin tíu svæði vítt um landið, sem hvert um sig spannaði skóglaust land, ungan skóg og 60+ ára skógarteiga. Lögð var áhersla á lífrænt kolefni í jarðvegi, leirefni/örefni (e. soil colloids), sem og ferli er lúta að vatnseiginleikum. Jarðvegurinn á öllum svæðunum reyndist fjölbreytileg eldfjallajörð (e. Andisols) sem einkennist af allófani, ferrihydríti og málm-húmus knippum. Rannsóknin sýndi að allófan í jarðveginum hafði afar breytileg Al/Si hlutföll, sem rekja mátti til áhrifa aldurs jarðvegsins, ryksöfnunarhraða og sýrustigs jarðvegs. Niðurstöðurnar sýndu fram á verulega kolefnisbindingu í gömlum birkiskógarjarðvegi, með kolefnisbirgðir upp á 7,4 kg/m^2 í efstu 30 cm moldarinnar (marktækt hærri en á skóglausu landi: 5,0 kg/m^2), og árlega kolefnisuppsöfnun upp á 0,04-0,07 kg/m^2 á ári. Bindingin var að mestu leyti rakin til sortueiginleika (e. andic properties) og örefna í moldinni, þar á meðal málm-húmus knippa, sem juku stöðugleika kolefnis. Miðað við þessar niðurstöður getur möguleg kolefnisbinding í jarðvegi birkiskóga numið um 7% af núverandi losun gróðurhúsalofttegunda á Íslandi ef þeir ná 5% þekju í samræmi við stefnumið stjórnvalda um endurheimt þeirra. Jarðvegur í gömlu skóglendi hélt mun meira vatni en ungur skógur og skóglaust land (63,5% við mettun, 45,6% við visnunarmark að meðaltali). Ísig var mjög ört (>586 mm/klst. á sumrin) á þeim stað sem það var mælt, vegna mikils holrýmis í jarðvegi og gróskumikils gróðurs á yfirborði sem örvar innflæðið og kemur í veg fyrir stöðvun á ísigi á veturna (sem er lykilatriði fyrir vatnsheilbrigði jarðvegsins). Í ljós kom að áfok (ákoma ryks) hafði mikil áhrif á jarðvegseiginleika, svo sem kolefnisdýnamík og efnasamsetningu allófans (Al/Si hlutfall), og einnig með því að jafna sýrustig jarðvegsins (böffer). Rykið grefur kolefni (allt að 0,026 kg/m^2 á ári þar sem áfok er mest), sem stuðlar að uppsöfnun kolefnis. Niðurstöðurnar sýna að birkiskóglendi á Íslandi mynda kolefnisríkan og frjósaman jarðveg með góða vatnsfræðilega eiginleika. Verndun og endurheimt birkiskóga þjóna því mikilvægu hlutverki í þágu umhverfisins í dag og fyrir Ísland framtíðarinnar.

Lykilorð: Eldfjallajörð (e. Andisols), *Betula pubescens*, jarðvegskolefni, sýrustig, allófan, leir, vatnsheldni, ísig, ryk, áfok.

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List of original papers

The thesis is based on three publications, which will be referred to throughout the thesis by their Roman numbers.

I. **Sanchez, S.**, Arnalds, Ó., Thorsson, J., Dahlgren, R., & Aradóttir, Á. L. (2025). Soil carbon stocks of regenerating Icelandic native birch woodlands: Effects of space and time. *Science of the Total Environment, 958*, 178063. https://doi.org/10.1016/j.scitotenv.2024.178063. [published]

II. **Sanchez, S.**, Arnalds, Ó., Dahlgren, R. A., Thorsson, J., & Aradóttir, Á. L. Colloidal and dust controls of soil processes and properties associated with birch woodland restoration in Icelandic Andisols. Under review, Catena. [submitted]

III. **Sanchez, S.**, Arnalds, Ó., Thorsson, J., & Aradóttir, Á. L. Soil water retention and infiltration across birch woodland chronosequences in Icelandic Andisols. In preparation. [manuscript]

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List of Abbreviations

Abbreviation	Full description
Al_{ox}	Ammonium oxalate extractable Al
Al_p	Ammonium pyrophosphate extractable Al
CEC	Cation exchange capacity
FC	Field capacity
Fe_{ox}	Oxalate extractable iron
Fe_p	Pyrophosphate extractable iron
MOCs	Metal-organic complexes
PAW	Plant available water
SOC	Soil organic carbon
WP	Wilting point
WRB	World Reference Base for Soil Resources

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1. Introduction

Land use has significantly impacted Earth's ecosystems over the last millennia, leading to land degradation and soil erosion in many areas of the world. The transition from natural to agricultural land has had a negative impact on biodiversity and soil health (Bajocco et al., 2012; Kanianska, 2016). Natural woodlands have been diminished by this agriculturally driven shift, being reduced to 31% of the world's land cover (FAO and UNEP, 2020). These woodlands have high ecological and environmental value, and their restoration is crucial from both social and environmental perspectives, such as soil protection (Stanturf et al., 2014). Woodland restoration projects have increased significantly in the last few decades (e.g., Harrison et al., 2021; Moyo et al., 2021). Iceland is among the nations aiming to expand the coverage of natural ecosystems, particularly native birch woodlands. For a successful woodland restoration and land recovery, it is important to understand the temporal dynamics of the woodland soil properties. One way to approach this is through chronosequential studies in diverse geographical settings, reflecting both the initial conditions of the land as well as mature woodlands.

The research described in this thesis is part of a larger restoration research project, BirkiVist (EcoBirch in English), that seeks to understand the challenges and benefits of restoring birch woodlands from ecological, social, and cultural perspectives (Aradóttir et al., 2022).

This thesis focuses on soil dynamics in relation to birch woodland ecosystems and their restoration. Samples were collected from several chronosequences and analysed alongside other relevant data to gain new insights into soil dynamics associated with the development of birch woodlands. This study investigates the influence of woodland age and environmental factors on soil properties and their implications for climate. This introduction offers an overview of Icelandic Andisols and outlines the need for restoration plans targeting Icelandic birch woodlands. Finally, the climate implications of birch woodland restoration are examined, with a focus on soil carbon retention and CO_2 emissions.

1.1 Global and Icelandic Andisols

1.1.1 Andisols are unique

Andisols, meaning 'dark soil' in Japanese, are unique soils that differ remarkably from other common soils formed from parent materials such as limestone, sandstone, or granite (Wada, 1985; Arnalds, 2013). The parent material of Andisols consists mainly of volcanic ash, pumice, or other volcanic ejecta (Nanzyo, 2002). The volcanic materials, particularly basaltic vitric components, often weather rapidly due to their low resistance to chemical weathering (Gíslason, 2008). This results in soil profiles rich in metal-organic complexes and nanocrystalline clay minerals, such as allophane, imogolite, and ferrihydrite (Parfitt, 1990;

Dahlgren et al., 2004; Arnalds, 2013). These clay minerals are not layer silicates (cohesive sheets), resulting in poor soil cohesion of the colloidal materials (McDaniel et al., 2012; Arnalds, 2015). Allophane, the most common clay mineral in Andisols, behaves differently than other clays due to having a hollow nano-sized spherular form that tends to aggregate into silt-size particles (Wada, 1985).

Colloidal materials, both organic complexes and clay minerals, give Andisols their distinctive characteristics and play an important role in developing the 'andic soil properties' (Arnalds, 2013). These properties develop from the weathering of tephra and other volcanic materials (Dahlgren et al., 2004; McDaniel et al., 2012). The properties include high carbon content (reaching up to 25% C), low bulk density, high phosphate retention, and high water retention (Wada, 1985; Soil Survey Staff, 2010). Soil classification systems use the oxalate extractable Al and Fe fraction, i.e., $(Al+½Fe)_{ox}$, to determine andic soil properties: soils must have $> 2\%$ $(Al+½Fe)_{ox}$ content to be considered having andic properties. However, lower values are allowed if the soils have $> 30\%$ volcanic glass composition (McDaniel et al., 2012), which is the case for most Icelandic Andisols, including the desert Vitrisols (Arnalds, 2015).

Well-developed Andisols are generally stable and fertile, rich in carbon (8% C on average), with longer carbon residence time than most other soil types, leading to low bulk densities (normally < 0.9 g/cm^3; Wada, 1985; McDaniel et al., 2012). Andisols usually also have high clay contents and infiltration rates (McDaniel et al., 2012; Sun et al., 2018). The lack of layer silicate clays and the low bulk density in disturbed or unvegetated Icelandic Andisols can lead to poor interparticle cohesion, making them quite vulnerable to wind and water erosion (Arnalds, 2015). Many factors contribute to the stability of Andisols, e.g., vegetation and type of vegetation cover on the surface, organic carbon, water retention, texture, clays, metal-organic complexes (MOCs), and infiltration characteristics (Weil and Brady, 2017). Moderately weathered Andisols entail more bonding interactions between carbon and soil colloids (Parfitt, 1990), important for soil carbon accumulation and stability in Andisols (Takahashi and Dahlgren, 2016). Organic carbon increases aggregation in soils, and thereby porosity, which is influential for water retention, infiltration/permeability properties, and plant growth (Weil and Brady, 2017). Allophanic clays often form silt-size aggregates that also improve soil water infiltration rates (Maeda et al., 1977). The high water retention capacity and silty texture of the soil particles also exacerbate the effects of cryoturbation or freezing processes, leading to changes in surface characteristics (Arnalds, 2015).

1.1.2 Dominant dryland soils in Iceland

Volcanic activity shapes the nature of Iceland and Icelandic soils (Thordarson and Höskuldsson, 2008), as do aeolian processes that result in pronounced dust deposition of vitric-basaltic composition (Arnalds, 2010). Due to the volcanic origin of their parent materials, most Icelandic soils are classified as Andisols (Arnalds, 2015), making that soil type the dominant dryland soil in the country, equaling 48% of the land cover and over 5% of all Andisols in the world (Arnalds, 2004; Arnalds, 2005).

The main Andisol subtypes found in Iceland, following the Soil Taxonomy classification system (Soil Survey Staff, 2015), are Aquands in wetland areas, Cryands in colder regions, and Udands (moist landscape settings) or Ustands (dry) along the coastlines in the relatively warmer areas of the country. Many of these soils classify as vitric at the great-group level (e.g., Vitricryands) when volcanic glass dominates and both organic content and allophane contents are low. Organic Histosols, formed in decomposing organic matter (> 25% C; Soil Survey Staff, 2015), are also a common Iceland soil type in wetland areas farther from dust sources (Arnalds, 2004). An Icelandic classification scheme (see Arnalds, 2015), developed with reference to both Soil Taxonomy and the World Soil Reference Base (WRB), is designed to better separate Icelandic soils at the highest level, which includes Vitrisols, which are soils meeting criteria for Andisols, yet lacking organic carbon and allophanes (< 1.5% C and < 6% allophane). These are the dominating soils of barren areas ('deserts') in Iceland. Other common soil types under this scheme are Brown Andosols (drylands; 1.5-12% C), Gleyic Andosols (wetlands; 1.5-12% C), Histic Andosols (12-20% C), and Histosols (> 20% C). Reference is made to both the Soil Taxonomy and Icelandic systems throughout the thesis.

In Iceland, dust deposition is vitric in nature, mostly made of silt-sized particles of basaltic origin and often quite porous (Arnalds, 2004; Richards-Thomas et al., 2021). A massive redistribution of soil materials by wind erosion during the past millennia after the settlement of Iceland resulted in a 4-10-fold increase in dust deposition on remaining vegetation patches (reviewed by Arnalds, 2010 and 2015), leading to soil thickening and functional destruction of the most fragile ecosystems, while more resilient systems, such as wetlands, retained their functionality (Arnalds et al., 2023). However, as the barren land increased due to soil erosion, the dust sources have shifted to so-called dust hotspots related to proglacial and coastal areas (Arnalds et al., 2016). This volcanic dust, which presently is mostly made of basaltic volcanic glass (vitric materials), can have positive effects on soil and vegetation if the quantity is not excessive, since its surface area is high and chemical weathering is rapid (Gíslason, 2008; Arnalds, 2010; Gunnarsson et al., 2015). In addition, some Andisols form in lava, lahar, ignimbrite deposits, or other volcanic materials from multiple explosive volcanic eruptions (Arnalds, 2013), hence forming in parent materials of diverse nature (**Fig. 1**).

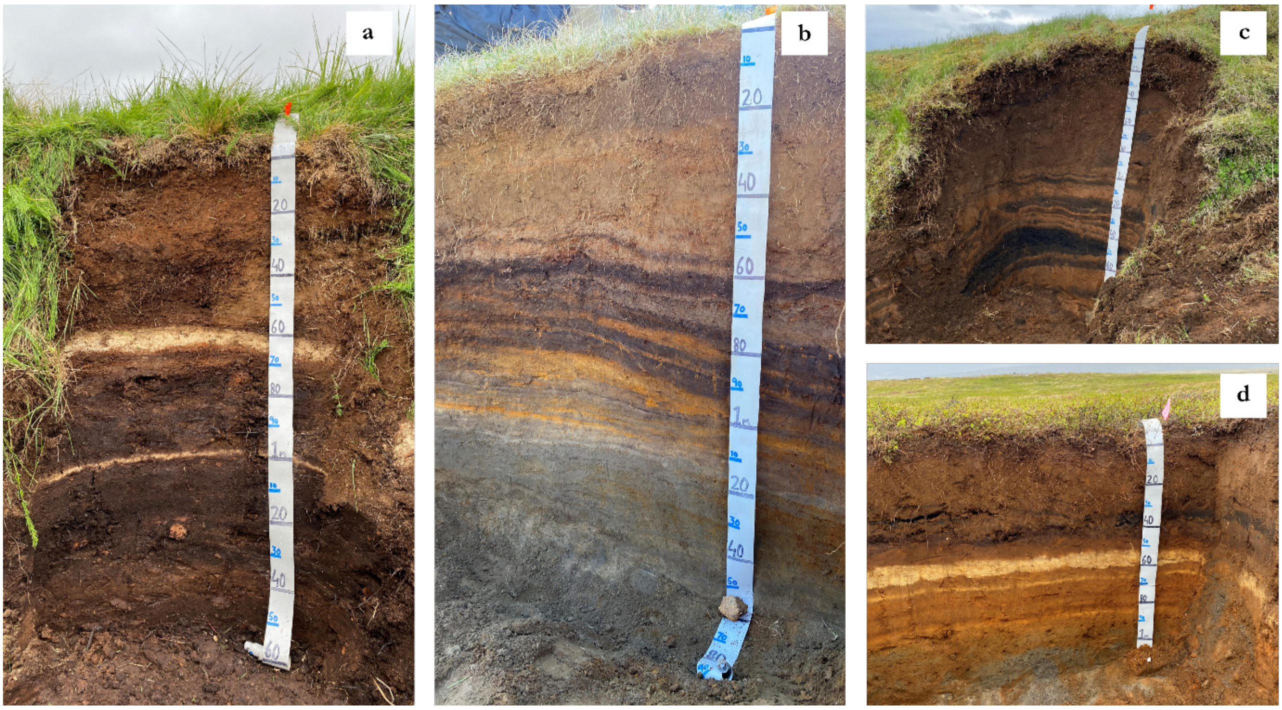

Figure 1. Icelandic Andisols with tephra layers from various volcanic eruptions and locations: a) drained histic wetland soil at Möðruvellir, North of Iceland, b) dryland soil at Breiðdalur, East of Iceland, c) thick Andisol at Myrdalur, South of Iceland, and d) typical dryland Andisol at Goðafoss, North of Iceland.

1.2 The effects of woodland degradation and restoration on soils

1.2.1 Changes and effects of woodland dynamics on soils

Vegetation and soils interact, forming diverse ecosystem dynamics and environments (Van Breemen and Finzi, 1998). Soil changes associated with woodland growth vary significantly depending on factors such as soil type, woodland species, and other local environmental factors (Weil and Brady, 2017). The impact of natural woodlands on soils is usually positive, leading to fertile, resilient soils and ecosystems (Cardoso et al., 2013). Their rich vegetation cover generally has a positive impact on soil dynamics as it, for example, increases the organic carbon in the soil through plant litter inputs and decomposition (Castellano et al., 2015). This often leads to a decrease in soil pH; however, the degree depends on the vegetation type (Jonczak et al., 2020). The roots of some tree species can significantly increase soil porosity and improve soil structure, leading to a healthy soil hydrological system with high water retention values and infiltration rates (Xiao et al., 2024). Woodlands also impact the colloidal environment of the soil (Van Breemen and Finzi, 1998). As they generally accumulate soil organic carbon, the colloidal content also increases, creating bonds between clay, minerals, and organic materials (Guggenberger et al., 1998). In general, it can be stated that natural woodlands can substantially improve soil health by enhancing soil fertility, nutrient cycles, and hydrological processes (Furey and Tilman, 2021).

The growth of Icelandic birch woodlands in Andisols has led to well-developed woodland soils, despite many receiving constant dust deposition, which rejuvenates the surface and buries older soils. Some of the woodland soils have undergone periods of degradation and erosion, with some entirely destroyed, while others have been partially disturbed, exhibiting lower carbon contents (Aradottir and Arnalds, 2001). The rich vegetation cover in most birch woodlands suggests that the soils are generally healthy and fertile. Nevertheless, mountain birch is also capable of colonizing disturbed and nutrient-poor areas (Aradottir and Halldorsson, 2018; Óskarsdóttir et al., 2022). Birch woodlands occur in a range of conditions throughout the country, under variable climates that influence soil dynamics and variable environmental factors, such as soil moisture and dust deposition, that affect soil formation processes. More understanding is needed of how these conditions influence soil dynamics and properties where birch woodlands have established in order to determine the feasibility of woodland restoration across the highly variable conditions of Iceland.

Few studies have examined Icelandic birch woodlands and their effect on soils. For example, Hunziker et al. (2019) studied soil carbon sequestration following birch afforestation, Orradóttir et al. (2008) estimated water infiltration rates in birch woodlands in comparison with other ecosystem types, and Ritter (2007) studied the content of soil constituents following afforestation with birch and larch. In addition, Arnalds has published an extensive review of Icelandic soils (see Arnalds, 2015), including their properties, dynamics, and current state.

The Icelandic government has set goals to increase birch woodland cover by 3.5% (from 1.5 to 5%), through restoration activities by 2031 (Ministry of Food, Agriculture and Fisheries, 2022). Considering this ambitious goal, there is a need for a better understanding of how Icelandic birch woodlands affect soil dynamics to ensure a successful and efficient restoration. This especially calls for studies of woodland chronosequences in diverse geographical areas with a range of ecological conditions. This thesis aims to fill these knowledge gaps.

1.2.2 The history of Icelandic birch woodlands

Mountain birch, *Betula pubescens*, is historically the only native woodland-forming tree species in Iceland (Blöndal, 1987), and mountain birch woodlands are considered a dynamic stable state (Sigurdsson, 1977; Arnalds, 1987). Following the settlement of Iceland in the ninth century, the woodlands underwent severe changes and later degradation due to human actions. Woodlands were logged and burned to obtain building materials and create grazing lands (Arnalds, 1987). Continuous sheep grazing significantly contributed to woodland degradation, as humans introduced sheep to a land where herbivores barely existed, and vegetation had not adapted to intensive grazing (Thorsteinsson et al., 1971; Jóhannesson, 2010). The woodland cover decreased from 25-40% at the time of settlement to just 1% in the last century (Sigurdsson, 1977; Aradottir et al., 2001). The near disappearance of woodlands weakened ecosystems' resilience to both human and natural disturbances, leading to widespread land desertification across the country (Arnalds et al., 2023). This led to reduced soil carbon reserves and often sandier soils (vitric) caused by aeolian material from nearby eroding areas (Arnalds, 2023). Previously healthy ecosystems transitioned into degraded stages dominated by unstable vegetation cover and expanding erosion spots, resulting in further loss of soil fertility and, in some areas, the replacement of vast woodland tracts with mostly denuded soil surfaces (Arnalds, 1987; Arnalds et al., 2023). Today, about 45-60% of the country's land cover is to some degree eroded or degraded (Arnalds et al., 2023).

The state of Icelandic birch woodlands has slightly improved in recent decades, with woodland increasing by 0.5% to now 1.5% of the land area. This growth is largely attributed to warmer climate, changes in land use, including protection of existing woodlands, and ongoing restoration efforts (Aradottir et al., 2001; Snorrason et al., 2016).

Mountain birch serves as a pioneer species colonizing disturbed areas when seed sources are available and grazing is not present or at least limited (Aradottir and Halldorsson, 2018; Óskarsdottir et al., 2022). It has proven to be a resilient tree species with a robust root system that enables it to grow in a wide range of soil conditions (Hunziker et al., 2014; Aradottir and Halldorsson, 2018; Lidman et al., 2023). Birch woodlands are also known to serve as a refuge for other plant species, fostering a great ecosystem biodiversity with forbs, mosses, grasses, and heathland species, among other vegetation types, dominating the understory (**Fig. 2**).

Figure 2. Photos of old woodland understories with diverse vegetation in three study areas: a) *Geranium sylvaticum* and *Ranunculus acris* were most abundant in the woodland floor in 6-THO, b) and c) *Rubus saxatilis* and grasses dominated the woodland floor in 1-LEY, and d) the woodland floor in 4-STEI was rich in moss and grasses.

1.2.3 Birch woodland and climate implications

Climate change is becoming evident in most parts of the world. In Iceland, glaciers are retreating (Aðalgeirsdóttir et al., 2006), new non-native plant and insect species are spreading (Von Schmalensee, 2010; Gerő et al., 2025), coastal fish population structures are changing, and vegetation productivity seems to be increasing (Björnsson et al., 2011).

Mountain birch has demonstrated the capacity to grow under a wide range of climatic conditions, including those that are relatively adverse. Warmer temperatures induced by climate change might facilitate the expansion of Icelandic birch woodlands, since an estimated minimum mean of 6.5°C for the four warmest months of the year is required for birch growth (Sigurdsson, 1977), and its optimal temperature for photosynthesis is at 35°C (Gudmundsdóttir and Sigurdsson, 2005). However, if the temperature keeps rising along with possible changes in precipitation, the birch woodlands could be negatively affected by drought, possibly increasing fire risks (Wöll, 2008; De Rigo et al., 2017) and insect pests (Halldórsson et al., 2013). Birch has, nevertheless, a wide adaptability to variable temperatures and will most likely not succumb to warming conditions.

The restoration of woodlands is currently being used as a mitigation action to reduce greenhouse gas levels in the atmosphere, since woodland soils can accumulate large amounts of carbon (e.g., Vesterdal et al., 2013). Soil carbon sequestration prevents carbon dioxide (CO_2) from going into the atmosphere and moves carbon from the dynamic atmospheric pool to the soil carbon pool, thereby decreasing the greenhouse gas impact and global warming effect (Lal, 2008). In many countries, woodland restoration projects have led to more balanced emission-sequestration systems, thereby mitigating the impact of greenhouse gas emissions through enhanced carbon sequestration (e.g., Bernal et al., 2018). The Icelandic government, for example, accepted the Bonn challenge in 2021, aiming to reduce net soil carbon emissions by restoring birch woodlands to 5% of the land cover by 2031 (Ministry of Food, Agriculture and Fisheries, 2022). Consequently, it is important to understand the magnitude of soil carbon stocks and accumulation rates in ecosystems, including birch woodland soils, for assessing the potential of birch woodland restoration as a viable climate change mitigation strategy in Iceland.

1.3 Research questions and objectives of the thesis

In this thesis, soil dynamics in birch woodland chronosequences are investigated, with an emphasis on the temporal development of soil properties. This thesis examines how these properties change over time and under variable geographical conditions (global, national, and regional), with a focus on soil organic carbon, soil colloidal materials, and hydrological characteristics. Special attention is given to how the soil properties interact, with a focus on andic soil properties and soil carbon dynamics.

Field measurements and data analysis were used to address the following research questions:

Q1. What are the soil carbon stocks in chronosequences of Icelandic birch woodlands of different ages?

To assess soil carbon stocks and the rate of change in Icelandic birch woodlands (**Paper I**), soil samples were collected from 10 different locations in the country from the top 30 cm of the soils and used the data to calculate the soil carbon content and stocks as a function of woodland age.

- **Q1.1. What are the soil carbon stocks in birch woodland chronosequences? (Paper I)**

  High soil carbon stocks and rates were expected in Icelandic birch woodlands, due to the generally high carbon accumulation observed within woodlands (Vesterdal et al., 2013) and the high carbon sequestration potential of Andisols (Shoji, 1985). In addition, the cold temperatures and andic soil properties were postulated to help preserve soil carbon (McDaniel et al., 2012; Arnalds et al., 2013).

- **Q1.2. What is the rate of soil carbon accumulation in birch woodland chronosequences? (Paper I)**

  A relatively fast rate of soil carbon accumulation was predicted over time since some of the non-forested soils were in an initially degraded stage (low starting point), and Andisols have high carbon contents and carbon residence time (McDaniel et al, 2012).

- **Q1.3. Which environmental factors affect the soil carbon stocks and their rate of accumulation? (Paper I)**

  Local surface conditions, which exhibited considerable variability, as well as climatic variability, such as temperature and precipitation, were expected to influence soil carbon stocks and their rate of accumulation since cold climates are associated with reduced decomposition rates and thus promote soil carbon accumulation (Arnalds et al., 2013).

Q2. What characterizes the chemical and colloidal soil environment of Icelandic birch woodlands, and how does it change with woodland age?

To characterize the chemical environment and identify the predominant soil colloids in Icelandic birch woodlands (**Paper II**), soil samples were collected in woodland soils across the country for carbon analysis. A subset of these samples was subsequently selected for characterization of the colloidal fraction.

- **Q2.1. Does the chemical soil environment change with woodland age? (Paper II)**

  It was expected that the chemical properties of the soil environment would vary with woodland age, as increased weathering and more developed vegetation communities are known to alter soil chemistry over time (McDaniel et al., 2012).

- **Q2.2. What is the relationship between soil colloids and the soil carbon content in Icelandic birch woodland chronosequences? (Paper II)**

  It was hypothesized that a relationship between the active Al and Fe fraction, i.e., soil colloids, and carbon content would exist, since it is known that the soil colloidal fraction of Andisols, such as allophane, ferrihydrite, and metal-organic complexes, form strong associations with soil carbon, thereby hindering decomposition and promoting carbon sequestration (Dahlgren et al., 2004; Takahashi and Dahlgren, 2016).

- **Q2.3. What are the main factors influencing the soil colloidal composition in Icelandic birch woodland chronosequences? (Paper II)**

  Factors such as soil pH were expected to impact the soil colloidal composition by influencing the formation of clay constituents and/or metal-organic complexes (Saigusa and Matsuyama, 1998). Factors influencing the soil pH were also of interest, especially in its relationship to dust (see **Q4**).

Q3. What characterizes the soil hydrological properties of Icelandic birch woodlands, and how do they change with woodland age?

To evaluate soil water retention and transport properties in Icelandic birch woodland soils, soil samples were collected from a range of geographic locations in Iceland and estimated their soil water retention at both field capacity and the wilting point, as well as the plant available water. Infiltration rates were also measured as a function of season in a birch woodland chronosequence at the core site of the EcoBirch project (**Paper III**).

- **Q3.1. What factors influence the soil water retention in Icelandic birch woodland chronosequences? (Paper III)**

  The andic soil properties were expected to influence soil water retention, since well-developed Andisols can retain large amounts of soil water, which is one of their unique characteristics (Dahlgren et al., 2004; McDaniel et al., 2012).

- **Q3.2. Does plant-available water availability increase with birch woodland age? (Paper III)**

  It was hypothesized that birch woodland ecosystems would influence plant-available water since mature woodlands generally have higher soil carbon content than young woodlands, which may positively impact water retention at both field capacity and the wilting point (Minasny and McBratney, 2018).

- **Q3.2. Are there seasonal changes in soil water infiltration in Icelandic birch woodland chronosequences? Does the terminal infiltration rate increase with birch woodland age? (Paper III**)

Appreciable changes in infiltration rates were predicted during contrasting seasons, particularly between winter and spring/summer, due to frozen soil conditions generally halting infiltration rates (Cerdà, 1997; Murray and Buttle, 2005). The increased birch woodland age was expected to increase the terminal infiltration rates due to its richer vegetation cover (Sun et al., 2018), and the non-forested site was expected to have lower winter infiltration rates due to the formation of different ice crystals in the soil (Orradóttir et al., 2008; Zaqout et al., 2022).

During the research, an evolving question developed:

Q4. How does dust deposition influence carbon stocks, soil pH, soil colloidal composition, and water retention/transport properties in Icelandic birch woodlands?

The study areas were categorized according to dust deposition rates (Gunnarsson et al., 2015), and their soil properties were compared among dust categories, i.e., the influence of dust deposition on carbon stocks (**Paper I**), the soil colloidal composition (**Paper II**), and water retention/transport properties (**Paper III**).

2. Methods

This thesis presents a comprehensive investigation of soil properties in mountain birch woodland ecosystems at ten study areas across Iceland, with a particular focus on carbon stocks (**Paper I**), soil colloidal characteristics (**Paper II**), and soil water properties (**Paper III**). Each theme was examined from a geographical variability point of view, by comparing the results with other soil types and with other Andisols worldwide, and by assessed how differences in climate and dust deposition intensities can affect soil carbon stocks (**Paper I**), soil colloids and soil pH (**Paper II**), and hydrologic properties of the soil (**Paper III**) within Iceland. Furthermore, soil properties change across chronosequences from non-forested to young and old woodlands.

Specific details on the methodology are given in the three individual papers in **Section 8**. In this chapter, a general explanation of the methods used in this research is provided, including a description of the study areas, the sampling procedure, the soil analyses following the order of the research questions presented above, and the main data analyses used.

2.1 Field data collection

2.1.1 Study areas

The research is based on ten study areas that were selected based on the requirement that three chronological stages were present: an old birch woodland, a young birch woodland, and an adjacent non-forested site undergoing active birch colonization. The selected areas were numbered in a clockwise order from N-Iceland (**Fig. 3**). Their distribution captures the environmental heterogeneity of Icelandic birch woodlands, including contrasting climate conditions (see **Paper I** for details), with 10-MJO having the lowest average annual temperatures (1.9°C) and 4-STEI the highest (5.4°C). The highest amount of average annual precipitation is found in the southern study areas and is especially high in 5-HRI (~1,460 mm), and lowest in the northern areas, e.g., 1-LEY (~530 mm).

All but three of the birch woodlands at the selected study areas had been protected from sheep grazing: 2-OX, 4-STEI, and 10-MJO. Dust deposition rates also varied among them, where areas closest to glacial margins and the sandy coastal shores received the highest dust deposition. The dust-deposition areas were classified following the methods presented by Gunnarsson et al. (2015), categorizing the areas from 1 to 7, based on the dust deposition intensity, 1 being low and 7 representing extremely high deposition rate (**Fig. 4**). The area 10-MJO received the lowest deposition (category 1), and the southern areas, 5-HRI and 6-THO, received the highest dust deposition (category 6; see **Paper II** for details).

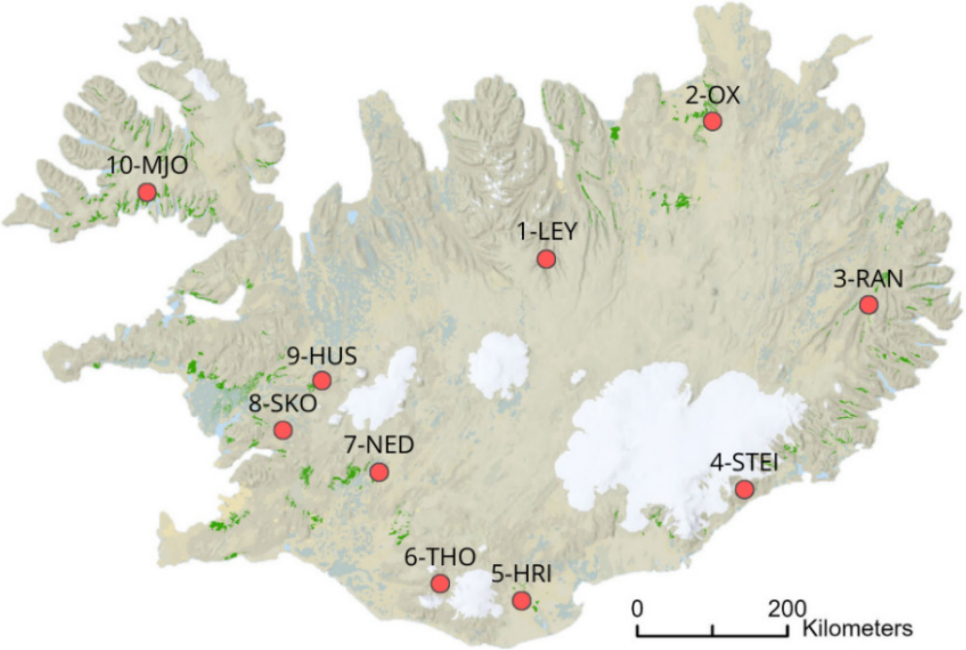

Figure 3. Map of Iceland showing the ten study areas with their corresponding acronyms and numbers in clockwise geographical order. The map includes the main glaciers in white and bodies of water in blue. The birch woodland cover from 2016 is presented in green (data modified from Snorrason et al. 2016).

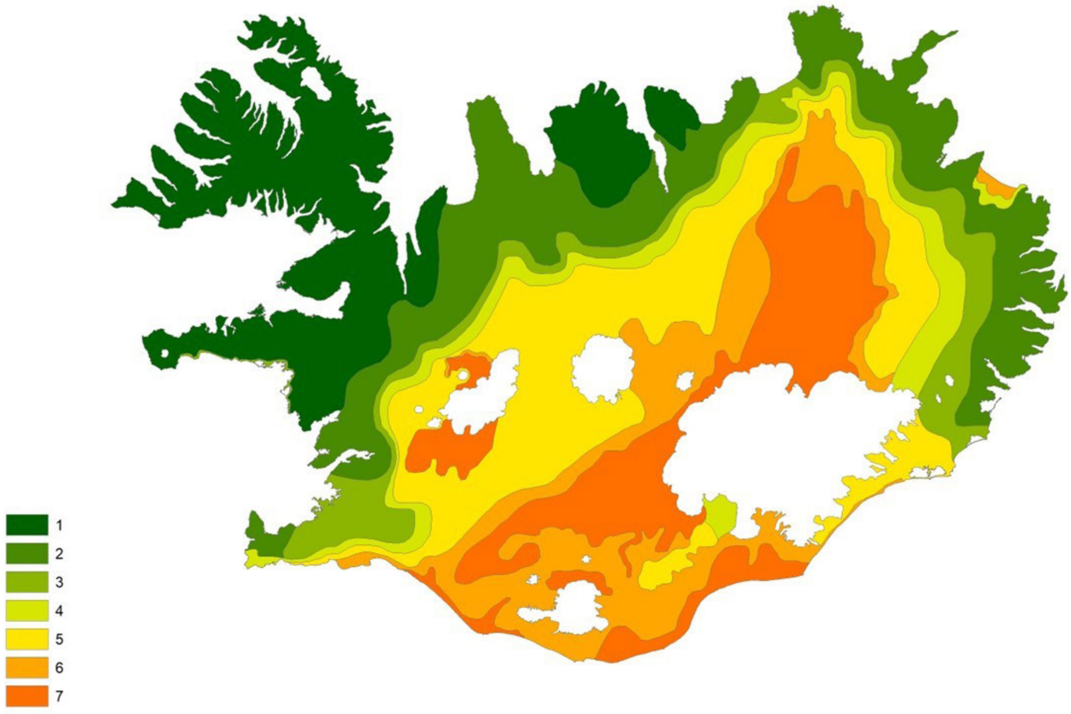

Figure 4. Map of dust deposition rates in Iceland from Arnalds et al. (2023), based on the method from Gunnarsson et al. (2015) and Arnalds (2010), classifying the country in dust deposition categories from 1 (very low) to 7 (extremely high).

Soils were classified according to the US Soil Taxonomy (Soil Survey Staff, 1999) and an Icelandic system (Arnalds et al., 2005). All soils were classified as Andisols, mostly Ustivitrands (low 15 bar (WP) water retention and containing volcanic glass) and Haplustands (well-drained). The exceptions were study area 7-NED, which was classified as Pachic Fulvudand (soil in a humid climate characterized by a light-colored melanic epipedon), and area 8-SKO, which was classified as Endoaquand (wetland soil with a mollic or umbric epipedon). The soils at 10-MJO were the only Cryands of this study, specifically Fulvi- and Hydrocryand, i.e., soils formed in cold regions with a fulvic (light melanic) epipedon (Fulvicryand) and a high 15 bar water retention (Hydrocryand), respectively (Soil Survey Staff, 2015; see **Paper I** for details).

2.1.2 Birch woodland stages

The chronosequences at each study area included three age stages, determined using aerial photos: non-forested site (N), young birch woodland (Y, ~30 years old), and old birch woodland (O, +60 years old). The area 7-NED had an additional stage, referred to as mature birch woodland (40-60 years old), and was selected as a core study area, where further measurements were taken. In the woodlands, the vegetation cover was 100% (**Fig. 5a** and **5b**). Most non-forested sites were classified as heathlands, e.g., 2-OX or 7-NED (**Fig. 5c**). However, in some areas, the non-forested sites were classified as a gravelly grassland (area 3-RAN; **Fig. 5d**) and as a poorly vegetated gravelly heathland (e.g., 6-THO; **Fig. 5e**). The non-forested site at 8-SKO had rich vegetation and hydromorphological properties, thus categorized as a heath-/wetland.

Figure 5. Photos of several plots in different study areas: a) old woodland in 8-SKO, b) young woodland in 5-HRI, c) non-forested site (classified as heathland) in 2-OX, d) non-forested site (classified as gravelly grassland) in 3-RAN, and e) non-forested site (classified as a poorly vegetated gravelly heathland) in 9-HUS.

2.1.3 Sampling design

Soil sampling took place at all three age stages within each study area during the summer of 2021. At each study area, three transects were established passing through each age stage, with a 50-100 m distance. Two plots were laid out at each transect, making a total of six plots at each chronosequence stage (**Fig. 6**). One soil core was retrieved from each plot, with up to five cores, and divided into two depths (0-10 cm and 10-30 cm). In rocky areas, it was not possible to collect samples, reducing the number to 328 out of an expected 360 samples (see **Paper I** for details).

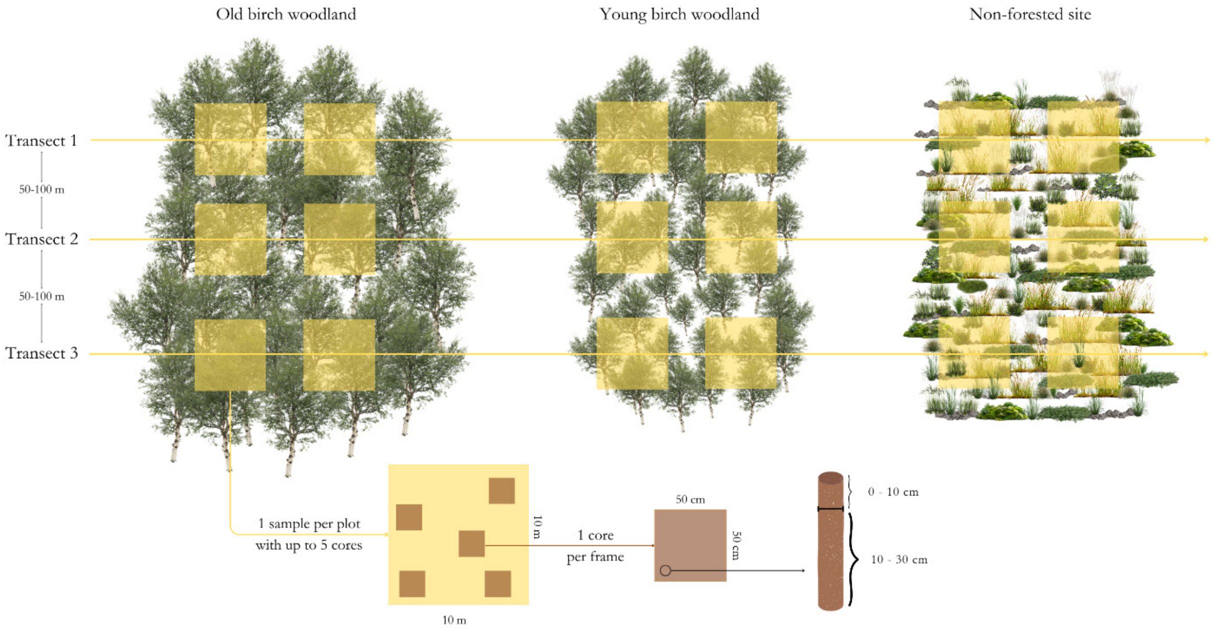

Figure 6. Sampling scheme for each of the ten study areas. The yellow boxes (10 x 10 m) represent the sampling plots, where five frames were laid out. In each frame, one soil core was collected. One soil sample was retrieved from each plot, with up to 5 cores per sample. The soil core was then divided into two sample depths: 0-10 and 10-30 cm.

