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How erosion and other natural forces have changed the Icelandic landscape – is Nootka lupine fixing any of these problems?

Luonnon muovaama Islanti: Alaskanlupiinin (*Lupinus nootkatensis*) kiistanalaisuus maisemassa ja ekosysteemissä

Roosa Hautala & Jaana Kulmala

Iceland's location in northern Atlantic leads to extreme weather conditions. These together with islands geological history means its' soil structure to be fragile, frost-susceptible, and vulnerable to erosion. Anthropogenic influence on Iceland has been extensive ever since the first human population from Norway settled in the 9th century. The general aim in Iceland for more than a century has been to halt the ongoing erosion, to preserve the remaining native birchwood forests, to establish commercial forests in various locations across the country and to strengthen the easily erodable soils. As lupin can colonize disturbed soil, increasing the organic matter and nitrogen content of the soil which then creates new growth potential to other plants like birch (*Betula pubescens*), Alaskan lupine (*Lupinus nootkatensis)* was introduced to Iceland in the beginning of the 20th century. At the time, introducing a non-native species was not seen as problem, and Nootka lupine's ability to adapt to the nutrient-poor and dry soils of the island, was desired. Today, lupine is classified as invasive in Iceland. A more comprehensive examination and an open discourse is required on the management of lupine, especially considering the global biodiversity and climate crisis. Northern regions, such as Iceland, may encounter more profound climate and environmental transformations than more southern regions, potentially influencing the behaviour of various invasive species.

Soil formation and its influence on erosion in Iceland

Iceland is an island located in the North Atlantic Ocean. It was formed 70 million years ago when North American-Eurasian landmass started to break up. This movement created a new mid-ocean ridge called "Mid-Atlantic Ridge" the central volcanic plateau of which is still active and can be seen above the sea level in Iceland. Iceland has a volcanic system that erupts frequently, pushing large amounts of lava and tephra (airborne pyroclastic fragments) on the surrounding land and into the atmosphere (Thordarson & Höskuldsson 2008). Sometimes the volcanic eruptions can also happen below the large glaciers which have been covering Iceland throughout its history (Thordarson & Hoskuldsson 2002). For the first time, 2.2 million years ago, Iceland was fully covered in glaciers (Thordarson 2012). Nowadays glacier cover is about 10% of the surface area (Björnsson & Pálsson 2008).

When the eruptions happen under thick layers of ice, they cause great outputs of volcanic ash and heavy floods from the meltwater, flushing soil particles like sand, silt and gravel all the way to the ocean shore. Glaciers also melt during the non-volcanic activity, for example due

to hot-spring areas underneath the glaciers, and these melt waters may get trapped in subglacial lakes (Björnsson 2002). Once enough water has gathered to lift the glacier load up, abrupt outburst event "*jökulhlaup*" will happen. Jökulhlaup can transfer large amounts of water and sediment to the surrounding areas (Thordarson 2012). It has been estimated that during these severe subglacial lake outbursts, up to 10^8 tonnes of sediment could be carried away (Björnsson 2002; Fig. 1).

Glacier and volcanic activity are not the only natural forces affecting Iceland's landscape. Subarctic Iceland is located in the middle of the North Atlantic Ocean where weather conditions combined with ocean activity create fluctuating environmental conditions. Temperature and precipitation vary between different locations and altitudes, for example in the southern part of Iceland, annual rainfall can reach up to 2000 mm, whereas in the north of Vatnajökull glacier it rains annually about 500 mm (Arnalds et al. 2001). The warm North Atlantic current affects the monthly and daily temperatures, creating frequent freeze-thaw cycles that can be seen in the soil structure as cryoturbation (Arnalds 2015). Oceanic islands tend to also experience strong winds, and Iceland is no exception. Strong winds cause wind erosion and transport volcanic ash and eroded soil particles around the island. Because Iceland experiences these extreme weather conditions, together with islands geological history, its' soil structure has been described as fragile, frost-susceptible, and vulnerable to erosion. One of the reasons is a lack of cohesion in soil particles, typical for Andosols (Arnalds 2015). Icelandic soils are primarily classified into Andosols, Vitrisols and Histosols (Arnalds 2015). However, the classification of soils includes a wide range of subcategories. Andosols are the dominant soils in the vegetated areas of Iceland where volcanic activity is present. These soils have high organic content, high water-holding capacity but they lack cohesion, making them easy to erode (Arnalds 2015; Fig. 2.). Vitrisols are the dominant soils of non-vegetated areas in Iceland, located in dry, volcanic regions where eolian input of tephra is very high and organic matter content is low. Vitrisols are also very likely to erode and experience various frost actions like cryoturbation (Arnalds 2015). Histosols are dominated by organic matter and are found in wetland areas away from active volcanoes where eolian input of tephra is low (Arnalds 2015).

