Reviewed research article

Soils of Iceland

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Abstract — *Icelandic soils are dominated by Andosols when covered by vegetation, Vitrisols in desert areas (Icelandic classification scheme), and highly organic Histosols in some wetland areas. Andosols are not common in Europe but are found in active volcanic areas of the world. They develop distinctive properties such as high organic content, extremely high water holding capacity and lack of cohesion. Icelandic soils are in many ways special on a global scale due to the environmental conditions for soil development, which include: i) basaltic tephra parent material; ii) steady eolian sedimentation of volcanic materials to the soil surface; and iii) many freeze-thaw cycles acting on frost susceptible soils, causing intense cryoturbation. Iceland has extensive barren desert areas in a cold-humid climate that comprise the largest sandy tephra areas on Earth. Many of the wetland soils have a distinctive combination of andic (volcanic soil properties) and histic (organic) properties. Soil erosion and desertification is more active in Iceland than in any other Northern European country. Erosion has severely degraded many ecosystems with formation of barren surfaces devoid of vegetation in several areas.*

INTRODUCTION

Icelandic soils differ from most other soils of Europe and the world because of a unique soil environment. Icelandic soils form in parent materials that are of recent volcanic origin, usually consisting of basaltic tephra. Soils that form in volcanic materials develop distinctive characteristics that separate them from other types of soils as *Andosols* (FAO, 1998; IUSS Working Group WRB, 2006). Most Icelandic soils are Andosols, making them the largest area in Europe dominated by such soils (Arnalds, 2007). Active eolian processes, frequent tephra deposition events, and a sub-arctic climate with frequent freeze-thaw cycles greatly modify the soils. One of the unique characteristics of Icelandic soil environments is the presence of extensive deserts, in spite of a moist climate in much of the country. Man and nature have inflicted great environmental change since Iceland was first settled about 1200 years ago, which has partly resulted in the development of deserts. Desertification processes still continue to be very active in some areas of the country, but many deserts can be considered, at least in part, as natural deserts at high altitudes and as a result of volcanism.

The purpose of this paper is to give an overview of Icelandic soils and their development, and to describe erosion and desertification processes that characterize the country and modify the soils.

THE ICELANDIC SOIL ENVIRONMENT

Iceland is situated far north on the mid-Atlantic Ridge (63°23'–66°32'N; 13°30'–24°32'W), resulting in climates that range from cold-temperate to arctic in the highlands. The interior highlands rise above 400 m elevation to >1000 m. Precipitation generally varies between 600 mm and 1500 mm yr^{-1} in lowland areas, but large tracts of northeast Iceland receive less than 600 mm yr^{-1}. Much of the precipitation falls as snow in winter in the northern part of the country and particularly in the highlands, but winter thaw events are common, especially in the southern part. The northerly oceanic climate is characterized by nu-