2.1.4 Infiltration measurements

Infiltration measurements were only undertaken at 7-NED, the core area of the EcoBirch research project, due to labor and time constraints. Rings (20 cm in diameter, 30 cm in height) were inserted into the soils of the four successional stages (N, Y, M, and O), following the same transects as the soil sampling (**Fig. 7**). A cluster of three single rings was introduced at each transect and age stage (see **Paper III** for details).

The infiltration measurements took place in 2022: April (winter), June (spring), July (summer), and October (autumn). Due to the inherent variability of Icelandic winters, the winter measurements were repeated in February 2023. In each ring, the infiltration rate was measured every 5 minutes for a 60-minute period (see **Paper III** for details).

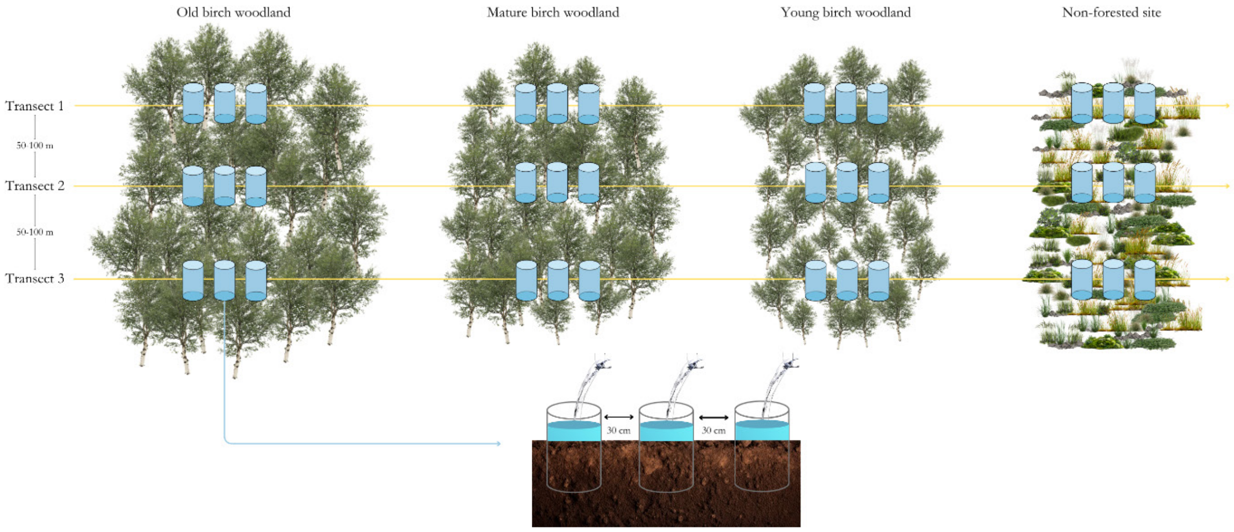

Figure 7. Soil water infiltration measurement scheme for the study area 7-NED. It includes four age stages. The three transects follow the same layout as for the soil sampling scheme (Fig. 6). Nine rings (blue cylinders) were inserted into the soil at each age stage (three at each transect). The rings of each cluster were placed 50 cm apart.

2.2 Assessing soil carbon and nitrogen stocks (Q1)

Carbon and nitrogen (%) were assessed to estimate the carbon/nitrogen stocks of the 328 samples. The samples were weighed, dried at 40°C, and sieved through a 2-mm sieve. The bulk densities (g/cm^3) were estimated using the weight of the samples and their active volume (total volume – CF). Subsamples (< 2 mm) were ball-milled into fine powder for carbon (C, %) and nitrogen (N, %) analysis (see **Paper I** for details).

Soil carbon and nitrogen stocks were determined for all 330 soil samples, using the following formula (Tadiello et al., 2022):

$$\text{SOC or SN (kg/m}^2\text{)} = \text{OC or N} \cdot \text{LT} \cdot \text{BD} \cdot (1 - \text{CF}) \cdot 10,$$

where OC is the organic carbon content (%), N is the nitrogen content (%), LT is the layer thickness (m), BD is the bulk density (g/cm^3), and CF is the coarse fragments (< 2 mm). The SOC/SN were calculated for each depth interval (0-10 and 10-30 cm) and then summed to obtain the SOC/SN for the 0-30 cm soil layer.

2.3 Characterizing soil pH and colloids (Q2)

Soil pH of all 330 samples was measured following a method outlined by Blakemore et al. (1987). It involved a 1:5 soil:H_2O suspension with a measurement after a 120-minute equilibrium period.

Soil colloids were characterized by ammonium oxalate and pyrophosphate extractions, following methods outlined by Blakemore et al. (1987), but only on selected samples due to the time-consuming and costly procedures. A selection of 80 samples was used for the ammonium oxalate extraction, i.e., the determination of the active Al and Fe fraction, which includes allophane, imogolite, ferrihydrite, and metal-organic complexes. For the pyrophosphate extraction, i.e., the determination of metal-organic complexes (MOCs), 30 samples were selected (see **Paper II** for details).

The extractions were carried out using inductively coupled plasma (ICP) instrumentation. The results used in this thesis from the oxalate (ox) and pyrophosphate (p) extractions were: Al_{ox} (aluminium in allophanic clays and bound to MOCs), Fe_{ox} (iron in ferrihydrite and bound to MOCs), Si_{ox} (silica in allophanic clays), Al_p (aluminium bound in MOCs), and Fe_p (iron bound in MOCs). The allophanic content (%), its Al/Si molar ratio, and the ferrihydrite content (%) were calculated as shown below. Clay content (%) was the result of the sum of allophanic materials and ferrihydrite.

$$\text{Allophanic materials\%} = Si_{ox} \times 1.36\ [(Al_{ox} - Al_p)/\ Si_{ox}]^2 - 1.76\ [(Al_{ox} - Al_p)/Si_{ox}) + 5.44]$$

(Watanabe, et al., 2023; based on method suggested by Parfitt, 1990).

$$\text{Al/Si molar ratio of allophane} = ((Al_{ox} - Al_p)/26.98)/(Si_{ox}/28.09)$$

(Parfitt, 1990).

$$\text{Ferrihydrite\%} = 1.7 \times Fe_{ox}$$

(Parfitt and Childs, 1988).

2.4 Assessing soil water retention properties (Q3.1 & Q3.2)

Soil water retention properties and soil texture were determined for a selection of 120 soil samples (see **Paper III** for details). The samples were maintained field-moist level until they could be processed. Prior to the measurements, they were sieved at 2 mm and placed in ceramic pressure plates, following the methods from Cassel and Nielsen (1986). The samples were subjected to 0.33 and 15 bar pressures, and oven dried at 105°C for 24 hours. The procedure resulted in the water content at field capacity (FC%, 0.33 bar), water content at the wilting point (WP%, 15 bars), and the plant available water (field capacity – wilting point).

The soil texture was assessed by the sand component of the samples using hand texturing in the lab. The soil porosity of the samples was estimated using the bulk density and a particle density estimation of 2.4 g/cm^3, except for area 7-NED, where the particle density estimation was 2.7 g/cm^3. From the porosity and the water retention properties, the percentages of macro-, meso-, and micropores were estimated.

2.5 Estimation of terminal infiltration rates (Q3.3)

Each ring's infiltration measurement took place over a 60-minute period, recording the poured water volume every 5 minutes. Terminal infiltration rates (TIRs, mm/h) were estimated as the mean infiltration rate at 50, 55, and 60 minutes (see **Paper III** for details).

2.6 Data analysis

All analyses throughout this thesis were performed using the RStudio program and R statistical software 4.2.3 (R Core Team, 2023). To determine the differences in the data, linear, non-linear, and stepwise regression models were used. One-way analysis of variance (ANOVA) and post-hoc analyses were used to determine the strength of the effects of fixed effects, such as woodland age and soil depth, on dependent variables. In addition, a structural equation model (SEM) defined the relationship between the main soil properties.

3. Results

3.1 Soil carbon stocks and rates in Icelandic birch woodlands (Paper I)

Soil carbon stocks and carbon sequestration rates in the top 30 cm of soils increased with age in birch woodland chronosequences, with the highest mean carbon stocks in the old woodlands (7.4 kg/m^2), followed by young woodlands (5.3 kg/m^2), and non-forested sites (5.0 kg/m^2; **Q1.1**). The results indicate more rapid carbon accumulation with increasing woodland age. The rate of accumulation from non-forested sites to young woodlands was estimated as 0.01 $kg/m^2/yr$, and the accumulation rates from young to old woodlands, assuming a 30-60-year-old difference, were 0.04-0.07 $kg/m^2/yr$ for the top 30 cm of soils (**Q1.2**). In addition, the estimated carbon burial by dust deposition varied greatly depending on the dust deposition category, from 0.000026 to 0.026 $kg/m^2/yr$ (see **chapter 3.4**).

The observed variation in carbon stock changes across the study areas suggests a strong influence of environmental factors. The climate data, i.e., temperature and precipitation, and the andic properties, $(Al+½Fe)_{ox}$, did not show significant correlations with carbon stocks in this study. Dust deposition did, however, show a negative correlation with carbon stocks. High carbon levels in the non-forested site at 8-SKO indicated the presence of relic carbon from previous woodlands in the soil of the non-forested site (**Q1.3**).

3.2 Chemical and soil colloidal composition in Icelandic birch woodlands (Paper II)

3.2.1 Changes in chemical and soil colloidal composition with woodland age

The chemical soil environment of the samples changed with age along with the birch chronosequences (**Q2.1**). Soil pH decreased with woodland age ($N > Y > O$), but organic carbon showed an opposite trend. The soil pH was lowest in the old woodlands, but all values were higher than pH 5. Only part of the soil colloidal composition changed with woodland age. For example, the allophane content did not vary between age stages, and all soil samples, regardless of their age, were classified as allophanic, i.e., dominated by allophane. The Al/Si ratio of the allophane did, however, change with woodland age and carbon content. The ratios were highest in old woodlands with high carbon contents. As for the allophane clays, the ferrihydrite clay content did not vary within age stages. In the 0-10 cm depth, metal-organic complexes (MOCs) were more abundant in old woodland soils (Al-MOCs: 0.57% and Fe-MOCs: 0.67%), compared to young woodlands (Al-MOCs: 0.26% and Fe-MOCs: 0.26%) and non-forested sites (Al-MOCs: 0.29% and Fe-MOCs: 0.24%), indicating an increase of MOCs with woodland age. However, the difference between stages was not statistically significant ($p > 0.05$), due to high data variability.

3.2.2 Soil colloids and organic carbon relationships

The soil colloids identified in this study, i.e., allophane, ferrihydrite, and MOCs, had different degrees of relationships with organic carbon (**Q2.2**). Clay content increased with increasing carbon content, indicating that clays play a role in carbon accumulation in the samples of this study. However, the correlation between carbon content and clays (allophane and ferrihydrite) was only significant for the 10-30 cm depth interval, with $R^2 = 0.41$ for allophane and 0.27 for ferrihydrite. Differences in clay content between the age of the woodlands were not significant. On the other hand, the combination of active Al and Fe with organic matter (metal-organic complexes) played an important role in carbon accumulation, as Al-MOCs and Fe-MOCs showed strong relationships with organic carbon at both depths ($R^2 = 0.83$ for both).

3.2.3 Main influences on soil colloidal characteristics

Structural equation modeling (SEM) and linear regressions indicated that soil pH and precipitation were key factors influencing soil colloid characteristics (**Q2.3**). Soil pH showed a positive relationship with Al in allophane ($Al_{ox} – Al_p$) and a negative relationship with Al bound to MOCs, indicating that higher soil pH favors allophane rather than Al-MOCs. Higher soil pH also favored more iron (Fe_{ox}), a constituent of both ferrihydrite and Fe-MOCs. Precipitation showed positive and significant relationships with Al-MOCs and Fe_{ox}, suggesting that more precipitation would increase the Al-MOCs and Fe_{ox} content in the soil. Precipitation did not have a relationship with soil pH, but the results showed a slight decrease in pH with higher precipitation. Lastly, dust deposition had a highly negative relationship with both clays and Al-MOCs, with lower clay and Al-MOCs contents present in areas of high dust deposition. It is, however, noted that higher dust rates cause burial and deeper soils (see **section 3.4**).

3.3 Soil water properties of Icelandic birch woodlands (Paper III)

The water retention (FC and WP) of the soil samples was mostly linked to soil porosity, organic carbon, soil texture, $(Al+½Fe)_{ox}$ (representing the colloidal properties), and bulk density (**Q3.1**). Water retention was significantly highest in the old woodlands (63.5% at FC and 45.6% at the WP), where bulk density was lowest, and porosity, carbon, and $(Al+½Fe)_{ox}$ were highest.

Based on a stepwise regression, the plant available water (PAW) was most affected by andic properties, i.e., $(Al+½Fe)_{ox}$, which had a stronger influence than carbon or bulk density. PAW increased with woodland age, showing the highest values in old woodlands (17.9% vs 14.8% in young woodlands and 13.7% in non-forested sites), but the difference was not significant (**Q3.2**). The same pattern was found for terminal infiltration rates (TIRs): the rates were highest in the old woodlands in most seasons, but were not significantly higher. Differences in TIRs were found within seasons. There was a positive relationship between TIRs and air temperature, which aligned with seasonal results: TIRs were consistently higher in spring and lower in winter (**Q3.3**).

3.4 Dust deposition influences on carbon and soil colloidal composition in Icelandic birch woodlands (Q4)

During the course of the study, dust deposition emerged as an important factor influencing the measured soil properties. Categorizing the study areas by dust intensity revealed clear trends and differences in soil properties depending on dust deposition rates.

Study areas with high dust deposition rates had lower carbon content and stocks, lower nitrogen stocks in the sampling intervals, and higher bulk densities than areas with low dust deposition rates. However, by burying carbon in deeper layers, dust deposition led to carbon accumulation. The estimated carbon accumulation ranged from 0.000026 to 0.00026 kg/m^2/yr in the lowest deposition categories (1-2) and up to 0.00099-0.026 kg/m^2/yr in the highest categories (5-6). Thus, despite lower carbon content in the upper 30 cm soil in areas with high dust deposition, the overall carbon stocks across the full soil profile may, in fact, be greater due to deeper carbon accumulation facilitated by ongoing dust inputs (**Paper I**; **Q4**).

Based on post-hoc tests, I estimated the influence that dust deposition has on the chemical and colloidal composition of the soil samples (**Paper II**; **Q4**). The results revealed that areas receiving high dust deposition had a higher soil pH and contained less active Al, although dust deposition did not impact overall allophane contents. However, dust seemed to alter the allophane Al/Si molar ratio, with a lower ratio at higher rates of dust deposition.

There was also a weak relationship between water retention and dust deposition, showing how high dust deposition slightly lowered water retention values (**Paper III**; **Q4**).

4. Discussion

This thesis examines soil properties as a function of birch age in chronosequences of Icelandic birch woodlands. The results revealed multiple interactions among soil properties. The woodland soils were characterized by andic soil properties, comparable to other Andisols globally. However, the high levels of dust deposition in Iceland contributed to a distinct pedological signature, setting them apart from global volcanic soils. Many factors, such as climate, land-use history, and levels of degradation, in addition to variable dust deposition rates, contributed to the geographical variability between study areas. Additionally, variations in woodland age and the extent of development along the birch chronosequences further contributed to the observed heterogeneity.

4.1 Soil carbon is an important ecosystem parameter

Soil organic carbon (SOC) is often used to assess land condition, as it is a measure of soil/ecosystem resilience to degradation, by providing a source for nutrients, such as soil nitrogen, facilitating aggregate formation, increasing soil porosity, lowering bulk density, forming bonds with mineral complexes, and enhancing soil water retention and infiltration (Gaiser and Stahr, 2013; Weil and Brady, 2017). In our study, most areas had high SOC content, comparable to undisturbed Andisols (Arnalds, 2004), yet with a pronounced difference between chronosequence ages. Old woodlands had the highest SOC content and stocks (**Paper I**), but also the strongest bonds between organic and mineral compounds (**Paper II**), lowest sand content, and highest porosity and water retention values (**Paper III**). High SOC content is generally linked to fertility and ecosystem productivity (Gaiser and Stahr, 2013), suggesting that the old birch woodlands have the most resilient, fertile, and productive soils in this study.

Soil organic carbon can reflect previous and current land use (Post and Kwon, 2000; Lal et al., 2015). The non-forested sites in this study exhibited considerable variability in SOC content compared to the young and old woodland stands (**Paper I**). Notably, the highest SOC, found in 8-SKO, showed signs of legacy effects from previous woodlands as ‘relic’ SOC. The SOC content in the non-forested site at 8-SKO, partially influenced by high soil moisture (poor drainage), was almost equivalent to the old woodland soil (17 vs 19%, respectively). The overall high SOC contents in the 8-SKO samples and most other woodland samples were attributed to the capacity of Andisols to accumulate SOC to higher levels than other soil types, with carbon having a long residence time in the soils. This thesis encourages the explicit study of relic/legacy SOC, with special attention to the age of the carbon and determination of its residence time in Icelandic Andisols. Areas with low C content, on the other hand, were generally disturbed due to regular episodes of degradation in their history, with some non-forested sites having experienced soil removal by erosion. Some soils of the non-forested sites were classified as Vitrisols under the Icelandic classification scheme due to their low carbon (< 1.5%), allophane (< 6%), and water content at the wilting point (5-30%; Arnalds, 2015). The most degraded soils were located in areas disturbed by fluvial processes (3-RAN and 4-STEI) with unstable surface conditions. In 4-STEI and 10-MJO, grazing appeared to impede vegetation recovery at the non-forested sites, resulting in unstable gravelly sites with low SOC values. However, grazing did not seem to affect the old woodland sites in the grazed research areas, which had comparable SOC values to other study areas. This firmly supports the notion that the old woodlands have resilience towards natural disturbances and land-use pressures such as grazing. It is important to acknowledge that other factors, such as climate, soil moisture, and dust deposition, also play significant roles in shaping SOC dynamics within Icelandic soils. These influences are discussed in detail across all of the papers included in this thesis.

4.2 The soil colloidal composition of the Icelandic birch woodlands

The soil colloidal composition in Andisols is the result of the rapid weathering of the volcanic parent materials (Dahlgren et al., 2004). It is mostly characterized by nanocrystalline clays, such as allophane, imogolite, ferrihydrite, and sometimes halloysite, and Al- and Fe-metal-organic complexes (MOCs; Wada, 1985; **Paper II**). These colloids exert an important influence on soil fertility, SOC accumulation, and water retention of Andisols (Parfitt, 1990; Takahashi and Dahlgren, 2016). The Andisol clay constituents differ remarkably from conventional aluminum-silicate clay minerals, which are most often layered in structure ("sheets"). Allophanes and imogolite are especially chemically reactive, since they are shallow spherical (allophane) or thread-like (imogolite) units about 5 nm in diameter with immense surface area (Henmi and Wada, 1976). These particles often form silt-size aggregates, with limited cohesion (Warkentin and Maeda, 1980; Parfitt, 1990). The small size and large surface area of allophane enhanced both water retention (due to being a clay) and infiltration rates (due to its silty-clay aggregates) in this study (**Paper III**).

Soil colloids were quite abundant in some of the samples, with up to 37% clay, especially considering the young age of the soils and cool temperatures, which would tend to slow chemical weathering (**Paper II**). Precipitation increased clay contents, since it increases the chemical weathering kinetics of basaltic materials, leading to more active iron and aluminum in the soil. Precipitation is also known to decrease the soil pH due to cation leaching (Rengel, 2011), which also influences what soil colloids dominate the Andisols: allophanic clays at pH > 5, MOCs in pH < 5 (Saigusa and Matsuyama, 1998; McDaniel et al., 2012). All the soils in this study, like most Icelandic Andisols (Wada et al., 1992), were dominated by allophanic clays rather than MOCs, since the pH was only slightly acidic (5-7). Woodlands generally tend to cause lower soil pH as their soils develop (Salisbury, 1992). However, the pH of the soils in this study did not experience a pronounced drop in soil pH, even in the soils with high SOC. This is explained by the rapid weathering of the basaltic parent material, which releases a large amount of cations (Stefánsson and Gíslason, 2001; Óskarsson et al., 2012), and the influence of the dust deposition, steadily adding fresh basaltic materials to the soils (see **subchapter 4.3**). It is noted that the pH buffering capacity of the basaltic parent materials positively affects the cation exchange capacity (CEC), which is highly dependent on soil pH in Andisols (pH-dependent charge), with rising CEC values at higher pH values (not part of this study).

Clay content was found to be relatively consistent across soils of varying woodland age within the chronosequences, i.e., not increasing with woodland age as might be expected (**Paper II**). This is likely attributed to the inherently slow formation of clay minerals (100s and 1000s-year timeframe) and the stability of the existing clay (Parfitt, 1990), with clays remaining even though the SOC reserves become depleted due to soil degradation. Therefore, the timeframe of woodland development examined in this study (30-100 years) is insufficient to capture measurable changes in clay contents. The results indicate a general increase in MOCs with woodland age, suggesting that MOCs formation responds more rapidly to the development of woodland cover than the comparatively slow process of clay mineral formation. Although clays are the dominant soil colloids in the soils, the increased MOCs content further enhances beneficial soil properties, such as nutrient and water retention (McDaniel et al., 2012; Takahashi and Dahlgren, 2016).

The stable clay present in the soils is likely a relic or legacy material derived from previous ecosystem states, as was the case for the relic carbon in 8-SKO. Legacy SOC is sometimes found in previously vegetated, now severely degraded soils, targeted for restoration and soil carbon sequestration, which can influence perceived SOC accumulation rates. Determining clay content where SOC is in soils of such areas can indicate if the SOC found is relic (in the presence of the clays) or newly accumulated (lower clay values).

The rapid SOC accumulation rates observed in this study were primarily attributed to the accumulation of organic matter under resilient ecosystems conditions in cold climates, as well as stabilization of SOC through association with ferrihydrite, and Al- and Fe-metal-organic complexes (MOCs; **Paper II**), aligning with the general Andisol literature (Matus et al., 2006; Wagai et al., 2020). The samples had high ferrihydrite and Fe-MOCs values, suggesting iron (Fe) to be an active component in SOC accumulation, particularly in the old woodlands. Its role was larger than previously recognized, especially compared to what has been reported elsewhere for Andisols (Takahashi et al., 2012). This was attributed to the high Fe content of the Icelandic parent material (~10%; Baratoux et al., 2011; Arnalds et al., 2014) released during the generally rapid weathering of these materials (Stefánsson and Gíslason, 2001; Óskarsson et al., 2012). However, it is important to note that Fe-oxalate values may overestimate ferrihydrite and Fe-MOC, due to contributions from maghemite and magnetite during the extraction. The stronger association between SOC and ferrihydrite in the old woodlands was most likely due to more developed soils, allowing more time for weathering. Allophane did, surprisingly, not show significant relationships with SOC in the soils, as it does in most other Andisols around the world (e.g., Garrido and Matus, 2012). The slow process of stable allophane bonds with SOC is probably the reason for the non-significance (Parfitt, 1990), as the soils in this study are rather young. Furthermore, the decrease in soil pH with higher SOC, a common trend (Jonczak et al., 2020), can inhibit or reduce allophane formation, making Al more available for MOCs instead (Shoji, 1985; Arnalds, 2015). Due to the important role of MOCs in SOC accumulation, a deeper study on these colloids and their abundance in Icelandic Andisols should be carried out. The soils were, however, allophanic since the pH did not decrease below the $pH < 5$ threshold that inhibits allophanic material formation.

Carbon content and pH did, interestingly, alter the Al/Si molar ratio of the allophane, as the ratio was found to be significantly lower in low-SOC and high-pH soils, compared to Al/Si ratios in higher SOC and lower pH soils, possibly due to lower Al^{3+} and $AlOH^{2+}$ availability during allophane formation at higher pH values (Arnalds, 2023; **Paper II**).

4.3 The curious influence of dust deposition on soil variables

Some of the most fertile areas in the world are formed in loess parent materials, as they have a favorable pH, are rich in silt-sized particles, and have high water retention capacities (Birkeland, 1999; Busacca and Sweeney, 2005; Buol et al., 2011). In Iceland, dust deposition by aeolian redistribution of volcanic materials may be classified as 'volcanic loess'. While similar in depositional process to other loess formations, it is distinct in that it is composed entirely of volcanic materials (Arnalds, 2015). The deposition of dust particles is a defining process of the Icelandic soil environment (Arnalds, 2010). The deposited materials are generally silt-sized particles of basaltic origin, which tend to weather rapidly once exposed to the soil environment, releasing Al, Fe, and Si, which are the backbones for the formation of andic soil clay constituents and MOCs (Dahlgren et al., 2004; **Paper II**). The dust currently being deposited contains insignificant amounts of organic SOC and primarily originates from silty dust-hotspots in proglacial areas, along the southern coastline, and in glacio-fluvial environments subjected to periodic flooding (Arnalds, 2010). Yet during the most intensive periods of Icelandic ecosystem destruction, centuries ago, some or most of the dust consisted of redistributed soil materials, which are now present in subsurface horizons of the soils (Arnalds, 2015). This so-called 'erosion stage' is now mostly over, with much of the most vulnerable soil materials lost by wind and water erosion (Arnalds, 2015, 2023; Arnalds et al., 2016). As dust inputs help maintain a favorable pH (near neutral pH), it may be considered to have a positive effect on ecosystems. Gunnarsson et al. (2015) showed, for example, a positive relationship between dust deposition and bird densities. As birds occupy higher trophy levels, they can serve as indicators of overall ecosystem fertility (Mekonen, 2017).

The impact of dust deposition on the studied soil variables was highly significant. Dust seemed to decrease the SOC content in each depth increment of the soil (**Paper I**), as Arnalds and Óskarsson (2007) had already established. This was to be expected as dust particles low in SOC are periodically being deposited, diluting the SOC present in the upper soil layers. Subsequently, the bulk density increases with dust deposition intensity due to the relatively dense basaltic volcanic glass and lower SOC content (Arnalds, 2010). However, bulk density values remain generally low (mostly < 0.9 g/cm^3 and all < 1.3 g/cm^3), in part due to the porous nature of the dust particles (Richards-Thomas et al., 2021).

Although SOC values presented as proportion (%) were relatively lower in each depth increment where dust deposition rates were high, the total amount of SOC did not vary as much, as it is multiplied by the bulk density to obtain stock, hence, the higher bulk density in low SOC soils (**Paper I**). Dust deposition may be beneficial for total SOC accumulation, as the deposition of dust materials leads to soil thickening and SOC burial in deeper soil layers, where SOC can be stored and bound to mineral compounds. In this study, the estimated SOC burial in areas of high dust deposition was noteworthy (0.026 kg/m^2/yr). Given the extensive areas influenced by dust deposition, spanning thousands of square kilometers, the burial of organic material may exert a significant impact on the national SOC budget, and it merits more detailed studies.

Clay content in areas near dust hotspots was lower than in soils far from the main dust sources, as it was dominated by silt-sized particles (**Paper II**). This affected the water retention capacity of the soils, which was reduced in areas of higher dust deposition, due to a relatively low amount of clay-sized particles and SOC in the soil (**Papers I**, **II**, **and III**).

Dust deposition rejuvenates the soils, bringing fresh basaltic materials to the soil surface (**Paper II**). This results in a comparable dilution of the weathering products (e.g., allophane or Al-MOCs), as for organic SOC. This process is especially present in research areas with dry climates, since the lack of precipitation slows the otherwise fast-weathering process (Arnalds, 2004; Óskarsson et al., 2012). Dust also seemed to affect the allophanic Al/Si molar ratio, lowering the ratios in soils with high dust deposition rates. This is likely related to the lower C and higher pH in the soils with high dust intensity, as previously mentioned. The dust deposition of fresh basaltic glass helps maintain a higher pH, counterbalancing the pH drop from the increasing organic matter and chemical weathering (Stefánsson and Gíslason, 2001; Arnalds, 2015). This was especially noticed in the birch woodlands (where the pH should be low), since their vegetative canopy can be perceived as effective dust collectors, with the dust acting to neutralize the pH. Hence, dust does positively impact CEC, as it enhances it by raising the soil pH (Arnalds, 2015).

The dust influences not only Icelandic terrestrial ecosystems but also marine environments, as its deposition in surrounding ocean areas may increase primary productivity and potentially facilitate carbon uptake in the marine ecosystem (Arnalds et al., 2014). The positive effect of SOC burial on climate by reducing atmospheric CO_2 levels (and ocean deposition) is, however, counterbalanced by many negative effects of dust. Wittmann et al. (2016) pointed out that dust deposited in the Vatnajökull glacier reduces the albedo, increasing the snowmelt and having a strong negative impact on the glaciers in Iceland. Other negative effects have been discussed by Arnalds et al. (2016), Dagsson-Walhauserová et al. (2013), Sanchez-Marroquin et al. (2020), Meinander et al. (2021), and Baldo et al. (2023).

4.4 Soil health and importance of Icelandic birch woodlands

Soil health is defined as the ability of the soil to perform environmental functions as a living system, mostly characterized by the ability to sustain plant and animal productivity, resistance to being degraded, and resilience following perturbation (Doran and Zeiss, 2000; Lal, 2011). The 'relic' or 'legacy' SOC and clay from previous forested land in the presently deforested areas demonstrate the resilience of Andisols, following perturbation, and their ability to accumulate and store organic and mineral compounds, even after ecosystem disturbance. The relic SOC and clay content can substantially improve conditions for ecosystem restoration, as the soils have an existing healthy base, facilitating the recovery of birch woodlands.

Allen et al. (2011) identified biological, chemical, and physical indicators of soil health in relation to climate change. Some indicators match the properties studied in this project, e.g., SOC, soil pH, porosity, infiltration, and plant-available soil water (Allen et al., 2011). The birch woodland soils in this study have proven to have properties that are rated high compared to other soils, partly due to the andic soil properties, which can enhance soil fertility (McDaniel et al., 2012). Birch is known to act as an ecosystem facilitator, as it improves soil resilience and the nutrient and water retention capacity. In addition, diverse plant types grow on the old woodland floor (**Fig. 1**), increasing the ecosystem biodiversity. The sturdy root system in Icelandic birch woodlands also improves soil health, as does sufficient soil depth (Allen et al., 2011; Hunziker et al., 2014), which is enhanced by dust deposition.

The resilience of ecosystems is vital for mitigating the future, yet unknown, climatic conditions (Lal, 2011). The interaction between soil properties of woodland soils contributes to a resilient soil system with high organic SOC and soil colloidal contents, and strong bonds between them, even in areas of high dust deposition (**Paper II**). The high water retention properties of the woodland soils also allow them to support highly resilient vegetation, e.g., to drought events (McDaniel et al., 2012; **Paper III**). Healthy water retention capacities, together with favorable infiltration rates, are important regarding climate implications, as they can prevent runoff and flood events, which are becoming more common with climate change (Lal, 2011; Harisuseno and Cahya, 2020). Runoff and water erosion are, therefore, unlikely in Icelandic Andisols with birch woodlands, as they provide an excellent soil cover. In addition, infiltration is maintained in winter in birch woodlands due to the formation of porous ice (as opposed to concrete non-porous ice in barren areas), reducing soil frost damage and run-off (Orradóttir et al., 2008).

Carbon accumulation is also a critical climate mitigation action, as it can reduce atmospheric CO_2 (Lal, 2008). Old woodlands in this study had the highest accumulated SOC stocks, showing high accumulation rates from young to old woodlands (0.04 to 0.07 $kg/m^2/yr$; **Paper I**). According to the estimated SOC accumulation rate, SOC sequestration on the 3,500 km^2 targeted for birch woodland restoration, which the government plans to implement by 2030, would be equivalent to 7% of the nation's total annual CO_2 emissions (or 20% if emissions from LULUCF are not included) when reaching woodland maturity, i.e., within 60-90 years. In addition, it is important to note that the trees also accumulate C in their biomass, wood, and roots, increasing the total SOC accumulation by ~0.1-0.3 $kg/m^2/yr$ (Snorrason et al., 2002; Arnalds and Guðmundsson, 2020). Hence, birch woodlands in Iceland are important for climate change mitigation, in addition to their ecological and environmental values.

Birch has been a key species in facilitating ecosystem stability before the arrival of man. Therefore, protection and restoration of birch woodlands have been an important part of Icelandic national nature protection strategies (Government of Iceland, 2019; Ministry of the Environment, Energy and Climate, 2020). Other European countries have also advocated for the conservation of their natural woodlands (Wulf, 2003), e.g., the Royal Society of Edinburgh (2024), which has stressed the importance of natural woodlands, compared to commercial coniferous tree plantations, due to their important biodiversity and public benefits (also supported by Pörtner et al., 2021). Costa Rica is another example of a nation that has prioritized the regeneration of natural woodlands, increasing their woodland cover by 5% in the last decade (Nello et al., 2023).

5. Conclusions

This thesis addressed important knowledge gaps related to Icelandic woodland soils and provided insights for carbon and soil colloid dynamics in Andisols. It highlights the importance of birch woodlands on a national and global level. Main take-home messages include:

- Soil carbon stocks increased with age in birch woodland chronosequences (**Q1**). The SOC accumulation rate increased significantly with woodland age, mainly due to their andic soil properties, leading to important carbon pools in old woodland soils. If birch woodlands were restored to 5% of the country's land cover as planned, their SOC annual accumulation could equal 7% of total national greenhouse gas emissions.

- The chemical and colloidal soil environment became more complex with woodland age, as the bonds between soil colloids and carbon increased, the pH decreased, and the composition of allophane (Al/Si ratio) altered (**Q2**). MOCs proved to have a vital role in SOC accumulation, even though the soils were allophanic.

- Old woodlands had the highest water retention capacities in the birch woodland chronosequences, attributed to their high carbon and clay content, high porosity, silty textures, and low bulk density (**Q3**). The infiltration rates were highly dependent on vegetation cover and were vulnerable to soil frost during winter or cold periods.

- Dust deposition impacted all the soil properties studied in this thesis. From a soil perspective, it sometimes led to benefits, such as carbon burial (accumulation) and pH buffering (**Q4**). However, it can have negative effects in relation to climate, such as a reduction of the albedo of snow/glaciers. Therefore, this thesis highlights the need to restore woodlands, as they can act as "dust collectors" and reduce the impact of dust on more vulnerable areas where dust re-mobilization is possible.

- The restoration of Icelandic birch woodlands is hereby recommended, as it could be a useful tool for climate change mitigation purposes, among other benefits. Their restoration in degraded Icelandic land would lead to improved soil health, significant SOC sequestration, more efficient soil hydrology (reducing the risk of floods and droughts), and more stable soils (with bonds between soil colloids, as clays, and organic carbon). This thesis highlights the importance of **old** woodlands, thus also underlining the importance of conserving existing birch woodlands, as they and their soils have a large ecological value.

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8. Appendices

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Soil carbon stocks of regenerating Icelandic native birch woodlands: Effects of space and time

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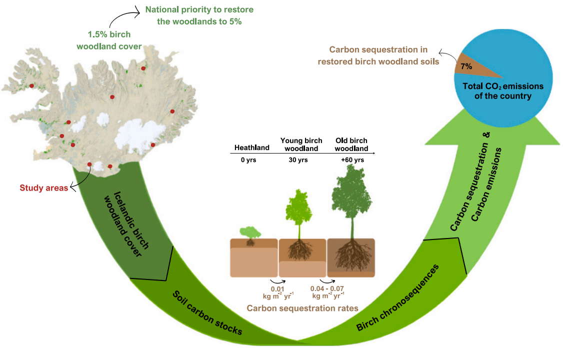
HIGHLIGHTS

- Age and geographic variability affect soil carbon stocks of birch woodlands.
- Highest C stocks were found in old woodlands, with rapid carbon sequestration rates.
- Dust deposition greatly influences carbon stocks through carbon burial.
- Restoration of Icelandic ecosystems can serve as a significant carbon sink.
- C sequestration of restored birch woodlands could equal 7 % of the total emissions.

GRAPHICAL ABSTRACT



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ABSTRACT

Icelandic native ecosystems and soils have been severely degraded since settlement in the 9th century. Today, barren landscapes occupy about 45 % of the land surface and only 1.5 % is covered by native birch woodlands versus 20–40 % in pre-settlement times. Iceland's soils are mainly Andisols, among the most carbon-rich soil orders owing to their unique colloidal characteristics. Hence, there is tremendous potential to sequester soil carbon in degraded soils through revegetation activities. The restoration of birch woodlands is considered a national priority, which may significantly impact the nation's carbon budget. The objective of this study was to determine soil carbon concentrations and stocks across chronosequences (0 to 60+ years) of birch woodlands under diverse geographical conditions comprised of ten study areas across Iceland. The highest carbon stocks were found in old birch woodlands with a mean of 7.4 kg C m^{-2} in the top 30 cm soils, which is unusually high compared to other Nordic deciduous woodlands. We attribute this to andic soil properties that effectively stabilize and sequester soil organic matter. Calculated soil carbon accumulation rates were 0.01 kg m^{-2} yr^{-1} for the first 30 years of birch woodland establishment and 0.04–0.07 kg m^{-2} yr^{-1} in mature woodlands (30–60 years old). These accumulation rates, if applied to large-scale birch woodland restoration plans, would amount to 20 % of the current total CO_2 emissions of Iceland (not counting LULUCF). Importantly, we found a significant impact of dust deposition (up to 1 mm yr^{-1}) on soil carbon stocks, contributing to carbon burial (~26 g m^{-2} yr^{-1}) in

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areas close to dust hotspots. Birch restoration further stabilizes soils from erosion and the above-ground biomass serves as an efficient dust collector. This study documents the potential of birch restoration as a highly effective strategy to address soil degradation and promote soil carbon sequestration across Iceland.

1. Introduction

Soils are vital to ecosystem and planetary health as they contribute to all four categories of ecosystem services: provisioning, regulating, cultural and supporting (Lal et al., 2021; Comerford et al., 2013). Soils are the second largest carbon storage pool after oceans, storing approximately 1500–2700 Pg C (Jackson et al., 2017; Smith, 2012; Lal, 2008). Hence, restoring degraded ecosystems, with subsequent sequestration of soil carbon from the atmosphere, contributes to the goals of the UN Convention on Biological Diversity, the UN Convention to Combat Desertification, and the UN Framework Convention on Climate Change (Wiese-Rozanov, 2022; Montanarella and Alva, 2015).

Andisols (Soil Taxonomy), the most common soil type in Iceland, include some of the most carbon-rich soils in the world (Zieger et al., 2018; Arnalds, 2015; McDaniel et al., 2012). Icelandic soils are mostly of volcanic origin and have developed under cold and humid climate conditions while commonly receiving steady dust (aeolian) deposition of volcanic glass with basaltic origin ranging from 0.01 to 1 mm yr^{-1} (Arnalds, 2015; Arnalds, 2010). The substantial quantities of volcanic glass play an important role in the development of Andisols (McDaniel et al., 2012; Dahlgren et al., 2004). Chemical weathering of these glassy materials leads to the formation of allophane, imogolite, and ferrihydrite together with metal-humus complexes (MHCs; Arnalds, 2015; Wada et al., 1992). These colloidal constituents contribute to the high soil organic matter concentration through physical and chemical interactions (Dahlgren et al., 2004).