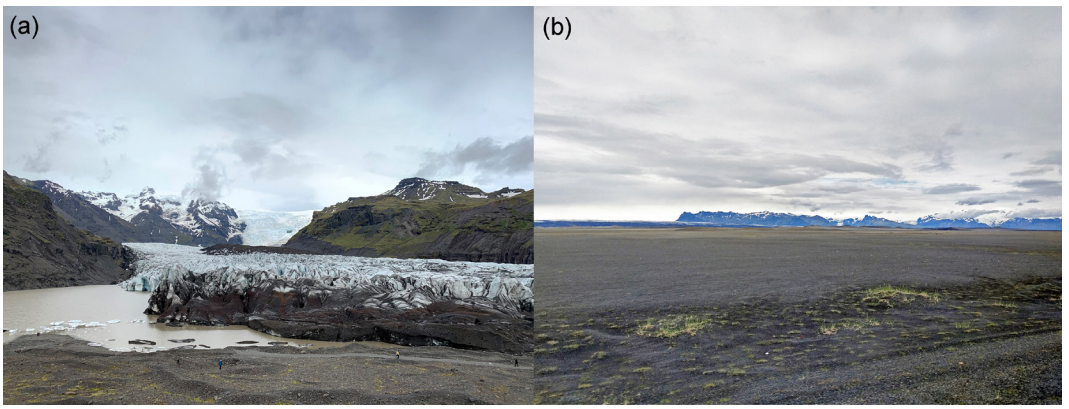

Fig. 1. During severe glacier river (a) outbursts, "*jökulhlaups*", large amounts of suspended sediments are washed away. These floods can create large-scale river deltas, *sandurs*, mainly containing fine material (Björnsson 2002). Probably one of the world's largest sandurs "Skeiðarársandur" (b) can be found in Iceland (Vatnajokulsthjodgardur 2022). Photos: Roosa Hautala (a), Jaana Kulmala (b).

Kuva 1. Jäätiköiden alla olevien vesivarastojen purkautuessa ympäristöön leviää tulvaveden mukana suuret määrät kivennäismaata. Näitä valtavia veden purkauksia kutsutaan nimellä "jökulhlaup". Tulvavedet voivat muodostaa kuivan maan deltoja eli sanduureja. Luultavasti yksi maailman suurimmista sanduureista – "Skeiðarársandur" – on Islannissa.