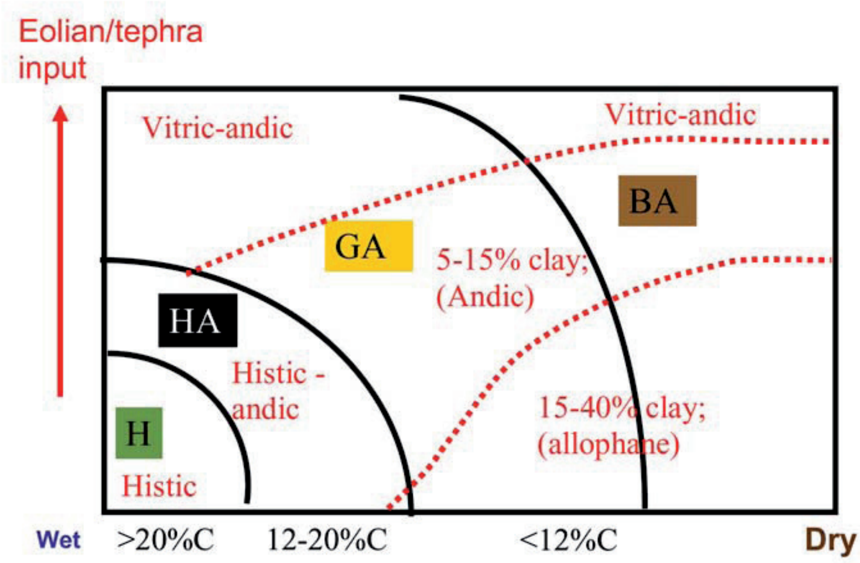

Figure 1. Separation of Icelandic Andosols and Histosols, based on drainage (X-axis) and eolian input (Y-axis). Organic soils (histic) are found in wetlands where there is little eolian input of tephra materials, but freely drained soils are Brown Andosols (BA). Gleyic Andosols occur in wetlands where there is substantial eolian input, lowering the organic content, or where there is some drainage. Highest clay contents are found in drylands with little eolian input, but vitric (tephra) properties become more dominating up the Y-axis (more eolian input). Adapted from Arnalds (2004) and Arnalds *et al.* (2005). – *Flokkun íslensks jarðvegs á grónu landi. Y-ásinn sýnir magn áfoks, en á x-ásinum er landið blautt vinstra megin. H: mójörð; HA: svartjörð, GA: votjörð, BA: brúnjörð. Þar sem áfok er minnst er moldin rík af allófani, þar sem áfok er mest er jarðvegurinn glerkenndur (vitric). Fjarri áfoki við votar aðstæður verða lífræn efni ráðandi, þar er lítið af leir en málm-húmus knippi eru ráðandi í svartjörðinni (HA) sem gefur henni einkenni eldfjallajarðar (sortueiginleikar).*

merous freeze-thaw cycles that greatly influence the surface geomorphology and soil properties.

Satellite images (LMI, 1993) show that land with relatively continuous vegetation covers about 28,500 km^2, but an additional 23,900 km^2 has less continuous or non-productive plant cover (total of 52,400 km^2). More than 37,000 km^2 are barren deserts, some of which have formed after settlement (874 AD). The vegetation composition of rangelands reflects sheep grazing, with species tolerant to grazing dominating most communities, such as small woody species and sedges (see e.g., Aradóttir and Arnalds, 2001). Birch woodlands used to cover a large proportion of the country (25–40%, see Aradóttir and Eysteinsson, 2005) but now only comprise about 1% due to land degradation processes (Aradóttir and Arnalds, 2001; Aradóttir and Eysteinsson, 2005).

Active eolian processes lead to a steady flux of eolian materials that are deposited to the surface of existing soils at a rate of <0.001 to >1 mm yr^{-1} (Thorarinsson, 1961; Arnalds, 2000), continuously modifying the soil environment by recharging the system with fresh parent material. This eolian activity has a dominating influence on soil formation in Iceland. The source of the eolian materials is mostly sandy desert areas located on the active volcanic zone, and glaciofluvial floodplains.

The permeability of the bedrock and the landscape position influence the drainage category of the soils, with wetlands commonly occurring within the less permeable Tertiary basalt areas, while well drained soils characterize the more permeable active volcanic regions of the country. Level plains with vegetation cover, such as the southern lowlands, tend to be dominated by wetlands regardless of parent materials and surface geology (ample precipitation, nearly level landscape gradient).

All of Icelandic soils are of Holocene age. Because of the flux of eolian materials, the surface is young, the eolian sediments burying older sequences of soils. In addition, many surfaces have been disturbed by erosion and cryoturbation processes, modifying the surface and the soil environment.

MAIN SOIL TYPES AND MORHPOLOGY

Icelandic soils have been divided into several categories (see Arnalds, 2004) according to a system that draws mostly from the FAO-WRB system (FAO, 1998; IUSS Working Group WRB, 2006). Two main groups are distinguished: soils under vegetation and the soils of deserts. Soils under vegetation are andic (Andosol properties) and/or histic (organic) in nature. The soils of the deserts are dominated by poorly weathered volcanic tephra and are termed Vitrisols (*Latin 'vitr': glass*). Other groups exist, such as permanently frozen Cryosols in the highlands, calcareous soils near the shore line in some areas, and both Regosols and Leptosols, but they have limited extent compared to the Andosols, Histosols and Vitrisols, and the nature of these soil types has not been investigated in detail.

The dominant influence of eolian and tephra input on one hand, and drainage on the other, are used for separating soils under vegetation (Figure 1). The progression of soil types with improving drainage condition (wet to dry) follows: Histosols (>20% C), Histic Andosols (12–20% C), Gleyic Andosols (< 12% C, poorly drained), and Brown Andosols (<12% C, freely drained). The trend towards wetter soil conditions and decreased eolian input (towards left and bottom) can be considered as the increasing distance from the active volcanic zones and sources of eolian materials, reducing eolian accretion to the surface of the soils. That results in increased organic content with Histosols (>20% C) in the lower left corner. If it was not for the volcanic (andic) influences, Icelandic wetland soils would largely be organic Histosols typical of the arctic environments.

The Vitrisols are the soils of the deserts. They have dark grayish colors and contain limited amount of organic carbon (<1%). They are infertile in contrast to the Andosols and are subjected to intense surface processes such as cryoturbation and erosion. Many of the Icelandic Vitrisols classify as Andosols according to the WRB and the US Soil Taxonomy (Andisols), although they are given a specific term for Icelandic conditions, i.e. Vitrisols (Arnalds, 2004). These soils are rather unique on global scale, as extensive black desert areas dominated by basaltic tephra are uncommon in the world (see Arnalds and Kimble, 2001; Arnalds *et al*., 2001a).