Icelandic soils commonly exhibit high soil organic concentrations typical of Andisols, but extensive land degradation and massive soil erosion over the past millennium have resulted in highly irregular spatial distribution of soil organic matter. Young Andisols are highly susceptible to wind and water erosion, especially those with limited vegetative cover, due to their low bulk density and low particle cohesion. This contributes to their vulnerabilities at higher latitudes where land mismanagement is often the driver of land degradation. Iceland has experienced several land-use practices not suitable for these vulnerable soils constantly exposed to harsh weather conditions and frequent volcanic eruptions (Arnalds et al., 2023; Barrio and Arnalds, 2022; Óskarsson et al., 2004). Icelandic Andisols close to dust hotspots receive continuous dust deposition from multiple dust sources that accumulate on the soil surface with pronounced effects on ecosystems. Some areas also receive airfall tephra deposition during volcanic eruptions, often decades or centuries apart (Arnalds, 2010).

During the roughly one thousand years of human settlement, Iceland has lost over 90 % of its original woodland cover (Aradottir et al., 2001; Ólafsdóttir et al., 2001). In 2008, forested land – both natural downy birch (*Betula pubescens*) woodlands and forest plantations – was estimated to cover about 1.5 % of the total land surface, a dramatic decline from the estimated 15–40 % woodland land cover at the time of settlement in the late 9th century (Snorrason et al., 2016; Traustason and Snorrason, 2008; Ólafsdóttir et al., 2001). Furthermore, degraded and eroded lands comprise about 45,000 km^2 or about 45 % of the country (Arnalds and Kimble, 2001) and only 26 % of the land has robust stable ecosystems (Arnalds et al., 2023; Marteinsdóttir et al., 2020). Eroded Icelandic soils can have carbon stocks as low as 0.01–0.03 kg m^{-2}, whereas the soils of natural birch woodlands can contain much higher amounts (>3 kg m^{-2}; Arnalds et al., 2013b). Hence, the restoration of degraded and desertified soils holds great potential for carbon sequestration (Lal, 2004).

To address degraded lands/ecosystems and reduce net greenhouse gas emissions from land, the Icelandic government has promoted a climate strategy that includes restoration of native birch woodlands (Government of Iceland, 2020). In 2021, it accepted the Bonn challenge, pledging an ambitious restoration target to increase the current cover of birch woodlands by 2030 to 5 % (~5000 km^2) of the land area (Government of Iceland, 2021). The research reported here is part of a transdisciplinary project (EcoBirch) that aims to support scaling-up of birch woodland restoration and assess some of its multi-faceted consequences, including carbon sequestration in soils.

Studies of carbon stocks in Icelandic birch woodlands are limited and have primarily focused on comparing carbon stocks among stands of different tree species (e.g., Sigurdsson et al., 2005; Snorrason et al., 2002). Hence, there is a critical need for an extensive study to evaluate how birch woodland restoration efforts impact soil carbon stocks across diverse regions and chronosequence stages in Iceland.

The purpose of this paper is to explore the potential of birch woodland restoration to increase carbon concentrations/stocks of soils across chronosequences (0 to 60+ years) of Icelandic birch woodlands and to determine what factors control the variability in soil carbon stocks. As such, this research provides vital background information for guiding birch restoration and identifies the potential benefits of such actions. Herein, we compare the carbon stocks in surface soils (0–30 cm) of younger and older birch woodlands to adjacent non-forested soils at ten locations across the diverse geographical/climate conditions representative of Iceland.

2. Methods

2.1. Geographical setting

Iceland, situated between 63°23′ N and 66°32′ N latitudes, is a volcanic island with a total area of 103,100 km^2. The climate is oceanic, characterized by moist-mild summers and cool winters, where the annual range of temperatures is relatively small and frequently fluctuates around 0 °C (Ólafsson et al., 2007; Einarsson, 1984). The annual average country-wide temperature and precipitation in 2022 was 4.5 °C and 1100 mm (Icelandic Met Office, 2022). Volcanic eruptions are frequent, occurring every 3 to 5 years, producing both basaltic lava and air fall tephra (Larsen and Eiríksson, 2008; Thordarson and Höskuldsson, 2008), which have a strong impact on soil properties (Arnalds, 2015).

2.2. Study areas

Ten study areas were selected to represent the diverse environments where birch woodlands occur in Iceland (Fig. 1). A prerequisite for study area selection was the existence of chronosequences of birch woodlands from young to old stands and active colonization of birch. Historical aerial photos were used to identify the different age stages. The areas were scattered throughout the country, resulting in variable environmental factors, such as climate and dust deposition (Table 1). Climate metrics, precipitation (mm), and temperature (°C), for each area were based on monthly averages from the nearest weather station of the Icelandic Met Office (n.d.). Dust deposition was categorized on a scale from 1 to 6, with 1 being very low (< 50 g m^{-2} yr^{-1}) and 6 extremely high (500–1000 g m^{-2} yr^{-1}), based on current observations (Gunnarsson et al., 2015). Study areas 2-OX, 4-STEI, and 10-MJO were the only areas currently grazed by sheep (Table S1 in supporting materials). The remaining areas are currently protected from grazing but were grazed in the past.

Sub-arctic mountain birch (*Betula pubescens*) varies greatly in height, ranging from low scrubs to 12 m tall trees (Jónsson, 2004). Chronosequences of birch woodlands were identified at all ten study areas, including old-growth birch woodlands (O, 60+ years old), a younger sub-stage of birch woodlands (Y, ~30 years old), and adjacent non-forested land (N). All old woodlands across the study areas consisted of trees taller than 2 m. Both O and Y stages had 100 % vegetation cover and often contained an understory of forbs, grasses, mosses and heath. Most of the non-forested sites were classified as heathlands with abundant vegetation cover, but some were stony and sparsely vegetated due to past land degradation and soil erosion. Sites with a single or few trees were considered non-forested. Study area 7-NED was selected as a core study area for the ecological investigation component of the overall study and its chronosequence included an additional mature stage (40–50 years old). See Figs. S1, S2 and S3 for photographs of selected plots.

2.3. Soil sampling

Soils were sampled in the summer of 2021 from all identified stages at each study area. Recent aerial photographs were used to establish three 300–1000 m long transects, spaced 50 to 100 m apart, each passing through the three (plus the fourth stage at 7-NED) age stages: old woodland, young woodland and non-forested land. For each of the three transects, two 10 × 10 m plots located 10 m apart were established, resulting in a total of six plots per age stage: 2 plots × 3 transects.

Soil samples were collected using an auger or core sampler 4.8 cm in diameter from two depth intervals: 0–10 cm and 10–30 cm. The sampling methodology was based on established protocols for the national inventory reporting to the UNFCC (LULUCF; Keller et al., 2023). The vegetation and litter layers were removed before sampling. The vegetation cover consisted predominantly of bryophytes (mosses) that sat on the soil surface; this material was removed to expose the mineral soil surface prior to inserting the auger. In some sampling sites, vascular plants predominated the land cover. In this case, care was taken to remove the vegetation layer from the mineral soil surface before sampling. Generally, each sample consisted of five cores taken from five quadrats (50 × 50 cm) randomly distributed within the 10 × 10 m plot (see Fig. S4). Some samples consisted of less than five cores as it was not always possible to collect the 10–30 cm soil samples due to rocky or shallow soil conditions, mainly in the non-forested sites. In some plots, no cores were collected for the same reasons. Hence, a total of 330 soil samples were collected instead of the planned 372 samples: 182 from the 0–10 cm depth and 148 from the 10–30 cm depth.

2.4. Soil measurements

Samples were stored in a cold room (10 °C) and subsequently weighed and split into halves. One half was dried at 40 °C and sieved at 2 mm. Weight (before and after drying) and volume were measured for all samples, as well as the coarse fragments (>2 mm). Coarse fragments, mainly composed of basaltic pebbles, stones, or thick roots, were excluded from the bulk density calculations, which were only applied to the volume and weight of the <2 mm soil fraction.

A subsample of soil (<2 mm) was ball-milled into a fine powder for

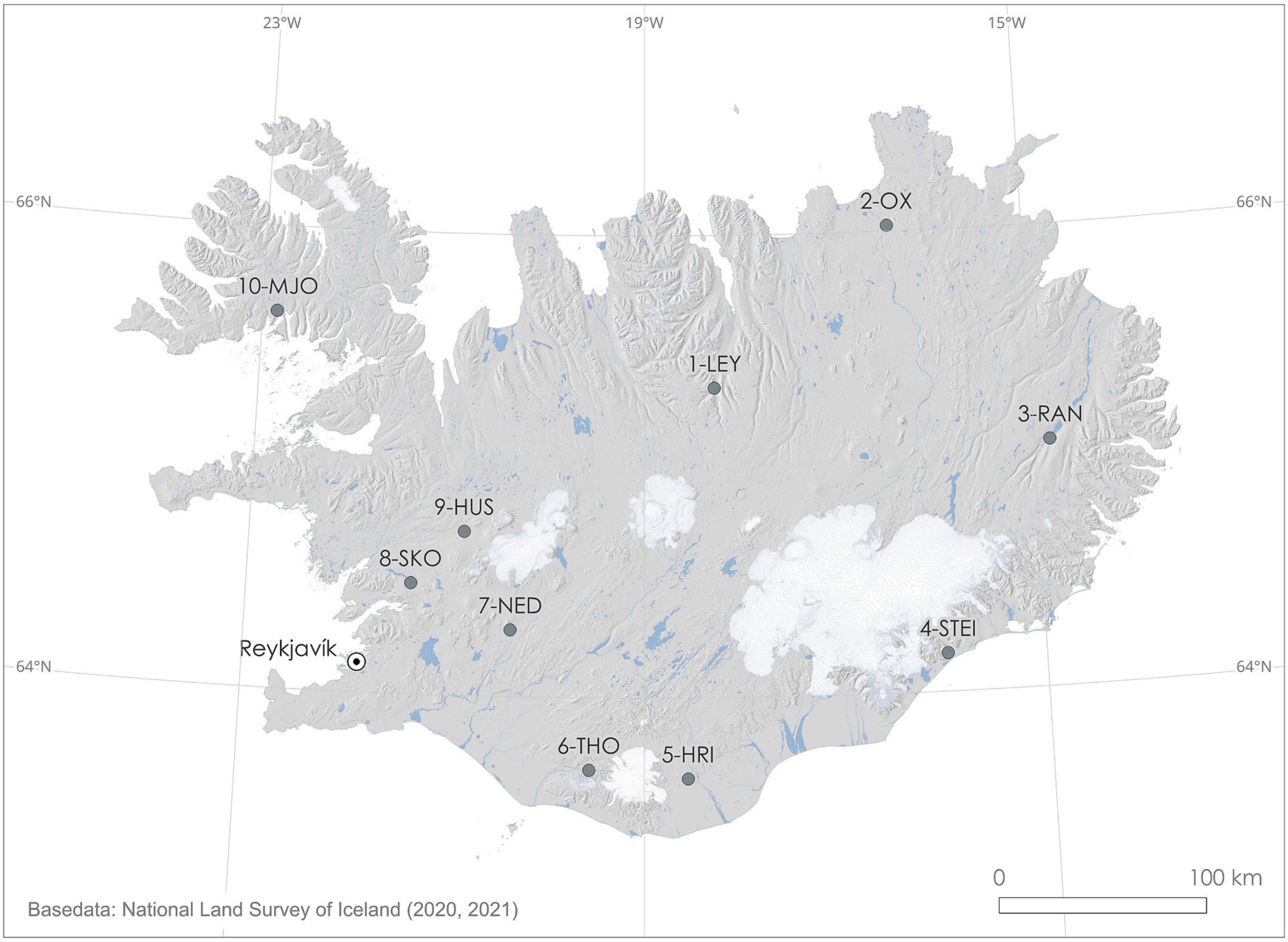

Fig. 1. Map of the study areas with their corresponding numbers and acronyms in clockwise geographical order.

carbon and nitrogen (%) analysis using a Retsch PM400 soil grinder. Carbon and nitrogen analyses were performed using an elemental analyzer Vario MAX cube applying the Dumas method (dry combustion, Elementar, Langenselbold, Germany; Bertsch and Ostinelli, 2019). As the soil samples were carbonate-free, we assumed that the total carbon was equivalent to the organic carbon concentration.

The C/N ratio is often used as an indicator of temporal changes in the quality of soil organic matter and its availability for higher organisms (Weil and Brady, 2017; Ostrowska and Porębska, 2015). The ratio was calculated on a mass basis by dividing the carbon concentration (%) by the nitrogen concentration (%).

2.5. *Additional bulk density samples*

An ancillary study was designed to assess the accuracy of the standard core method used here for bulk density (described above), which potentially may compact soil samples. Separate bulk density samples were collected in the summers of 2022 and 2023 at all study areas except 2-OX. The samples were collected using a thin-walled cylinder of 7.3 cm inner diameter driven horizontally into the soil profile and subsequently cut out with a sharp knife. Soil samples were collected from the old-growth woodland and the non-forested land as triplicates per depth interval (0–10 and 10–30 cm). A total of 74 samples from 9 of the 10 study areas were collected for this bulk density comparison (see Table S6 for full description). Processing of the bulk density samples followed the same procedures as for the standard core samples; these samples were analyzed for total carbon as described above.

2.6. *Calculation of carbon and nitrogen stocks*

Carbon and nitrogen stocks for the ‘active soil volume’ constituting the primary rooting zone (0–30 cm; Tadiello et al., 2022) were determined for each depth interval as follows:

$$\mathrm{SOC}\ \left(\mathrm{kg\ m^{-2}}\right) = \mathrm{OC} \bullet \mathrm{LT} \bullet \mathrm{BD} \bullet (1 - \mathrm{CF}) \bullet 10$$

where OC is organic carbon concentration (%), LT is the layer thickness (m), BD is the bulk density (g $\mathrm{cm^{-3}}$) of <2-mm fraction, and CF is the coarse-fragment (>2-mm) volume fraction. The same formula was used for nitrogen stocks, only substituting N% for OC%. The stocks from both depths (0–10 and 10–30 cm) were summed to obtain the carbon and nitrogen stocks for the 0–30 cm soil layer.

2.7. *Data analyses*

Statistical analyses were made using RStudio software version 2024.04.1 + 748 (Posit, 2024).

The Mahalanobis principle was performed to identify potential outlier values, using the packages *stats* and *factoextra*. We identified three samples from the non-forested site in 8-SKO as outliers, which were subsequently excluded from further data analyses.

Mean values were calculated for each soil property at each study area, age stage, and soil depth increment, using the RStudio packages *dplyr* and *Hmisc*. Mean values for the soil properties were calculated for each study area and independently for each age stage.

Boxplots were prepared using the package *ggplot2*. The boxes delineate the lower and upper quartile values and the horizontal line within the box represents the median value. The top and bottom of the vertical lines represent the maximum and minimum values, and outliers are displayed as single points.

One-way analysis of variance (ANOVA) was performed to assess significant differences between 1) study areas, 2) age stages, and 3) depths, respectively, using the packages *stats* and *ggpubr*. Subsequently, Tukey tests were performed for post-hoc mean separation using the package *stats*. Different analyses were performed for each soil property, e.g., carbon concentration, bulk density. Significant statistical differences were determined at $p < 0.05$. For the ANOVA and Tukey analyses, only data from the three age stages (N, Y, and O) were included. A separate analysis was executed for the 7-NED study area with all four stages, including the mature woodland (M).

A *t*-test was performed, using package *stats*, to assess statistical differences between the bulk density measurements by the standard core versus additional bulk density samples. The young woodland samples from the standard core method were not included in this test since the additional bulk density samples were not sampled at the young woodlands.

Linear regression models, packages *stats*, *ggpubr*, and *ggplot2*, were used to assess the statistical relationship between dust categories and 1) carbon concentration (%), 2) bulk density (g $\mathrm{cm^{-3}}$), 3) carbon stock (kg $\mathrm{m^{-2}}$) and 4) nitrogen stock (kg $\mathrm{m^{-2}}$) in the old woodlands. Mean values were used to capture the central tendency and simplify plot interpretation. Additionally, linear regressions for carbon (% and stock) vs. climate data (precipitation and temperature) were performed for each depth and age stage.

Exponential decay models were applied, using packages *nlstools*, *boot*, *ggplot2*, *stats*, and *dplyr*, to describe the relationship between carbon concentration (%) and bulk density (g $\mathrm{cm^{-3}}$) and assess the variability between the bulk density measurement methods. The models represent the relationship of the soil properties as follows:

$$\mathrm{C} = \mathrm{C_0} \bullet \mathit{exp}(-\mathrm{k} \bullet \mathrm{BD})$$

where C is the carbon concentration (%), BD is the bulk density (g $\mathrm{cm^{-3}}$), $\mathrm{C_0}$ is a constant representing the initial carbon concentration, and k is the decay constant that determines the rate of decrease in

Table 1

Geographical and meteorological data for the ten study areas.

Study areas	Names	Coordinates	Region	Dust deposition[a]	Av annual precipitation[b]	Av annual T[b]	Av July T[b]	Non-forested site
1-LEY	1. Leyningshólar	65°34′ N, 18°28′ W	North	4	529	4	11.5	Heathland
2-OX	2. Öxarfjörður	66°03′ N, 16°43′ W	Northeast	4	583	3.7	10.8	Heathland
3-RAN	3. Ranaskógur	65°07′ N, 14°84 W	East	4	928	4.3	11.2	Gravelly grassland
4-STEI	4. Steinadalur	64°16′ N, 15°98′ W	Southeast	5	1109	5.4	10.7	Mossy/gravelly soil
5-HRI	5. Hrífunes	63°65′ N, 18°57′ W	South	6	1459	5	11.7	Heathland
6-THO	6. Þórsmörk	63°69′ N, 19°54′ W	South	6	1198	4.4	11.2	Gravelly soil
7-NED	7. Neðri Dalur[c]	64°29′ N, 20°34′ W	West	3	1340	4.1	11.9	Heathland
8-SKO	8. Skorradalur	64°48′ N, 21°35′ W	West	2	1001	4.4	11.4	Heathland and wetland
9-HUS	9. Húsafell	64°71′ N, 20°82′ W	West	4	810	3.8	11.3	Gravelly soil
10-MJO	10. Mjóifjörður	65°63′ N, 22°85′ W	Westfjords	1	542	1.9	8.9	Gravelly soil

[a] Dust categories following Gunnarsson et al. (2015) methods.

[b] Years included in weather data averages: 1-LEY: 1949–2023. 2-OX: 1956–2016. 3-RAN: 1996–2023 (temperature), 2002–2023 (precipitation). 4-STEI: 2007–2023 (temperature), 2009–2020 (precipitation). 5-HRI: 2004–2023 (temperature), 2007–2021 (precipitation). 6-THO: 1961–2022. 7-NED: 1990–2023. 8-SKO: 1998–2023 (temperature), 1999–2022 (precipitation). 9-HUS: 1998–2023 (temperature), 1988–2016 (precipitation). 10-MJO: 2000–2023 (temperature), 1961–2003 (precipitation).

[c] 7-NED: Core ecological study area with an extra age stage: mature woodland.

carbon concentration with increasing bulk density. *P* values were determined using the Wald test.

2.8. Soil description and classification

Detailed soil descriptions for study areas 7-NED and 8-SKO based on Soil Taxonomy (Soil Survey Staff, 1999) and an Icelandic system (Arnalds et al., 2005) are presented in Fig. S5 and Tables S2 and S3. The remaining soils were tentatively classified (Table S4). Water content at the wilting point (% at −1.5 MPa) for each age stage at each of the 10 study areas was measured using a pressure plate and used for soil classification when required (Table S5). Many of the study areas were on the border of cryic-frigid climate regimes according to Soil Taxonomy. The soils in this study were all considered Andisols with the most common great group being Ustivitrands.

3. Results

3.1. Carbon, nitrogen, and C/N ratio

Soil carbon concentration ranged from 0.2 to 19.2 % and nitrogen from 0.02 to 1.04 %. Both carbon and nitrogen had a significantly higher concentration in the 0–10 cm than in the 10–30 cm layer ($p < 0.001$). Old-growth woodland stages had significantly higher carbon and nitrogen concentrations than either non-forested sites or young birch woodlands (Table 2).

The C/N ratio ranged from 11.1 to 50.5 and was significantly higher in the 0–10 cm depth layer ($p < 0.001$), due to litter inputs from the vegetation. In the 0–10 cm layer, the old woodlands showed the lowest C/N ratios (Table 2), whereas there were no differences in the C/N ratio in the 10–30 cm layer across age stages.

3.2. Bulk density

Soil bulk density from the woodland transects was generally low as expected for Andisols, with values ranging from 0.2 to 1.5 g cm^{-3}. Bulk density followed an inverse trend to that of organic carbon in both soil depths (N > Y > O) and was significantly lower in the 0–10 cm than at the 10–30 cm depth ($p < 0.001$, Table 3). A strong relationship following an exponential decay curve was determined between soil carbon concentration and bulk density from the standard core samples (Fig. 2).

3.2.1. Comparison of standard core vs thin core method for determining bulk density

Additional bulk density samples were collected from the non-forested and old woodland components of nine study areas to confirm the efficacy of the standard core methodology. The two bulk density measurements fell within a similar range for comparable carbon values (Fig. 3). However, the relationship between the carbon concentration and bulk density of the additional samples ($R^2 = 0.45$, $p < 0.001$) was not as strong as the relationship found in the core samples ($R^2 = 0.66$, $p < 0.001$).

While the standard core samples had a slightly higher mean bulk density than the additional bulk density samples (0.76 vs. 0.71 g cm^{-3}), the overall difference was not statistically different ($p \geq 0.05$), neither when considering depth (0–10 cm and 10–30 cm), nor stage (non-forested and old woodlands).

Table 3

Mean values ± SD for soil bulk density (g cm^{-3}) from native birch woodland areas as a function of age stages and soil depths. Acronyms for each age stage (N, Y, and O) are used within each soil depth to indicate significant differences between age stages ($p < 0.05$).

Depths	Non-forested soil	Young woodland	Old woodland
0–10 cm	$0.78 \pm 0.26^{O,Y}$	$0.67 \pm 0.24^{O,N}$	$0.55 \pm 0.16^{N,Y}$
10–30 cm	$0.98 \pm 0.28^{O,Y}$	0.84 ± 0.29^{N}	0.78 ± 0.18^{N}

3.3. Carbon and nitrogen stocks for EcoBirch study areas

Carbon stocks (kg m^{-2}) ranged from 1.6 to 15.4 kg m^{-2} in the 0–30 cm depth layer of soils. For all depth layers, the carbon stock increased with woodland age, N < Y < O, and was significantly higher in the old woodlands than the younger woodlands and the non-forested land (Fig. 4). This trend was found in all study areas except for 2-OX and 8-SKO which both had high carbon in the non-forested stage (Fig. 5). Study areas 7-NED and 8-SKO had the highest carbon stocks across all stages (mean 9.5–10 kg m^{-2} across all stages), while areas 3-RAN, 6-THO and 4-STEI had the lowest carbon stocks (mean 3.2–3.9 kg m^{-2}).

The core ecological study area (7-NED) included an additional age stage, a mature birch woodland (M). The carbon stocks in the top 30 cm of 7-NED soils ranged from 5.8 to 12.4 kg m^{-2}, with mean values of 9.1, 10.1, 9.3, and 10.9 kg m^{-2} for stages N, Y, M, and O, respectively. The differences in carbon stocks between individual stages at 7-NED were not statistically significant, except for O versus N ($p = 0.03$).

Nitrogen stocks were highest in the old woodlands but there was no significant difference between Y and N ($p = 0.90$). The same significance between age stages was found in each depth interval (Table 4).

3.4. Climate factors and carbon stocks

Mean annual temperatures (MAT) of the study areas ranged from 3.7 to 5 °C, with the exception of 10-MJO which had a MAT of 1.9 °C (Table 1). Mean annual precipitation (MAP) also varied greatly, ranging from 542 to 1459 mm yr^{-1}. We found no significant correlation between carbon (% and stocks) and climatic factors (MAT or MAP) in either depth or age stages. The coldest study area (10-MJO), however, had both the highest carbon concentration and stocks.

3.5. Effect of dust deposition on carbon and nitrogen concentration and bulk density in old woodlands

Fig. 6 shows the relationship between dust deposition (six categories) and the mean values for carbon (%), bulk densities (g cm^{-3}), carbon stocks (kg m^{-2}), and nitrogen stocks (kg m^{-2}) in the old woodlands of each study area. Carbon concentration (%) was generally lower in areas with greater amounts of dust deposition, in both depth intervals (Fig. 6, A and B). The opposite trend occurred for the bulk density, which showed a tendency to increase with higher dust deposition rates at both depths although the relationship was not significant (Fig. 6, C and D). There was a clear decline in carbon and nitrogen stocks in the top 30 cm of soils as the dust deposition rate increased (Fig. 6, E and F, respectively).

Table 2

Mean values and ± SD for carbon (C), nitrogen (N), and C/N ratio of ten native birch woodland areas as a function of age stages and soil depths. Acronyms for each stage (N, Y, and O) are used to indicate significant differences within each depth ($p < 0.05$).

Stages	Non-forested soil			Young woodland			Old woodland		
Depths	%C	%N	C/N ratio	%C	%N	C/N ratio	%C	%N	C/N ratio
0–10 cm	3.7 ± 3.8^{O}	0.19 ± 0.21^{O}	20.6 ± 7.4^{Y}	4.9 ± 4^{O}	0.23 ± 0.2^{O}	$23.1 \pm 5.8^{N,O}$	$7.3 \pm 3.9^{N,Y}$	$0.38 \pm 0.22^{N,Y}$	19.5 ± 2.3^{Y}
10–30 cm	2.1 ± 2.2	0.15 ± 0.17	15 ± 2.4	2.5 ± 2.3	0.17 ± 0.16	15.9 ± 3.3	3.1 ± 2.3	0.21 ± 0.15	15.1 ± 2.7

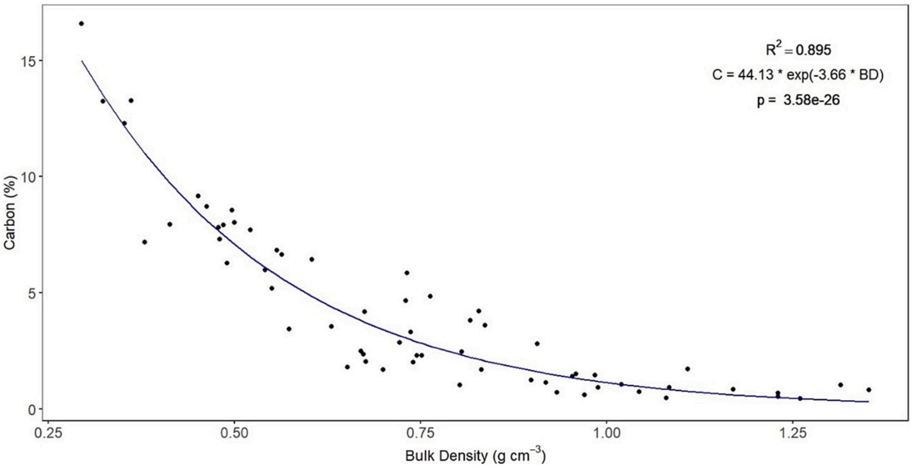

Fig. 2. Exponential decay relationship between carbon (%) and bulk density (g cm^{-3}) of the mean values for the core samples (n = 62) of the ten native birch woodlands based on mean values for each depth of each stage in each study area. The exponential decay shows a strong negative relationship between carbon and bulk density.

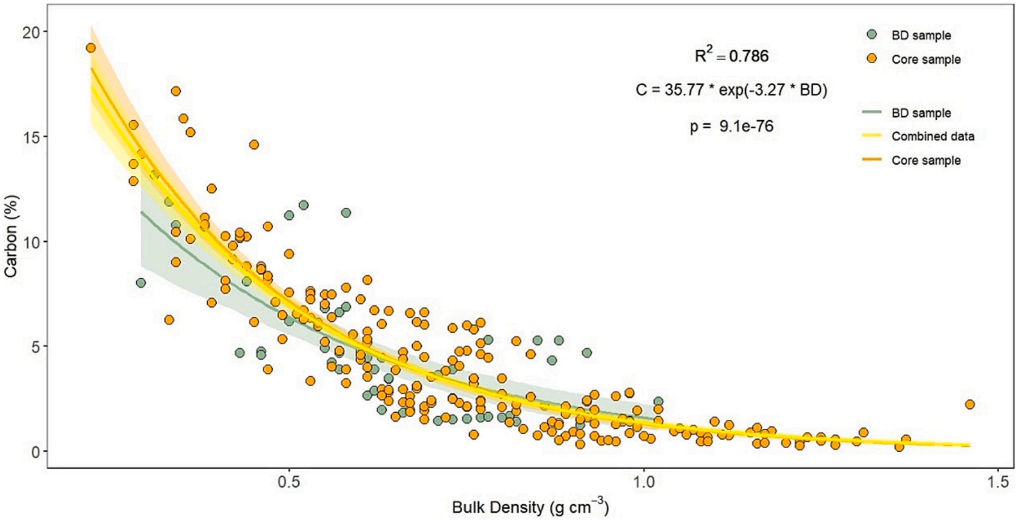

Fig. 3. Relationship between organic carbon (%) and bulk density (g cm^{-3}) of the standard core and additional bulk density (BD) samples. The three exponential decay curves with their 95 % confidence intervals (BD samples: n = 48, Core samples: n = 211). The equation and R^2 refer to the exponential decay of the combined data sets. All three regressions show a strong negative relationship between carbon and bulk density.

4. Discussion

4.1. Carbon stocks – global context

Carbon stocks of the EcoBirch study areas were highly variable, ranging from 1.1 to 15.4 kg m^{-2} in the top 30 cm, with a mean value of 7.4 kg m^{-2} for old woodlands. This value is relatively high compared to birch woodland soils in other countries. For example, mean carbon stocks in birch woodlands in Norway have 3.7 kg m^{-2} in the top 30 cm soil (Devos et al., 2022) and in Poland 4.3–6.2 kg m^{-2} in the 0–50 cm soil depth (Gawęda et al., 2019).

Woodlands of deciduous tree species like oak or beech can have high soil carbon stocks, such as (note variable depths), 5.3 kg m^{-2} in top 20 cm soil of a beech woodland in the Netherlands (Schulp et al., 2008), 10.4 kg m^{-2} in top 50 cm soil of a coniferous-dominated woodland in Austria (Jandl et al., 2021), 2.8 kg m^{-2} in top 30 cm soil of a tropical dry deciduous woodland in India (Gandhi and Sundarapandian, 2017), 3.8–5.7 kg m^{-2} in upper 15 cm soil of a Mediterranean oak woodland in California (Dahlgren et al., 2003), and 13.3 kg m^{-2} in top 25 cm soil of a Japanese Andisol with a native oak woodland (Takahashi et al., 2007). In contrast, wetland soils in Iceland accumulate appreciably more carbon (over 200 kg m^{-2}; Óskarsson et al., 2004). Our study area 8-SKO had a higher carbon stock mean (10 kg m^{-2}) than most of the other study areas, possibly owing to hydromorphic properties that may enhance carbon accumulation.

Andisols have the tendency to accumulate soil organic carbon (Shoji, 1985) and have a higher organic carbon residence times than other soil types (Baisden et al., 2013; McDaniel et al., 2012; Dahlgren et al., 2004). The EcoBirch results are consistent with these Andisol characteristics. Some Andisols have up to 25–30 kg m^{-2} in the top 100 cm (Zieger et al., 2018; Dincă et al., 2015), similar to values reported for the full soil depth of Icelandic dryland soils (primarily Ustands, Ustivitrands and Vitricryands; Óskarsson et al., 2004). Hunziker et al. (2019) reported carbon stocks of around 4 kg m^{-2} in the top 20 cm of soil in 26- and 97-year-old birch woodlands in an area with high dust deposition near Mt. Hekla in South Iceland. Hunziker's carbon stock would likely be slightly higher for the top 30 cm soil, considering high dust deposition that buries soil carbon below 30 cm. In comparison, carbon stocks in the top 30 cm of the EcoBirch old woodland sites had a mean value of 7.4 kg m^{-2} in the top 30 cm soil and Snorrason et al. (2002) reported similar carbon stock

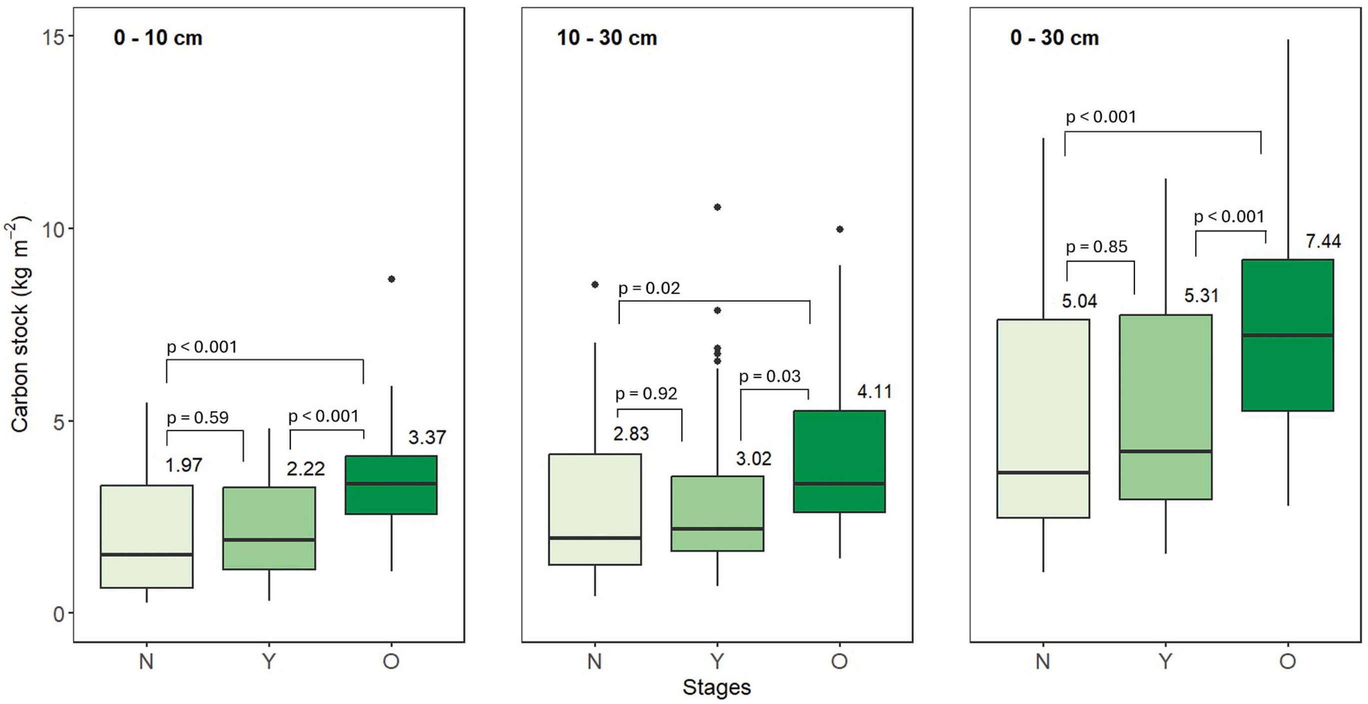

Fig. 4. Carbon stock (kg m^{-2}) across all ten study areas separated by soil depths and age stages: N: non-forested land ($n = 75$). Y: young woodland ($n = 94$). O: old woodland ($n = 112$). Mean values for each age stage and depth are placed on the top right of the boxplots, while the median values are represented by the centerline of each boxplot. Carbon stocks are significantly higher in old woodlands than in young woodlands and non-forested stages at all depths. Statistical differences were determined via *p*-values from ANOVA.

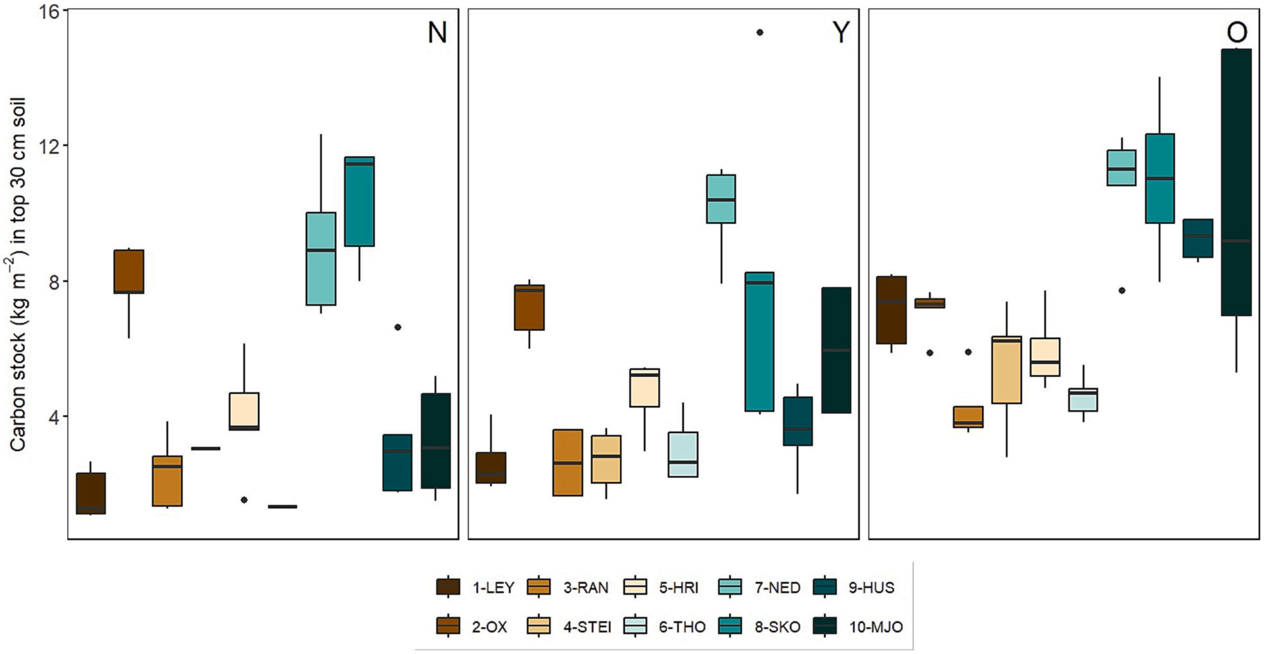

Fig. 5. Carbon stock (kg m^{-2}) in the top 30 cm soil by study areas and stages: N: non-forested land (n = 75). Y: young woodland (n = 94). O: old woodland (n = 112).

values of ~6.5 kg m^{-2} in the top 30 cm soil for a 54-year-old birch stand in Gunnarsholt, South Iceland.

We note that even though it has been suggested that birch woodlands have normally lower carbon stocks than other tree species like spruce or pine (Hansson et al., 2013; Vesterdal et al., 2013), the andic properties of Icelandic soils elevate carbon stocks in birch woodlands, resulting in higher values than the above-mentioned deciduous and coniferous woodlands.

4.2. *Carbon stock variability*

In this study, both carbon concentration and carbon stocks were highly variable depending on the geographic distribution (Fig. 5). The mean carbon concentration in the 0–10 cm depth of old woodlands (7.3 %) is typical for Icelandic Andisols, which are commonly reported to have values between 2 and 12 %, maximum 25 % (Arnalds, 2010; Arnalds and Oskarsson, 2007; Óskarsson et al., 2004). The mean C

Table 4
Mean values ±SD for nitrogen stock (kg m^{-2}) for the ten native birch woodland areas separated by age stages and soil depths. Acronyms for each age stage (N, Y, and O) are used within each depth to indicate significant differences between stages from ANOVA tests at $p < 0.05$.