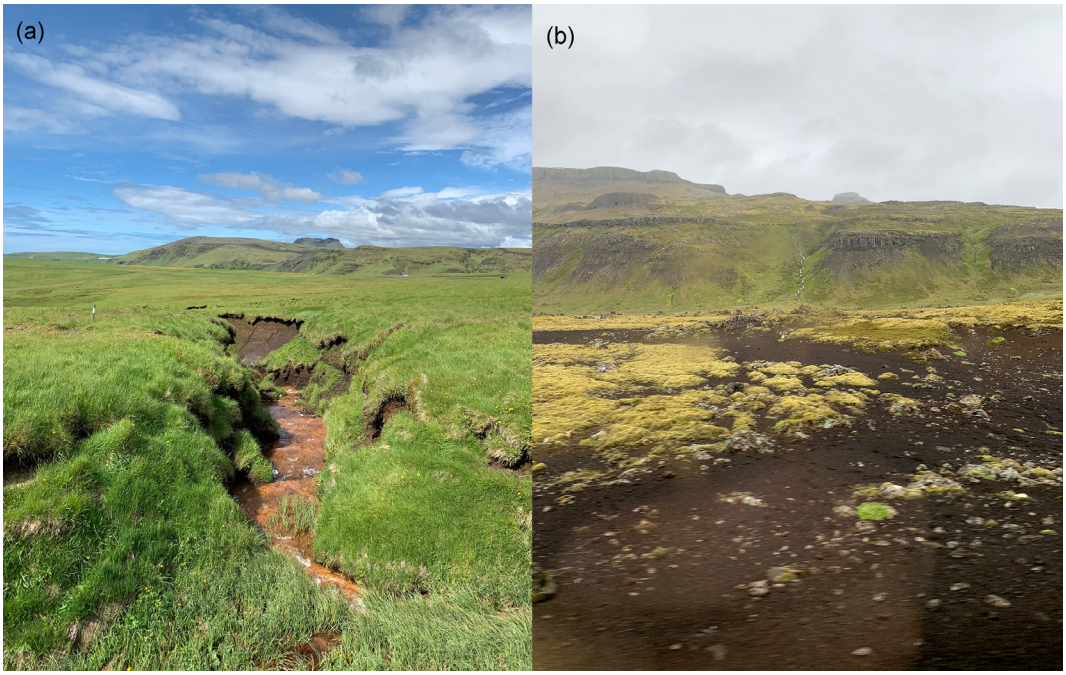

Fig. 2. Andosols are a mixture of different volcanic soil properties: high soil water retention and organic matter content but lack of cohesion between the soil particles, which makes them vulnerable to erosion (Arnalds 2015). When vegetation changes from birch woodland type towards grassland vegetation (e.g., due to grazing), decreased infiltration rate makes the soil even more vulnerable to different natural forces like frost, wind, and rain, which promotes, for example, gully erosion (e.g., Branson et al. 1981; Thurow 1991). Photos: Roosa Hautala 2022.

Kuva 2. Andosol-maannokset ovat sekoitus erilaisista tuliperäisen maaperän ominaisuuksista: vedenpidätyskyky ja orgaanisen aineksen määrä. Maaperän partikkelien välillä on pieni koheesio, minkä vuoksi nämä maannokset erodoituvat helposti. Kasvillisuuden muuttuessa koivuvaltaisista metsiköistä ruohovaltaisiksi esim. laidunnuksen seurauksena, pienentynyt veden läpäisynopeus altistaa maaperän vielä enemmän erilaisille luonnonvoimille, kuten pakkaset, tuulet ja sateet. Tämä edistää mm. rotkoeroosiota.

Human impact on soil qualities and natural vegetation

Anthropogenic influence on Iceland has been extensive ever since the first human population from Norway settled in the 9th century, especially in the uplands (Dugmore et al. 2009). It has been estimated that before the Norse settlement began, around 54% to 65% of the total land area (103 000 km^2) was covered in vegetation (Thorsteinsson 1986; Ólafsdóttir et al. 2001; Dugmore et al. 2009). The introduction of settlers, their livestock and agricultural practices resulted in overgrazing, cutting trees, digging ditches and overall changes in the vegetation (Amorosi et al. 1997; Vésteinsson 1998). Deforestation continued for centuries, and by the mid-20th century, Iceland had retained only 25% of its initial vegetation cover and only 5% of the original forest cover (Benediktsson 2015; Eysteinsson 2017). The combination of Iceland's volcanic soils, the cool climate during the Little Ice Age and loss of natural vegetation, created an unfortunate scenario for widespread soil erosion (Benediktsson 2015; Figs. 3, 4).

In the beginning of the 20th century, awareness of the issues concerning Iceland's soil and vegetation problems began to spread, which led to the establishment of two governmental agencies: The Icelandic Forest Service (IFS) and Soil Conservation Service of Iceland (SCSI) (Crofts 2011; Benediktsson 2015). Their main aim was