Icelandic Andosols often contain tephra layers, especially in the proximity of the most active volcanoes, such as Mt. Hekla and Katla. Rhyolitic tephra layers are fewer in number than basaltic, but tend to be very distinctive with light color in contrast to the darkish brown colors of the Andosols (Figure 2). The rhyolitic tephra weathers much more slowly than the basaltic tephra and seems to have little influence on soil acidity. Near the active volcanic area and within erosion areas, distinctive sedimentary features are quite noticeable, while such characteristics are less evident with increased distance from eolian source areas.

The Agricultural University of Iceland (Arnalds and Grétarsson, 2001) has compiled a soil map in the scale of 1:250,000. The aerial extent of major soil types is presented in Table 1.

It reveals that Brown Andosols (BA: 17,640 km^2 plus part of the 28,280 km^2 BA/GA complex) are the most common soils, together with the Cambic Vitrisols (17,640 km^2 plus part of MV/SV complex). Gleyic Andosols, the wetland soils of the active volcanic belt, are also common, covering 2390 km^2 and also occurring with Brown Andosols (BA/GA complex, 28,280 km^2). Vitrisols (Cambic and Arenic Vit-

Table 1. Soil types, their main diagnostic criteria, and classification according to Soil Taxonomy (S. T.) and the WRB. Areal extent for each class, according to a coarse grained (1:250,000) map is given, but the classes often occur in complexes on the map units (bottom of the Table). – *Jarðvegsflokkar, helstu greiningareinkenni þeirra og samsvarandi flokkar í Soil Taxonomy (S. T.) og WRB. Tákn jarðvegsflokka miðast við ensk heiti flokka. Svartjörð (HA), votjörð (GA) og brúnjörð (BA) teljast til eldfjallajarðar (Andosol), en melajörð (MV) og sandjörð (SV) teljast til glerjarðar (Vitrisol), sem endurspeglast í táknum jarðvegsflokkanna.*

Soil Type	Symbol	Diagn.pr.[1]	Extend	%	S.T.[2]	WRB.[3]
Histosol	H	>20% C	1077	1	Histosol	Histosol
Histic Andosol	HA	12–20% C	4700	5	Aquand	Gleyic/Histic Andosol
Gleyic Andosol	GA	<12% C; gley and/or mottles	2600	3	Aquand	Gleyic Andosol
Brown Andosol	BA	<12% C, dry; > 6% allophane	14,300	14	Cryand	Haplic/Mollic Andosol
Cambic Vitrisol	MV	<1,5% C < 6% allophane	17,600	17	Cryand	Vitric Andosol/ Regosol/Leptosol
Arenic Andosol	SV	Sand	4600	4	Cryand	Vitric Andosol/ Arenosol/Leptosol
Leptosol	L	Rock/Scree	7300	7	Entisol	Leptosol
Cryosol	C	Permafrost	?		Gelisol	Cryosol
Brown and Gleyic Andosol	BA-GA		27,200	26		
Complex	*SV-L*		4800	5		
Complex	*MV-SV*		6000	6		
Complex	*C-GA*		140	0		

1: Simplified diagnostic properties. 2: US Soil Taxonomy equivalent. 3: FAO – WRB equivalent.

risols and Leptosols) of desert areas total > 40,000 km^2. The coarse scale of the map should be noted, and more detailed data (unpublished data) suggest that extent of wetland soils are overestimated by the numbers above.

Figure 2. Icelandic Andosol from Northeast Iceland. Scale is in cm. Cryoturbated (moved by frost action) rhyolitic tephra layers, light in color to the left on picture. Dark colored layers to the right are basaltic tephra layers. The soil toward the bottom is >4000 yrs old, while the top 20–40 cm have developed in tephra and eolian deposits younger than 600 yrs. – *Brúnjörð á Norðausturlandi. Ljósu gjóskulögin frá Heklu sýna vel frosthreyfingu moldarinnar, en einnig eru dökk basísk gjóskulög ofarlega hægra megin í sniðinu.*

SOIL DEVELOPMENT

Weathering

Basaltic tephra weathers rapidly compared to most other soil parent materials (Gíslason, 2005; Taboada *et al.*, 2007). Weathering rates in Iceland are therefore considerable, in spite of the dry/cold climate (e.g., Gíslason, 2005). Much of the dissolved weathering products are removed from the soil systems, while some, such as Al, Fe and Si, re-precipitate as poorly ordered clay minerals characteristic of the world Andosols: allophane, imogolite and ferrihydrate. However, halloysite, a common clay mineral in Andosols, is uncommon in Icelandic soils (Wada *et al.*, 1992). Clay minerals in Andosols are formed in situ, not by translocation or leaching and precipitation in a subsurface argillic (Bt) horizon. Both allophane and ferrihydrate are common in the Icelandic soils (imogolite is a minor constituent), with clay contents usually ranging between 10 and 35% (Arnalds, 2004). As these clays are not phyllosilicates, they lack the cohesion properties characteristics of common soil clays such as smectite and kaolinite, and their presence is therefore elusive with common methods of identification, both in the field and in the laboratory, such as by hand texturing, grain size determination and XRD. However, allophane and ferrihydrate have a large surface area comparable to smectite. The profile horizon sequence is usually a A-Bw-C, but the use of "b" and "2" for buried and new phases in development is quite cumbersome and complicated in soil descriptions. Light colored tephra layers (i.e. rhyolite) near the surface have sometimes been mistaken as E horizons (eluvial) common in Podzols, but Podzols have not been identified in Iceland, although they are frequently found in the boreal forests of neighboring countries.