Depths	Non-forested land	Young woodland	Old woodland
0–10 cm	0.12 ± 1.2^{O}	0.11 ± 0.8^{O}	$0.19 \pm 0.8^{Y,N}$
10–30 cm	0.22 ± 1.8^{O}	0.22 ± 1.8^{O}	$0.31 \pm 1.8^{N,Y}$
0–30 cm	0.35 ± 2.8^{O}	0.33 ± 2.5^{O}	$0.5 \pm 2.2^{Y,N}$

concentration for the 10–30 cm samples was considerably lower (3.3 %). The reduction in C concentrations with depth reflects the lower inputs of fresh organic matter to deeper soil layers due to soil burial. Lower organic C concentrations in subsoil horizons can result from burial (dilution by low C% dust) by aeolian deposition. This is supported by relatively higher subsurface values in areas of low dust deposition rates (less C burial) at 8-SKO and 10-MJO. Lower mean values for non-forested and young woodland stages reflect a transition towards more developed soils under birch woodlands as organic matter inputs from above-ground litter and root death contribute to the soil organic matter (SOM) pool.

The relatively weak relationship between $(\mathrm{Al} + \mathrm{Fe}½)_{\mathrm{ox}}$ (i.e., andic soil properties) and carbon stocks ($R^2 = 0.19$) suggests that factors in addition to andic soil properties may affect the carbon accumulation in the study areas. The high latitude of the EcoBirch study areas and the associated cold climate could, for example, contribute to the relatively high carbon concentration found in the old woodlands. Decomposition of organic materials is slower in colder temperatures and hence residence time of organic carbon is longer (Buczko et al., 2017; Lal et al., 2015; Arnalds et al., 2013b; López-Ulloa et al., 2005; Gudmundsson et al., 2004). Ample precipitation is known to boost carbon accumulation (Matus et al., 2014; Egli et al., 2012). The EcoBirch areas did, however, not show any relationship between carbon stock and MAP, suggesting that other factors have a greater influence on soil carbon accumulation, such as vegetation cover, soil moisture regime, colloidal constituents, and/or dust deposition.

4.3. The effect of dust deposition on geographic variability

Dust deposition has been shown to enhance soil fertility as demonstrated by higher bird densities with increasing dust deposition in Iceland (Gunnarsson et al., 2015). Dust deposition, generally composed of volcanic glass and poorly crystalline materials, has pronounced impacts on soil properties, such as organic carbon dynamics (Arnalds, 2023). There was a strong relationship between dust deposition rates (six categories used) and soil carbon concentration (%) of the EcoBirch soils in the old woodlands ($R^2 = 0.67$ for 0–10 cm and $R^2 = 0.69$ for 10–30 cm depth). Only results from the old woodlands are used since these

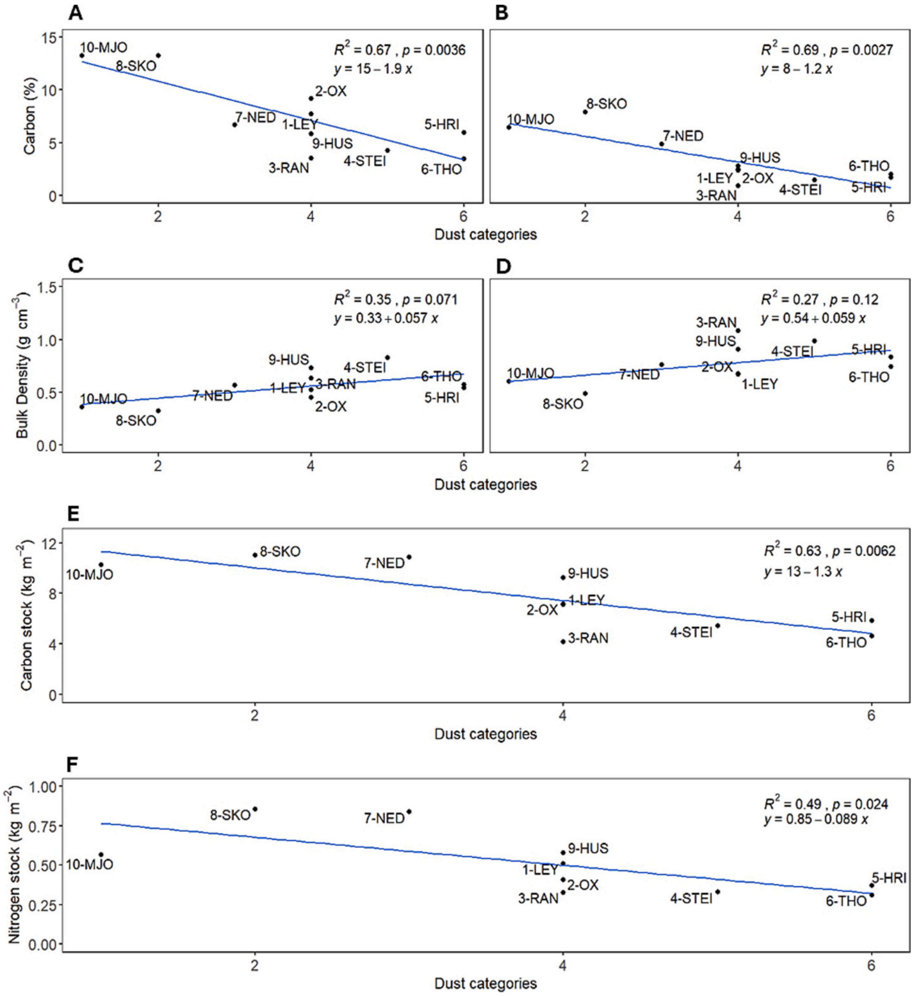

Fig. 6. Relationship between dust deposition categories and mean values for carbon concentration (%; A: 0–10 cm, B: 10–30 cm), bulk density (g cm^{-3}; C: 0–10 cm, D: 10–30 cm), carbon stock (kg m^{-2}; E: 0–30 cm), and nitrogen stock (kg m^{-2}; F: 0–30 cm) in the old woodlands of each study area ($n = 10$). Carbon (%) and bulk density (g cm^{-3}) graphs are separated by depth: 0–10 cm and 10–30 cm. The trends between dust deposition with %C and C and N stocks were significant but not significant for BD.

ecosystems are considered to be relatively stable due to their age and therefore represent a more realistic representation of the influence of dust on the soil carbon and bulk density. Areas with higher dust deposition had generally lower C concentration and a higher bulk density, as previously suggested by Arnalds and Oskarsson (2007) and Arnalds et al. (2016; Fig. 6). This negative correlation between organic carbon and bulk density can be attributed to humus accumulation, which increases soil porosity through promotion of soil structure. Higher bulk density within high dust deposition areas is thus due to less organic materials and a higher concentration of relatively dense basaltic volcanic glass (Arnalds, 2015). This interaction between carbon and bulk density caused by dust deposition makes carbon and nitrogen stocks less variable between study areas compared to carbon concentration per se (Fig. 6). The mean values for carbon stocks of this project are high considering the proximity of some study areas to dust hotspots. However, dust deposition hotspots decrease the soil carbon concentration but increase soil depth with appreciable organic carbon accumulation (Arnalds, 2023).

This study considered only the top 30 cm of the soils in calculating organic carbon stocks. In areas of continuous high dust deposition rates to soils (e.g., 5-HRI and 6-THO), the overall soil depth increases with time, resulting in burial of soil carbon at depths lower than 30 cm. Hence total stocks on an entire soil profile basis can be as high or higher in greater dust deposition areas compared to shallower soils with higher stocks per each depth interval in low dust deposition areas. The estimation of overall carbon sequestration presented in Table 5 is based on dust deposition rates (amount of dust per deposition category) and the mean organic carbon and bulk density of each deposition category from the EcoBirch results. As dust deposition does not contain any significant amount of organic carbon (Arnalds, 2023), this calculation only considers carbon burial effects on the existing soils with 1–7 % C in their surface horizon. The dust deposition burial effects range from negligible amounts (0.026 g m^{-2} yr^{-1}) in low deposition areas to 26 g m^{-2} yr^{-1} in high deposition areas. These values apply to 1000's of km^2, so burial due to dust accumulation has a pronounced effect on the carbon budget of Icelandic soils, which increases as dust deposition rates increase (Table 5). This effect is more pronounced when dust accumulation is rapid, such as in the birch woodlands (up to 26 g m^{-2} yr^{-1} for 5 % C).

4.4. Land use and history

Land management history has a pronounced effect on carbon stocks (Hu et al., 2021; Lal et al., 2015; Post and Kwon, 2000) and carbon accumulation in soils depends on multiple factors such as soil type, ecosystem characteristics, climate, and other environmental factors (e.g., Wiesmeier et al., 2019), with dust deposition playing an especially important role in Iceland (Arnalds, 2010).

The carbon stocks in this study generally increased with woodland age. However, there are exceptions to this trend – which may be related to historical land-use/land-cover conditions in each study area. A statistical analysis identified three samples from the non-forested stage in 8-SKO as outliers which were excluded due to their extremely high carbon stock (e.g., microsite pockets of high organic matter). However, the carbon stocks in the adjacent non-forested land (N) were still higher than in the young woodlands (Y) and comparable to the old woodland (O) stocks (Fig. 5). The reason for this anomaly (N carbon stock > Y carbon stock) is most likely because the currently non-forested area was part of a preexisting birch woodland (called 'Vatnshorn-forest' by Skorradal Lake) that was deforested in the past 100 years due to sheep-grazing and harvesting of firewood (Icelandic Forestry Service, n.d.). The carbon concentration is relatively stable in these soils due to stabilization by andic soil properties, which helps preserve the organic carbon concentration in spite of the lack of input from recent vegetation.

Table 5

Estimation of carbon accumulation divided by deposition rates and carbon concentration of the EcoBirch samples. Note that the lower %C range (1–5 %C) is assigned to medium and high dust deposition areas than in the low dust category (3–7 %C).

Deposition categories	Rates (mm yr^{-1})	% C[a]	Calc. BD (g cm^{-3})[b]	Carbon accumulation due to dust burial	
				g m^{-2} yr^{-1}	kg ha^{-1} yr^{-1}
Low (1–2)	0.001–0.01	3–7	0.37–0.88	0.026–0.26	0.26–2.6
Medium (3–4)	0.01–0.1	1–5	0.49–0.93	0.093–2.5	0.93–24.5
High (5–6)	0.1–1	1–5	0.52–0.99	0.99–26	9.9–260

[a] Common carbon values for each dust deposition category.

[b] Calculated mean bulk density (g cm^{-3}) values for each common carbon value and dust deposition category.

Sheep grazing is considered a primary driver of land degradation in Iceland (Arnalds et al., 2023), especially by creating degraded areas with open soil patches in cases of overgrazing (Mulloy et al., 2021). Only three study areas in this project were affected by sheep grazing at the time of the study (2-OX, 4-STEI, and 10-MJO) but some of the other areas were likely grazed in the past. Both 4-STEI and 10-MJO have a gravelly surface at their non-forested stage with limited vegetation cover and sheep grazing is likely to restrain the recovery of vegetation on these degraded soils. In general, it is difficult to assign the overall impact of grazing in this study due to the large differences between land-use history and the lack of detailed records. One can, however, assume that heavy grazing and wood harvesting existed prior to the middle of the last century, with a high number of sheep roaming freely.

4.5. The effect of time

4.5.1. Carbon stocks

Carbon stocks of the EcoBirch soils increased with woodland age, as demonstrated by consistently higher carbon concentration and stocks in the old woodland compared to the young woodland and non-forested sites (Fig. 4). This agrees with general trends for woodlands which can increase soil carbon stock by 200–500 % (Vesterdal et al., 2013). The old-growth woodlands also had the lowest C/N ratio indicating more robust nutrient cycling and presumed fertility (Gawęda et al., 2019). The highly variable C/N ratios in non-forested and young woodlands reflect great spatiotemporal variability during these stages, with variable levels of disturbance, ground cover and age stages.

A change in soil carbon stocks from about 5.3 kg C m^{-2} (Y) to about 7.4 kg C m^{-2} (O, Fig. 4) over the 30–60-year difference, indicates an accumulation rate of about 0.04–0.07 kg m^{-2} yr^{-1} which can be considered rapid sequestration rates in woodlands (Lal, 2008). The carbon accumulation rate from non-forested to young woodlands, assuming a 30-year time difference, was ~0.01 kg m^{-2} yr^{-1}. It is, however, difficult to infer sequestration rates for birch ecosystems, as the soils of the initial stages of some of the non-forested and young birch woodlands in Iceland may have legacy effects from previous ecosystems, often woodlands. Fig. 7 shows the potential SOC accumulation in birch woodlands, based on the above-mentioned rates and an estimated accumulation of 0.04 kg m^{-2} yr^{-1} for the 60- to 100-year-old woodland growth stage. A similar range is reported in the National Report for Iceland to the Climate Convention for soils undergoing restoration/revegetation of barren areas (0.03–0.09 kg m^{-2} yr^{-1}; Keller et al., 2023). These sequestration rates are also comparable to rates for relatively young volcanic soils (0.03–0.06 kg m^{-2} yr^{-1}; Zehetner, 2010), for reclamation of severely degraded soil in Iceland (0.06 kg C m^{-2} yr^{-1}; Arnalds et al., 2000), and for carbon enrichment over 200 years following the Tambora volcanic eruption (0.01–0.06 kg m^{-2} yr^{-1}; Anda et al., 2023). Hunziker et al. (2019) found a carbon sequestration rate of 0.04 kg m^{-2} y^{-1} in the top 30 cm soil after 35 years of birch growth (from 15 to 50 years old birch woodlands). A similar level of carbon enrichment took only about 30 years in the EcoBirch birch woodlands (from Y to O) indicating relatively rapid organic carbon accumulation rates across a wide range of conditions in Iceland (Fig. 4).

The current land cover of birch woodlands in Iceland is estimated as

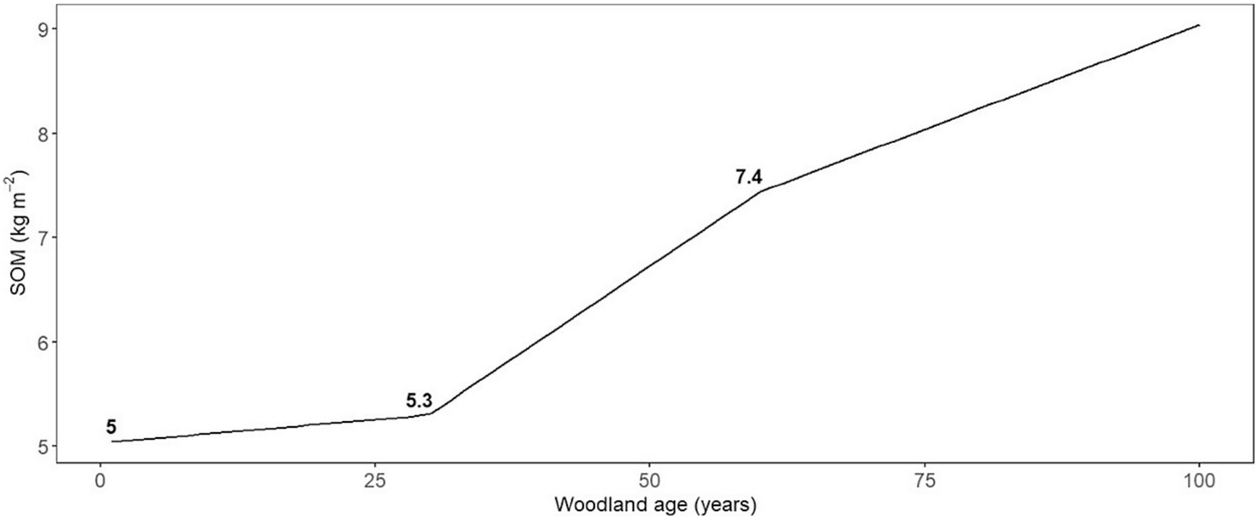

Fig. 7. Soil organic matter (SOM; kg m^{-2}) accumulation by woodland age (years). The calculated carbon accumulation rates are as follows: 0.01 kg m^{-2} yr^{-1} in first 0–30 years, 0.07 kg m^{-2} yr^{-1} in 30–60 years, and 0.04 kg m^{-2} yr^{-1} in 60–100 years. Mean values for carbon stock (kg m^{-2}) of 0- (non-forested), 30- and 60-year-old woodlands are presented in the graph.

1500 km^2 but the Icelandic government's target is to increase it to 5000 km^2. Here we estimate the future potential sequestration of the newly restored birch woodlands (3500 km^2), considering the change in sequestration rates with time. Assuming a soil organic carbon accumulation rate of 0.01 kg m^{-2} yr^{-1} in the first 30 years (N to Y) from the establishment, we predict 35,000 t yr^{-1} of C sequestration in soils, equivalent to 128,450 t yr^{-1} of CO_2. After 60–90 years from establishment from the onset of the restoration projects and assuming a 0.04–0.07 kg m^{-2} yr^{-1}C accumulation rate, we predict 140,000–245,000 t yr^{-1} of C sequestration in soils (513,800–899,150 t yr^{-1} of CO_2). The CO_2 removal by sequestration equals 7 % of the total emissions in Iceland, but 20 % when emissions derived from land use (LULUCF: Land Use, Land-Use Change and Forestry) are not included (Keller et al., 2023). An increase in above-ground biomass would add substantially to these values. The above-ground biomass in birch woodlands has been reported as 0.4 to >1.3 kg m^{-2} (total) or about 0.2 to >0.7 kg C m^{-2} (Snorrason et al., 2019). The sequestration rates in above-ground biomass for birch woodlands have been estimated at slightly below 0.1 kg m^{-2} yr^{-1} (Snorrason and Brynleifsdóttir, 2017) which should yield higher numbers for total above-ground biomass with time than was reported for the birch woodlands by Snorrason et al. (2019), suggesting further research is needed on the subject. However, these numbers indicate that the soils of the birch woodlands become a larger sink of carbon than the above-ground biomass with time. Notably, soil carbon sequestration rates are substantially higher than those of carbon accretion in vegetation biomass reflecting the importance of soil carbon storage in Andisols.

The accumulation of carbon in soils will eventually reach a steady-state balance in surface soils of mature old woodlands. Dust deposition causes continual burial of carbon, which in high dust deposition

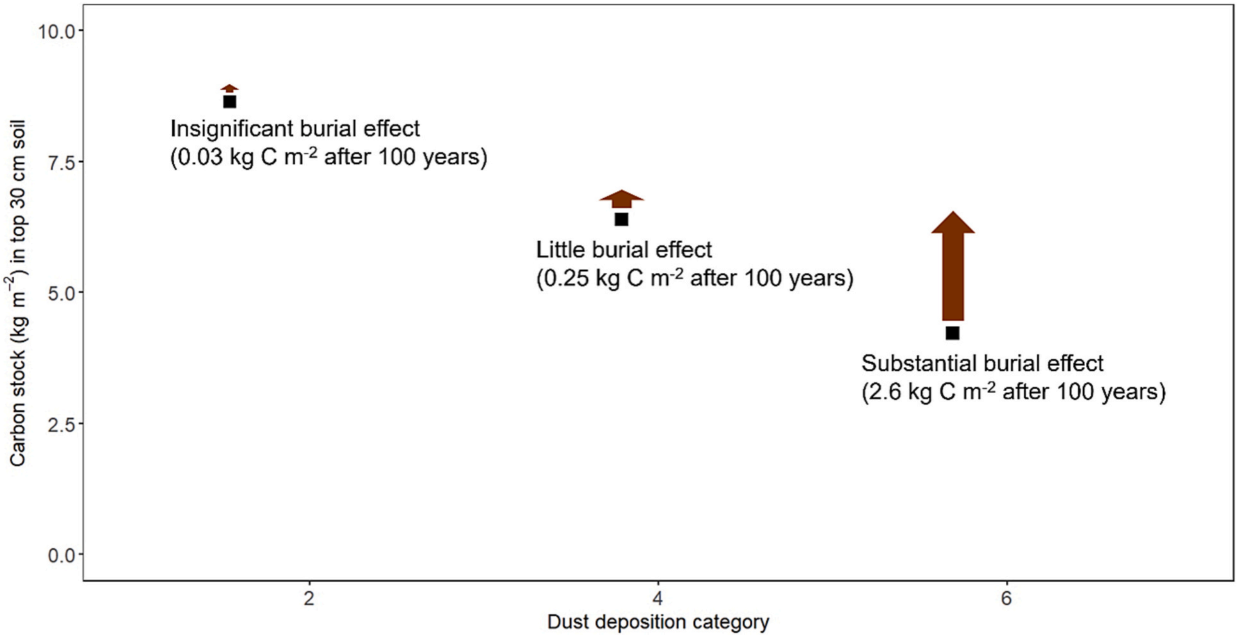

Fig. 8. Carbon stocks (kg m^{-2}, black box points) in the dust deposition categories and the potential carbon burial after 100 years (brown arrows). This conceptual representation is based on the data of the current research (modified from Arnalds, 2023).

areas could increase carbon sequestration rate by 25–50 % (up to max 260 kg ha^{-1} yr^{-1}). The impact of dust deposition on carbon burial/sequestration after 100 years is illustrated in Fig. 8. Our results indicate that dust deposition has a major effect on carbon accumulation in Icelandic soils, affecting soil carbon concentration, bulk density, and depth, the major variables controlling soil carbon stocks. Burial by dust deposition brings organic materials into intimate association with mineral components (i.e., physical and chemical stabilization), reduces aeration (i.e., oxygen availability), and decreases interactions with soil macro- and mesofauna whose processing greatly enhances decomposition rates (Dahlgren et al., 2004).

4.5.2. Nitrogen stocks

Nitrogen is generally the primary limitation to net primary production on young volcanic soils owing to the lack of nitrogen in volcanic ejecta (Dahlgren et al., 2004). Thus, the availability of nitrogen is a key factor determining organic matter production by vegetation and its subsequent accumulation in soils. The nitrogen accumulation rate varied from 0.003 to 0.006 kg m^{-2} yr^{-1} assuming ages of 30 and 60 years for the Y and O age stages, respectively. Revegetation and land restoration efforts in Iceland commonly result in the carbon accumulation of 0.04–0.08 kg m^{-2} yr^{-1} (Keller et al., 2023; Arnalds, 2015; Arnalds et al., 2013a; Thorvaldsson et al., 2009). Given these accumulation rates and considering common C/N ratios of 15–25 results in calculated nitrogen accumulation of 0.003–0.004 kg m^{-2} yr^{-1}, which is very similar to the range found across the EcoBirch sites. Deep burial of nitrogen is not considered in these numbers, only the N in the top 30 cm soil.

Rainfall inputs of N in Iceland are on the order of 1–2 kg ha^{-1} yr^{-1} (Gíslason et al., 1996), thereby representing <1 % of the soil N accumulation rate across the EcoBirch sites. Some nitrogen-fixing soil crusts may be present during the primary succession stages. The past vegetation history of the sites may also have contributed nitrogen prior to the land-use transformations that rendered the soils barren. Nitrogen may not be a limiting factor to birch growth and soil organic matter accumulation as commonly found in young volcanic soil deposits (Anda et al., 2023; Fiantis et al., 2016). As vegetation establishment occurs, the system becomes highly efficient at adding nitrogen by biological fixation. This has been shown in general vegetation research in Iceland and can fuel future net primary productivity (Arnalds, 2015).

5. Conclusions

Icelandic birch woodlands have been largely eliminated due to human activities during the nearly 1200 years of settlement. Birch woodland restoration is deemed important as a climate change mitigation strategy, hence restoration is considered a high national priority. Our study demonstrated how soil carbon concentration, bulk density, andic soil properties, and dust deposition interact to regulate soil organic carbon stocks – conditions rather unique to Iceland. We show that birch woodland ecosystems, with typical andic soil properties, accumulate carbon at relatively rapid rates (0.04–0.07 kg m^{-2} yr^{-1}), which renders birch restoration important for the carbon budgets of Iceland. These rates become even more rapid when burial by dust deposition and increased above-ground biomass are considered. If applied to the target restored birch woodland land cover (3500 km^2), this amounts to 20 % of the current total CO_2 emissions of the country (LULUCF not included), increasing substantially the carbon sequestration through extensive restoration efforts. Other factors such as precipitation and annual temperature did not affect carbon stocks. We further document that areas with high dust deposition have lower C concentrations with higher bulk density and deeper overall soils. This deposition leads to the burial of carbon-rich soil horizons which is important to take into consideration when calculating overall soil carbon accumulation rates. Furthermore, the presence of high soil carbon levels in some non-forested areas is associated with historical land-use/land-cover conditions, resulting in legacy carbon that needs to be considered in calculating soil organic C accumulation rates.

This study demonstrates the potential of birch woodland restoration to sequester soil carbon for long-term soil storage via stabilization by andic soil properties and soil burial. These restored ecosystems will subsequently provide several other important ecological services, such as soil erosion attenuation, wildlife habitat, seed source/genetic material conservation, and enhanced biodiversity for these high-latitude ecosystems.

CRediT authorship contribution statement

Sólveig Sanchez: Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ólafur Arnalds:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Data curation. **Jóhann Thorsson:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Data curation. **Randy Dahlgren:** Writing – review & editing, Supervision, Data curation. **Ása L. Aradóttir:** Writing – review & editing, Project administration, Methodology, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Asa L. Aradottir, Olafur Arnalds, and others reports financial support was provided by The Icelandic Centre for Research. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.178063.

Data availability

The data used in this study is available upon request.

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Table S1. Grazing intensity in the ten study areas.

Study area	Name	Current grazing	Intensity	Observations
1-LEY	1. Leyningshólar	No	0	Protected from grazing
2-OX	2. Öxarfjörður	Yes	Medium	Farms[1] close to the area
3-RAN	3. Ranaskógur	No	0	Protected from grazing
4-STEI	4. Steinadalur	Yes	Low	Protected from grazing
5-HRI	5. Hrífunes	No	0	Protected from grazing
6-THO	6. Þórsmörk	No	0	Protected from grazing
7-NED	7. Neðri Dalur	No	0	Horses in one plot in N
8-SKO	8. Skorradalur	No	0	Protected from grazing
9-HUS	9. Húsafell	No	0	Protected from grazing
10-MJO	10. Mjóifjörður	Yes	Very low	Farms quite far away[1]

[1] Farms refer to sheep farms.

References: Map.is

Figure S1. Successional stages in 9-HUS, starting from left with the non-forested land, young birch woodland in the center and old birch woodland to the right.

Figure S2. Examples of plots in non-forested stages from three different study areas emphasizing the variability between non-forested successional stages between the areas. Starting from the left: a stony surface at the 1-LEY area, poor heathland cover at 9-HUS and more vigorous heathland at 2-OX.

Figure S3. Successional stages in the core area, starting with the non-forested land (N) on the left, followed by the young (Y) and mature (M) woodlands, and finally the old woodland (O) on the right.

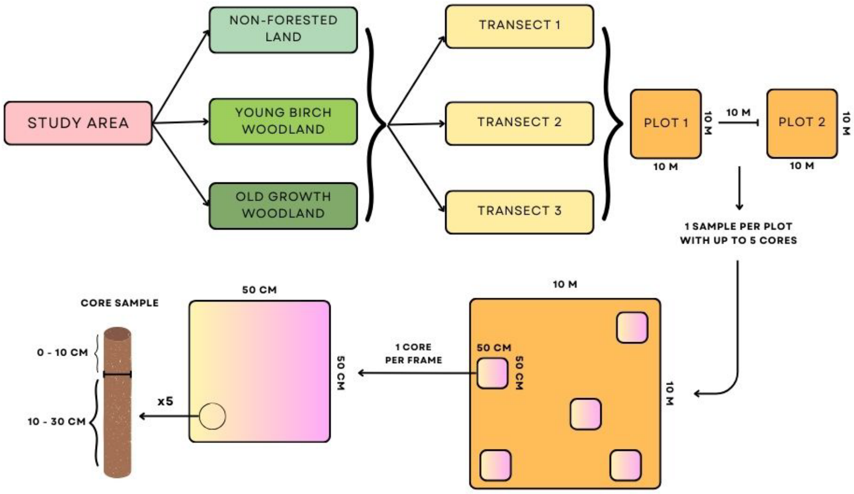

Figure S4. Soil sampling scheme. There are 10 study areas, where three stages were sampled on three transects, each having two plots where 5 cores from two depth intervals were combined as one sample. Total samples for each study area were 3 successional stages (4 stages in the core area 7-NED) x 3 transects x 2 plots (made of 5 cores each) x 2 depth intervals = 36.

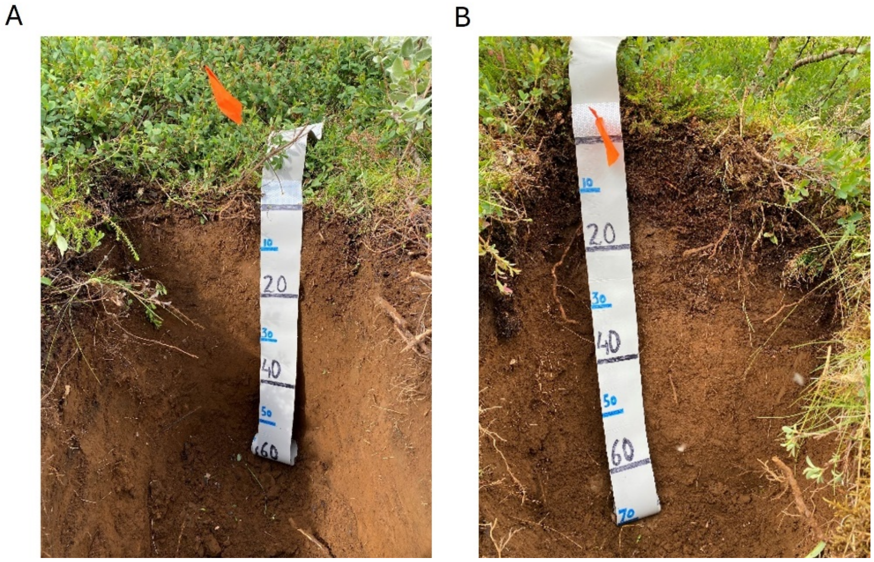

Figure S5. Soil pits were dug in the old growth woodland at areas 7-NED and 8-SKO (Figure A and B) while further soil analysis of the core samples allowed for classification for the other areas. The soils were classified according to Soil Taxonomy (Soil Survey Staff, 1999). The pits were described down to about 60 cm in 7-NED and 70 cm in 8-SKO. ***A)*** *In 7-NED the pit in the old growth woodland had a 5% slope, in a toe-slope position at the woodland edge. The soil was found deeper than 1 meter using a sharpened rod. The vegetation cover consisted mostly of bog blueberry (Vaccinium uliginosum) and blackberry (Empetrum nigrum) shrubs, and woolly willow (Salix lanata) with birch trees hoovering over the area. There were 20 to 30 cm high "thufur" or hummocks (caused by cryoturbation) at this moderately well drained site with no signs of mottles within the top 60 cm of the soil. A typical andic dryland soil of Icelandic woodlands in South Iceland. This soil was classified as Pachic Fulvudand.* ***B)*** *The pit in the old growth woodland in 8-SKO also had a 5% slope. The pit was located at the woodland edge with bog blueberry (Vaccinium uliginosum) and blackberry (Empetrum nigrum) shrubs dominating the plant composition, together with grasses and horsetails. Note the thick organic surface layer extending down to about 15 cm depth. This soil was classified as Histic Endoaquand.*

Table S2. Soil description for old growth woodland in 7-NED.

Layer	Depth (cm)	Color	Description
Oi	0 – 1		Too thin to sample.
A1	1 – 7	10YR 2/2	Silt loam. Weak fine to medium granular structure. Very friable. Many fine and moderately few medium roots. Indistinct black aeolian deposition layers. Very abrupt, wavy boundary.
A2	7 – 19	10YR 3/2	Silt loam. Very weak fine to medium granular structure. Very friable. Common fine roots. Ends at a black 3mm coarse tephra layer. Abrupt, wavy boundary.
2C/Bw1	19 – 38	7.5YR 3/4	Silt loam. Very weak fine to medium blocky structure. Few fine roots. Gradual, wavy and boundary.
Bw2	38 – 60+	7.5YR 3/4	Silt loam. Very weak fine to medium blocky structure. Gradual, wavy and boundary. Very few fine roots. Friable. At 60 cm there are cryoturbated pockets of the settlement tephra layer (ca. 900AD).

Table S3. Soil description for old growth woodland in 8-SKO.

Layer	Depth (cm)	Color	Description
Oi	0 – 14	5YR 3/2	Fresh organic materials with little signs of decomposition. Scraps of old moss, heather, trees, and roots. Abrupt, wavy and boundary.
A	14 – 30	5YR 3/3	Silt loam. Weak very fine and fine granular structure. Friable. Common very fine and fine roots. No visible mottles. No rocks. Clear, wavy boundary.
Bw	30 – 60	5YR 4/3	Silt loam. Very weak, very fine to fine blocky structure. Very few very fine roots, and few medium roots. No mottles. Very abrupt wavy boundary.
2C/Bw	60+		Gravel mixed with Bw materials.

Table S4. Soil classification of each successional stage in all ten study areas.

Study area	Successional stage	Soil type
1-LEY	Non-forested land	Typic Ustivitrand
	Young woodland	Humic Ustivitrand
	Old woodland	Humic Haplustand
2-OX	Non-forested land	Humic Haplustand
	Young woodland	Humic Haplustand
	Old woodland	Humic Haplustand
3-RAN	Non-forested land	Lithic Ustivitrand
	Young woodland	Typic Ustivitrand
	Old woodland	Typic Ustivitrand
4-STEI	Non-forested land	Lithic Ustivitrand
	Young woodland	Lithic Ustivitrand
	Old woodland	Typic Ustivitrand
5-HRI	Non-forested land	Thapic Haplustand
	Young woodland	Thapic Haplustand
	Old woodland	Thapic Haplustand
6-THO	Non-forested land	Lithic Ustivitrand
	Young woodland	Typic Ustivitrand
	Old woodland	Typic Ustivitrand
7-NED	Non-forested land	Pachic Fulvudand
	Young woodland	Pachic Fulvudand
	Old woodland	Pachic Fulvudand
8-SKO	Non-forested land	Histic Endoaquand
	Young woodland	Pachic Fulvudand
	Old woodland	Histic Endoaquand
9-HUS	Non-forested land	Lithic Ustivitrand
	Young woodland	Typic Ustivitrand
	Old woodland	Typic Ustivitrand
10-MJO	Non-forested land	Lithic Vitric Cryand
	Young woodland	Typic Fulvicryand
	Old woodland	Typic Hydrocryand

Table S5. Water content at wilting point (15 bar) for all samples in all study areas, stages and depths for soil classification.

Area	Stage	Depth	%WC at wilting point
1-LEY	N	0-10	20.5
1-LEY	N	10-30	23.9
1-LEY	Y	0-10	15.6
1-LEY	Y	10-30	28.7
1-LEY	O	0-10	44
1-LEY	O	10-30	30.6
2-OX	N	0-10	42
2-OX	N	10-30	22.4
2-OX	Y	0-10	42
2-OX	Y	10-30	21.6
2-OX	O	0-10	47.1
2-OX	O	10-30	30.1
3-RAN	N	0-10	15.3
3-RAN	N	10-30	6.6
3-RAN	Y	0-10	22.2
3-RAN	Y	10-30	12.7
3-RAN	O	0-10	28.2
3-RAN	O	10-30	17.4
4-STEI	N	0-10	12.7
4-STEI	N	10-30	18.8
4-STEI	Y	0-10	16.2
4-STEI	Y	10-30	6.7
4-STEI	O	0-10	22.5
4-STEI	O	10-30	15.5
5-HRI	N	0-10	47.5
5-HRI	N	10-30	18.4
5-HRI	Y	0-10	51
5-HRI	Y	10-30	21.1
5-HRI	O	0-10	45.2
5-HRI	O	10-30	28.8
6-THO	N	0-10	18.9
6-THO	N	10-30	17.2
6-THO	Y	0-10	24.6
6-THO	Y	10-30	32.3
6-THO	O	0-10	24
6-THO	O	10-30	25.7
7-NED	N	0-10	54.6
7-NED	N	10-30	36.2
7-NED	Y	0-10	67
7-NED	Y	10-30	56.3
7-NED	M	0-10	67.5
7-NED	M	10-30	49
7-NED	O	0-10	55.8
7-NED	O	10-30	49.8
8-SKO	N	0-10	73.3
8-SKO	N	10-30	74.4
8-SKO	Y	0-10	40.6
8-SKO	Y	10-30	59.4
8-SKO	O	0-10	96.5
8-SKO	O	10-30	78.4
9-HUS	N	0-10	7.9

9-HUS	N	10-30	11.8
9-HUS	Y	0-10	10.1
9-HUS	Y	10-30	13.5
9-HUS	O	0-10	30.7
9-HUS	O	10-30	30.5
10-MJO	N	0-10	9.1
10-MJO	N	10-30	14.5
10-MJO	Y	0-10	37.6
10-MJO	Y	10-30	63.9
10-MJO	O	0-10	118
10-MJO	O	10-30	61.3

Table S6. Additional bulk density samples.

Study area	Bulk density collected samples		
	Non-forested stage	Old woodland	Total samples
1-LEY	-	Sampled at 5 and 20 cm depths	3
2-OX	-	-	0
3-RAN	-	Sampled at 5 and 20 cm depths	3
4-STEI	-	Sampled at 5 and 20 cm depths	3
5-HRI	Sampled at 5 and 20 cm depths	Sampled at 5 and 20 cm depths	12
6-THO	Sampled at 5 and 20 cm depths	Sampled at 5 and 20 cm depths	8
7-NED	Sampled at 5 and 20 cm depths	Samples collected following the horizons present in the soil pits	16
8-SKO	Sampled at 5 and 20 cm depths	Samples collected following the horizons present in the soil pits	10
9-HUS	Sampled at 5 and 20 cm depths	Sampled at 5 and 20 cm depths	12
10-MJO	Sampled at 5 and 20 cm depths	Sampled at 5 and 20 cm depths	7

II

Colloidal and dust controls of soil processes and properties associated with birch woodland restoration in Icelandic Andisols

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Colloidal and dust controls of soil processes and properties associated with birch woodland restoration in Icelandic Andisols

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Abstract

Land degradation has had negative effects on many global natural ecosystems. In Iceland, birch woodlands once covered > 20% but have been reduced to ~1% of the land area, resulting in severe land degradation. A national goal aims to restore birch (*Betula pubescens*) woodland cover to 5%, with an ancillary goal of carbon sequestration. The impact of birch woodland restoration on soil properties has not been extensively studied, especially in Andisols of volcanic regions. This study focuses on understanding how birch restoration over a 60-year timeframe affects soil processes in 10 spatially distributed Icelandic Andisols, wherein we examined interactions among carbon, soil pH, soil colloids, and dust deposition. Soil pH decreased with increasing birch age; however, it was maintained at a relatively stable level (pH = 6-7) due to inputs of fresh basaltic dust originating from glacial outwash. Major soil colloids showed contrasting trends; metal-organic complexes (MOCs) increased, whereas allophanic materials did not change with increasing birch age. Birch restoration increased soil carbon accumulation with increasing woodland age, and MOCs were associated with carbon accumulation. Dust deposition had a significant effect on soil properties, such as decreasing carbon and colloid contents via dilution and increasing soil pH. Moreover, the higher soil pH appears to decrease the Al/Si ratio (0.8-1.3) of allophanic materials from the more globally common ratio of 2.0. Overall, this study documents the success of birch woodland restoration for carbon sequestration and the important role of volcanogenic dust inputs in regulating soil processes and properties of Andisols.

Keywords: Andisols, *Betula pubescens*, soil carbon, pH, allophane, metal-organic complexes, volcanic soils.

1. Introduction

Many of Earth's natural landscapes have undergone intense degradation over the last centuries, mainly caused by human interactions (UNCCD, 2022). Ecosystem degradation has led to a severe deterioration of soil health worldwide, altering the soil composition and the interactions between soil properties (Kuzyakov et al., 2020). Today, there is an urgent need for ecosystem restoration on a global scale (UNCCD, 2022). The dramatic decrease of natural woodlands, now only covering 31% of the world's land cover, is another example of the urgency of restoration (FAO & UNEP, 2020). Restoration efforts affect the development of soil properties, which are important to understand for planning successful actions.