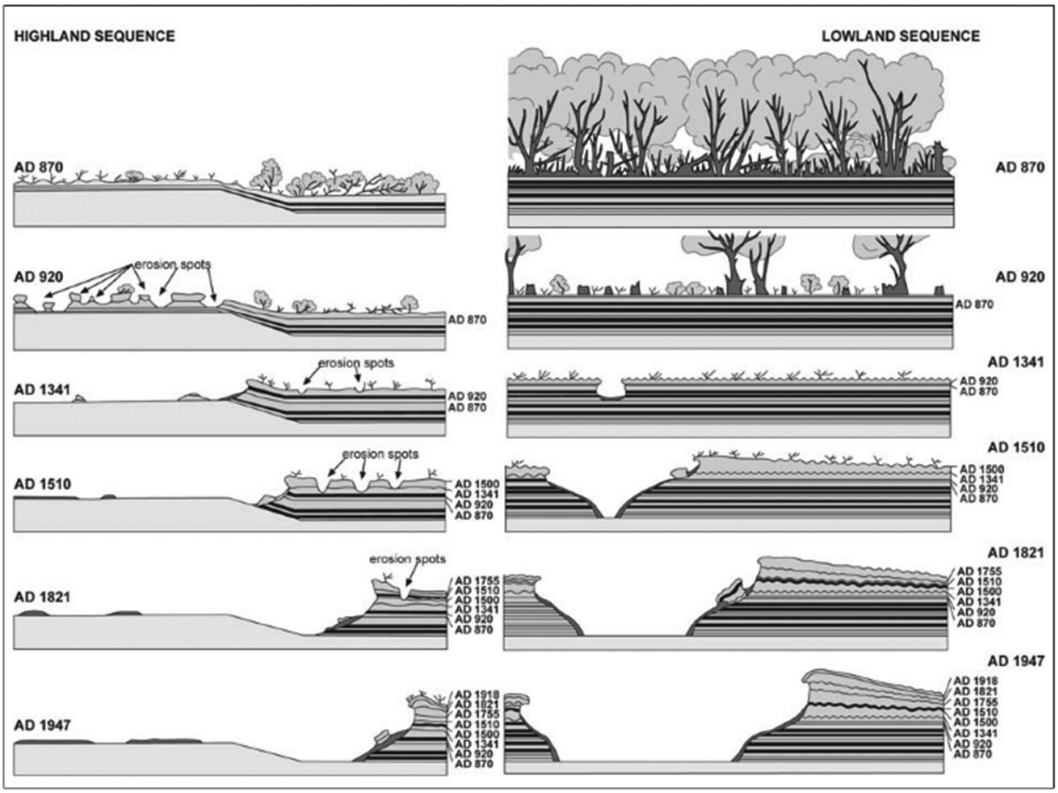

Fig. 3. Dugmore *et al*. (2009) reconstructed 1200 years (A.D. 870–1947) of Icelandic soil erosion using tephrachronology. The model shows how landscape has changed ever since human settlement started in the early 9th century. Image: Dugmore et al. 2009, available under CCBY 4.0 license.

Kuva 3. Dugmoren ym. (2009) tefrakronogian avulla hahmottelema 1200 vuoden pituinen Islannin maaperän eroosio (A.D. 870–1947). Kuvasta nähdään, miten maisema on muuttunut asuttamisen jälkeen 800-luvun alusta.

Fig. 4. Large herbivores like horses have been grazing the Icelandic landscape since human settlement. In Neðri-Dalur, Agricultural University of Iceland has been studying the effects of horse grazing on birch woodlands. Photo: Roosa Hautala.

Kuva 4. Suuret laiduntajaeläimet, kuten hevoset, ovat laiduntaneet Islannin maaperällä heti asuttamisen jälkeen. Neðri-Dalurin alueella Islannin maatalousyliopisto on tutkinut hevoslaidunnuksen vaikutuksia koivumetsiin.

and still is, to halt the ongoing erosion. Other aims are to strengthen the easily erodable soils for example by re-establishing vegetation, to preserve the remaining native birchwood forests of Iceland and to establish commercial forests in various locations across the country (Icelandic Forestry Service 2023; Benediktsson 2015).

After these two agencies were established, novel tree and other vascular plant species were introduced and experimented in Iceland, but only in the sense of ornamental gardening (Magnusson et al. 2003). One of the introduced species was the Alaskan lupine (*Lupinus nootkatensis*) (Schierbeck 1886). In 1940s Hákon Bjarnason, the director of IFS, took a trip to Alaska (Helgason 1911; Bjarnason 1952; Benediktsson 2015). He was convinced that the Nootka lupine would be the answer to Iceland's problems and started promoting this highly resistant pioneer and nitrogen fixing species to other foresters and the public, as a tool to revegetate the island (Stepkowski et al. 2007; Benediktsson 2015). At the time, introducing a non-native species was not seen as problem, and Nootka lupine's ability to adapt to these nutrient-poor and dry soils, was desired (Stepkoski et al. 2007; Kristinsson 2010).