Another important characteristic of Andosols in general is their tendency to accumulate organic matter (see Dahlgren *et al.*, 2004; Arnalds, 2008). There are two main pathways of organic accumulation in Andosols of the world: the formation of allophane-organic matter complexes and metal-humus complexes (mostly Al-organic substances). In addition, the cold climate in Iceland favors organic buildup, especially in water saturated wetland situations. The steady flux of eolian materials and tephra additions leads to burial of the organic rich surfaces, increasing the total content of organic material in the soils. Icelandic soils therefore tend to have appreciable amounts of organic matter, and the wetland soils exhibit a unique combination of histic (organic) and andic soil characteristics that is uncommon elsewhere. However, the eolian influence reduces the proportion of organic matter that would otherwise accumulate within a given depth interval or horizon, especially on and near the active volcanic zone, while the burial can lead to high total amount of carbon per unit area (e.g., kgC m^{-2} or tC ha^{-1}) (Óskarsson *et al.*, 2004).

The eolian input affects the soil pH, which tends to correlate with the eolian flux as the weathering of the basalt releases ions that rejuvenate (i.e. increase) the soil pH. Lowest pH soils (<4) are found at the greatest distance from the active volcanic zone such as in West Iceland and at the Westfjord Peninsula (Vestfirðir) (e.g., Arnalds *et al*., 2005). The eolian and drainage trends, which were used to explain the division of Icelandic soils above, have therefore a dominating effect on clay content, organic content and the pH of the soils, as shown in Figure 3.

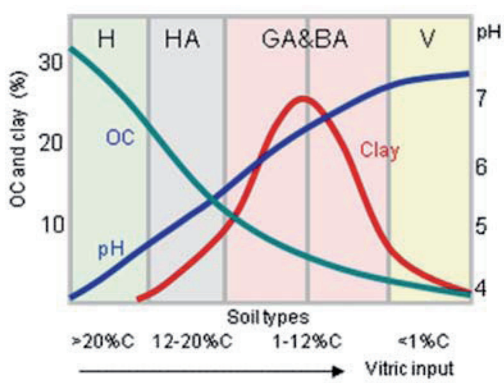

Figure 3. Relationship between soil types (X-axis) and pH, carbon and clay content. Vitrisol (V) far on the right, but the organic Histisol (H) is on the left. HA represents Histic Andosol, GA Gleyic Andosol and BA Brown Andosol. Soil pH becomes lower as the organic content rises. Low pH impedes allophane formation in the Histic Andosol (HA) and Histisol (H). The organic C content is used to differentiate between soil classes. Adapted from Arnalds *et al.* (2005). – *Tengsl jarðvegsflokka (X-ás) við sýrustig, kolefnismagn og leir. Glerjörð (V) er sýnd lengst til hægri en mójörð (H) lengst til vinstri. HA merkir svartjörð, GA votjörð og BA brúnjörð. Leirmagn (rauð lína) er mest í votjörð og brúnjörð, en lágt sýrustig kemur í veg fyrir myndun allófans í svartjörð, en eins og sjá má fellur pH (blá lína) niður til vinstri á grafinu. Magn lífrænna efna (græn lína) er notað til að skilgreina skil á milli flokkanna.*

Vitrisols lack the vegetation cover that is necessary for the formation of typical Andosols. Soil formation is much slower, and while both allophane and ferrihydrate are found in young Vitrisols, organic content is low. The pH remains above neutral (often 7.5) as the system is charged with ions released by weathering without the influence of organic acids that would lower the pH. However, the pH drops very rapidly when vegetation cover is restored by restoration efforts, more than 0.5 units within 10 years (unpublished data).

The Holocene history

An example of the Holocene history of Andosols following deglaciation in Iceland is illustrated in Figure 4. It shows how the soils gradually become thicker with increasing time as the surface rises due to eolian and tephra additions. Older soils are constantly being buried under younger materials, with weathering being most active at the surface. The pedon has clear light colored tephra layers (from Mt. Hekla rhyolite) and some darker basaltic layers. The major tephra layers in Icelandic soils are often easily identifiable, which allows for dating of the different sections of the soils.