In Iceland, terrestrial ecosystems have been subjected to large-scale natural and anthropogenic disturbances, resulting in degradation of a large proportion of the land area (Barrio and Arnalds, 2022; Arnalds et al., 2023). After the settlement of Iceland in the late 9th century, most of the native downy birch (*Betula pubescens*) woodlands, which historically covered > 20% of the island, were cut, burned, and overgrazed, resulting in their large-scale destruction (Ólafsdóttir et al., 2001; Traustason and Snorrason, 2008). Native Icelandic birch woodlands are a priority for conservation and ecological restoration at the national level, with plans to increase their coverage to 5% (from a current 1.5%) of the country (Ministry for the Environment and Natural Resources, 2014; Government of Iceland, 2021). Yet relatively little is known about the restoration effects on various soil properties, such as pH, soil colloids, and C contents, in highly degraded or established woodland soils.

Non-forested, young volcanic soils in Iceland are extremely susceptible to erosion due to the light and often silty nature of the soil particles and poor cohesion associated with a lack of layer silicate clays and organic matter. Intense soil erosion has subsequently stripped the soil surface, leaving barren surfaces across 45% of the land area (Arnalds and Kimble, 2001; Arnalds, 2015; Arnalds et al., 2023). Highly degraded Icelandic soils contain low carbon stocks (0.1-0.3 kg/m^2), whereas Andisols supporting mature birch woodland have much higher carbon stocks ranging from 2.7-14.9 kg/m^2 in the top 30 cm soil, as shown in a recent study by the authors (Sanchez et al., 2025). Hence, Icelandic soil carbon concentrations and stocks vary greatly depending on land-use history and ecosystem conditions, as well as the dust deposition rates that are a key component of this paper.

The ability of soils to store soil organic matter (SOM) varies considerably between soil types (Vulević et al., 2015), with Histosols and Andisols generally having the greatest SOM stocks. The most common soils in Iceland are Andisols, together with Histosols and various sandy vitric soils (Arnalds, 2015). The high active Al and Fe fraction (i.e., acid oxalate extractable Al_{ox} and Fe_{ox} fraction) associated with Andisols strongly affects the physical, chemical, and biological properties of soils. This fraction consists of soil colloids dominated by nanocrystalline Al, Si, and Fe components, such as allophane, imogolite, ferrihydrite, and metal-organic complexes (MOCs). It plays an important role in SOM preservation, interacting with organic matter by chemical and physical stabilization mechanisms, such as organo-metal complexing, ligand exchange, van der Waals bonding, and formation of stable silt-size aggregates (Dahlgren et al., 2004). Therefore, assessing the active Al and Fe fraction is important for understanding the carbon dynamics in Andisols (Dahlgren et al., 2004; Ashida et al., 2021).

Andisols can either be allophanic or non-allophanic in nature, depending on their main colloidal constituents (Dahlgren et al., 2004; McDaniel et al., 2012). Allophanic Andisols have allophane, imogolite, and ferrihydrite as their dominant colloidal constituents. These colloids are mainly formed in soils with a $pH > 5$ and often contain up to 10% C in surface horizons. Some allophanic soils can, however, be very carbon-rich, with up to ~25% C in some horizons of European Andisols (García-Rodeja et al., 2004). In contrast, non-allophonic Andisols are dominated by MOCs, have lower pH values ($pH < 4.9$), and generally contain higher SOM concentrations (Saigusa and Matsuyama, 1998; McDaniel et al., 2012). Icelandic Andisols are mostly allophanic and have pH values greater than 5.0 (Wada et al., 1992; Arnalds, 2015).

Most Icelandic soils receive steady dust additions from glacial outwash dominated by silt-sized particles composed of basaltic volcanic glass that continually rejuvenates the surface soil. These dust accumulations are unique among the world's Andisols (Arnalds, 2015), as most Andisols form in ejecta from volcanic eruptions, while in Iceland, there is a steady accumulation of dust (> 2 mm/yr in some locations). Dust inputs are a major focus of this research with respect to the role of dust in regulating andic soil properties and their subsequent controls on soil C stocks.

Properties of Icelandic Andisols in the early stages of soil formation have been previously investigated (e.g., Arnalds et al., 2013; Hunziker et al., 2019; Bonatotzky et al., 2022). However, there is a distinct knowledge gap concerning changes in soil properties following the natural succession or restoration of deciduous woodlands. Our study involves ten areas distributed throughout Iceland where birch woodlands have been expanding through natural colonization, with each area containing a chronosequence of birch successional stages (0 to 60+ years). The aim of this study is to understand soil and environmental factors (e.g., soil colloids, pH, and dust deposition) that affect soil C dynamics of birch woodlands in Iceland, with an emphasis on andic soil properties. We attempt to understand 1) the effect of birch restoration time on soil properties employing multiple chronosequences, 2) the relationship between soil colloids and C in Icelandic Andisols, and 3) the effect of dust deposition on the soil properties of birch woodland soils. The results of this research provide knowledge on SOM stabilization mechanisms operating during woodland restoration that contribute to increased soil organic C stocks in mature birch woodlands across the diverse geographical and climatic conditions representative of Iceland.

2. Methods

2.1. Geographical setting

Iceland is a 103,100 km^2 island in the northern Atlantic Ocean between 63°23' and 66°32'N latitudes. The climate is oceanic, characterized by frequent strong winds, mild summers, and cool winters

(Einarsson, 1984; Ólafsson, 2007). The average temperatures during winter and summer are -0.3°C and 8.1°C, respectively, with higher temperatures registered at lower elevations. Mean precipitation ranges between 400 and 1500 mm/y but can reach > 3000 mm/y on higher mountains in South Iceland. Precipitation is generally lower in the island's northern part (Ólafsson, 2007; Icelandic Met Office, 2022). Volcanic activity is frequent due to a stationary 'hot spot' under the island and the tectonic plate boundaries that dissect the country (Thordarson and Höskuldsson, 2008).

2.2. Study areas

The research reported here is part of EcoBirch, an interdisciplinary research and development project aiming to improve the understanding of birch woodland dynamics and develop effective strategies for birch woodland restoration for climate change mitigation and biodiversity conservation (Aradóttir et al., 2022; Behrend et al., 2025). The EcoBirch research areas were selected to incorporate the multiple goals of the project, including the ecology of birch (Behrend et al., 2025), soil C dynamics (Sanchez et al., 2025), landscape aesthetics, and social issues (see birkivist.is). The project's ten study areas distributed across Iceland are referred to by number and site acronyms as listed in Table 1. Their mean annual temperatures range from 1.9 to 5.4°C and precipitation from 529 to 1459 mm/yr (Sanchez et al., 2025). Soils of the study sites were predominantly classified as Andisols (Table 1), based on Soil Taxonomy (see Sanchez et al., 2025).

Table 1. Geographical information for the ten study areas. The areas are ordered from 1 in central-north Iceland, clockwise around the country, to areas in west Iceland (8, 9, and 10).

Study area	Name	Coordinates	Region	Dust deposition†	Soil classification	Non-forested site
1-LEY	Leyningshólar	65°34' N, 18°28' W	North	4	Ustivitrand & Haplustand	Heathland

2-OX	Öxarfjörður	66°03’ N, 16°43’ W	Northeast	4	Haplustand	Heathland
3-RAN	Ranaskógur	65°07’ N, 14°84 W	East	4	Ustivitrand	Gravelly grassland
4-STEI	Steinadalur	64°16’ N, 15°98’ W	Southeast	5	Ustivitrand	Heathland soil, bare soil, presence of rhyolite
5-HRI	Hrífunes	63°65’ N, 18°57’ W	South	6	Haplustand	Heathland
6-THO	Þórsmörk	63°69’ N, 19°54’ W	South	6	Ustivitrand	Gravelly soil
7-NED	Neðri Dalur	64°29’ N, 20°34’ W	West	5	Fulvudand	Heathland
8-SKO	Skorradalur	64°48’ N, 21°35’ W	West	2	Endoaquand	Heath- and wetland
9-HUS	Húsafell	64°71’ N, 20°82’ W	West	4	Ustivitrand	Gravelly soil
10-MJO	Mjóifjörður	65°63’ N, 22°85’ W	Westfjords	1	Cryand	Gravelly soil, with cryoturbation

[†] Dust deposition categories obtained from Gunnarsson et al. (2015), see Figure 1.

Chronosequences representing three age stages of birch woodlands at each study area were identified from historical aerial photographs: old-growth birch woodland (60+ years old, O), young birch woodland (30-60 years old, Y), and adjacent non-forested land (N, few or no trees). The old-growth and young woodlands have 100% vegetation cover and are dominated by birch, forbs, mosses, and grasses. Most non-forested stages were classified as heathlands, but some areas had limited vegetation cover (bare soils) and poorly developed soils.

One of the key processes that influence soil formation in Iceland is dust deposition (0.01 to > 2 mm/year) from a variety of dust ‘hotspots’ that are primarily associated with fine dust emanating from pro-glacial areas, several glacial-fed rivers, and beach environments (Arnalds, 2010). The dust has a silty texture and is mostly composed of vitric material of basaltic composition (Arnalds et al., 2014). Dust deposition rates were categorized from 1 (< 50 g/m^2/yr) to 6 (500-1000 g/m^2/yr; Table 1; Gunnarsson et al., 2015). Generally, higher dust deposition rates occur in the southern part of the country and lower rates in the Westfjords as dictated by the presence of the major dust-source areas and prevailing winds (Figure 1; Arnalds et al., 2023).

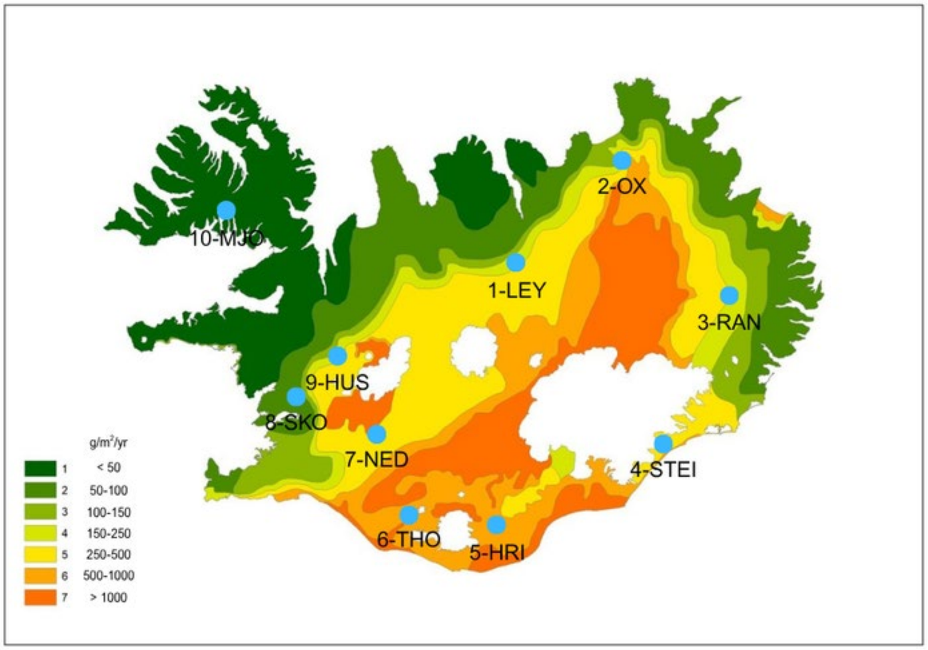

Figure 1. Dust deposition map of Iceland showing seven dust deposition categories of increasing dust intensity, ranging from < 50 g/m^2/yr to > 1000 g/m^2/yr. Study areas are marked in blue. No sample sites occurred within the dust categories 3 and 7. Modified from Arnalds et al. (2023), based on Gunnarson et al. (2015).

2.3. Experimental design and soil sampling procedures

Soil sampling took place in the summer of 2021. Three transects located 50-100 m apart were established within each age stage. On each transect, two 10 x 10 m plots were established 10 m apart. Soil samples were collected from the 0-10 cm and 10-30 cm depths in each plot (Figure 2). These depths were selected to capture the primary rooting depth of the birch woodlands. Each soil sample was a composite of ~5 cores, one from each of five randomly placed quadrats within each plot. While this design should have resulted in a total of 360 samples (10 study areas × 3 stages × 3 transects × 2 plots × 2 depths), in some instances, physical constraints, such as shallow soil or extreme rockiness, prevented the collection of samples from the 10-30 cm depth. As a result, the final number of soil samples was 328: 180 from 0-10 cm and 148 from 10-30 cm.

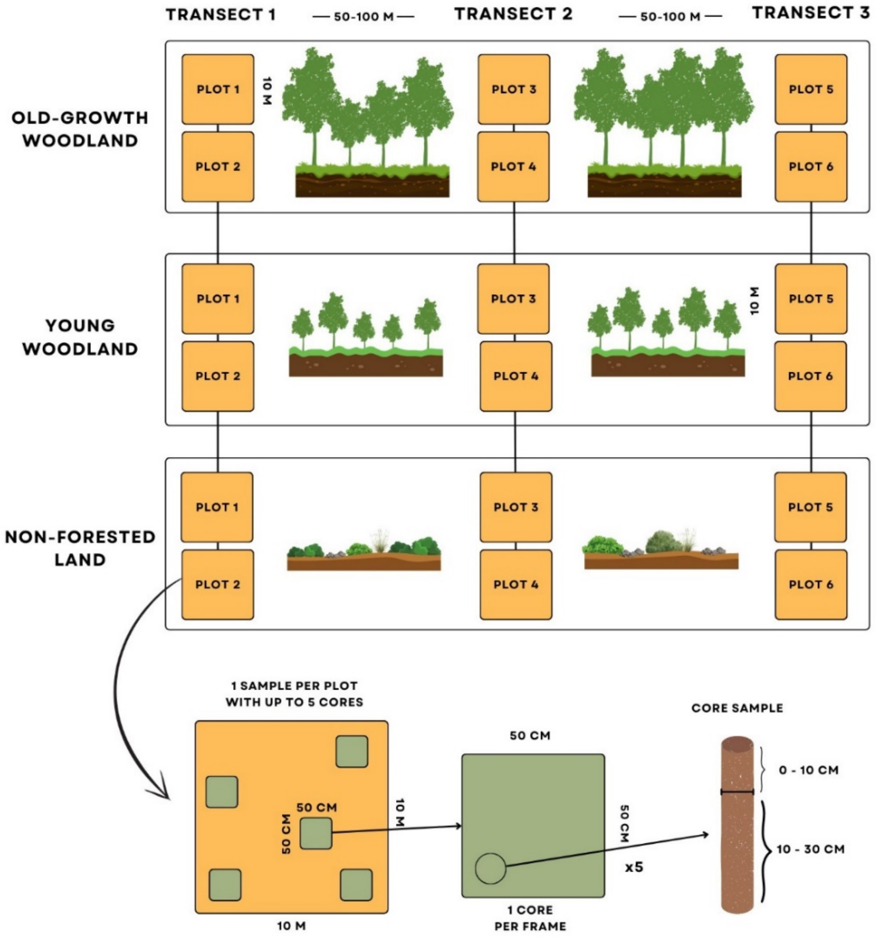

Figure 2. Soil sampling scheme. Each study area had three age stages: non-forested land, young woodland, and old-growth woodland. At each age stage, three transects with two 10 × 10 m plots (orange) were established. Composite samples for the 0 - 10 and 10-30 cm depths were taken from each plot and consisted of 5 randomly selected soil cores (brown): one core from each quadrant (green).

2.4. Soil analyses

Soil samples were stored in the dark at 10°C after sampling. A subsample was dried at 40°C and passed through a 2-mm sieve for subsequent physicochemical analyses. The dried < 2 mm fraction of the 0-10 cm samples was mildly ground to break up soil aggregates for C and selective dissolution analyses. The 10-30 cm samples were non-cohesive and did not contain stable soil aggregates, making further grinding unnecessary.

Soil carbon (%) was measured with a Vario MAX cube analyzer (Elementar, Langenselbold, Germany) using the Dumas method (dry combustion). Icelandic soils do not contain carbon associated with carbonate materials, except for very minor amounts on rare occasions (Arnalds, 1995, 2015). Hence, the total C was considered as the soil organic carbon fraction. Soil pH was measured in a 1:5 soil:H_2O suspension after a 120-minute equilibration period (Blakemore et al., 1987).

The active Al and Fe fraction (i.e., allophane, imogolite, ferrihydrite, and metal-organic complexes) was determined by ammonium oxalate extraction in a subset of 80 samples (Blakemore et al., 1987). Budget constraints did not allow for oxalate and pyrophosphate analysis of all 328 samples as performed for carbon analysis. For this subset, we attempted to maximize the effectiveness of the subsamples, with a statistician consultant, by selecting samples nearest to the average C% content for each study area, age stage, and depth as a representative selection (1 sample × 10 study areas × 3 age stages × 2 depths = 60 samples). An additional 20 samples from the old woodlands, including the highest and lowest C% at 0-10 cm depth from each study area, were included as the old woodland stage represents the most stable ecosystem stage. We used the 60 samples to compare the areas, age stages, and depth, and the 20 additional samples for old woodland differences.

Given the moderately acidic to neutral pH values (5-7.6), organically complexed Al and Fe (Al_p and Fe_p) values were expected to be low (Saigusa and Matsuyama, 1998). Hence, we performed a limited number of pyrophosphate extractions (30 samples) to quantify the extent of metal-organic complexes (MOCs) comprising the active Al and Fe fraction following the method outlined by Blakemore et al. (1987). The 30 samples were from the 60 representative samples selected for oxalate extractions, except only 1 depth from each study area and age group was selected, alternating soil depths to obtain data for both depths. All soil chemical results are reported on an oven-dry weight basis (105°C).

Allophane and ferrihydrite contents were estimated as follows:

$$\text{Allophane\%} = \text{Si}_{ox} \times 1.36\,((\text{Al}_{ox} - \text{Al}_p)/\,\text{Si}_{ox})^2 - 1.76\,((\text{Al}_{ox} - \text{Al}_p)/\text{Si}_{ox}) + 5.44),$$

(Watanabe et al., 2023; based on method reported by Parfitt, 1990).

$$\text{Ferrihydrite\%} = 1.7 \times \text{Fe}_{ox},$$

(Parfitt and Childs, 1988).

Total clay (%) was estimated by summing allophane and ferrihydrite contents, as layer silicate (phyllosilicates) clays occur at only trace levels in young Icelandic soils (Arnalds, 2015; Bonatotzky et al., 2021). Ammonium oxalate extraction does not distinguish between allophane and imogolite morphologies; hence, we refer to this fraction as allophanic materials. The chemical composition of allophanic materials is variable, which is reflected by the Al/Si ratio calculated as $(\text{Al}_{ox} - \text{Al}_p)/\text{Si}_{ox}$ (Parfitt, 1990). In the samples where the Al_p content was not determined, mean values of Al_p for each study area were used to calculate this ratio, since there was no significant difference between age stages in each study area. Ferrihydrite in Icelandic soils and most soils of basaltic origin might be overestimated since ammonium oxalate may partially extract Fe from other sources, such as magnetite and maghemite (Dahlgren, 1994; Anda et al., 2023).

2.5. Data analysis

Statistical analysis was conducted using RStudio (R Core Team, 2023). The *tidyverse* package was used to organize and filter the dataset (Wickham et al., 2019). The Mahalonobis principle was performed to identify outliers using the packages *stats* and *factoextra* (R Core Team, 2013; Kassambara and Mundt, 2020). Three samples from the non-forested stage at 8-SKO were excluded based on outlier analysis. The outliers were attributed to wetland soil conditions scattered within the non-forested stage of this area.

Mean and standard deviation values for each soil property were calculated for the six plots within each study area, age stage, and soil depth increment using the packages *dplyr* and *Hmisc* (Wickham et al., 2023; Harrell, 2025). The overall mean values were calculated for each study area, as well as for each age stage. Depth-weighted mean values for soil properties were calculated for each dust category, using the formula:

$$\text{Depth-weighted mean} = ((X_{0\text{-}10} \times 10) + (X_{10\text{-}30} \times 20)) / (10 + 20)$$

Boxplots were used to visualize most data using the *ggplot2* package (Wickham, 2016). The boxes represent the interquartile range, with the lower and upper quartiles as the box edges and the median marked as a horizontal line inside the box. The vertical lines (whiskers) extend to the maximum and minimum values, while outliers are shown as individual points.

One-way analysis of variance (ANOVA) was used to assess differences in soil properties across various independent factors with a p-value < 0.05, using the packages *stats* and *ggpubr* (R Core Team, 2013; Kassambara, 2023). Data were assessed for normality and homogeneity of variance prior to analysis, which verified normally distributed data. Separate ANOVA tests were conducted to compare soil properties for 1) the ten study areas, 2) the age stages (N, Y, and O), and 3) soil depths, each as main effects. Additional ANOVA tests were performed between stages, specifically within each depth, and further ANOVA tests were conducted to examine soil property differences between soil depths separately within each age stage. Subsequently, Tukey tests were performed for post-hoc mean separation, using the package *stats* (R Core Team, 2013).

Additional tests were carried out using dust deposition as a categorical variable to test differences in soil properties between dust categories (1-7). A Levene test was carried out to check for the equality of the variances using the package *car* (Fox and Weisberg, 2019). Due to the variances not being equal, Welch's ANOVA and Games-Howell post-hoc tests were carried out using the package *PMCMRplus* (Pohlert, 2024).

A non-linear model was used to describe the relationship between C content (%) and soil pH, using packages *nlstools*, *boot*, *ggplot2*, *stats*, and *dplyr* (R Core Team, 2013; Baty et al., 2015; Wickham, 2016; Wickham et al., 2023; Canty et al., 2024) with the following formulation:

$$C = C_0 \cdot \exp(-k \cdot pH),$$

where C is the C content (%), C_0 is a model constant representing the extrapolated C concentration at pH = 0, and k is the decay constant that determines the rate of decrease in C content with increasing pH. A Wald test was used to determine *p*-values.

Relationships between soil properties were assessed for each age stage, using linear regression with the package *stats*, *dplyr*, *ggpubr*, and *ggplot2* (R Core Team, 2013; Wickham, 2016; Kassambara, 2023; Wickham et al., 2023).

A structural equation model (SEM), defined as a multivariate statistical framework (Stein et al., 2012), was used to visualize the relationship between soil and environmental properties for all the soil samples, using the packages *lavaan*, *semPlot*, *car*, and *qgraph* (Epskamp et al., 2012; Rosseel, 2012; Epskamp et al., 2017; Fox and Weisberg, 2019). Derived (e.g., Al_{ox} and allophane) and correlated soil properties (e.g., C and nitrogen) were not included in the analysis. Organic C, $Al_{ox} – Al_p$ (Al in allophane), Fe_{ox}, and Al_p (Al-organic complexes), and pH were the main soil variables, and dust deposition, precipitation, and birch age stage were considered environmental variables.

3. Results

3.1. Carbon content

The C content of the soils varied greatly between study areas and stages (Figure 3), ranging from 0.2 to 19.2%. Depth-weighted mean C values (0-30 cm) were 2.2, 3.3, and 5.7% for non-forested (N), young woodland (Y), and old-growth woodland (O), respectively. Carbon was significantly higher in the 0-10 cm than the 10-30 cm interval at all stages ($p \leq 0.01$), and old woodlands had the highest C content at both depths. The study areas with the highest C content were 8-SKO and 10-MJO, the two sites receiving low dust inputs. Detailed mean values for each study area, age stage, and depth for each soil variable are presented in Table S1.

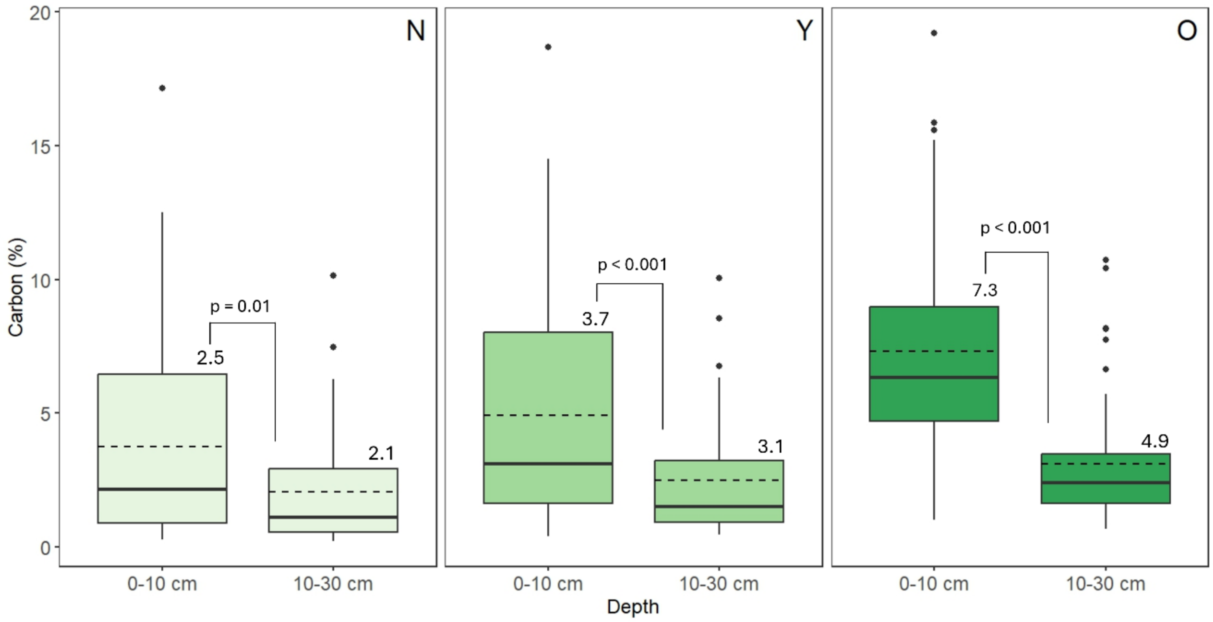

Figure 3. Boxplots representing carbon contents across all ten study areas separated by depths and age stages: 0-10 cm: N (n = 58), Y (n = 56), O (n = 60), and 10-30 cm: N (n = 38), Y (n = 47), O (n = 56). Median values for each age stage and depth are represented by horizontal lines, and mean values by dashed lines and written values. Shown are p-values for ANOVA tests of differences between depths.

3.2. Soil pH

Soil pH varied from 5.2 to 7.6 across all sites (Figure 4). The soil pH was significantly lower in old woodlands than in the non-forested stage ($p < 0.001$), while the pH in young woodlands was not significantly different from the pH in old woodlands ($p = 0.47$) but was significantly lower than the non-forested stage ($p = 0.007$). Soil pH at 0-10 cm was always lower than at 10-30 cm.

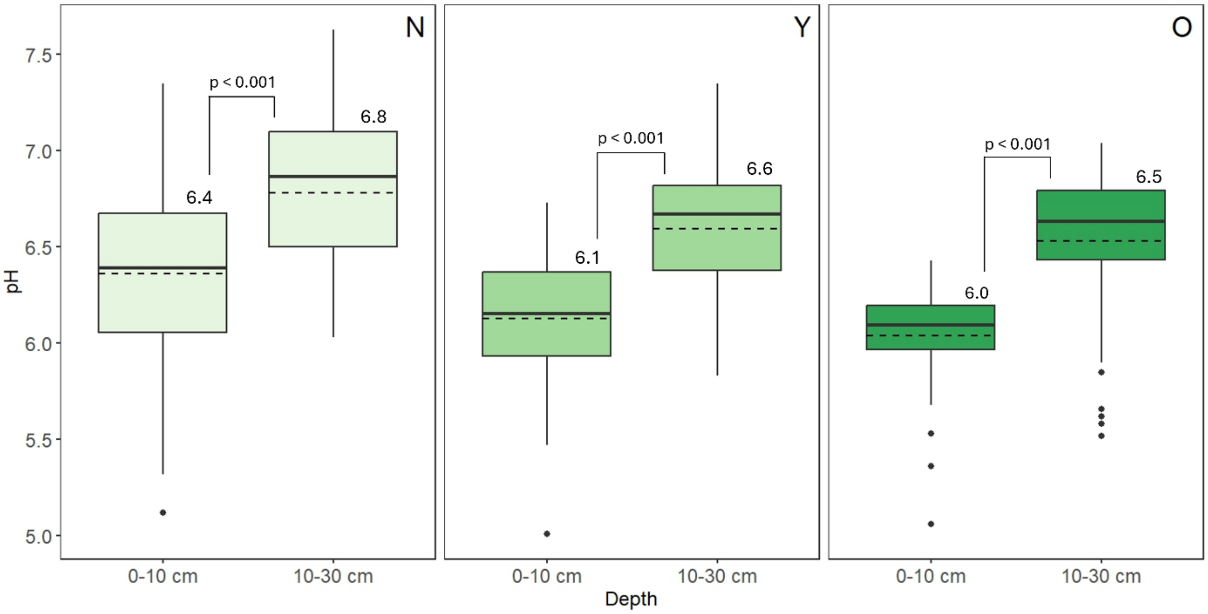

Figure 4. Boxplots representing soil pH across all ten study areas separated by depths and stages: 0-10 cm: N (n = 58), Y (n = 56), O (n = 60), and 10-30 cm: N (n = 38), Y (n = 47), O (n = 56). Median values for each age stage and depth are represented by horizontal lines, and mean values by dashed lines and written values. Shown are p-values for ANOVA tests of differences between depths.

Soil pH decreased with increasing C contents (R^2 ranged from 0.50 to 0.58 for the different stages and was 0.58 for the overall dataset; Figure 5). The results from the study areas 4-STEI and 10-MJO were considered outliers and excluded from this regression as they contained a surface layer of an acidic rhyolitic tephra deposit, resulting in appreciably lower pH values (see discussion).

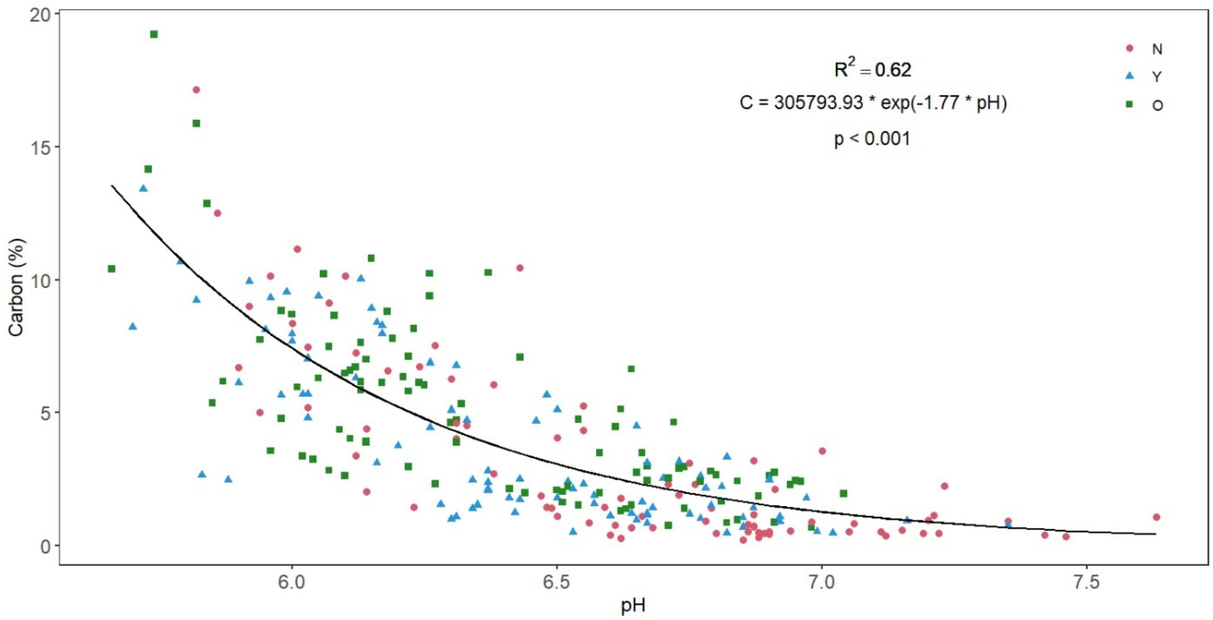

Figure 5. Exponential decay relationship between pH and organic carbon content (%) from eight native birch woodland areas, including both depth intervals. Symbols and colors indicate different age stages: N: non-forested land (n = 80) in red circles, Y: young woodland (n = 87) in blue triangles, and O: old woodland (n = 94) in green squares. Study areas 4-STEI and 10-MJO were excluded due to acidic properties of their parent material.

3.3. Soil colloids and relationships with organic carbon

Mean values for Al in allophane ($Al_{ox} – Al_p$), Al-organic complexes (Al-MOCs, Al_p), Fe in ferrihydrite ($Fe_{ox} – Fe_p$), Fe-organic complexes (Fe-MOCs, Fe_p), Al_p/Al_{ox}, and Fe_p/Fe_{ox} separated by stages and depths are shown in Table 2, and detailed results are presented in Table S2. Most oxalate-extractable Al originates from allophane ($Al_{ox} – Al_p$) and Fe from ferrihydrite ($Fe_{ox} – Fe_p$), with much lower Al-MOCs (Al_p) and Fe-MOCs (Fe_p) values (Table 2). Higher Al-allophane and Fe-ferrihydrite values were found in the 10-30 cm depth interval (only Fe in ferrihydrite was significantly higher), whereas values for MOCs were relatively similar for both depth increments and stages. Individual values ranged considerably: 0.45-6.39% for Al-allophane, 0.02-1.45% for Al-MOCs, 1.22-5.83% for Fe-ferrihydrite, and 0.02-1.99% for Fe-MOCs, and no significant differences were found between age stages. Allophane was, however, more abundant than ferrihydrite in soils of all age stages. The allophane and ferrihydrite contents were similar between stages ($p > 0.05$); the stage means for allophane were 10.9-11.1% and 6.1-6.7% for ferrihydrite.

Table 2. Mean values for Al in allophane (%, $Al_{ox} – Al_p$), Al bound to MOCs (%, Al_p), Fe in ferrihydrite (%, $Fe_{ox} – Fe_p$), Fe bound to MOCs (%, Fe_p), Al_p/Al_{ox}, and Fe_p/Fe_{ox} across all ten study areas separated by depths and stages.

Stages	Non-forested soil		Young woodlands		Old woodlands	
Depths	0-10 cm n = 5	10-30 cm n = 5	0-10 cm n = 5	10-30 cm n = 5	0-10 cm n = 6	10-30 cm n = 4
Al – Allophane	1.87 ± 1.14	2.14 ± 0.82	1.81 ± 0.69	2.75 ± 2.21	1.42 ± 0.76	2.24 ± 0.92
Al – MOCs	0.29 ± 0.36	0.13 ± 0.13	0.26 ± 0.17	0.41 ± 0.47	0.57 ± 0.51	0.11 ± 0.06
Fe – Ferrihydrite	2.85 ± 1.18	4.13 ± 1.35	3.38 ± 1.00	4.20 ± 1.15	2.56 ± 1.06	3.93 ± 1.14
Fe – MOCs	0.24 ± 0.38	0.12 ± 0.09	0.26 ± 0.14	0.30 ± 0.29	0.67 ± 0.67	0.12 ± 0.04
Al_p/Al_{ox}	0.11 ± 0.09	0.05 ± 0.04	0.12 ± 0.07	0.10 ± 0.07	0.26 ± 0.12	0.05 ± 0.02
Fe_p/Fe_{ox}	0.07 ± 0.08	0.03 ± 0.02	0.08 ± 0.05	0.06 ± 0.05	0.19 ± 0.14	0.03 ± 0.07

The percentage of MOCs comprising the active Al and Fe fraction ranged from 5 to 26% for Al and 3 to 19% for Fe, with higher percentages in the upper soil layer and the old woodland stage. The relationship between organic C with Al and Fe in MOCs was strongly significant for both depths, whereas the relationship between organic C with Al in allophane was only significant in the 10-30 cm depth interval (Figure 6). The mean for $(Al_p + ½Fe_p)/C$ molar ratios (C refers to total organic C) was 0.03 for the 0-10 cm and 0.06 for the 10-30 cm depth interval. The MOC content ($Al_p + 1/2Fe_p$) displayed a general exponential decrease with increasing pH values, even when combining data for both depth increments (Fig. S1).

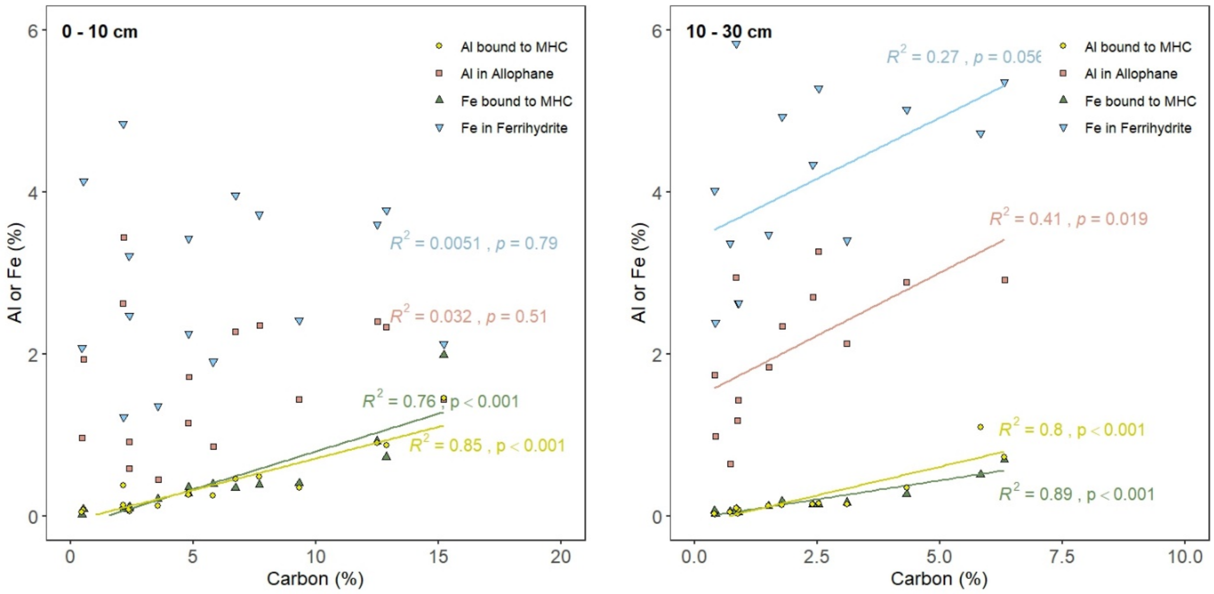

Figure 6. Relationship (linear regression) between carbon content and Al bound to MOC (yellow circles; n = 30), Al in allophane (pink squares; n = 30), Fe bound to MOC (green triangles; n = 30), and Fe in ferrihydrite (blue inverted triangles; n = 30) across all ten study areas and age stages combined.

Ammonium oxalate extractable Al and Fe, presented as $(Al + ½Fe)_{ox}$, is indicative of the colloidal materials responsible for andic soil properties. Most $(Al + ½Fe)_{ox}$ values were > 2%, apart from two samples. The highest $(Al + ½Fe)_{ox}$ value was 10.2% in Y at 10-MJO (lowest dust deposition), while the lowest value was 1.3% found in O at 6-THO (highest dust deposition). Carbon contents reached 7.5% in the non-forested samples, showing strong andic properties ($(Al + ½Fe)_{ox} > 2.5\%$; Table S2) with a weak yet significant relationship between these properties overall ($R^2 = 0.21$, $p = 0.04$). The data were more scattered in the young and old woodlands, with higher C content and the lowest $(Al + ½Fe)_{ox}$ value of 1.9%. The relationship between C and $(Al + ½Fe)_{ox}$ in young ($p = 0.46$) and old ($p = 0.07$) woodlands was not significant. The mean for $(Al + ½Fe)_{ox}$/C molar ratios (C refers to total organic C) was 0.19 for the 0-10 cm and 0.65 for the 10-30 cm depth interval.