Fig. 5. Nootka lupine (*Lupinus nootkatensis*) spreading on a mountain site in southern Iceland. It can be found all around the island even at the most barren areas. Photo: Jaana Kulmala 2022.

Kuva 5. Alaskanlupiini (Lupinus nootkatensis) leviämässä vuoristoon eteläisessä Islannissa. Laji on levinnyt koko Islannin alueelle kaikkein karuimpia kolkkia myöden.

Special characteristics of the Nootka lupine

Nootka lupine (*Lupinus nootkatensis*, Fig. 5) is a perennial pea plant that is related to Garden lupin (*Lupinus polyphyllus*) and is native to western North America, from Alaska to British Columbia. It was introduced to Europe in the late 18th century and is now common in Iceland as well as southern and central Norway and Greenland but can also be found as a garden ornamental in the Faroe Islands (Magnusson 2010).

Nootka lupine usually grows in tall bushes to a height of about 0.2 to 0.9 meters (Kristinsson 2010) and it has a special appearance which makes it difficult to mix it with other common plants in Iceland. Like many other lupine species, *Lupinus nootkatensis* is also able to self-fertilize, therefore it does not depend on pollinators to reproduce its' seeds (Kristinsson 2010). One individual plant has the capacity to produce more than 2000 seeds in a single season, and these seeds can disperse to novel areas through various means, including water, landslides, storms, and over longer distances by birds (Baldursson 1995; Magnusson 2010).

In Iceland, lupines were initially introduced to enhance soil nitrogen levels and prepare the soil for the growth of other plant species (Fig. 6). As member of the pea family (*Fabaceae*), it can fix atmospheric nitrogen into organic form through symbiotic bacteria living in their roots. Thanks to this ability, lupines have been cultivated as an important leguminous plant since ancient times (Lambers et al. 2013). Although lupines do not form mycorrhizae (Lambers et al. 2013), certain lupine species can exhibit a response to phosphorus deficiency by developing a type of root known

Fig 6. Lupin can colonize disturbed soil, increasing the organic matter and nitrogen content of the soil which then creates new growth potential to other plants like birch (*Betula pubescens*) (Lambers et al. 2013; Halldorsson 2021). Photo: Roosa Hautala 2022.

Kuva 6. Lupiini voi vallata häiriintyneitä alueita ja lisätä niiden maaperän orgaanisen aineksen ja typen määrää. Tämä parantaa maaperää ja muiden kasvien, kuten hieskoivun, leviämismahdollisuuksia alueille (Lambers ym. 2013; Halldorsson 2021).

as cluster roots. Cluster roots are predominantly found in the protea family (*Proteaceae*), but a few other plant species also possess this specialized root adaptation (Watt & Evans 1999).

The debate surrounding Nootka lupine

The ability to self-fertilize, thrive in poor conditions, disperse large amounts of resilient seeds, and suppress other native plants are the features of an invasive species. However, neither the public nor the authorities noticed anything negative about it (Magnusson 2010; Benediktsson 2015). In contrast, these were precisely the features that formed people's interest in this species and its potential for reforestation and revegetation projects in Iceland during the 1970s to 1980s (Stępkowski et al. 2007; Benediktsson 2015). This created a massive expansion of Nootka lupin in Iceland. After a few years the invasive charateristics of Nootka lupin began to worry conservationists and ecologists (Benediktsson 2015), and the nation started to divide in two parties: pro- and anti-lupine.