The wetlands preserve pollen that can be used to deduce the vegetation history of Iceland (see Einarsson, 1999). This story was recently reviewed by Hallsdóttir and Caseldine (2005). Such analysis shows two periods dominated by birch (mountain birch, *Betula pubescens*), from about 8500 to 6000 yr BP and again, at least in some areas from 4000 to 2500 BP, but wetland vegetation dominates between these periods and at present. It is interesting to note that many of the current wetlands were covered with birch forests during the birch periods, and sizeable stems (>10 cm in diameter) are found deep in the soil profiles. These fluctuations follow global and regional trends (Hallsdóttir and Caseldine, 2005), but resulting variation in seasonal soil frost is likely to be an important contributing factor to drainage conditions. The pollen history reveals that the most pronounced change in vegetation composition occurred at the time of settlement, with birch and flowery plants being replaced by more grazing tolerant species such as grasses and dwarf heath (Hallsdóttir and Caseldine, 2005).

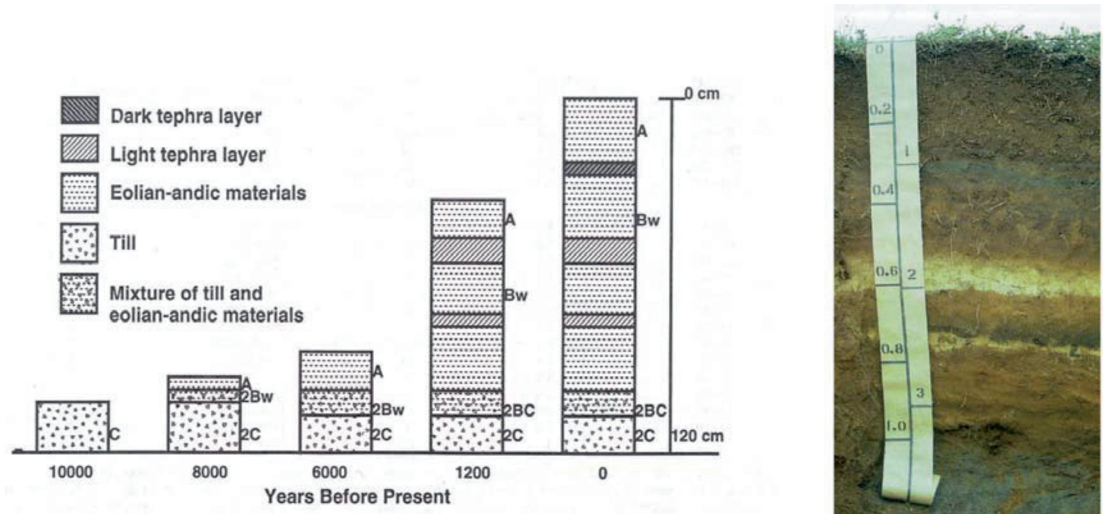

Figure 4. Development of typical Andosol in Iceland that has formed in tephra and eolian materials. Adapted from Arnalds *et al*. (1995) and Kimble *et al*. (2000). The soil is from near Goðafoss in North Iceland. Glacial till (about 9000 BP) is at the bottom of the profile. The soil has gradually become thicker with eolian and tephra additions to the top. Distinctive light colored tephra layers are from Mt. Hekla (rhyolite) but the dark colored tephra layer closer to the top is tephra layer "a" from 1480 AD. These thick tephra layers show limited signs of weathering, especially the rhyolite (C horizons), T horizons according to Arnalds *et al*., (1995). The soils between the tephra layers of known age give an indication of environmental conditions during the period. More clay and OC accumulate during climatic favorable periods. – *Þróun jarðvegs frá ísöld, brúnjörð á þurrlendi. Jarðvegurinn þykknar smám saman en efnaveðrun er örust við yfirborðið á hverjum tíma. Ljós gjóskulög frá Heklu setja svip sinn á sniðið en ofarlega er dökka gjóskulagið „a"sem talið er frá 1480. Leirmagn, lífræn efni og fleiri þættir gefa til kynna umhverfisaðstæður á hverjum tíma á milli gjóskulaganna.*

Cryoturbation

Frost activity is intense in Iceland due to more frequent freeze-thaw cycles than elsewhere in arctic regions. Many distinctive cryoturbation features are formed, such as hummocks (Figure 5), solifluction lobes and terraces, patterned ground, and rocky surface (desert pavement) due to frost heaving. Icelandic soils under vegetation are very frost susceptible because of their andic soil properties. These properties include very high to extreme water retention capacity, rapid permeability and a lack of cohesion in the absence of phyllo-silicates (layer-silicates). These properties lead to the formation of the hummocks, which characterize Icelandic landscapes, but the highest hummocks are usually found under a shallow water table (water transmitted to a stationary freezing front; Jóhannesson, 1960). These properties also explain how Icelandic soils are susceptible to landslides (e.g., Warkentin and Maeda, 1980). The Vitrisols of deserts have different characteristics in terms of cryoturbation. Rocks, when present, are heaved to the surface to create a lag-gravel surface that has the appearance of typical desert pavement. The type of ice crystals formed in desert soils is non-conductive to water infiltration (massive ice), in contrast to more porous ice crystals in the Andosols formed under vegetation (Orradóttir *et al*., 2008), which results in large scale water erosion during thaw events in winter.