The Al/Si molar ratios of allophanic materials, calculated as $(Al_{ox} – Al_p)/Si_{ox}$ (using molar ratios), ranged from 0.7 to 1.4, except for two areas, 8 SKO and 10 MJO, which had appreciably higher ratios ranging from 1.4 to 2.5. The difference in the Al/Si ratios was not significant between depths ($p = 0.73$) or age stages (p = 0.84). There was a significant positive relationship between Al/Si ratios and C content (%) at both depths and stages (Figure 7), with the Al/Si ratios rising with increased C content. Similarly, there was a general decrease in the Al/Si molar ratio with increasing pH values (Fig. S2).

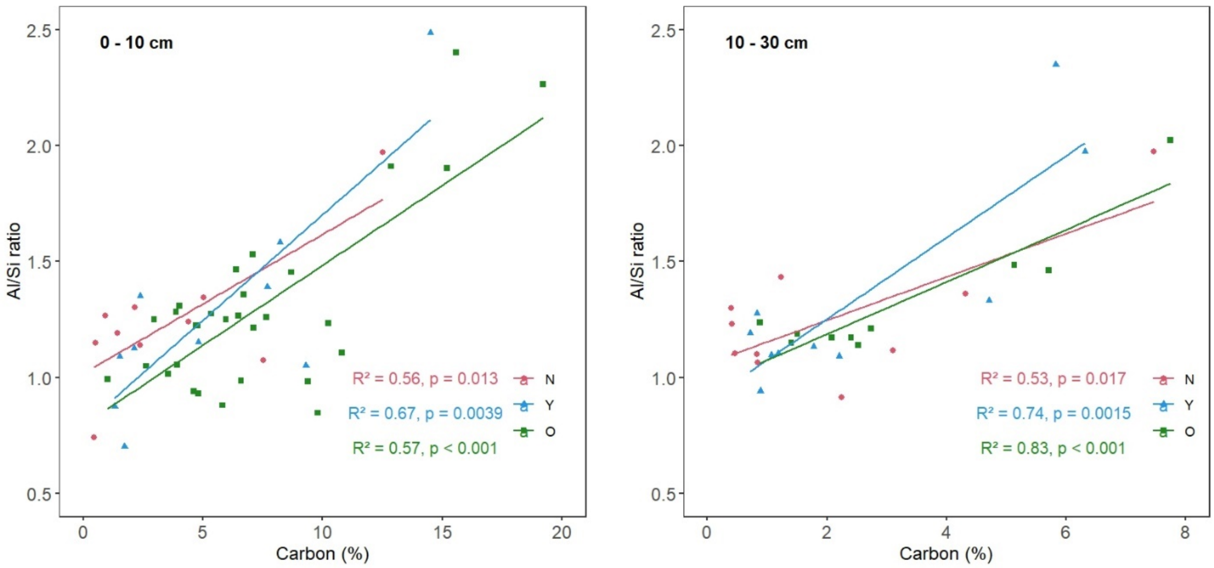

Figure 7. Relationship (linear regression) between Al/Si ratio and carbon (%) from ten birch woodlands areas separated by depths and colored by age stages: 0-10 cm: N (n = 10) in red circles, Y (n = 10) in blue triangles, O (n = 30) in green squares, and 10-30 cm: N (n = 10) in red circles, Y (n = 10) in blue triangles, O (n = 10) in green squares.

Clay content (allophane + ferrihydrite) was significantly higher in the 10-30 cm depth than in the 0-10 cm depth increments ($p < 0.001$). The study areas 1-LEY, 7-NED, 8-SKO, and 10-MJO had the highest C and clay contents, especially in the old woodlands (Table S1). The relationship between total clay and C content was not significant for either depth increment.

3.4. Dust deposition

Differences in soil properties between dust categories showed a general threshold change between categories 1-2 (low deposition) vs 4-6 (high deposition), especially for C values (no areas fell within categories 3 and 7; Table 3). The results revealed a tendency for lower C, higher pH, lower Al_{ox}, and lower Al/Si ratios with higher dust deposition. There was no predominant change in allophane content and Fe_{ox} (apart from the high values in dust category 2).

Table 3. Depth-weighted mean values of both depths for the main soil properties separated by dust deposition categories. Superscripts for each dust category (1-7) indicate which categories had significantly different values using Games-Howell post-hoc tests at $p < 0.05$. There were no study areas within the dust categories 3 and 7.

	Dust 1	Dust 2	Dust 4	Dust 5	Dust 6
Carbon (%)	$6.5^{4,5,6} \pm 5.6$	$8.7^{4,5,6} \pm 3.8$	$2.6^{1,2} \pm 2.9$	$3.7^{1,2,6} \pm 2.6$	$2.1^{1,2,5} \pm 1.8$
Soil pH	$5.9^{4,5,6} \pm 0.5$	$6.1^{4,6} \pm 0.3$	$6.7^{1,2,5,6} \pm 0.4$	$6.3^{1,4,6} \pm 0.3$	$6.5^{1,2,4,5} \pm 0.4$
Al_{ox} (%)	4.2 ± 1.7	$4.0^{4,5,6} \pm 1.0$	$2.0^{2} \pm 0.9$	$2.2^{2} \pm 1.3$	$2.1^{2} \pm 0.8$
Fe_{ox} (%)	$2.9^{2} \pm 1.4$	$5.8^{1,4} \pm 1.4$	$3.5^{2} \pm 1.2$	4.4 ± 5.5	4.2 ± 1.4
Allophane (%)	14.9 ± 7.1	13.9 ± 4.2	11.1 ± 4.9	10.5 ± 2.7	12.0 ± 4.7
Al/Si ratio	1.8 ± 0.6	$1.9^{4,5,6} \pm 0.2$	$1.1^{2} \pm 0.2$	$1.3^{2} \pm 0.2$	$1.1^{2} \pm 0.1$

3.5. Relationship between soil and environmental properties

The SEM shows a direct and/or indirect influence of dust deposition, soil pH, and precipitation on soil colloidal properties and soil C (mostly $p < 0.001$), whereas age stage had only a significant relationship with C (Figure 8). Dust had a negative relationship with Al_p, Fe_{ox}, and $Al_{ox} – Al_p$. Soil pH showed significant negative relationships with C and Al_p, but a positive relationship with Fe_{ox} and $Al_{ox} – Al_p$. Precipitation had a significant positive relationship on Al_p, Fe_{ox}, and $Al_{ox} – Al_p$, but a negative relationship on C. Organic C, a key variable of interest to the EcoBirch project, was influenced by all variables, with the strongest influence from Al_p and soil pH. It should be noted that the comparative fit index for the model to the data was 0.88, which is lower than the ideal of > 0.95.

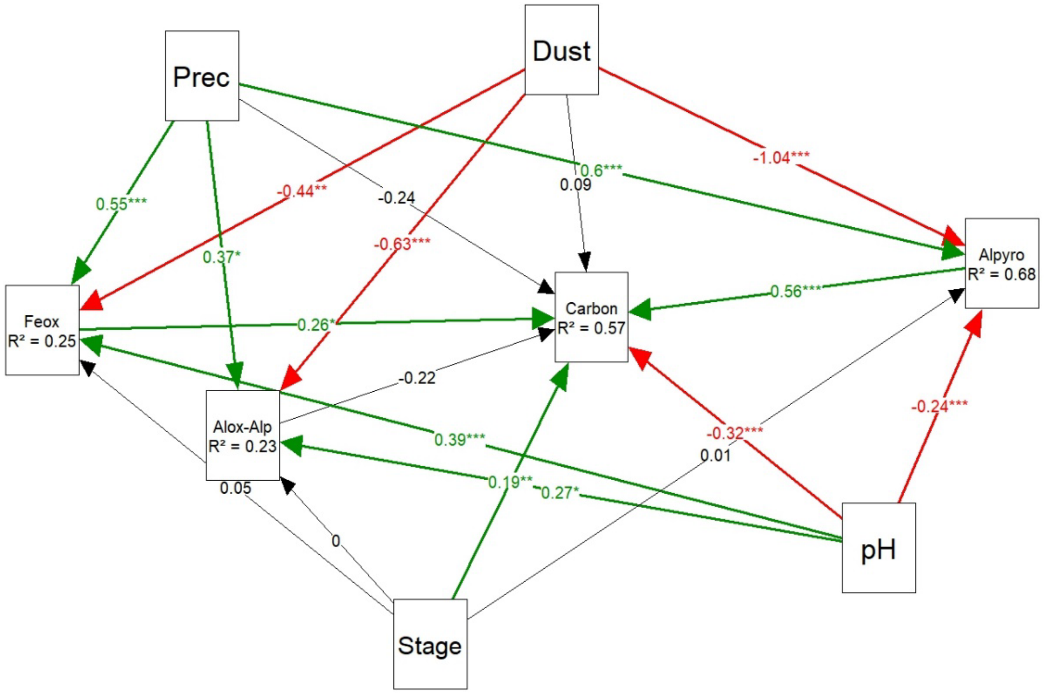

*Figure 8. Structural Equation Model (SEM) including the main soil properties. The significant relationships are marked in color: red for positive and green for negative relationships. Asterisks: '***' $p < 0.001$, '**' $p < 0.01$, '*' $p < 0.05$. The numbers in the middle of the arrows (β) represent the strength of the relationships between properties. R^2 values represent the degree of influence of the variables assessed. Properties acronyms: Carbon: soil organic carbon, Prec: precipitation, Feox: Fe oxalate, Alox-Alp: Al oxalate minus Al pyrophosphate (representing Al in allophane), Alpyro: Al pyrophosphate, Stage: birch age stage, Dust: dust deposition.*

4. Discussion

4.1. Soil carbon levels

Carbon content in soil samples from ten woodland areas in Iceland (EcoBirch areas) varied greatly (0.2-20%). The organic C content (%) was more abundant in the 0-10 cm than in the 10-30 cm depth interval, as expected from the greater vegetation C inputs to the surface horizons. Still, in Andisols, C is often preserved in deep soil layers due to stabilization by andic soil properties, burial by volcanic events, and in Iceland, burial by dust deposition (Óskarsson et al., 2004; Arnalds and Óskarsson, 2007; Li et al., 2019; Sanchez et al., 2025). The old woodlands (O) had higher C content than the non-forested sites (Figure 3), which is consistent with studies in other countries (e.g., Vesterdal et al., 2013; Gawęda et al., 2019). The measured C content of the woodland soils was both in line with undisturbed Andisols in general (Arnalds, 2004; Dahlgren et al., 2004; McDaniel et al., 2012) and deciduous boreal woodlands (Devi, 2021).

The high carbon contents are attributed to additions of organic material in the vigorous birch woodlands, the cold boreal climate (slow decomposition), and the andic soil properties. The positive association between birch age stage and organic matter demonstrates the key role of organic matter inputs from vegetation in increasing the soil organic carbon concentrations and stocks (Figure 8).

The C contents of the non-forested land (N) and the young woodlands (Y) reflect the level of disturbance at each site, with relatively barren surfaces (lacking vegetation cover) having < 1% C in some areas (e.g., 6-THO, 9-HUS). In contrast, the high C content of N and Y in the 8-SKO area (6-12% C) signals a relatively recent deforestation and land degradation (Icelandic Forestry Service, n.d.; Höskuldsson, 1977), wherein the soils still contain high levels of C typical of forested stages (i.e., legacy C). The legacy effect on these high C soils near birch woodlands illustrates the importance of not only protecting the remaining birch stands but preventing further degradation in the vicinity of woodland remnants as these soils contain C reserves that could otherwise be lost due to CO_2 emissions and/or removal by erosion (Sanchez et al., 2025). Such relic C levels in Andisols have been reported elsewhere, where native forest cover has been completely altered to grasslands or agricultural areas, e.g., in New Zealand (Parfitt et al., 2002), Chile (Matus et al., 2006), and Indonesia (Anda and Dahlgren, 2020).

4.2. Soil pH

We attribute the relatively narrow pH range (5.0-7.6) to cation release by rapid weathering of the vitric basaltic parent material (Stefánsson and Gíslason, 2001; Arnalds, 2015), including dust inputs of fresh basaltic glass. The acidifying effect of organic C is demonstrated by an exponential decrease in pH with increasing organic C contents (Figures 5 and 8). Soil pH was significantly lower in the young woodlands than in the non-forested sites, and lowest in the old woodlands. The reduction in pH occurs within decades after woodland cover is established (estimated 30 years from N to Y), concurrently with the increase in organic matter following woodland regeneration (Salisbury, 1922; Malik et al., 2018; Jonczak et al., 2020). The pH was significantly lower in the more organic-rich, 0-10 cm layer than in the 10-30 cm depth interval, as more leaching and root exudates of acidic compounds contribute to acidification in the shallow surface layer. Soil pH was furthermore affected by differences in parent material composition (rhyolite, which is rare, vs basalt), dust deposition, and annual precipitation/leaching.

Study areas 4-STEI and 10-MJO were outliers in the relationship between pH and soil C content (Figure 5). This anomaly was attributed to the presence of rhyolitic tephra mixed in the surface layer, which contributes a lower acid neutralizing capacity than basalt (Bonatotzky et al., 2022), and a higher annual precipitation (>1100 mm/yr; Table 1). However, the old woodland at 4-STEI has a similar pH to other old woodlands in the study, implying that the acidifying effects related to rhyolitic materials and greater precipitation are less pronounced following the establishment of birch woodlands. We postulate that the enhanced dust collection efficiency of the vegetative canopy, which reduces wind speeds near the surface, subsequently results in greater basaltic dust inputs, thereby contributing an additional acid neutralization capacity.

Deciduous woodlands are generally considered to have less effect on soil acidification than coniferous forests (Augusto et al., 2002; Jonczak et al., 2020). Coniferous plantations in Iceland are generally young, and research on their impact on soil pH is contradictory. The ICEWOOD (*Skogvist*) project (near 3-RAN) showed limited soil acidification in 30- to 50-year-old Siberian larch woodlands, although the pH drop was faster in larch plantations than in birch woodlands (Bos, 2021). Conversely, an exploratory study suggested a considerable drop in pH (up to 0.8 units) for a 30- to 80-year-old Sitka spruce stand in South Iceland (near 4-STEI) and North-Central Iceland (Pedersen, 2022). In comparison, our results for birch woodlands suggest limited soil acidification from birch woodland establishment, with pH values relatively stable within the pH 6 to 7 range, regardless of location in Iceland.

4.3. Soil colloidal composition

Chemical weathering of basaltic volcanic parent materials in Icelandic soils (mostly glass) is rapid owing to their high surface area, porosity, and permeability, and the high dissolution kinetics of volcanic glass (Stefánsson and Gíslason, 2001; Arnalds, 2015). The rapid release of Al, Fe, and Si leads to the preferential formation of nanocrystalline materials (allophane and ferrihydrite; Schwertmann and Taylor, 1989; Wada, 1989) and associations with organic matter as metal-organic complexes (MOCs). The active Al and Fe fraction (Al_{ox} and Fe_{ox}) in this study were relatively high, considering the young age of the soils and the cool soil temperatures, which highlights the rapid chemical weathering kinetics of basaltic materials and the silty nature of the dust inputs. Yet, both values for $(Al + ½Fe)_{ox}$ and total clay contents (allophane + ferrihydrite) were highly variable (Table S1). In general, lower clay contents (~10% clay) were found in relatively dry areas with abundant dust deposition (e.g., 3-RAN, 8-HUS), whereas higher clay contents (~15-20%) are characteristic of areas with lower dust deposition and/or humid climate (e.g., 8-SKO, 10-MJO). Precipitation had a positive effect on the products of chemical weathering (e.g., Fe_{ox}, allophane [Al_{ox}-Al_p], and Al_p), which is expected given the role of water in promoting chemical weathering (Figure 8). Furthermore, we found a significant relationship between dust intensity and clay content ($p = 0.03$). This can be explained by the relatively younger surface soils that are found in high dust deposition areas, as fresh basaltic materials dominated by silt-size particles are continually being added to the soil surface, thereby resulting in a dilution of the in-situ weathering products (see section on dust).

4.3.1. Allophanic materials

Allophanic material content ranged from 2.7 to 26.8%, with the highest values close to the maximum reported for Icelandic soils (30%; Arnalds, 2004). The highest allophanic content occurred at 10-MJO, a well-drained area where dust deposition is low (Figure 1). All soils in this study were dominated by allophane rather than MOCs ($Al_p/Al_{ox} < 0.5$; Table 2), except for one old-woodland sample at 10-MJO ($Al_p/Al_{ox} = 0.6$). All the soils had $Si_{ox} > 0.6\%$, which is typical of allophanic soils (defined by $Si_{ox} > 0.5\%$; Saigusa and Matsuyama, 1998), apart from two birch stages at 4-STEI. The two stages (N and Y) at 4-STEI were situated on a rocky fluvial plain with intermixed rhyolitic materials and appear more highly eroded than the old woodland located slightly above the fluvial plain.

The Al/Si molar ratio of allophane from the global literature generally ranges from 0.8 to 2 (Parfitt et al., 1980), with most Andisols commonly having an Al/Si ratio of ~2 (Parfitt and Kimble, 1989). In our samples, the Al/Si ratio was generally lower, with most values < 1.3, consistent with previously reported values for Icelandic soils (Arnalds, 2004; Arnalds, 2015). The C content and Al/Si ratios were strongly related, especially in the 10-30 cm depth interval of old woodlands (Figure 7), and there was an inverse relationship between the Al/Si ratio and pH. As the C content is inversely related to pH, the lower Al^{3+} and $AlOH^{2+}$ solubility at the near-neutral pH values (~ 6-7) may contribute to the lower Al/Si ratios due to lower availability of Al for incorporation into allophane (Arnalds, 2023). Moreover, higher pH values favor the formation of IV-coordinated Al as opposed to VI-coordinated Al at more acidic pH values. As IV-coordinated Al is more prevalent in allophanes with lower Al/Si molar ratios in both natural (Ildefonse et al., 1994; Hiradate, 2005) and synthesized allophanes (Lenhardt et al., 2021), soil pH may play a key role in regulating the Al/Si molar ratio of the allophanic materials through regulating the Al coordination. For example, many global occurrences of allophanic materials with Al/Si ratios near 2 are commonly found in soils with pH values in the 5-6 range, where Al^{3+} is more soluble and VI-coordinated Al is dominant (Shoji et al., 1993).

Aluminum complexed as MOCs does not appear to inhibit the formation of allophane in these soils as the pH becomes lower with more C. However, the pH is maintained above 5 even where C contents are high, thereby not falling below the pH < 4.9 threshold where allophane formation is inhibited (Saigusa and Matsuyama, 1998). This pH limit for allophane formation has been shown to be very pronounced in

Icelandic surface soils (Arnalds 2023, p. 164). We attribute the higher pH values and thus dominance of allophanic materials versus MOCs in Icelandic Andisols to the rapid weathering of the basaltic parent materials, which is continuously replenished by aeolian dust inputs rich in volcanic glass.

The fate of the Si released by chemical weathering in Icelandic soils, apart from forming the tetrahedra units in allophane, is unclear. The fine texture and high porosity of the fresh basaltic dust inputs lead to the rapid release of Si from the parent material and likely maintain high dissolved Si concentrations. The lack of layer silicate clays (Arnalds, 2015; Bonatotzky et al., 2021) and opaline silica (Stefánsson and Gíslason, 2001) in Icelandic soils renders the dissolved silica largely available for allophane formation. Hence, the preferential incorporation of Si into allophanic materials may be another factor explaining the lower Al/Si ratio in Icelandic Andisols.

There was not a significant relationship between allophane and C concentrations in this study, only a moderate relationship for the 10-30 cm depth of the old woodlands. In contrast to ferrihydrite and MOCs, the allophane content did not increase with increasing C content. Arnalds (2015) suggested that high C and its often-associated lower pH values may slow or inhibit allophane formation, which might explain this trend. In addition, the relatively limited time of development of the birch woodlands in the study (30-100 years) is unlikely to have a strong influence on the allophane content, whereas organic C can accumulate at a much faster rate. However, the significant relationship between Al in allophane and C in 10-30 cm depth (Figure 6), i.e., in older soil materials where C content is overall lower, suggests that organic matter present in the lower layer may be partially stabilized by allophane-organic matter interactions as described by Parfitt (1990).

4.3.2. Ferrihydrite

Icelandic soil parent materials and the dust distributed throughout the country are rich in iron (commonly 9-10% as Fe; Baratoux et al., 2011; Arnalds et al., 2014). Hence, high ferrihydrite values (1-8%) are common in Icelandic Andisols (Arnalds, 2004). In this research, ferrihydrite ranged from 2.2 to 13.4%, generally on the higher end of the ferrihydrite values reported for Icelandic soils (Arnalds, 2015). The ferrihydrite content might be somewhat overestimated since oxalate can extract some iron from primary minerals present in soils (Dahlgren, 1994; Anda et al., 2023).

Ferrihydrite content was generally lower than allophane, which is common for Andisols (Parfitt et al., 1988; Dahlgren et al., 2004). Bonatotzky et al. (2019) found significantly more ferrihydrite than allophane in poorly drained Icelandic Histosol samples (interlayered with mineral horizons) located in a relatively high dust deposition area. This could be explained by the iron-rich dust deposition and aquic soil conditions that lead to redoximorphic iron accumulations. In some of our samples, ferrihydrite was also more abundant than allophane. However, our overall results do not show a significant relationship between ferrihydrite and dust deposition. One might expect high dust deposition to dilute ferrihydrite concentrations due to burial by fresh dust materials. This may indicate that redoximorphic processes play a more important role in explaining ferrihydrite contents than dust accumulation rates, contrary to allophane, which is not affected by redox alterations. There were also no differences in ferrihydrite contents between the successional stages (N, Y, O).

Ferrihydrite may play a role in C accumulation and stabilization in the soils of this study. The relationship between ferrihydrite and organic C was strongest in the old woodlands ($R^2 = 0.41$), which had considerable quantities of iron at the lower depths and the lowest pH values among succession stages. Möckel et al. (2023) found a relationship between ferrihydrite and labile C in Icelandic peat soils. In our research, the relationship between soil pH and ferrihydrite was only weakly significant at the 10-30 cm depth interval ($R^2 = 0.29$), which is mostly dominated by more humified, non-labile C.

4.3.3. Metal-organic complexes

Metal-organic complexes (MOCs) are immobile organic compounds formed by bonds between metal ions (such as Al or Fe) and organic matter, which preferentially form in volcanic soils with lower pH values ($pH < 4.9$; Shoji, 1985; McDaniel et al., 2012). MOCs, both Al- and Fe-MOCs, are purported to contribute to C stabilization in Andisols (Dahlgren et al., 2004; Takahashi and Dahlgren, 2016). Relatively high values for Al_p and Fe_p bound as MOCs were found at 8 SKO (1.4-1.8% $Al_p + Fe_p$) and 10 MJO (0.5-3.5% $Al_p + Fe_p$), while comparable values were generally < 0.3% at the other study sites. The study areas with high $Al_p + Fe_p$ had higher C content and lower pH values. It is generally expected that C and pH covary as organic matter tends to lower the pH, making Al and Fe more soluble, which facilitates the formation of MOCs (Shoji, 1985; Figure 8).

The strong relationship between total C with Al_p and Fe_p bound in MOCs (Figure 6) supports the role of Al- and Fe-MOCs in organic carbon stabilization in Icelandic soils. Several studies emphasize that MOCs tend to be more efficient in facilitating C accumulation than aluminosilicate clays (Percival et al., 2000; Rasmussen et al., 2018; Wagai et al., 2020), as found in Chilean Andisols (Matus et al., 2006). Al-MOCs generally play an important role in accumulating soil C (Matus et al., 2006; Dümig et al., 2011; McDaniel et al., 2012; Takahashi et al., 2012), whereas Fe-MOCs are generally less abundant than Al-MOCs in Andisols because Fe is more thermodynamically stable in Fe-(hydr)oxides than Fe-MOCs (Wada and Higashi, 1976).

Our results suggest that Fe-organic complexes may play a more important role in organic carbon stabilization of Icelandic Andisols than previously recognized for most globally distributed Andisols. The similar content of Fe- and Al-MOCs on a weight basis indicates that Fe-MOCs are twice as prevalent as Al-MOCs on a molar basis (Fe 55.9 mol versus Al 27.0 mol), which indicates a strong tendency to form Fe-MOCs in Icelandic soils. ThomasArrigo and Kretzschmar (2022) noted that Fe associated with MOCs showed a stronger relationship with organic C than ferrihydrite in Icelandic soils, a finding also reported by Mankasingh and Gísladóttir (2019) and Linke et al. (2024a). Collectively, our data along with these previous studies indicate that Fe-MOCs play a more important role than Al-MOCs in Icelandic Andisols compared to studies reported in other countries, such as Japan (Takahashi et al. 2012). The higher Fe_p values relative to Al_p in Iceland can be attributed, in part, to the high Fe content of Icelandic volcanic materials (~10%).

4.4. The role of dust

Our results show a pronounced influence of dust deposition on several properties of Icelandic soils (Table 3; Figure 8), which can be attributed to the diluting of the organic matter concentration by the dust deposition (Arnalds and Óskarsson, 2007; Sanchez et al., 2025). For example, 1 mm per year of dust deposition would add 6 cm of fresh basaltic material, having non-detectable organic C content, to the soil surface during a 60-year period of birch growth. In fact, the vegetative canopy of the birch forest could also contribute to the trapping of dust, thus increasing dust accretion even more. The progressive burial of organic carbon results in an important organic C stabilization mechanism that greatly increases organic C stocks on a whole soil profile basis (Dahlgren et al. 2004). Dust inputs also maintain a relatively stable soil pH due to the rapid release of basic cations during chemical weathering (Arnalds et al., 2016; Linke et al., 2024b), and can counterbalance the drop in soil pH instituted by the increased organic matter input during birch woodland succession and in areas experiencing higher precipitation/leaching (Arnalds, 2010; Rengel, 2011; Figure 5).

By influencing pH and organic C content, dust has a wide-ranging influence on other soil properties, such as generating relatively younger soil surfaces with lower MOCs and clay contents in areas of high dust deposition (Figure 8). The higher clay-content soils in this study were mostly associated with low dust deposition rates and/or relic soils. Furthermore, the composition of allophanic materials in 'high dust deposition areas' tends to have a considerably lower Al/Si ratio than in areas of low deposition (Table 3), which we ascribe to the higher soil pH and possibly higher C content. Finally, it should be noted that with time, dust deposition accumulates relatively thick deposits that are modified by soil development while surface soil is gradually buried under more recent dust deposits (Sanchez et al., 2025). This is in contrast with soils that form in single or periodic volcanic ash deposits, with each deposit representing a single volcanic event in time. These distinct tephra deposits, sometimes of considerable thickness, cause a rejuvenation of soil-forming processes, back to time zero, and often the formation of polygenetic soil profiles, which is distinctively different than the continuous dust inputs experienced by Icelandic soils. Although the dust deposition in Iceland is rather unique (Arnalds et al., 2016), other countries, mainly located within the so-called 'global dust belt', have areas receiving high dust deposition rates, commonly characterized by quartz or phyllosilicates (Lawrence & Neff, 2009). Given the big impact of dust on Icelandic soils demonstrated in this study, it can be inferred that it is important to determine the effect of dust deposition on the soil in other dust-receiving countries in relation to potential restoration efforts.

4.5. Conclusions

The organic carbon levels in the old woodland stands in this study were comparable to those reported for Andisols throughout the world. Soil pH tended to decrease slightly with increasing woodland age as C accumulated, and the nature of the colloidal materials (active Al and Fe) changed. The higher C contents of old birch woodlands also influence several soil properties that affect fertility and overall ecosystem resilience. With greater nutrient richness and the ability to hold more plant-available water in a thicker soil profile than young woodlands and non-forested sites, old woodlands become more resistant to soil erosion.

The amount of clays and MOCs in the studied soils was highly variable, especially in the non-forested areas and young woodlands. The clay fraction changed, however, much more slowly than the accumulation of C in the soils, and their presence in the more degraded soils of this study reflects soil remnants or 'relic' properties. While soils in our study areas were allophanic, MOCs increased with increasing birch age (N < Y < O) owing to increasing organic C and lower pH values with increasing birch succession time. MOCs appear to have a greater stabilizing effect on organic C than allophanic materials. Increasing annual precipitation boosted the colloidal content of soils by promoting chemical weathering rates. The cold climate in Iceland would be expected to be a principal factor in C accumulation in general, yet it did not play a significant role in explaining differences in organic C contents across our study sites, perhaps due to the small temperature range (2.5°C) among our study areas.

This study is the first to directly address the influence of dust originating from glacial outwash sources across a nationwide dust gradient. Dust enhances chemical weathering of vitric soil materials with the rapid release of Al, Fe, and Si that promotes preferential formation of nanocrystalline constituents and maintains a near-neutral pH range (6-7). The role of dust deposition in regulating the Al/Si ratios of allophanes via its influence on soil pH has not been previously reported and warrants further investigation in volcanic areas globally. While dust deposition decreased organic C contents by dilution, the progressive burial of organic C increases soil profile organic C stocks with time, thereby resulting in an important C sequestration mechanism. Furthermore, the andic soil properties (i.e., active Al and Fe) played a central role in carbon accumulation along with the steady influx of vitric dust materials that make soil carbon sequestration in Icelandic Andisols unique from a global perspective. We showed that Icelandic Andisols of birch woodlands have similar qualities to other allophanic Andisols around the world, but have uniqueness due to the influences from dust deposition. This study does, therefore, encourage the research of dust impacts on soil dynamics in other volcanic areas in the world.

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Supplemental materials

Table S1. Values from ten birch woodlands areas for carbon (%), soil pH, and ammonium oxalate (ox) extractions separated by study areas, stages, and depths. Note that 82 samples were analyzed by ammonium oxalate extraction. Therefore, the properties marked with '' have n = 1. 'Sample %C' represents the specific carbon content in the selected 82 samples. 'Mean %C' represents mean values for the six plots in each depth and stage: N: non-forested land, Y: young woodland, and O: old woodland.* Si_{ox} *is used to calculate allophane and* Fe_{ox} *for ferrihydrite, which are combined for clay in the last column.* $(Al + ½Fe)_{ox}$ *is indicative of andic soil properties.*

Area	Stage	Depth	Mean %C	Sample %C	Mean pH	Si_{ox} %*	Al_{ox} %*	Fe_{ox} %*	$(Al + ½Fe)_{ox}$ %*	$(Al_{ox} – Al_p)/Si_{ox}$ $\%^{*\$}$	Allo-phane $\%^{*\$}$	Ferri-hydrite %*	Clay $\%^{*\$}$
1-LEY	N	0-10	1.3	0.9	7.4	1.6	2.1	3.7	3.9	1.3	10.9	6.3	17.2
1-LEY	N	10-30	0.6	0.4	7.4	1.4	1.8	4.1	3.8	1.3	9.3	6.9	16.3
1-LEY	Y	0-10	2.0	2.1	6.4	2.4	2.8	5.0	5.2	1.1	15.8	8.4	24.3
1-LEY	Y	10-30	1.0	1.1	6.9	3.8	4.2	6.8	7.6	1.1	25.0	11.6	36.6
1-LEY	O	0-10	7.7	7.7	6.2	2.3	2.9	4.3	5.0	1.2	7.8	7.3	15.1
1-LEY	O	10-30	2.5	2.5	6.7	3.0	3.4	5.4	6.1	1.1	19.5	9.2	28.7
2-OX	N	0-10	8.0	7.5	6.3	1.7	2.0	3.1	3.6	1.1	11.2	5.3	16.5
2-OX	N	10-30	2.9	3.1	6.8	2.0	2.3	3.6	4.1	1.1	12.9	6.1	19.0
2-OX	Y	0-10	8.7	9.3	6.0	1.4	1.8	2.8	3.2	1.1	9.2	4.8	14.0
2-OX	Y	10-30	2.3	2.2	6.8	1.9	2.2	3.6	4.0	1.1	12.4	6.1	18.5
2-OX	O	0-10	9.2	9.2	6.1	1.3	1.6	2.4	2.8	1.1	5.6	4.1	9.7
2-OX	O	10-30	2.3	2.4	6.8	2.4	2.8	4.5	5.1	1.2	15.7	7.6	23.3
3-RAN	N	0-10	1.5	1.4	6.5	0.7	0.9	2.3	2.0	1.2	4.8	3.9	8.7
3-RAN	N	10-30	0.4	0.4	6.9	0.8	1.0	2.4	2.2	1.2	5.5	4.1	9.6
3-RAN	Y	0-10	2.3	2.4	6.4	0.7	1.0	2.6	2.7	1.4	4.8	4.4	9.2
3-RAN	Y	10-30	0.7	0.8	6.7	0.8	1.0	3.2	2.6	1.3	5.4	5.5	10.8
3-RAN	O	0-10	3.5	4.7	6.3	0.9	1.1	2.4	2.3	1.2	5.8	4.1	10.0
3-RAN	O	10-30	0.9	0.9	6.9	1.0	1.2	2.7	2.5	1.2	6.6	4.6	11.1
4-STEI	N	0-10	2.5	2.4	6.1	0.5	0.7	3.3	2.3	1.1	3.5	5.6	9.1
4-STEI	N	10-30	0.8	0.8	6.3	0.6	0.7	3.2	2.3	1.1	3.7	5.4	9.1
4-STEI	Y	0-10	1.4	1.3	5.7	0.4	0.5	2.9	1.9	0.9	2.7	4.9	7.6
4-STEI	Y	10-30	0.7	0.7	6.4	0.6	0.7	3.4	2.4	1.2	3.7	5.8	9.5
4-STEI	O	0-10	4.2	4.8	6.0	1.3	1.4	2.6	2.7	0.9	8.3	4.4	12.7
4-STEI	O	10-30	1.5	1.4	6.1	1.5	1.8	3.6	3.6	1.1	10.1	6.1	16.2
5-HRI	N	0-10	4.2	4.4	6.1	1.4	1.8	3.4	3.6	1.2	9.3	5.8	15.1
5-HRI	N	10-30	0.9	0.8	7.1	2.9	3.0	5.9	6.0	1.1	18.7	10.1	28.8
5-HRI	Y	0-10	5.3	4.8	6.0	1.6	2.0	3.7	3.9	1.2	10.2	6.3	16.5
5-HRI	Y	10-30	1.1	1.2	6.8	2.4	2.7	5.1	5.2	1.1	15.5	8.7	24.1
5-HRI	O	0-10	6.0	6.0	6.0	1.3	1.7	3.3	3.4	1.2	5.9	5.6	11.5
5-HRI	O	10-30	1.7	1.5	6.6	1.6	2.0	3.6	3.8	1.2	10.6	6.1	16.7
6-THO	N	0-10	0.7	0.5	6.9	1.8	2.0	4.2	4.1	1.1	11.5	7.2	18.6
6-THO	N	10-30	0.5	0.5	7.2	2.2	2.4	5.0	5.0	1.1	14.2	8.6	22.8
6-THO	Y	0-10	1.7	1.5	6.3	1.0	1.1	2.6	2.4	1.1	6.3	4.4	10.6
6-THO	Y	10-30	1.8	1.8	6.4	2.2	2.5	5.1	5.0	1.1	14.1	8.7	22.8
6-THO	O	0-10	3.4	3.6	6.0	0.5	0.6	1.6	1.4	1.0	3.0	2.7	5.6
6-THO	O	10-30	2.0	2.1	6.5	2.1	2.4	4.6	4.7	1.2	13.6	7.8	21.4
7-NED	N	0-10	6.8	5.0	5.9	1.8	2.7	4.5	5.0	1.3	12.0	7.7	19.7
7-NED	N	10-30	3.6	4.3	6.6	2.2	3.2	5.3	5.9	1.4	15.0	9.0	24.0
7-NED	Y	0-10	7.8	7.7	6.0	1.8	2.8	4.1	4.9	1.4	12.0	7.0	19.0
7-NED	Y	10-30	4.7	4.7	6.3	2.5	3.5	5.9	6.5	1.3	16.5	10.0	26.5
7-NED	O	0-10	6.7	6.7	6.1	1.7	2.7	4.3	4.9	1.4	11.8	7.3	19.1
7-NED	O	10-30	4.9	5.1	6.6	2.6	4.2	6.5	7.4	1.5	18.4	11.0	29.3
8-SKO	N	0-10	12.3	12.5	5.9	1.3	3.3	4.5	5.6	2.0	10.3	7.7	18.0
8-SKO	N	10-30	7.9	7.5	6.0	1.8	4.3	5.8	7.2	2.0	14.9	9.9	24.8
8-SKO	Y	0-10	8.6	8.2	5.7	1.0	2.4	3.4	4.1	1.6	7.2	5.8	13.0
8-SKO	Y	10-30	6.3	6.3	6.1	1.5	3.6	6.1	6.7	2.0	12.5	10.3	22.8
8-SKO	O	0-10	13.2	12.9	5.8	1.3	3.2	4.5	5.5	1.9	10.1	7.7	17.8
8-SKO	O	10-30	7.9	7.7	5.9	2.5	5.7	7.9	9.6	2.0	20.7	13.4	34.1
9-HUS	N	0-10	0.5	0.5	6.8	1.4	1.0	2.1	2.1	0.7	8.8	3.6	12.3
9-HUS	N	10-30	1.0	2.2	7.2	1.8	1.7	2.8	3.1	0.9	11.6	4.8	16.4
9-HUS	Y	0-10	1.7	1.7	6.4	1.2	0.9	2.3	2.1	0.7	7.7	3.9	11.6
9-HUS	Y	10-30	0.8	0.9	6.9	1.6	1.5	2.7	2.8	0.9	10.2	4.6	14.7

9-HUS	O	0-10	5.8	5.8	6.2	1.0	1.1	2.3	2.3	0.9	6.5	3.9	10.4
9-HUS	O	10-30	2.8	2.7	6.7	1.8	2.3	4.0	4.3	1.2	12.2	6.8	19.0
10-MJO	N	0-10	3.3	2.1	5.9	2.8	3.8	1.3	4.7	1.3	18.4	2.2	20.7
10-MJO	N	10-30	1.1	1.2	6.3	2.2	4.0	1.5	4.8	1.4	15.2	2.6	17.8
10-MJO	Y	0-10	16.6	14.5	5.5	0.8	2.8	2.7	4.2	2.5	7.8	4.6	12.5
10-MJO	Y	10-30	7.2	5.8	5.9	2.8	7.5	5.2	10.1	2.3	26.8	8.9	35.7
10-MJO	O	0-10	13.3	15.2	5.9	0.8	2.9	4.1	5.0	1.9	6.3	7.0	13.3
10-MJO	O	10-30	6.4	5.7	5.6	1.5	3.0	2.7	4.4	1.7	10.2	4.5	14.7

* Only 1 sample behind this data.

$^{\$}$: values in red use Al$_p$ based on the mean for Al$_p$ for each study area (30 samples were analyzed by pyrophosphate extractions), in order to obtain % allophane according to the formula by Parfitt (1990) and Al/Si ratios (see methods).

Table S2. Pyrophosphate extractions, %C, and soil pH values for selected samples separated by study areas, stages, and depths. There is 1 sample behind each value.