The fact that lupine was able to spread across Iceland in 40 years, almost without any resistance (Benediktsson 2015), allowed it to establish a strong foothold in Iceland's nature. During the 1990s, research started focusing on how exactly Nootka lupine behaved on already vegetated ground, and it was discovered that it was also able to suppress and even replace native species (Magnusson et al. 2003; Svavarsdóttir et al. 2004). In Iceland, the native undergrowth is very low, therefore, fast growing lupine easily dominates native species like low growing mosses, lichens, and shrubs (Butler 2006), which is detrimental to Iceland's revegetation intentions. Even though winter and spring grazing has been largely stopped since the 1970s, the native vegetation has not naturally reclaimed the eroded areas; instead, the lupine has managed to establish itself (Arnalds and Barkarson 2003; Aradóttir et al. 2013). Research suggests that this is due to lupines abilities to fix nitrogen and rapidly form large dense canopies at sites, where no native species can manage (Butler 2006; Arnalds 2015). Other reason could be that lupines have naturally high alkaloid content (Magnússon and Sigurðsson 1995; Thórsson and Hlíðberg 1997) and sheep tend to avoid Nootka lupine if other fodder is available (Reichert 2020), which puts even more grazing pressure on native species.

However, sometimes a stable coexistence of Nootka lupine and native species have been detected as well. A study made by Riege & Sigurgeirsson (2009) states that planting native downy birch (*Betula pubescens*) and Hooker willow (*Salix hookeriana*) with Nootka lupine increased seedlings growth potential of both species. Another finding from IFS (Halldorsson 2021) states similar findings from North-Iceland, Graystone Heath, where young downy birch was planted together with Nootka lupine. Years later, a typical birch woodland ecosystem with rich biodiversity was formed.

As we can see, research results around this topic are varying and the decades long battle between the pro- and anti-lupine sides continues.

The cultivation of lupine in Iceland has decreased from that of earlier decades, and in nature reserves, sowing of lupine is not allowed anymore. Today, lupine is classified as invasive in Iceland (Benediktsson 2015). A more comprehensive examination and an open discourse is required on the management of lupine, especially considering the global biodiversity and climate crisis. Northern regions, such as Iceland, may encounter more profound climate and environmental transformations than more southern regions, potentially influencing the behaviour of various invasive species. Failing to investigate these consequences could worsen the challenges in conserving Iceland's fragile ecosystems.

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Tiivistelmä

Islannin maaperä ja maisema ovat jatkuvassa myllerryksessä luonnonvoimien, erityisesti tulivuorten ja sään, vaikutuksesta. Maaperä on hyvin altis eroosiolle, ja ihmisen pitkäaikainen toiminta, erityisesti laidunnus ja metsien käyttö ovat lisänneet eroosiota ja siitä johtuvia ongelmia. Tämä näkyy muun muassa alkuperäisten metsäalueiden ja kasvipeitteisyyden katoamisena.

Alaskanlupiini (*Lupinus nootkatensis*) on osa Islannin maiseman tarinaa. Alun perin kasvi tuotiin saarella 1900-luvun alussa maaperän parantamiseksi, ja se sopeutui nopeasti Islannin olosuhteisiin. Lupiinin alkuperäinen tarkoitus oli sitoa typpeä maaperään ja näin edesauttaa muiden lajien leviämistä, mutta lupiinin kilpailukyky ja invasiiviset piirteet näitä kotoperäisiä lajeja kohtaan alkoivatkin ottaa ylivallan. Tämä johti viranomaisia, asukkaita ja ympäristönsuojelijoita jakavaan keskusteluun.

Lupiinin leviämistä ja sen vaikutuksia paikalliseen kasvillisuuteen on tutkittu Islannissa jo useita vuosikymmeniä, mutta laji on edelleen kiistanalainen. Joillain alueilla lupiini näyttää voivan edistää muiden kasvien, kuten hieskoivun, kasvua, toisilla alueilla se taas aiheuttaa merkittäviä haittoja syrjäyttäen alkuperäisiä lajeja.

Tämä herättää siis edelleen kysymyksiä: kuinka lupiinia tulisi Islannissa käyttää ja minkälaiset sen mahdolliset pitkäaikaisvaikutukset ovat saaren herkille ekosysteemeille? Nykyään lupiini luokitellaan Islannissa haitalliseksi vieraslajiksi, ja sen leviämistä pyritään hillitsemään, mutta muuttuvassa ilmastossa kaikkia lajiin liittyviä käänteitä ei pystytä ennustamaan, eikä sen ekologista asemaa määrittämään.