Figure 5. Hummocks (thufur) in Iceland. Much of Icelandic surfaces are characterized by various cryoturbation features such as these hummocks. – *Þúfur í yfirborði. Yfirborð landsins einkennist af ýmiss konar frostfyrirbrigðum.* Photo/*Ljósm.* Sigmar Metúsalemsson.

SOIL CHARACTERISTICS

Andosols exhibit unique physical, chemical and mineralogical properties that place them apart from other soils. Both the poorly ordered minerals and the organic materials of Andosols give rise to the specific Andosol (andic) soil properties (see Dahlgren *et al.*, 2004; Arnalds, 2008). The clay constituents form stable silt-size aggregates that give rise to rapid hydraulic conductivity and infiltration. The soils have very low bulk density (Icelandic Andosols usually 0.3–0.8 g cm^{-3}) but water holding capacity can be very high (often >50% at 0.3 bar tension). The soils do not cohere well and can easily reach the liquid limit upon disturbance when water saturated, hence the common occurrence of landslides. Water relations can be disturbed by the presence of coarse grained tephra layers in the soils, which impede unsaturated water movement in soil. The Vitrisols have different physical characteristics which most often are typical of sandy soils, such as low water holding capacity and rapid water infiltration in summer.

The chemical properties of the Andosols and Histosols reflect high surface area soils, rising both from clay constituents and organic materials. Andosols have a natural tendency to accumulate carbon and freely drained Andosols of the world often store about 6% carbon (Nanzyo *et al.*, 1993). The Icelandic Brown Andosols found in freely drained areas are quite typical Andosols, and they commonly have up to 6% C in horizons not disturbed by thick tephra deposits or intense land use. Intense eolian activity on or near the active volcanic belt reduce the organic content in each horizon, while burial of soils leads to accumulation of organic matter and considerable organic pools (kg m^{-2}). The carbon content of the Gleyic Andosols also depends on the flux of eolian materials (often 2–8% C), but at greater distance from eolian sources, the C content of soils rises above 12% C (Histic Andosols). Cation exchange capacity is high (CEC at pH = 7 often >30 $cmol_c$ kg^{-1}). The charge is pH dependent and increases with higher pH. Soil pH usually ranges between 5.5 and 6.5 in Andosols, 4.5–5.5 in Histosols, and 7–7.5 in Vitrisols. The Andosols and Histosols can be considered fertile soils; however, Andosols have a tendency to immobilize P resulting in P deficiency for cultivated crops (e.g., Gudmundsson *et al.*, 2005).

The Vitrisols do contain colloids with active surface areas, often 1–5% allophane content. The tephra also tends to be porous and has considerable surface area. Therefore, the Vitrisols have considerable cation exchange capacity and appreciable water holding capacity, but are nutrient deficient due to low organic content (< 1% C, often near 0.2% in the sandy Arenic Vitrisols).

SOIL EROSION AND DESERTIFICATION

Soil erosion has been extremely active in Iceland over the past 1200 years resulting in formation of many barren desert areas. Soil erosion processes in Iceland vary considerably, and many erosion processes may occur at the same site. The erosion is rarely associated with cultivation of land, as is most common elsewhere in Europe, but rather rangelands or open lands that are most often used for grazing by sheep and horses. A comprehensive survey of soil erosion in Iceland was published in English in 2001 (Arnalds *et al.*, 2001b,

Figure 6. An Icelandic rofabard landscape. Sheep provide a scale. The non-cohesive Andosols under the root-mat are undermined by erosion forces, leaving bare, gravelly desert behind (Vitrisols). – *Landslag sem einkennist af rofabörðum. Hin lausa eldfjallajörð (sortujörð) undir rótarmottunni á yfirborðinu er rofin burt fyrir tilverknað vatns og vinda. Eftir situr auðn með glerjörð (Vitrisol).*

translated from original publication in 1997). The following discussion is a brief overview and draws mostly from this assessment and related publications. The assessment of soil erosion in Iceland is based on a classification of erosion forms that can be identified in the landscape. The erosion forms can be grouped in two main categories, i) erosion associated with loss of soils under vegetation (Andosols), and ii) erosion on deserts (Vitrisols).