Area	Stage	Depth	%C	pH	Si_{ox} %	Al_{ox} %	Fe_{ox} %	Al_p %	Fe_p %	Al_p/Al_{ox}	Fe_p/Fe_{ox}	$(Al_{ox} – Al_p)/Si_{ox}$
1-LEY	N	10-30	0.4	7.4	1.4	1.8	4.1	0.03	0.06	0.02	0.02	1.3
1-LEY	Y	0-10	2.1	6.4	2.4	2.8	5.0	0.13	0.11	0.05	0.02	1.1
1-LEY	O	10-30	2.5	6.7	3.0	3.4	5.4	0.15	0.15	0.04	0.03	1.1
2-OX	N	10-30	3.1	6.8	2.0	2.3	3.6	0.14	0.17	0.06	0.05	1.1
2-OX	Y	0-10	9.3	6.0	1.4	1.8	2.8	0.34	0.40	0.19	0.14	1.1
2-OX	O	10-30	2.4	6.8	2.4	2.8	4.5	0.14	0.14	0.05	0.03	1.2
3-RAN	N	10-30	0.4	6.9	0.8	1.0	2.4	0.02	0.03	0.02	0.01	1.2
3-RAN	Y	0-10	2.4	6.4	0.7	1.0	2.6	0.06	0.11	0.06	0.04	1.4
3-RAN	O	10-30	0.9	6.9	1.0	1.2	2.7	0.03	0.05	0.02	0.02	1.2
4-STEI	N	0-10	2.4	6.1	0.5	0.7	3.3	0.08	0.10	0.12	0.03	1.1
4-STEI	Y	10-30	0.7	6.4	0.6	0.7	3.4	0.05	0.06	0.08	0.02	1.2
4-STEI	O	0-10	4.8	6.0	1.3	1.4	2.6	0.26	0.36	0.19	0.14	0.9
5-HRI	N	10-30	0.8	7.1	2.9	3.0	5.9	0.10	0.09	0.03	0.02	1.1
5-HRI	Y	0-10	4.8	6.0	1.6	2.0	3.7	0.29	0.28	0.14	0.08	1.2
5-HRI	O	10-30	1.5	6.6	1.6	2.0	3.6	0.13	0.13	0.06	0.04	1.2
6-THO	N	0-10	0.5	6.9	1.8	2.0	4.2	0.08	0.09	0.04	0.02	1.1
6-THO	Y	10-30	1.8	6.4	2.2	2.5	5.1	0.14	0.18	0.05	0.04	1.1
6-THO	O	0-10	3.6	6.0	0.5	0.6	1.6	0.12	0.21	0.21	0.13	1.0
7-NED	N	10-30	4.3	6.6	2.2	3.2	5.3	0.34	0.27	0.10	0.05	1.4
7-NED	Y	0-10	7.7	6.0	1.8	2.8	4.1	0.48	0.39	0.17	0.10	1.4
7-NED	O	0-10	6.7	6.1	1.7	2.7	4.3	0.46	0.35	0.17	0.08	1.4
8-SKO	N	0-10	12.5	5.9	1.3	3.3	4.5	0.90	0.93	0.27	0.20	2.0
8-SKO	Y	10-30	6.3	6.1	1.5	3.6	6.1	0.72	0.70	0.20	0.12	2.0
8-SKO	O	0-10	12.9	5.8	1.3	3.2	4.5	0.88	0.73	0.27	0.16	1.9
9-HUS	N	0-10	0.5	6.8	1.4	1.0	2.1	0.05	0.02	0.05	0.01	0.7
9-HUS	Y	10-30	0.9	6.9	1.6	1.5	2.7	0.08	0.05	0.05	0.02	0.9
9-HUS	O	0-10	5.8	6.2	1.0	1.1	2.3	0.25	0.39	0.23	0.17	0.9
10-MJO	N	0-10	2.1	5.9	2.8	3.8	1.3	0.4	0.09	0.10	0.07	1.3
10-MJO	Y	10-30	5.8	5.9	2.8	7.5	5.2	1.1	0.5	0.15	0.10	2.3
10-MJO	O	0-10	15.2	5.9	0.8	2.9	4.1	1.5	2.0	0.50	0.48	1.9

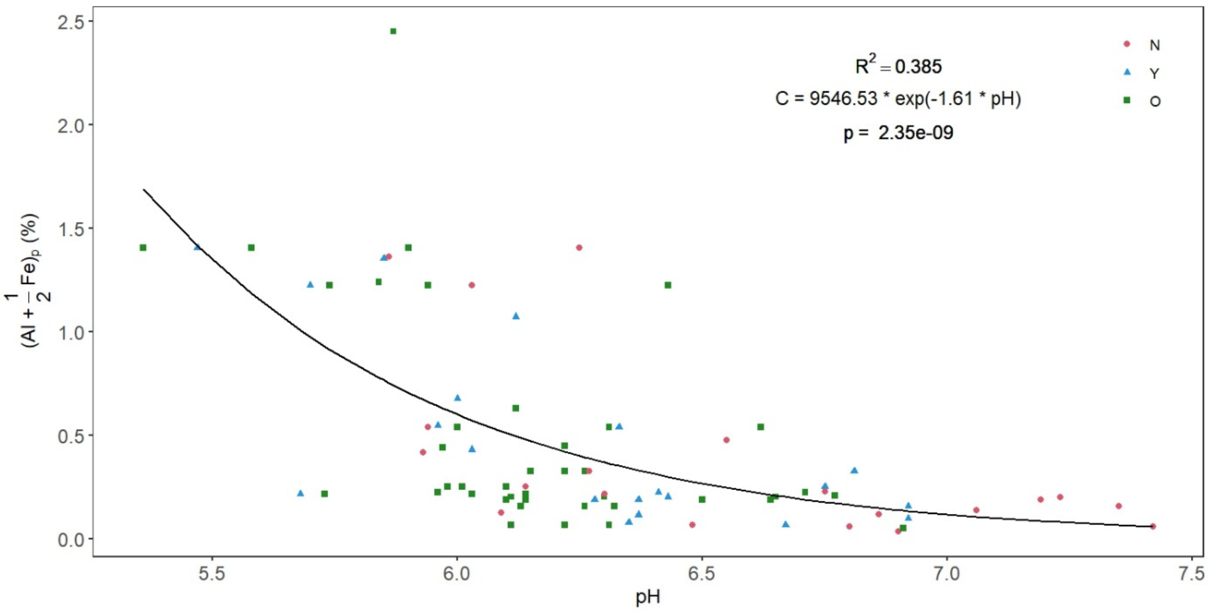

Figure S1. Exponential relationship between metal-organic complex content (represented by $(Al+½Fe)_p$ (%)) and pH from the ten birch woodland areas, including all stages (N: non-forested land in red circles, Y: young woodland in blue triangles, and O: old woodland in green squares) and both depth intervals.

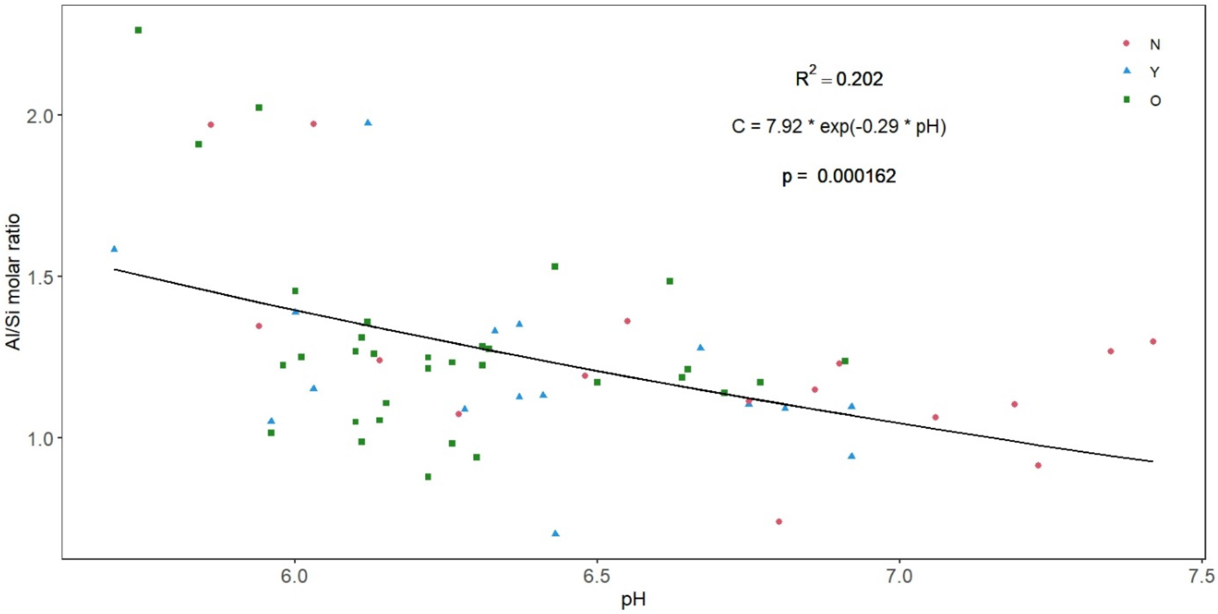

Figure S2. Exponential relationship between the Al/Si molar ratio of allophane and pH from the ten birch woodland areas, including all stages (N: non-forested land in red circles, Y: young woodland in blue triangles, and O: old woodland in green squares) and both depth intervals. Study areas 4-STEI and 10-MJO were excluded due to differences in soil parent material.

III

Soil water retention and infiltration across birch woodland chronosequences in Icelandic Andisols

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Abstract

Iceland has set goals to restore birch (*Betula pubescens*) woodlands to up to 5% of the land cover. Considering this goal and the Earth's changing climate patterns, it is essential to understand the woodland's impact on soil hydrology. This study focuses on recognizing the water retention capacities and infiltration rates in birch woodland soils, using chronosequences from old woodlands (+60 years) to adjacent non-forested land, in ten geographically distributed Icelandic Andisols. We show that old woodlands have the highest water retention values at field capacity and wilting point, explained by their higher carbon content (porosity) and lower bulk density. Plant available water values were highest in old woodlands and lowest in non-forested sites classified as Vitrisols (Icelandic system). Andic soil properties appear to control the plant available water. Infiltration rates were high, due to the soils' silty textures, and were dependent on seasonality. A rich vegetation cover proved to be crucial to prevent infiltration blockage in winter soils.

Keywords: *Betula pubescens*, soil hydrology, organic carbon, andic soil properties, allophane, woodland restoration.

1. Introduction

Hydrological properties of soils are a key factor in defining the fertility and resilience of ecosystems (Weil and Brady, 2017). A large part of Earth's dryland ecosystems has been disturbed, resulting in areas in poor condition that require restoration efforts. Today, there is a global consensus to conserve and restore natural ecosystems, as highlighted by the Secretariat of the Convention on Biological Diversity (2020) and the United Nations Convention to Combat Desertification (2024). This is further underlined by the current UN Decade for Ecosystem Restoration, reiterated by the Bonn Challenge. Iceland signed the Bonn Challenge in 2020 with national aims that include increasing the native birch woodland cover up to 5% by 2031 (Ministry of Food, Agriculture and Fisheries, 2022). Large-scale ecosystem restoration has pronounced effects on all ecosystem components, such as soils. With plans to expand birch cover in Iceland, it is important to improve the understanding of what ecosystem changes can be expected, including hydrological properties. It is also of great value to enhance understanding of factors that influence the success of ecosystem restoration projects.

Water holding capacity of soils is reflected by the water content at field capacity (FC), water content at the wilting point (WP), and plant available water (PAW; Cassel and Nielsen, 1986; Weil and Brady, 2017). The water content at FC is the water remaining in the soil when gravitational water has drained from the soil, at which point the soil is considered saturated with respect to bound water. Water content at the WP is the amount of soil water remaining when the soil is dry, and it is not considered available for vegetation. Plant available water is the difference between the water content at FC and the WP, i.e., the water useable by the vegetation (Cassel and Nielsen, 1986).

Water retention in soils is mostly determined by the grain size, mainly the amount of soil colloids, and the amount of organic matter (Weil and Brady, 2017), including metal-organic complexes (MOCs) in Andisols, which have a large total surface area (Dahlgren, 1994). Andisols, a ‘volcanic’ soil that predominates in Iceland (Arnalds, 2015), are known to have a high water retention capacity (Shoji, 1985; Saigusa and Matsuyama, 1998), which allows them to support rich ecosystems (McDaniel et al., 2012). They are generally fertile and carbon-rich, characterized by andic soil properties, such as low bulk density, high organic content, and a dominance of nano-crystalline colloidal constituents (Dahlgren et al., 2004; Jiménez et al., 2006; McDaniel et al., 2012); but when disturbed, Andisols are vulnerable to wind and water erosion due to poor particle cohesion in part caused by a lack of layer silicate clays (McDaniel et al., 2012; Arnalds, 2015). Icelandic Andisols can reach >100% in water content by mass at FC (Arnalds, 2015), which is high compared to average values for other soil orders (Rab et al., 2011). Well-developed Icelandic Andisols can reach >100% water content by mass at WP (hydric soil properties) due to the high surface areas of Andisol colloids (e.g., allophane, ferrihydrite) and/or metal-organic complexes (MOCs; McDaniel et al., 2012). High water retention values benefit the ecosystems while a lack of water retention can hinder woodland establishment, regeneration, and restoration efforts, affecting seedling growth, and leading to water stress (Engelbrecht et al., 2005; Wu et al., 2016). The optimal PAW for root growth is considered to be > 20%, though 15% is adequate (Reynolds et al., 2009). Common PAW values for volcanic soils are 20-40% (Mosquera et al., 2021; Dec et al., 2022).

Infiltration rate, defined as the velocity of water entry into the soil, is another important soil water parameter (Weil and Brady, 2017). Infiltration rate is important for water conservation, including the ecosystem's ability to receive and utilize water, and to prevent possible runoff and subsequent erosion (Patle et al., 2019; Harisuseno and Cahya, 2020). The infiltration rate is mainly controlled by vegetation, root types, and soil properties (Jiménez et al., 2006; Wu et al., 2016), but also varies by season, especially in areas experiencing soil freezing (Cerdà, 1997). Therefore, land use, which affects vegetation and possibly soil parameters, can impact infiltration rates (Wu et al., 2016; Sun et al., 2018).

Undisturbed Andisols can have high infiltration rates, especially in carbon-rich soils (Warkentin and Maeda, 1980). As an example, Jiménez et al. (2006) showed high infiltration rates in mature Andisols (Haplustands) in Tenerife, Spain, ranging from 152 to 362 mm/h. Orradóttir et al. (2008) found higher infiltration rates in birch woodlands than in other vegetation types in an Icelandic study, ranging from 3 mm/h (in winter) to 369 mm/h, with the highest values in sandy Andisols. Zaqout et al. (2022) showed twenty times higher infiltration rates in the summer and fall compared to the winter season, and Orradóttir et al. (2008) observed a similar trend. Hence, the infiltration rates in Iceland vary greatly between seasons and are affected by soil freezing.

Mountain birch (*Betula pubescens*) is the only native woodland-forming species in Iceland (Blöndal, 1987). Soil hydrology in Icelandic birch woodlands has received limited attention to date, apart from general water retention values published by Arnalds (2004, 2015). Only two published infiltration studies have been made in Iceland, one contrasting different vegetation cover types, including birch woodlands (Orradóttir et al., 2008), and another focusing on grass swales, lupines, and barren terrains in an urban setting (Zaqout et al., 2022). In this study, we focus on hydrological processes affected by birch woodland succession: 1) the effects of succession on water retention and infiltration rates, and 2) how soil and environmental parameters, such as dust deposition and seasonality, influence water retention and infiltration rates in birch woodland soils.

This study is part of a multidisciplinary project titled EcoBirch (birkivist.is), focusing on Icelandic birch woodlands from an ecological, environmental, and cultural point of view. As part of this project, Behrend et al. (2025) studied the natural colonization of birch woodlands, and Sanchez et al. (2025) provided knowledge about carbon stocks and colloidal dynamics (Sanchez et al., 2025b – in review) in the soils of birch chronosequences in study areas scattered around the country.

2. Methods and materials

2.1. Geographical setting

Iceland is a 100,000 km^2 island between 63°23'N and 66°32'N latitudes. The climate is oceanic, influenced by the warm Gulf Stream, and characterized by mild summers and cool winters (Einarsson, 1984; Ólafsson et al., 2007). Precipitation is generally abundant, ranging between 800-1500 mm in the south, with the highest rainfall received along the coastal mountains, while commonly 500-800 mm in the northern part (Ólafsson et al., 2007; Icelandic Met Office, 2022). Volcanic eruptions are frequent, and basaltic composition is most common for lava and tephra (Thordarson and Höskuldsson, 2008). The most common soil type in Iceland is Andisols (Arnalds, 2015), which is generally a fertile and carbon-rich soil order (McDaniel et al., 2012). Tephra deposition is common in the vicinity of the major volcanic systems (Larsen and Eiríksson, 2008). Dust deposition reaches all areas of Iceland but is most prevalent in areas close to 'dust hotspots' that are mainly located at glacial margins and along the southern coastline (Arnalds, 2010). The dust is mainly composed of vitric materials of basaltic origin (Baratoux et al., 2011; Arnalds et al., 2014).

2.2. Study areas

Ten study areas with native birch woodland ecosystems expanding into adjacent open land were selected throughout Iceland (Table 1). Coordinates for each study area are presented in Sanchez et al. (2025). Dust deposition categories were determined for each site based on Gunnarsson et al. (2015), who defined seven deposition groups from 1-very low (< 50 g m^{-2} yr^{-1}) to 7-excessive (>1000 g m^{-2} yr^{-1}). Climate metrics represent average annual values from the weather station closest to each study area (Icelandic Met Office, n.d.). The general soil classification for the birch woodland soils at each study area is presented in Table 1, along with a more detailed soil classification for each age stage in Table S1.

Table 1. Study areas with native birch woodlands and their geographical, meteorological, and pedological information.

Study area	Name	Region	Dust deposition[a]	Av annual P[b]	Av annual T[b]	Soil type	Non-forested site
1-LEY	Leyningshólar	North	4	529	4.0	Ustivitrand & Haplustand	Heathland
2-OX	Öxarfjörður	Northeast	4	583	3.7	Haplustand	Heathland
3-RAN	Ranaskógur	East	4	928	4.3	Ustivitrand	Gravelly grassland
4-STEI	Steinadalur	Southeast	5	1109	5.4	Ustivitrand	Heathland soil
5-HRI	Hrífunes	South	6	1459	5.0	Haplustand	Heathland
6-THO	Þórsmörk	South	6	1198	4.4	Ustivitrand	Gravelly soil
7-NED	Neðri Dalur	Southwest	5	1340	4.1	Fulvudand	Heathland
8-SKO	Skorradalur	West	2	1001	4.4	Endoaquand	Heath- and wetland
9-HUS	Húsafell	West	4	810	3.8	Ustivitrand	Gravelly soil
10-MJO	Mjóifjörður	Westfjords	1	542	1.9	Cryand	Gravelly soil

[a] Dust categories based on Gunnarsson et al. (2015).

[b] Years included in climate metrics: 1-LEY: 1949–2023; 2-OX: 1956–2016; 3-RAN: 1996–2023 (temperature), 2002–2023 (precipitation); 4-STEI: 2007–2023 (temperature), 2009–2020 (precipitation); 5-HRI: 2004–2023 (temperature), 2007–2021 (precipitation); 6-THO: 1961–2022; 7-NED: 1990–2023; 8-SKO: 1998–2023 (temperature), 1999–2022 (precipitation); 9-HUS: 1998–2023 (temperature), 1988–2016 (precipitation); 10-MJO: 2000–2023 (temperature), 1961–2003 (precipitation).

Three different age groups, referred to as age stages were identified within all ten study areas based on historical aerial photos (Behrend et al. 2025): old-growth birch woodland (O, 60+ years old), young birch woodland (Y, 30-60 years old), and an adjacent non-forested site (N). Vegetation cover in the old and young birch woodlands was 100% in all study areas, with forbs, grasses, mosses, and dwarf shrubs dominating the understory. The vegetation cover in non-forested sites varied between study areas; most had a good ecosystem condition, whereas some were gravelly and some partly barren, showing evidence of soil erosion (Table 1). The 7-NED area served as a core ecological study area, where water infiltration measurements were carried out.

2.3. Soil sampling

Soils were sampled in the summer of 2021 in all ten study areas. The samples were obtained from the three age stages: non-forested sites, young woodlands, and old woodlands. Three transects (50-100 meters apart) were laid out, each crossing the three age stages. Two plots (10 x 10 m) were placed on each transect at every age stage, making a total of six plots per age stage. Two soil samples were collected from each plot: one from the 0-10 cm depth interval and another from the 10-30 cm depth interval. More than 95% of the Icelandic mountain birch root biomass is in the upper 30 cm of the soil (Hunziker et al., 2014), making that depth interval the most important for analyzing soil water properties of Icelandic woodlands.

For this research, the 0-10 cm and 10-30 cm depth interval samples from plots 2 and 4 of each age stage and study area were selected, making a total of 120 soil samples: 2 depths x 2 plots x 3 stages x 10 study areas. Each sample consisted of up to five soil cores (composite sample) taken from quadrants (50 x 50 cm) randomly distributed in each plot. The vegetation and litter layers were removed before the sampling.

2.4. Water content measurements

Soil samples were stored at 10°C and field-moist conditions. Samples were gently sieved through a 2-mm sieve before water content measurements. Pressure plates placed in pressure chambers were used to determine the soil water contents at different water tensions (Cassel and Nielsen, 1986). Sieved soil subsamples were set inside 5 cm diameter rings (without compressing), ranging from 7 to 27 grams of soil, due to variable soil consistencies, and placed on a porous ceramic pressure plate. The soil samples were subsequently rewetted, and pressure adjusted to 0.33 bar (33 kPa) to obtain the water content at field capacity. The pressure was applied until water was no longer seeping out of the chamber, generally after 24 hours. After weighing, the samples were rewetted and rearranged on another ceramic pressure plate, and 15 bars pressure (1500 kPa) was applied for another 24 hours to reach the permanent wilting point. After treatment in the pressure chambers, the samples were weighed and oven-dried at 105°C for 24 h (Jamison and Kroth, 1958; Cassel and Nielsen, 1986; Bauer and Black, 1992). The dry weight (DW) was used to calculate the water content at field capacity (FC; 0.33 bar) and the wilting point (WP; 15 bars) on a mass basis:

$$\text{Water content at FC or WP (\%)} = [(\text{Weight (g) after 0.33 or 15 bars} - \text{DW}) / \text{DW}] \times 100$$

The plant available water was estimated as %PAW = Water content at field capacity – Water content at the wilting point (Cassel and Nielsen, 1986). To calculate the water content at field capacity and the wilting point on a volumetric basis, the water content on a mass basis was multiplied by the bulk density (BD) determined during field sampling (see Sanchez et al., 2025 for bulk density). The water content at FC and WP on a volumetric basis was used to calculate the PAW in cm for each depth interval:

$$\text{PAW (cm)} = [(\text{FC} \times \text{BD}) - (\text{WP} \times \text{BD})] \times \text{soil depth (cm)}$$

Soil porosity of the samples was estimated as follows:

$$\text{Porosity (\%)} = (1 - D_b/D_p) \times 100$$

where D_b is the bulk density (g/cm^3) and D_p is the particle density, which was assumed to be 2.4 g/cm^3. This density reflects the approximate range of solid particles in Icelandic soils, from porous vitric materials (often 1.5 g/cm^3) to heavy non-porous basaltic particles (D_p > 2.7 g/cm^3; Arnalds, 1990). At the core study area 7-NED, the particle density was estimated as 2.7 g/cm^3, due to sand inputs from the nearby Hagavatn area dust hotspot, containing a higher level of crystalline basalt fragments (Arnalds, 2010; Baratoux et al., 2011).

Three pore-size classes were operationally defined for the purpose of this study based on the -0.33 and -15 bar water contents, on a volumetric basis, determined from pressure-plate measurements (Weil and Brady, 2017):

Macropores (%) = porosity (%) – water content at field capacity (%)

Mesopores (%) = water content at field capacity (%) – water content at the wilting point (%)

Micropores (%) = water content at the wilting point (%)

The sand fraction was determined by hand texturing in the lab (Page et al., 1982). The method was blind, and the samples were selected in random order. The sand percentage was estimated to the nearest 5% increment, e.g., 5%, 10%, 15%. The samples containing only trace amounts of sand were classified as 5% sand.

2.5. Water infiltration

Water infiltration rates were measured at the core area 7-NED in southwest Iceland in all three identified age stages on the transects used for soil sampling. Five months prior to measuring water infiltration, i.e., at the end of November 2021, single rings (20 cm in diameter, 30 cm in height) were inserted into the soil, leaving ~10 cm of the ring exposed above the surface of the soil. Plastic rings were used to avoid additional water freezing associated with cold metal surfaces at cold temperatures.

At each of the three age stages, three single rings were inserted in each transect about 30 cm apart (Figure 1), for a total of 36 rings. As soon as the measurements started (five months after insertion), it became apparent that two ring insertions had failed. They were excluded, resulting in a total of 34 usable infiltration rings. Infiltration was measured for 60 minutes for each ring. Water was poured into the ring, maintaining about 5 cm of water level above the surface. The water inputs were cold to reduce the risk of ice melting in the soil. The amount of water required to refill the ring was recorded every 5 minutes. Each ring's terminal infiltration rate (TIRs, mm/h) was calculated using the mean of the last three measurements (i.e., 50, 55, and 60-minute measurements).

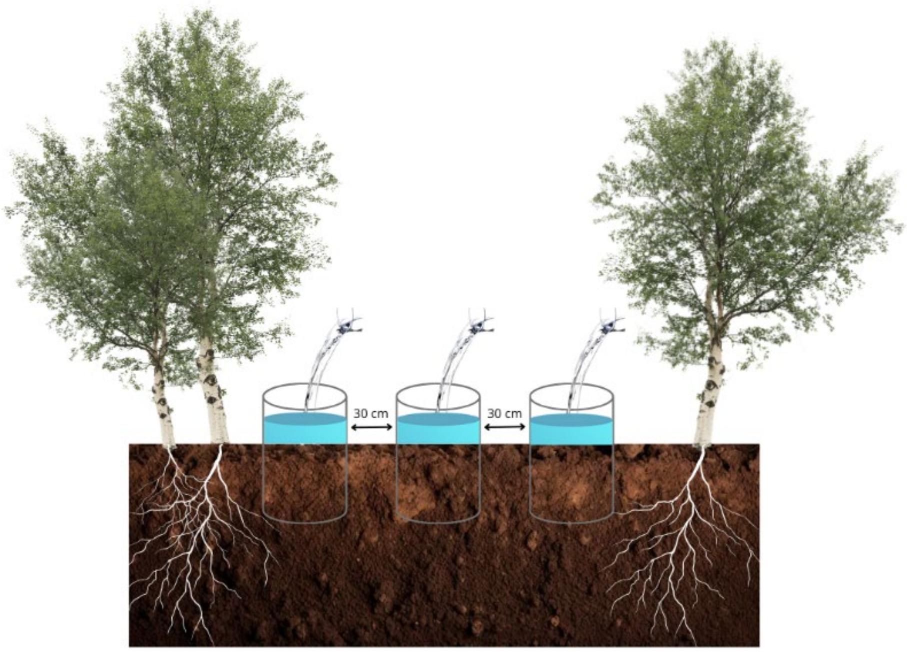

Figure 1. Schematic of single infiltration rings placed on an old woodland site.

The infiltration measurements took place on five separate occasions, covering different seasons: April 2022 (winter), June 2022 (spring), July 2022 (summer), and October 2022 (autumn). These dates were selected considering the appropriate/normal weather of each season. Due to variable winter conditions in Iceland, a winter measurement was repeated in February 2023.

The single-ring method (as opposed to double rings) was used (Figure 2), even though the double-ring infiltration measurements are recommended and widely used (e.g., Jiménez et al., 2006, or Singh et al., 2017). Frost-heave and soil movements caused by alternating freezing and thawing cycles of Icelandic soils create a difficult condition for water infiltration measurements. Frost-heaving and soil disturbances can damage and jeopardize the inserted rings, with the double ring insertion more likely to be influenced than a single ring. Therefore, double rings do not guarantee more accuracy in these areas (Zaqout et al., 2022). In addition, frost-cracks in the soil can lead to rapid preferential water flowpaths deep into the soil, resulting in unrealistically high infiltration results. For those reasons, the single-ring method is likely to be less affected by frost disturbances, as pointed out by Zaqout et al. (2022), who used single rings in their experiments in urban areas of Iceland.

Figure 2. A plastic infiltration ring, 20 cm in diameter, was inserted into the soil in an old woodland at 7-NED. Photo taken in the fall of 2022.

2.6. Data analysis

Data were analyzed using RStudio (R Core Team, 2023) and the package *tidyverse* to organize datasets (Wickham et al., 2019). Two datasets were utilized: one including all ten study areas with water retention and other soil properties, and the other including only the core area for infiltration rates, water retention, and other soil properties.

The Mahalanobis principle was performed to determine outliers in both datasets, using the packages *stats* and *factoextra* (Kassambara and Mundt, 2020; R Core Team, 2023). Four samples from the non-forested site in 8-SKO were identified as outliers and excluded from the dataset. The Mahalanobis principle also identified outliers in the infiltration dataset: three outlier values from winter season 1, and two from spring. A few other infiltration outliers were excluded visually, as the infiltration in some rings increased over time, suggesting that other factors were affecting the measurements. For instance, the melting of ice in the soil during water pouring could lead to leakage next to the plastic infiltration rings.

Mean values were calculated for each water retention property at each age stage, using the packages *dplyr* and *Hmisc* (Wickham et al., 2023; Harrell, 2025). Means and standard deviations were calculated for terminal infiltration rates for each season in each age stage. Boxplots were prepared to present water retention properties and terminal infiltration rates, using the *ggplot2* package (Wickham, 2016).

One-way analysis of variance (ANOVA) was performed to assess significant differences between 1) water retention values at each depth, 2) water retention values within each age stage, 3) infiltration rates between age stages within each season, and 4) infiltration rates between seasons within each age stage using packages *stats* and *ggpubr* (Kassambara, 2023; R Core Team, 2023). Subsequently, Tukey tests were performed for post-hoc mean separation using the package *stats* (R Core Team, 2023). Significant statistical differences were determined at $p < 0.05$.

Linear regressions were performed to investigate relationships between soil properties, using the packages *stats*, *dplyr*, *ggpubr*, and *ggplot2* (Wickham, 2016; Kassambara, 2023; R Core Team, 2023; Wickham et al., 2023). Regressions between water retention properties and 1) carbon, 2) active Al and Fe $(\mathrm{Al}+\frac{1}{2}\mathrm{Fe})_{\mathrm{ox}}$, and 3) bulk density, were carried out for each age stage. In addition, linear regressions between terminal infiltration rates and 1) carbon, 2) bulk density, and 3) air temperature were performed.

Stepwise regressions were used to determine the best model fit for 1) water content at field capacity, 2) water content at the wilting point, 3) plant available water, and 4) terminal infiltration rates, using the statistical packages *MASS* and *car* (Venables and Ripley, 2002; Fox and Weisberg, 2019). For the stepwise regressions with water retention properties, the variables carbon content (%), $(\mathrm{Al}+\frac{1}{2}\mathrm{Fe})_{\mathrm{ox}}$ (%), and bulk density ($\mathrm{g/cm^3}$) were included in the initial fit. The $(\mathrm{Al}+\frac{1}{2}\mathrm{Fe})_{\mathrm{ox}}$ is an indicator of soil colloids, such as clays and metal-organic complexes, responsible for andic soil properties (Dahlgren et al., 2004). For the regression of the terminal infiltration rates, the initial fit included the variables carbon, $(Al+½Fe)_{ox}$, bulk density, air temperature, and air humidity.

3. Results

3.1. Soil water content

All measured water retention properties varied considerably between study areas (Figure 3; Table S2). Areas 7-NED, 8-SKO, and 10-MJO showed the highest average water contents and plant-available water values, whereas areas 3-RAN had the lowest average values. The three water retention properties did not differ significantly between depths ($p = 0.99$ for FC, $p = 0.32$ for WP, and $p = 0.06$ for PAW).

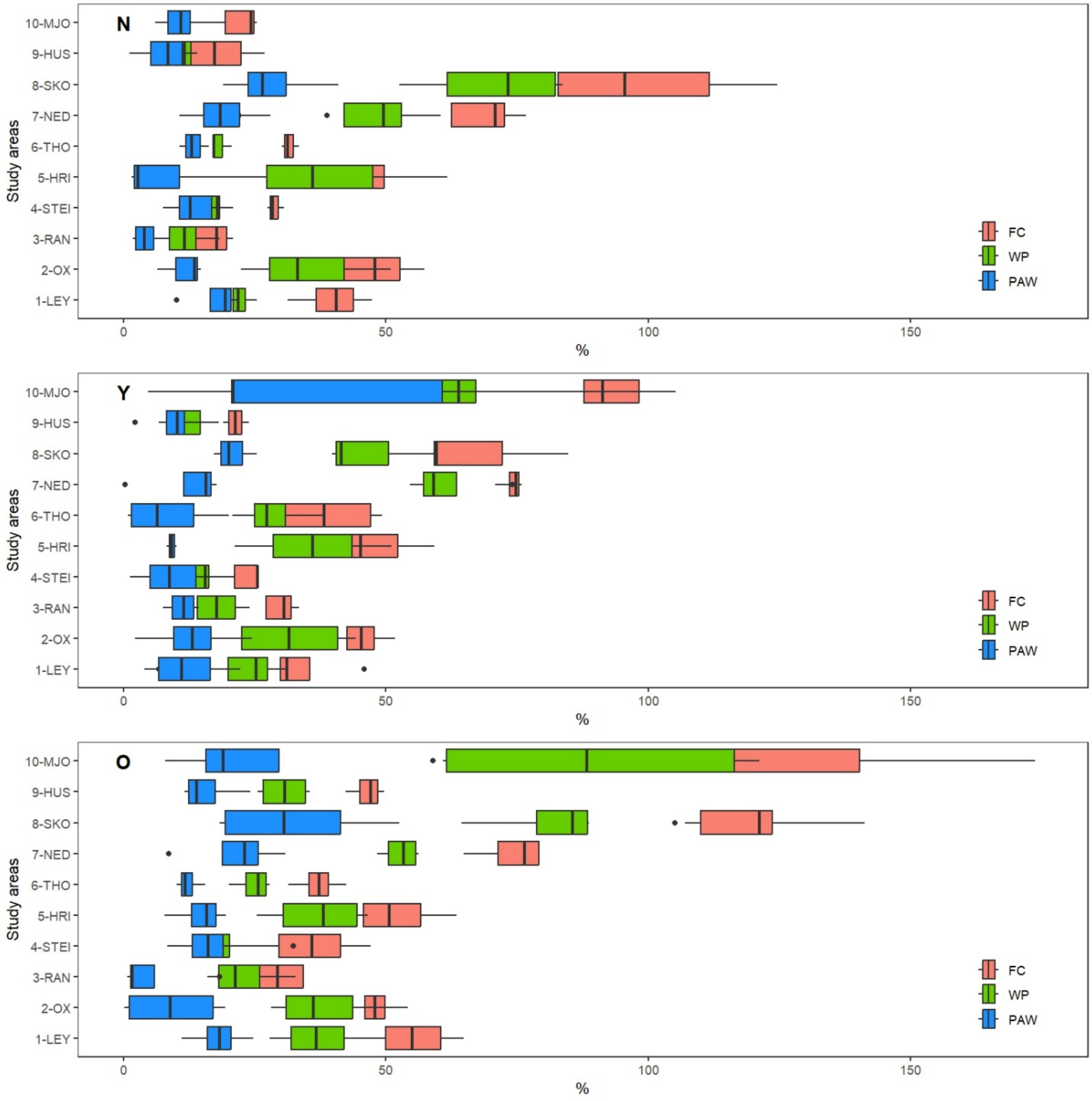

Figure 3. Boxplots representing the water content at field capacity (FC%, in red), at wilting point (WP%, in green), and plant available water (PAW%, in blue) for ten birch woodlands in Iceland divided by study areas at each age stage: N in the top (non-forested site, n = 36), Y in the middle (young woodlands, n = 35), and O in the bottom (old woodlands, n = 40). The top and bottom of the horizontal lines represent the maximum and minimum values, and outliers are displayed as single points.

Old woodlands showed the highest values for all three water retention parameters (Figure 4). Old woodlands (O) had significantly higher water content at FC than both young woodlands (Y) and non-forested sites (N), but the difference between Y and N was not significant (*p*-values of 0.03, 0.006, and 0.85 for O-Y, O-N, and Y-N, respectively). The same pattern was seen for water content at the WP (*p*-values of 0.02, 0.005, and 0.88 for O-Y, O-N, and Y-N, respectively). The lowest average FC and WP values were found in non-forested soils with low organic content, with average FC values of 42% and 29% WP (Figure 4; Table S2). There was no significant difference in plant available water contents (PAW) between the three age stages (*p*-values from 0.34 to 0.93). The PAW was also calculated in millimeters from the bulk density. In the 0-10 cm layer, there was an average PAW of 8.1 mm in N, 7.6 mm in Y, and 6.7 mm in O. In the 10-30 cm layer, there was a PAW average of 28.5 mm in N, 24.2 mm in Y, and 30.3 mm in O, yet with no significant differences between stages in either depth interval.

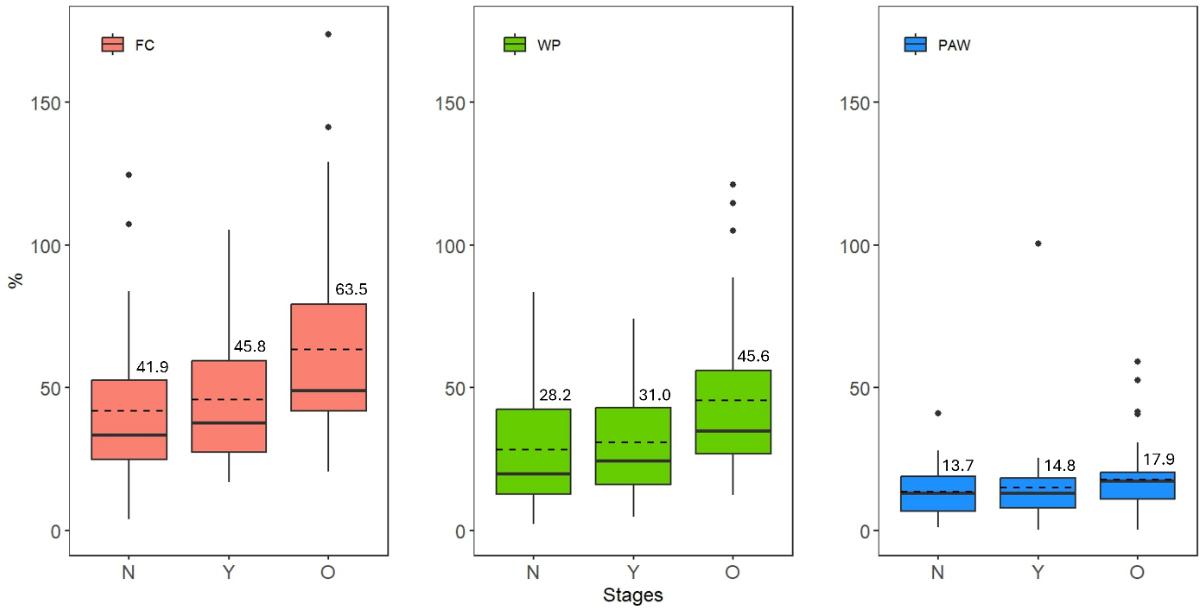

Figure 4. Boxplots presenting the water content summarized for all 10 research areas at field capacity (FC%, in red), water content at wilting point (WP%, in green), and plant available water (PAW%, in blue) on a mass basis divided by age stages: N (non-forested land, n = 36), Y (young woodlands, n = 35), and O (old woodlands, n = 40). Median values for each age stage are represented by horizontal lines, and mean values by dashed lines and written values positioned on the top right of each boxplot.

3.2. Soil texture and porosity

The mean sand content in each age stage was 14.5% at N, 13.6% at Y, and 7.2% at O, and was significantly lower in the O compared to Y ($p = 0.01$) and N ($p = 0.003$). The sand content was especially high in the N sites at 10-MJO (50-60% sand), 3-RAN (50% sand), and 1-LEY (35% sand). Some Y sites also had a high percentage of sand, such as 1-LEY (30-40%), or 6-THO (25%). There was no significant difference in sand content between depth intervals at any age stage. In N sites, the sand fraction showed a general negative trend with water content at FC ($R^2 = 0.26$, $p = 0.002$) and WP ($R^2 = 0.22$, $p = 0.004$), and PAW ($R^2 = 0.16$, $p = 0.02$), with higher retention and available water values in samples containing a lower sand content. In Y and O, there was no significant relationship between the sand content and water properties ($p > 0.05$).

The soils in this study have a weak blocky structure (‘very’ weak), which is the norm for most Icelandic Andisols, especially for the soils influenced by volcanic and aeolian processes (Arnalds, 2015). Sanchez et al. (2025) presented soil pedon descriptions for the study areas 7-NED and 8-SKO, classifying the structures of the soil layers as either very weak, very fine blocky structure, or weak fine granular structure.