Erosion of Andosols

The most distinctive erosion form in Iceland is an erosion escarpment (Figure 6), termed 'rofabard' in Icelandic (see Arnalds, 2000). They form in thick (usually 0.5–>2 m) non-cohesive Andosols (Gleyic and Brown Andosols) which overlie more cohesive materials such as glacial till or lava. The relatively loose Andosols beneath the root mat are undermined by erosion, creating escarpments, or rofabards. Rofabards retreat as a unit, with fully vegetated soils on top, but leaving barren desert behind.

Advancing sand fronts (*Icelandic: áfoksgeirar*) are important erosion forms that have resulted in large scale desertification over the years. They are active, usually tongue-shaped sandy surfaces extending into vegetated areas. The advancing fronts move with the prevailing dry winds, e.g., southbound in South Iceland and northbound in North Iceland. These fronts begin as sedimentary features (encroaching sand, Figure 7), that abrade and bury the vegetation with sand and destroy it. After that, the soils below the vegetation become unstable and are added to the pool of eolian materials that continue to move downwind, but deserts are left behind, and the landscape has been lowered, typically by 0.5 to > 2 m in their path, depending on the original Andosol thickness. The point of origin for advancing sand fronts is dependent on an available source of loose sandy materials, such as sediments formed by tephra deposition and floods leaving sandy deposits. Many advancing fronts have origins in glacial margins, lakes that have filled with sediments, and sandy plains near glacial rivers. Advancing fronts have been a major problem in Iceland that threaten fully vegetated systems, and can advance over 300 m in a single year (see Arnalds *et al*., 2001b). Encroaching sand has desertified large areas in South and Northeast Iceland, especially during the last part of the 19^{th} century. The Icelandic Soil Conservation Service (Landgræðsla ríkisins) was originally established in 1907 largely to battle moving sand associated with these erosion features, but it is one of the oldest operating soil conservation institutions in the world.

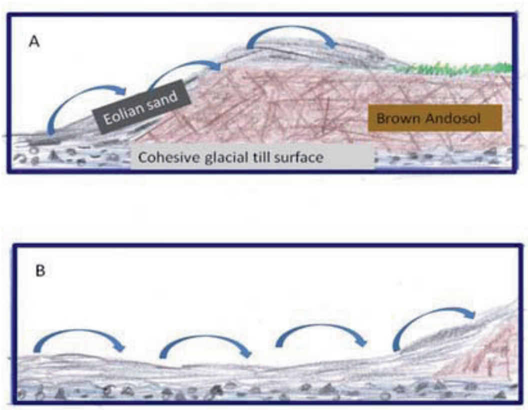

Figure 7. Encroaching sand. Sand is moved downwind (illustration A) over a desert surface (glacial till or lava), towards a vegetated surface with Brown Andosol (1 m thick on the illustration). The sand buries the vegetation and erodes the Brown Andosol, truncating the surface by about 1 m. The Brown Andosol lacks cohesion while the till (or lava) surface is more cohesive. An unstable sandy desert surface is left in the path (illustration B), and the sand advancement continues down-wind. A steady flux of sand from a source such as glacio-fluvial flood plain is assumed. – *Áfoksgeiri; sandur gengur yfir gróið land. Sandurinn grefur gróðurinn og rýfur burt brúnjörðina, svo yfirborðið lækkar. Eftir situr sendin auðn. Gert er ráð fyrir stöðugri uppsprettu áfoksefna, svo sem sandsvæði við jökul eða jökulár.*

Erosion spots are very common erosion features but erosion is usually not as severe as erosion associated with rofabards and advancing sand. They are a clear sign of overgrazing when they occur in lowland areas. Their formation is often associated with hummocky surface relief. Erosion spots that form on slopes with solifluction features are considered separately under the Icelandic erosion classification, as such spots are subjected to running water with the potential development of severe erosion. Water channels or gullies are also common on slopes in certain areas, such as East Iceland, but rofabards can develop from the channels. Landslides are common throughout the country.

Erosion of Vitrisols

The barren deserts of Iceland usually have unstable surfaces. The barren surfaces were classified into lag-gravel (Icelandic: melur), sandy surfaces (Icelandic: sandar), lava surfaces (Holocene lavas), scree slopes, and the sandy lag-gravel areas (Icelandic: sandmelar), and sandy lava surfaces (Icelandic: sandhraun), where eolian sand has accumulated on top of the lag gravel and lava surfaces. The desert surfaces are subjected to intense wind erosion, especially the sandy surfaces, but also on the lag-gravel surfaces during high intensity dry storms (e.g., >20 m sec^{-1}). Papers describing wind erosion on these surfaces, in addition to the erosion assessment publication (Arnalds *et al*., 2001b), include an overview of sandy surfaces by Arnalds *et al*. (2001a) and a description of eolian processes south of Langjökull glacier by Gísladóttir *et al*. (2005). Water erosion is also common, especially during rainfall events in winter on frozen ground, intensified by rapid snow-melt.