The average total porosity was highest in the old woodland samples, showing significant differences between O and N ($p = 0.003$; Figure 5). The macropores and mesopores did not differ significantly between age stages, but micropores were highest in the older woodlands (*p*-values 0.03 and 0.01 for O-Y and O-N, respectively).

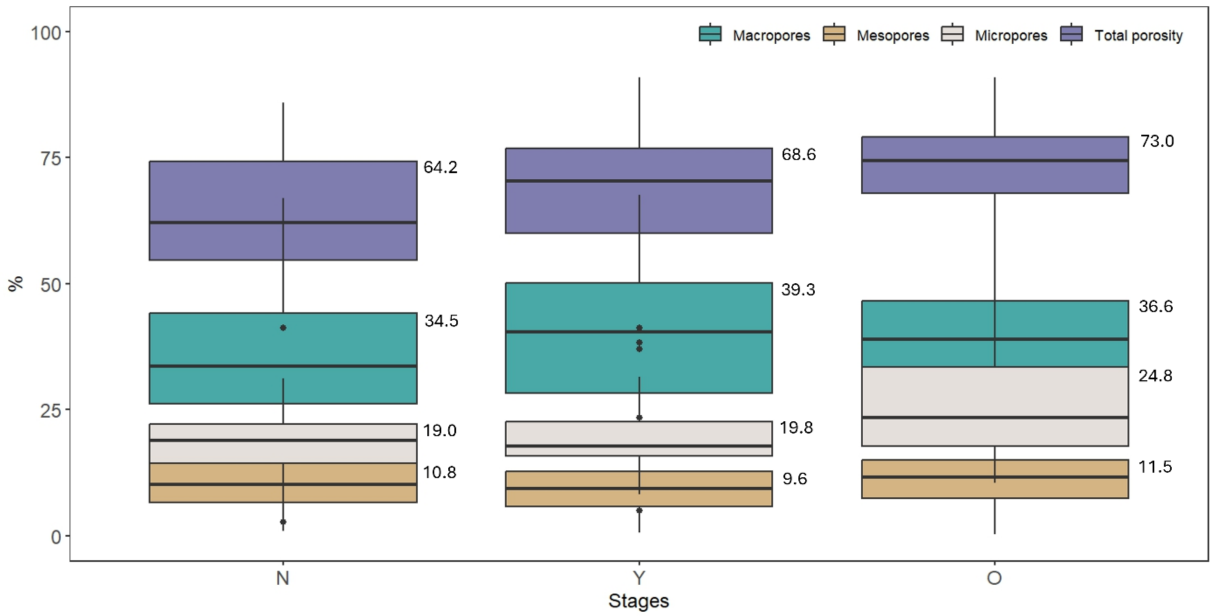

Figure 5. Boxplots of total porosity (%, in purple), macropores (%, in green), mesopores (%, in brown), and micropores (%, in gray) for each age stage (N: non-forested site, Y: young woodland, and O: old woodland) of ten birch woodland sites in Iceland. Mean values for each property at each stage are positioned on the top right of each boxplot.

3.3. Water and soil properties

There was a significant positive relationship between carbon and the three water retention properties at all three age stages (Figure 6). Water content at FC and PAW had the strongest relationships with %C in Y ($R^2 = 0.71$ and 0.37, respectively; both $p < 0.001$), and the water content at the WP had the strongest relationship with %C in O ($R^2 = 0.79$, $p < 0.001$). There was a significant positive relationship between $(Al+½Fe)_{ox}$ and FC for Y ($R^2 = 0.49$, $p = 0.01$) and O ($R^2 = 0.40$, $p = 0.02$). However, the relationship between $(Al+½Fe)_{ox}$ and WP was only significant for Y ($R^2 = 0.45$, $p = 0.02$), and between $(Al+½Fe)_{ox}$ and PAW only for O ($R^2 = 0.62$, $p < 0.001$). There was a strong negative relationship between bulk density and water properties at all stages ($p < 0.001$), although the relationship between bulk density and PAW was only significant at N ($R^2 = 0.19$, $p = 0.001$).

Stepwise regressions for each water retention property showed that carbon and $(Al+½Fe)_{ox}$ gave the best fit for the water content at FC (adjusted $R^2 = 0.87$), carbon, $(Al+½Fe)_{ox}$, and bulk density gave the best fit for water content at WP (adjusted $R^2 = 0.85$), but $(Al+½Fe)_{ox}$ alone was the most influential variable for PAW (adjusted $R^2 = 0.44$).

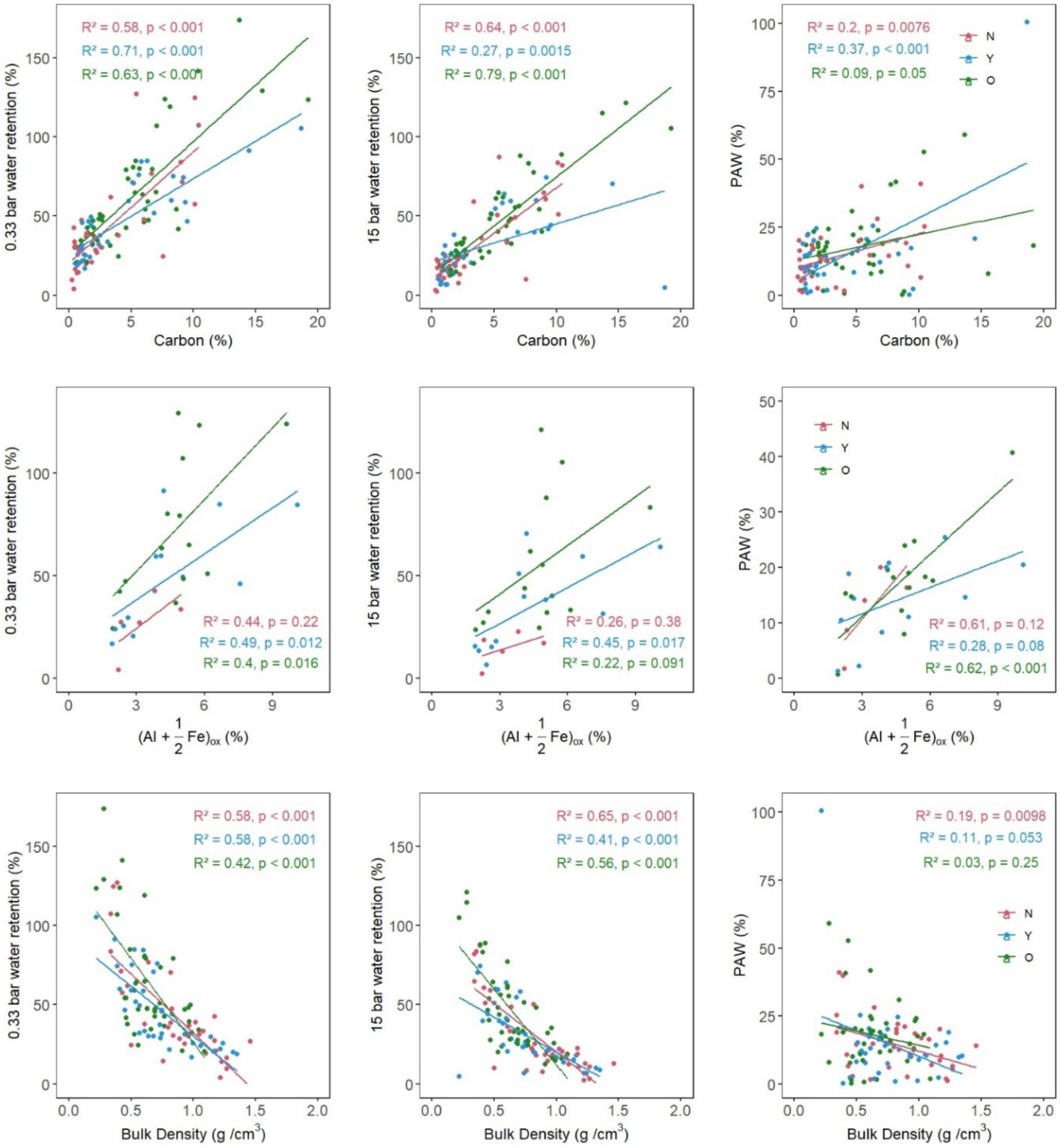

Figure 6. Relationships (linear regressions) between carbon (%C, n = 119), $(Al+½Fe)_{ox}$ (%, n = 31), and bulk density (g/cm^3, n = 119) and 0.33 bar water retention (%, water content at field capacity, on the left), 15 bar water retention (%, water content at

wilting point, in the middle), and PAW (%, plant available water, on the right). R^2, and p-values are shown for each age stage: N (non-forested site) in red, Y (young woodland) in blue, O (old woodlands) in green. Note the different scales for PAW (%).

3.4. Terminal infiltration rates

Terminal infiltration rates (TIRs, mm/h) were similar between stages and seasons (ranging from 0 to 1508 mm/h; n = 32), except that values were lower in winter than at other times of the year. The data shown in Table 2 and Figure 7 exclude outliers, and replicates where frost cracks were visible within the rings.

TIRs were generally highest in spring and lowest in winter. The temperatures during sampling of the infiltration rates were quite variable between seasons. The average temperature in winter season 1 was -0.9°C, in spring 9.0°C, in summer 12.6°C, in fall 6.9°C, and in winter season 2 0.8°C.

There were no significant differences between age stages in any season, apart from between N and Y in winter 2. However, the TIR means (colored circles in Figure 7) were consistently highest in O for all measurements, except winter season 2. The TIRs in the old woodlands were 23% higher than non-forested sites in winter season 1, 43% and 45% higher in spring and summer, 62% in fall, and up to 10 times higher in winter season 2 than non-forested sites. The average rates, including all seasons, were 325 mm/h in N, 407 mm/h in Y, and 500 mm/h in O.

Table 2. Mean values and standard deviations for terminal infiltration rates (mm/h; excluding cracks and outliers) in the study area 7-NED divided by seasons and age stages (N: non-forested, Y: young woodland, O: old woodland). Superscripts for each season (winter 1: W1, spring: Sp, summer: Su, fall: F, winter 2: W2) indicate significant differences between seasons within each age stage based on ANOVA ($p < 0.05$).

Season	Winter 1	Spring	Summer	Fall	Winter 2
Age stages	Data without outliers/cracks				
N (n = 8)	184.0 ± 169.1	514.6 ± 444.7^{W2}	404.9 ± 381.4	421.1 ± 320.5	27.7 ± 24.1^{Sp}
Y (n = 6)	207.9 ± 217.8	405.5 ± 198.7	375.6 ± 224.1	527.4 ± 263.8	436.5 ± 367.2
O (n = 9)	$228.9 \pm 304.2^{Sp, F}$	$740.4 \pm 328.6^{W1, W2}$	586.1 ± 297.7	683.5 ± 343.0^{W1}	287.6 ± 355.3^{Sp}

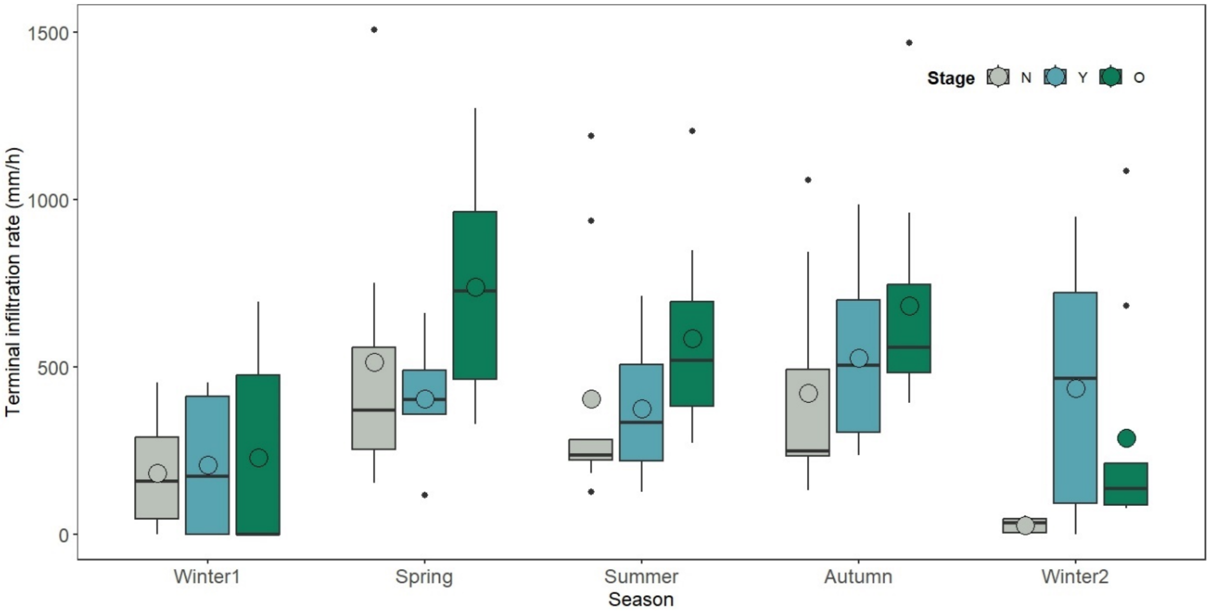

Figure 7. Boxplots for terminal infiltration rates (mm/h) divided by seasons and age stages: N in grey (non-forested site, n = 8), Y in blue (young woodland, n = 6), and O in green (old woodland, n = 9). Horizontal lines inside the boxplots represent the TIR medians, and colored circles the TIR means for each age stage in each season. Cracked soils and outliers have been excluded from this graph.

3.5. TIRs, soil properties, and climate data

A stepwise regression to assess the influence of carbon, $(Al+½Fe)_{ox}$, bulk density, air temperature, and air humidity on TIR showed that the best fit included carbon, bulk density, and air temperature (adjusted $R^2 = 0.17$ and $p < 0.001$).

There was a slight, yet significant positive relationship between TIRs and carbon ($R^2 = 0.03$, $p = 0.02$). This relationship was strongest for the winter data, combining both winter 1 and 2 ($p = 0.003$), but was not significant for the other seasons (*p*-values ranging from 0.2 to 0.66). Bulk density (BD) had a non-significant negative relationship with TIRs ($R^2 = 0.01$, $p = 0.21$). As with TIRs and carbon, the strongest relationship between BD and TIRs was found in the winter data ($p = 0.001$), while no relationship was found for the rest of the seasons. Lastly, there was a significant positive relationship between air temperature and TIRs ($R^2 = 0.11$, $p < 0.001$).

4. Discussion

4.1. Soil water retention – General context

From a global perspective, our soil samples from birch woodlands in Iceland exhibited high water retention values, with some reaching a water content by mass of over 100% at field capacity (FC) and even some at the wilting point (WP; Figure 3). The soils were all classified as Andisols, which are known to have high water retention, comparable to organic- and clay-rich soils, due to the high surface area and porosity of the colloidal materials (Maeda et al., 1977; McDaniel et al., 2012).

The range in water content in our study (4-174% at FC and 2-121% at WP) is comparable and sometimes higher than generally reported for other Andisols around the world. Woodland soils commonly retain more water than cultivated fields and other dryland systems (Harden and Scruggs, 2003). Values for forested Andisols usually range from 40-71% at FC and 20-58% at WP (e.g., Jiménez et al., 2006; Anda and Dahlgren, 2020; Kassaye et al., 2020; Roa García et al., 2020), whereas typical water content values for other dryland soil types (not Andisols) are generally lower: 6-50% at FC and 2-38% at the WP (Rab et al., 2015). The old woodlands of this project had substantially higher retention values than reported for various non-Andisols deciduous woodlands, usually ranging from 20-44% at FC and 3-22% at the WP (Finch, 2000; Gajić et al., 2008; Toriyama et al., 2008).

4.2. Water retention in Icelandic vegetation types

4.2.1. Water retention from non-forested sites to birch woodlands

Soil water retention values at FC and WP became higher from non-forested, to young woodland, to old woodland (N < Y < O; Figure 4), coinciding with an increase in organic carbon (C) with increased woodland age. This relationship has been widely cited, associated with higher surface area, porosity, more aggregates, and lower bulk density (Maeda et al., 1977; Fiantis et al., 2005; Weil and Brady, 2017; Minasny and McBratney, 2018). The significantly high amount of micropores in the old woodlands aligns with the research of Bartoli and Burtin (2007), who stated that Icelandic Andisols have capillary porosity with a limited amount of macropores. This study clearly indicates that water content at the WP increases with woodland age, while lower numbers were found in young forests and non-forested sites (Figure 6). Similar strong positive relationships between WP and C in horizons both with low and high C were also reported in Iceland by Arnalds (2015).

Young, poorly weathered soils generally have a higher sand content (part of the parent material) than more developed soils (Gerzabek et al., 2023), as seen in the results of this study, indicating, in part, the degree of soil evolution/formation. Sandy soils are known to have low water retention capacities and high infiltration rates, due to larger soil particles and pore spaces (Weil & Brandy, 2017). All samples in this study had > 10% water content at FC, except one from a non-forested site at 3-RAN (classified as Ustivitrand), which had 50% sand content at a gravelly site with a low vegetation cover located on recent fluvial deposits with soil in its initial stages of development. The coarse texture results in comparatively low water retention values in our study, however, comparable to many other soil types that support vegetation and agriculture globally (Soil Survey Staff, 2015). On the other hand, silty and clayey soils (more developed soils), such as the soils in the old woodlands in this study, generally have higher water retention capacities.

It is interesting to note that PAW is most closely related to andic soil properties in the study, $(\mathrm{Al}+\frac{1}{2}\mathrm{Fe})_{ox}$ (clays and other soil colloids), especially in the old woodlands, while organic carbon provides more explanation for water retention at FC and WP. High PAW, on the other hand, was only minimally related to carbon. Hudson (1994) explained that the often-observed negligible effect of organic C on PAW is due to C increasing the water content at the WP, hence lowering PAW. This highlights the importance of andic properties for high water availability in Andisols. The soil colloidal fraction is known to have an important influence on water retention (Saigusa and Marsuyama, 1998), since allophanic clays form silt-size aggregates that have both the characteristics of silt and the high surface area of clays, enhancing their affinity for water and increasing the soil PAW (Dahlgren, 1994; McDaniel et al., 2012).

4.2.2. Water retention comparison to previous findings

The samples from this project showed moderately to high water retention values (FC and WP) compared to published values of Icelandic Andisols, such as the range presented by Arnalds (2015) for Brown Andosols (Table 3). The woodland values are in the higher range, while the non-forested sites tend to be lower than these averages. The Arnalds et al. (1995 and 2015) datasets involve soil pedons with many well-developed subsurface soil horizons rich in clays and having high water retention values, which may explain lower values for the surface horizons in our research. Due to the large variability of the non-forested sites (N), four N-samples from 3-RAN and 4-STEI containing < 1.5% C are presented separately in Table 3, labeled as Vitrisols in line with the Icelandic classification system, separating soils with low carbon and allophane contents (soils with < 1.5% C and < 6% allophane; Arnalds, 2015). The range of water properties in Vitrisols in this study falls well within the range of the Vitrisols presented by Arnalds (2015).

The old woodland samples in 8-SKO and 10-MJO showed extremely high FC values (174% and 141% respectively). These soils were classified as Histic Endoaquand and Typic Hydrocryand, respectively, falling under the Histic Andosol range presented by Arnalds (2015; Table 3). Orradóttir et al. (2008) similarly found very high FC values in organic layers (Oi, 5-8 cm depth) of diverse vegetation types. The retention was, however, lower in the A1 horizon (~7 cm depth) or ≤ 81% in all vegetation types.

Our results add a considerable amount of data to previously published water retention values in Iceland, with good geographic representation. They are mostly in line with previously published results, when separated by soil classes and horizons as shown in Table 2, yet demonstrating considerable variability, which can be related to variable clay and organic contents. The notably high water retention in old woodlands is noteworthy, underscoring the importance of these systems for soil water regulation, resilience (e.g., to droughts), and fertility.

Table 3. Water retention at field capacity (%, 0.33 bar) and wilting point (%, 15 bar), and plant available water (%, PAW) values from the main studies on Icelandic Andisols.

	Water content at pressures			
Sample	0.33 bar	15 bar	PAW	Reference
Histic Andosol > 12% C*	100-200	75-150	50-125	Arnalds (2015)
Brown Andosols < 12% C*	30-100	15-70	15-40	Arnalds (2015)
Vitrisols < 1.5% C*	5-40	5-30	5-15	Arnalds (2015)
A1-A4 in heathland	38-87	17-60	14-40	Arnalds et al. (1995)$
Oi-A1 (0-8 cm) in birch woodland	54-162	-	-	Orradóttir et al. (2008)
Non-forested (0-30 cm)#	10-84	3-65	15 (17 mm)	Present study
Non-forested Vitrisol* (0-30 cm)	4-27	2-19	6 (11 mm)	Present study
Young birch woodland (0-30 cm)	17-105	5-74	15 (15 mm)	Present study
Old birch woodland (0-30 cm)	21-174	13-121	18 (19 mm)	Present study

**Icelandic classification system (Arnalds, 2015).*

$Arnalds et al. (1995): Seven A horizons ranging from 0-8 to 12-28 to 43-60 cm depth.

#Two samples from 8-SKO have been excluded due to being outliers: FC 125% and 107%, and WP 83% and 82%.

The plant available water (PAW) values reported in this study are slightly lower than those reported in other Icelandic vegetation types (Table 3). The soils with the lowest PAW values (mostly non-forested sites) may be vulnerable to prolonged droughts. During sampling, wilted seedlings were observed in some non-forested Vitrisols, such as 3-RAN, possibly caused by drought stress. However, most non-forested sites (non-Vitrisols) have considerably high PAW values, which are comparable to woodlands elsewhere. This might aid forest development in the vicinity of the woodlands towards fully developed birch-woodlands where other environmental factors are favorable, e.g., seed sources, or not limiting, such as grazing (Óskarsdóttir et al., 2022; Behrend et al., 2025). In addition, birch characteristically has deep root systems (Jonczak et al., 2020) that extend potential sources for water, thus reducing the impact of low PAW values in surface horizons. The ability of the birch to draw water from greater depths in soils with relatively low PAW and/or where surface soils tend to dry out during dry spells is an important component of the pioneer species traits of the birch (Aradottir, 2007). We conclude that all samples from the woodland sites in this study showed water retention properties with PAW values conductive to robust ecosystems (> 15%, Reynolds et al., 2009); and that water retention is generally not considered a limiting factor for the development of birch woodlands in Iceland from non-forested to forested systems.

The low bulk density of our Andisol samples yields lower average water contents available to plants than might be expected from the high PAW% values when the water content is converted to mm of water, with a tendency to even out differences (high carbon, high clay, lower BD). The average water retention generally ranges between 7-8 mm of water in the top 10 cm of soil, or about 33-38 mm in the top 30 cm of soil (no significant difference between stages). This reflects considerable capacity to absorb and store water during high-intensity rainfall events when the soils are relatively dry.

Unpublished AUI results show a remarkable difference between 0.1 and 0.33 bar values for assessing FC in some Icelandic soils. It is possible that using 0.1 bar for FC may be better suited than the standard method of 0.33 bar used for measuring PAW for water retention estimates in Andisols, including Icelandic Andisols, yielding considerably higher PAW values. Yet, the question of whether 0.1 bar values are more representative of the water storage and ecosystem behavior for Icelandic Andisols would require specific studies dedicated to this question.

4.3. The effect of dust deposition on soil water retention

Some sites in this study receive continuous dust deposition in large amounts (Table 1), consisting mostly of volcanic glass, deriving from pro-glacial and sandy coastal areas (Arnalds, 2010). This vitric glass is often highly porous and vesicular, with the ability to retain water (McDaniel et al., 2012), yet it consists of silt-size particles (silty texture), hence, not of clays that subsequently form in the soil. The 'dustier' areas are therefore expected to have lower clay and carbon content in the surface soils (via dilution) and very high silt content (Arnalds and Óskarsson, 2007; Sanchez et al., 2025). We found a weak, yet significant, negative relationship between the water properties and dust deposition. However, the water retention can still be considered high in more dust-influenced soils, in spite of relatively lower clay and organic carbon content.

The study areas most affected by dust deposition are also located in the vicinity of volcanic activity and so-called dust hotspots. Soils in these areas can contain numerous tephra (ash) layers from volcanoes such as Katla or Hekla (Arnalds, 2015). Coarse-grained ash layers can play an important role in soil hydrology as they can prevent capillary water transfer to the surface, leading to shallower root systems. The relatively deep woodland root systems, compared to grass or heathland ecosystems, are more likely to extend through the coarse tephra layers in sub-surface horizons, thus having positive effects on water availability for the system within the volcanic areas.

4.4. Terminal infiltration rates

Terminal infiltration rates (TIRs) in this research, with a total average of 380 mm/h ± 337, can be considered very high compared to most other soils, with a general range often reported from 10 to > 30 mm/h (FAO, n.d.). However, other Andisols studies show similar TIR results, e.g., 152 to 362 mm/h in mature Andisols in Spain (Jiménez et al., 2006), 400 mm/h TIRs in the summer in birch woodlands in Iceland (Orradóttir et al., 2008), and 980 to 630 mm/h in Icelandic grasslands (Zaqout et al., 2022).

Some of our results greatly exceeded the range mentioned in these studies, e.g., 1508 mm/h TIR in a non-forested site during spring. This extremely high value could be caused by cracks generated by frost-heave disturbance (cryoturbation). Another plausible explanation is the single-ring methodology, possibly leading to higher TIR values (e.g., Fooladmand and Mazloom, 2017) compared to the more conventional double-ring method. However, this may be debated since some single vs double ring comparison studies did not find differences in TIRs (e.g., Burgy and Luthin, 1956; Verbist et al., 2010; Lewis et al., 2021).

The soils of all stages in 7-NED were classified as Pachic Fulvudand, an Andisols suborder characterized by having a thick humus-rich epipedon (Soil Survey Staff, 2015; ~6% C mean for all stages). We attribute the high TIRs to the high soil carbon content in addition to the andic soil properties, with stable aggregates and abundant pore space in the soil.

4.4.1. TIRs in birch woodland succession

The TIR values in this project did not vary significantly between woodland age stages. However, the old woodlands had the highest values in most seasons (Figure 7), aligning with other studies on woodland succession, which show significant increases in infiltration rates (20-600% higher infiltration) with woodland succession, shifting from grassland/shrubland/cultivated land to woodlands (Gajić et al., 2008; Thompson et al., 2010; Sun et al., 2018).

In the studied infiltration area at the 7-NED area, the age stages had similar soil properties and vegetation understory, which may be the reason for the non-significant difference in infiltration between stages with the same soil classification (Pachic Fulvudand; Table S1), and a 100% vegetation cover. The carbon content and the Al and Fe fraction, $(Al+½Fe)_{ox}$, in the top 30 cm of soils were similar and high in all stages (Table S2), enhancing the infiltration, due to the clays (mainly allophanes) forming silty aggregates (Maeda et al., 1977), in contrast to layer silicates that generally slow infiltration (Weil and Brady, 2017). Lastly, all soils had similar macroporosity, which is known to have a strong positive relationship with water infiltration rates (Cleophas et al., 2022). The macroporosity is known to remain rather stable in mature soils, i.e., it stops increasing with soil development after reaching a certain percentage (around 10%), reducing the difference in macroporosity between mature and younger soils (Nanzyo, 2002).

Our research shows that runoff events and water erosion are unlikely to occur from the surface of Icelandic Andisols with a healthy vegetation cover, judging from the high infiltration rates, in addition to the shelter (i.e., soil cover) provided by the vegetation. The hummocky terrain further slows down possible surface flow. However, if vegetation cover is impaired or lacking and the soils are bare to some degree, Icelandic Andisols can be highly vulnerable to water erosion, due to their silty grain size and low bulk density (Barrio et al., 2018), in addition to the pronounced disturbance caused by soil freezing (the influence of frost is discussed below).

4.4.2. Seasonal impact on TIRs

Seasonal changes can have pronounced impacts on soil infiltration rates (Cerdà, 1997), especially in Iceland, since freezing temperatures can occur during most months (Einarsson, 1984; Ólafsson et al., 2007). In this study, seasonality had an impact on TIRs, showing significant differences between winter and spring (Table 2). The highest TIRs were found consistently during the spring season, typically when soils are quite moist, with limited evaporation from the soil and vegetation, enhanced by snowmelt (Murray and Buttle, 2005), and possibly disturbed by cryoturbation.

The TIRs were higher at higher air temperatures, which is explained by low TIRs in frozen soil. Infiltration rates can be mostly halted under freezing temperatures (Dai et al., 2019). Orradóttir et al. (2008) similarly showed a significant negative correlation between TIRs and soil frost depth. Their TIRs were near zero in barren plots where concrete ice (non-porous) was formed, while sites with robust vegetation cover formed more porous ice with less effect on TIRs in winter. In our project, the TIRs were low during freezing periods, especially at the non-forested sites in winter 2 (Figure 7), yet never reaching total blockage (i.e., zero TIR). This is likely due to the rich vegetation cover (heathland and forest) in all our sites, in contrast to Orradóttir's barren plots, highlighting the importance of vegetation for attenuating soil freezing and allowing for water infiltration in winter. Interestingly, the relationship between C and infiltration in this study was strongest in the winter data, highlighting the importance of carbon (and hence, vegetation) in freezing periods, preventing total infiltration blockage.

5. Conclusions

Birch woodlands are the native forests of Iceland that previously covered much of the drylands at lower elevations. Much of these woodlands were destroyed by long-term land use over the past millennia. In Iceland, as globally, there is a growing drive for conserving and restoring natural ecosystems. Consequently, it is important to understand the old native ecosystems and the changes in soil properties associated with such large-scale restoration efforts. Here, we have focused on hydrological properties associated with the restoration of the native birch woodlands in Iceland.

The Andisols in this study revealed high water retention values both for field capacity and wilting point, higher than reported for most other soil types, yet comparable to both Icelandic and global Andisols. The relatively high variability between geographical areas in Iceland is worth noting, with factors such as carbon, clay content, and vegetation cover (e.g., woodland age) being important in explaining the variability. The old woodlands have favorable water retention properties and were on the higher end of the water retention range of Icelandic Andisols. Non-forested sites, on the other hand, especially those classified as Vitrisols, were on the lower end of the range, signifying a gradient towards improved hydrology associated with the restoration of birch woodlands.

Soil organic carbon, silty textures, and clays proved to play an important role in the water retention capacity of the soils. Dust deposition also affected the soil's water retention capacities, diluting the carbon and clay content and, therefore, decreasing the retention capacities. We infer that birch woodlands are valuable in volcanic areas with coarse-textured tephra layers, since their long roots (compared to heath and grasslands) are likely to extend through the layers, increasing the water acquisition soil volume.

Icelandic Andisols have high infiltration rates compared to other Andisols and other dryland soils, which we attribute to the high carbon and silty nature of the soils. The research showed that infiltration rates are very dependent on seasonal variability, with spring showing the highest and winter the lowest terminal infiltration rates. However, the rich vegetation cover at all stages in the 7-NED research area prevented an infiltration blockage during the winter, i.e., infiltration rates did not drop to zero, as can be experienced in areas of poor vegetation cover. Our study supports the notion that winter infiltration rates are critical to soil hydrology and clearly shows the importance of a vegetation cover in wintertime for successful infiltration.

In conclusion: birch woodlands can be seen as ecosystem engineers, as they colonize degraded sites and make their soil habitable by enhancing the soil water retention and infiltration rates. This emphasizes the importance of protecting birch-woodland ecosystems and increasing their coverage in a country characterized by severely degraded land. The positive influence of these woodlands on the hydrological properties of the woodland ecosystems further highlights the benefits of birch restoration.

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Supporting materials

Table S1. Soil classification of each successional stage in all ten study areas.

Study area	Successional stage	Soil type
1-LEY	Non-forested land	Typic Ustivitrand
	Young woodland	Humic Ustivitrand
	Old woodland	Humic Haplustand
2-OX	Non-forested land	Humic Haplustand
	Young woodland	Humic Haplustand
	Old woodland	Humic Haplustand
3-RAN	Non-forested land	Lithic Ustivitrand
	Young woodland	Typic Ustivitrand
	Old woodland	Typic Ustivitrand
4-STEI	Non-forested land	Lithic Ustivitrand
	Young woodland	Lithic Ustivitrand
	Old woodland	Typic Ustivitrand
5-HRI	Non-forested land	Thaptic Haplustand
	Young woodland	Thaptic Haplustand
	Old woodland	Thaptic Haplustand
6-THO	Non-forested land	Lithic Ustivitrand
	Young woodland	Typic Ustivitrand
	Old woodland	Typic Ustivitrand
7-NED	Non-forested land	Pachic Fulvudand
	Young woodland	Pachic Fulvudand
	Old woodland	Pachic Fulvudand
8-SKO	Non-forested land	Histic Endoaquand
	Young woodland	Pachic Fulvudand
	Old woodland	Histic Endoaquand
9-HUS	Non-forested land	Lithic Ustivitrand
	Young woodland	Typic Ustivitrand
	Old woodland	Typic Ustivitrand
10-MJO	Non-forested land	Lithic Vitric Cryand
	Young woodland	Typic Fulvicryand
	Old woodland	Typic Hydrocryand

Table S2. Mean values for %C: carbon, BD: bulk density, $(Al+1/2Fe)_{ox}$, clay (allophane + ferrihydrite), %FC: water content at field capacity, %WP: water content at the wilting point, and %PAW: plant available water from ten birch woodlands separated by study areas, stages, and depths. Note that means for C, BD, $(Al+1/2Fe)_{ox}$, and clay are n < 6.

Area	Stage	cm Depth	% C	g/cm^3 BD	% $(Al+1/2Fe)_{ox}$	% Clay	% Sand	% FC	% WP	% PAW
1 LEY	N	0 – 10	1.3	0.9	3.9	17.2	27.5	34.9	20.5	14.4
1 LEY	N	10 – 30	0.6	1.0	3.8	16.3	10	45.0	23.9	21.0
1 LEY	Y	0 – 10	2.0	0.7	5.2	24.3	30	30.5	15.6	15.0
1 LEY	Y	10 – 30	1.0	0.8	7.6	36.6	15	38.0	28.7	9.3
1 LEY	O	0 – 10	7.7	0.5	5.0	15.1	5	61.9	44.0	17.9
1 LEY	O	10 – 30	2.5	0.7	6.1	28.7	11	48.9	30.6	18.3
2 OX	N	0 – 10	8.0	0.5	3.6	16.5	5	52.6	42.0	10.6
2 OX	N	10 – 30	2.9	0.7	4.1	19.0	10	35.9	22.4	13.5
2 OX	Y	0 – 10	8.7	0.5	3.2	14.0	10	49.1	42.0	7.2
2 OX	Y	10 – 30	2.3	0.8	4.0	18.5	7.5	40.9	21.6	19.3
2 OX	O	0 – 10	9.2	0.5	2.8	9.7	5	47.9	47.1	0.8
2 OX	O	10 – 30	2.3	0.7	5.1	23.3	7.5	47.9	30.1	17.8
3 RAN	N	0 – 10	1.5	1.0	2.0	8.7	10	20.0	15.3	4.8
3 RAN	N	10 – 30	0.4	1.3	2.2	9.6	30	10.1	6.6	3.5
3 RAN	Y	0 – 10	2.3	0.7	2.7	9.2	10	32.5	22.2	10.3
3 RAN	Y	10 – 30	0.7	1.2	2.6	10.8	17.5	24.8	12.7	12.1
3 RAN	O	0 – 10	3.5	0.6	2.3	10.0	10	29.4	28.2	1.1
3 RAN	O	10 – 30	0.9	1.0	2.5	11.1	7.5	27.5	17.4	10.1
4 STEI	N	0 – 10	2.5	0.8	2.3	9.1	5	29.5	12.7	16.8
4 STEI	N	10 – 30	0.8	1.2	2.3	9.1	10	27.4	18.8	8.7
4 STEI	Y	0 – 10	1.4	1.0	1.9	7.6	20	21.2	16.2	5.0
4 STEI	Y	10 – 30	0.7	1.0	2.4	9.5	5	25.5	6.7	18.8
4 STEI	O	0 – 10	4.2	0.8	2.7	12.7	15	34.0	22.5	11.5
4 STEI	O	10 – 30	1.5	1.0	3.6	16.2	10	35.9	15.5	20.4
5 HRI	N	0 – 10	4.2	0.7	3.6	15.1	12.5	49.6	47.5	2.1
5 HRI	N	10 – 30	0.9	1.0	6.0	28.8	25	37.0	18.4	18.5
5 HRI	Y	0 – 10	5.3	0.6	3.9	16.5	5	59.2	51.0	8.2
5 HRI	Y	10 – 30	1.1	0.9	5.2	24.1	20	31.2	21.1	10.1
5 HRI	O	0 – 10	6.0	0.5	3.4	11.5	5	58.9	45.2	13.7
5 HRI	O	10 – 30	1.7	0.8	3.8	16.7	7.5	44.6	28.8	15.8
6 THO	N	0 – 10	0.7	0.9	4.1	18.6	10	30.7	18.9	11.8
6 THO	N	10 – 30	0.5	1.1	5.0	22.8	10	33.5	17.2	16.3
6 THO	Y	0 – 10	1.7	0.7	2.4	10.6	10	25.9	24.6	1.3
6 THO	Y	10 – 30	1.8	0.7	5.0	22.8	17.5	47.9	32.3	15.6
6 THO	O	0 – 10	3.4	0.6	1.4	5.6	7.5	34.7	24.0	10.7
6 THO	O	10 – 30	2.0	0.7	4.7	21.4	5	39.6	25.7	13.9
7 NED	N	0 – 10	6.8	0.6	5.0	19.7	5	74.0	54.6	19.4
7 NED	N	10 – 30	3.6	0.8	5.9	24.0	5	54.6	36.2	18.4
7 NED	Y	0 – 10	7.8	0.5	4.9	19.0	7.5	74.7	67.0	7.7
7 NED	Y	10 – 30	4.7	0.7	6.5	26.5	6.5	73.4	56.3	17.1
7 NED	O	0 – 10	6.7	0.6	4.9	19.1	5	72.1	55.8	16.3
7 NED	O	10 – 30	4.9	0.8	7.4	29.3	5	76.4	49.8	26.6
8 SKO	N	0 – 10	12.3	0.4	5.6	18.0	4	95.5	73.3	22.2
8 SKO	N	10 – 30	7.9	0.4	7.2	24.8	4	110.6	74.4	36.2
8 SKO	Y	0 – 10	8.6	0.5	4.1	13.0	15	59.2	40.6	18.6
8 SKO	Y	10 – 30	6.3	0.5	6.7	22.8	3	84.8	59.4	25.4
8 SKO	O	0 – 10	13.2	0.3	5.5	17.8	3	115.2	96.5	18.6
8 SKO	O	10 – 30	7.9	0.5	9.6	34.1	4	117.2	78.4	38.8
9 HUS	N	0 – 10	0.5	1.2	2.1	12.3	25	11.7	7.9	3.8
9 HUS	N	10 – 30	1.0	1.3	3.1	16.4	15	23.9	11.8	12.2
9 HUS	Y	0 – 10	1.7	1.1	2.1	11.6	15	23.0	10.1	12.9
9 HUS	Y	10 – 30	0.8	1.4	2.8	14.7	17.5	19.7	13.5	6.2
9 HUS	O	0 – 10	5.8	0.7	2.3	10.4	4	44.2	30.7	13.4

9 HUS	O	10 – 30	2.8	0.9	4.3	19.0	4	48.9	30.5	18.4
10 MJO	N	0 – 10	3.3	0.7	4.7	20.7	37.5	19.4	9.1	10.3
10 MJO	N	10 – 30	1.1	1.0	4.8	17.8	50	25.4	14.5	10.9
10 MJO	Y	0 – 10	16.6	0.3	4.2	12.5	12.5	98.3	37.6	60.7
10 MJO	Y	10 – 30	7.2	0.4	10.1	35.7	20	84.4	63.9	20.5
10 MJO	O	0 – 10	13.3	0.4	5.0	13.3	16.5	151.5	118.0	33.5
10 MJO	O	10 – 30	6.4	0.6	4.4	14.7	10	80.3	61.3	19.0