Desertification

Desertification is rarely expressed as vividly as in Iceland. Fully vegetated systems have in places been replaced by barren deserts with limited plant production. A large part of the vegetated systems are also degenerated, with poorer plant composition such as heath and sedges, often with abundance of erosion spots and other erosion features, replacing birch-, willow-, or flowery plant dominated systems in drylands (Arnalds, 1987; Aradóttir and Arnalds, 2001).

A model of this degradation was provided by Aradóttir *et al*. (1992), with general amendments by Archer and Stokes (2000). The causes for the severe degradation are related to the interaction between land use, unfavorable natural events such as cold spells and volcanic eruptions (e.g., Arnalds, 1987; Arnalds, 2000; Arnalds *et al*., 2001b; Aradóttir and Arnalds, 2001; Edwards *et al*., 2003). Haraldsson and Ólafsdóttir (2003, 2006) have stressed the climatic factor of this degradation. Like in other areas of the world subjected to desertification, the land use was driven by poverty, the potential of the land determining the number of people that survived for a given period (e.g., Simpson *et al*., 2001).

A cooling trend that began 2500 BP and growing sources for eolian sand associated with the formation of glaciers, may be primary factors in some areas, especially along the coastline and near glacial margins at higher elevations. However, major change with accelerated erosion occurred at the time of settlement (874 AD) with eolian deposition rates multiplying. There is no documented evidence for such massive country-wide erosion in Iceland before settlement.

Massive restoration efforts are currently under way in Iceland, by government agencies (Soil Conservation Service, Forestry Service), farmers, NGO's (e.g., Forestry Society), and individuals in association with summer houses and recreation activities. Restoration efforts usually involve stabilizing the soil surface by grass seeding and fertilizing 1–3 years, allowing for natural succession and afforestation projects (Magnusson, 1997; Aradóttir *et al*., 2000). Such restoration efforts are important for carbon sequestration and the green-house budgeting in Iceland (e.g., Aradóttir *et al*., 2000).

CONCLUSIONS

In this paper, an attempt was made to give a general description of Icelandic soils and soil erosion, based on a review of the published research. The Icelandic soils are youthful as new materials are constantly being added to the top of soil profiles and the cold climate limits rates of pedogenic processes. However, the rapid weathering rate of the basaltic tephra does lead to appreciable amounts of clays such as allophane, ferrihydrate, and some imogolite. Relatively neutral pH 5.5–7 is maintained by bases released by weathering of the basaltic tephras. The clay minerals are different from the layer silicates such as smectite, illite and kaolinite, by lacking cohesive properties used to identify them in the field, and clay content is therefore often underestimated. Icelandic soils do have most of the characteristics typical of the world's Andosols, with high organic content, water retention and permeability.

The soils of the deserts, the Vitrisols, are quite unique in a world perspective and are the large. The extensive erosion in Iceland has received widespread attention and the country is considered one of the world's erosion hotspots (e.g., Boardman, 2006). Desertification under such humid conditions is noteworthy and is a good remainder that all marginal lands are susceptible to degradation and intense erosion when land use reduces the resilience of ecosystems and stability thresholds are crossed. Dry climate and drought are the most common stresses in combination with land use to cause desertification. In Iceland, cold climate and tephra fall events under intensive land use have similar consequences with similar ecological pathways.

ÁGRIP

Í greininni er teknar saman upplýsingar um íslenskan jarðveg og jarðvegsrof. Íslenskur jarðvegur telst til *eldfjallajarðar eða sortujarðar* (Andosol) en svo nefnist jarðvegur eldfjallasvæða. Gjóska veðrast einkar ört, ekki síst basísk gjóska og við það falla út sérstakar leirsteindir, svo sem allófan, ímógólít og ferrihýdrít. Jarðvegur á grónu landi er lífrænn sé um votlendi að ræða, en lífrænt innihald minnkar þó ört eftir því sem áfok og gjóskufall eykst. Fjærst gosbeltunum finnst eiginleg *mójörð* (Histosol), en síðan tekur við *svartjörð* (Histic Andosol) og *votjörð* (Gleyic Andosol) á votlendi næst gosbeltunum. Brúnjörð einkennir gróin þurrlendi landsins. Á auðnum er margvísleg *glerjörð* (Vitrisol) ráðandi.

Jarðvegsrof hefur verið mikið á Íslandi í aldanna rás. Jarðvegsrof hefur verið flokkað í svokallaðar rofmyndir, svo sem rofabörð, rofdílar og áfoksgeirar. Jarðvegsrofi á Íslandi svipar um margt til eyðimerkur-

myndunar á þurrari svæðum jarðar, sem sýnir ljóslega að á öllum jaðarsvæðum heimsins er hætt við myndun auðna, ekki aðeins þar sem úrkoma er lítil.

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