Dust sources and deposition of aeolian materials in Iceland

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ABSTRACT

Iceland has about 22,000 km^2 of sandy deserts that are a major source of atmospheric dust. Icelandic dust is mostly basaltic volcanic glass, which is rather unique for global dust sources. The dust comes mostly from two sources: confined plume areas and extensive sandy deserts. Major plume sources are identified by field observations and satellite images, while Icelandic sandy deserts have been mapped. Measured erosion fluxes commonly reach 500 to > 2,000 kg m^{-1} day^{-1} during storms. A map showing major plume areas and their deposition areas and a map showing deposition from sandy areas are produced and subsequently combined to obtain an overview of aeolian deposition in Iceland. Deposition rates range from < 25 g m^{-2} yr^{-1} far from aeolian sources to > 500 g m^{-2} yr^{-1} near or within major sandy areas. These numbers are higher than deposition rates reported for other major global dust areas. The spatial distribution of aeolian deposition has a key influence on important soil parameters, such as clay content and organic matter.

Keywords: Atmospheric dust, aeolian processes, plumes, wind erosion, volcanic dust

YFIRLIT

Áfok er gríðarlega mikið á Íslandi. Uppruna þess má að stórum hluta rekja til afmarkaðra svæða, strókasvæða, en einnig til víðáttumikilla sandauðna. Strókasvæðin voru meðal annars ákvörðuð með hjálp gervihnattamynda, en sandsvæðin hafa þegar verið kortlögð. Meðal virkustu strókasvæðanna eru Dyngjusandur, Hagavatn, Landeyjarsandur og Skeiðarársandur. Sandfok á sandauðnum er oft >500 kg m^{-1} dag^{-1}, það er meira en hálft tonn fýkur yfir eins metra breiða línu. Minna er vitað um uppfok (kg m^{-2}) sem verður að ryki í andrúmsloftinu, en það nemur líklega 0,01 to 5 kg m^{-2} í hverjum stormi eftir aðstæðum. Áfokið á land er með því mesta sem þekkist á jörðinni (<25 to >500 g m^{-2} ári^{-1}). Jafnframt er efnasamsetning áfoksins sérstök og efnin veðrast auðveldlega. Áfok hefur mikil áhrif á íslensk vistkerfi á landi og trúlega langt á haf út. Mikilvægir eiginleikar jarðvegs, t.d. hlutfall leirs og kolefnis, mótast af hraða og grófleika áfoks.

INTRODUCTION

Atmospheric dust coming from the world's desert areas during major wind erosion events is an important contributor to the function of various aspects of Earth's ecosystems, including climate, soil formation and ecosystem fertility (Lawrence & Neff 2009). Dust emissions also can affect human health (e.g. Buzea et al. 2007). Global dust emissions are usually associated with arid and semi-arid regions, where

geomorphology or other factors lead to the accumulation of relatively fine-textured particles (Prospero et al. 2002, Lawrence & Neff 2009). Iceland is usually not considered among the major dust source areas (e.g. Prospero et al. 2002, Lawrence & Neff 2009), but is most likely a major source of atmospheric dust in spite of the northerly location and humid climate. Furthermore, the composition is unusual, being mostly basaltic volcanic glass (Arnalds et al. 2001a).

Icelandic soils are to a large extent Andosols, soils that form in deposited volcanic ejecta (Arnalds 2004, 2008). Soils vary considerably with environmental factors, such as landscape position, drainage, elevation and, importantly, rate of aeolian deposition of volcanic materials. Icelandic soils and geomorphic surfaces can be divided into two main categories: land with vegetation and barren land or deserts. Soils under vegetation show clear andic properties characteristic of Andosols. The deserts cover about 40,000 km², and include 1) lag gravel surfaces (till, fluvial); 2) lava surfaces; and 3) sandy surfaces (Arnalds et al. 2001b). In a recent classification scheme for Icelandic soils (Arnalds & Óskarsson 2009) the role of the aeolian deposition rate is emphasized in shaping the properties of Icelandic soils and it is reflected in the separation soil classes on a map of Icelandic soils (Arnalds et al. 2009).

Because of the dominant influence of aeolian deposition on soil formation in Iceland it is important to gain an understanding of sources of the aeolian materials and their distribution over the Icelandic land mass. The use of soil profiles for interpreting environmental changes over the last millennia also calls for making such an overview available. Furthermore, it is important to explore the activity of Icelandic dust sources because of possible wide-spread influence of the dust. In this paper an attempt is made to make an overview of dust sources and deposition of aeolian materials in Iceland.

Deserts in Iceland
There have been dramatic environmental changes since Iceland was settled about 870 AD. Massive erosion has resulted in widespread desertification and much of the remaining land has reduced production capacity as a result of species composition changes and loss of soil fertility. These environmental changes have been the subject of numerous publications such as Thórarinsson (1961), Guðbergsson (1975), Aradóttir et al. (1992), Aradóttir & Arnalds (2001), Haraldsson & Ólafsdóttir (2003, 2006), Dugmore et al. (2009) and Gísladóttir et al. (2010). Deposition rates of aeolian materials and the nature of soil materials between tephra layers of known age often plays a major role in interpreting environmental conditions and changes through the Holocene and notably after the settlement.

Most all Icelandic sandy deposits are volcanic in origin, with volcanic glass as a key constituent (see Arnalds et al. 2001a). Such desert areas are uncommon outside of Iceland (Edgett & Lancaster 1993). Globally, dust is mostly quartz, phyllosilicates (clay minerals), but feldspars and carbonate minerals are also common (Lawrence & Neff 2009). Quartz is often more local but phyllosilicates is a significant proportion of global dust (mostly illite and kaolinite). Icelandic dust is quite unique in this respect. The volcanic dust has much more surface area than the rather inert quartz and carbonates and the composition includes poorly crystalline olivine which is relatively unstable in weathering processes in soils. Hence weathering rates in Icelandic soils are rapid (see e.g. Gíslason 2008).

Aeolian transport
There are three major modes of soil transport by wind that need to be considered during wind erosion (see e.g. Woodruff & Siddoway 1965, Skidmore 1994). The largest grains, e.g. > 1 mm in diameter, creep along the surface while the smallest grains (clay and fine silt) are carried into suspension to form dust. The medium-sized grains, often ranging between 0.02 - 0.1 mm saltate along the surface in a bouncing motion, usually below 50 cm (AUI data) and even 20 cm height, colliding with other grains and detaching other grains on impact (e.g.

Stout & Zobeck et al. 1996a, van Donk & Skidmore 2001). This is the main force of wind erosion and often moves 70-90% of the materials during wind erosion. The saltating materials are also needed to detach the finer grains that form dust plumes. Bonds are formed between fine soil materials (clay and fine silt) that reduce the risk of wind erosion, while coarse grains have resistance to wind erosion due to their mass. The glacial materials and tephra that form the largest proportion of Icelandic sandy areas do not contain layer-silicates such as smectite or kaolinite, and the clay component can be considered small. Lack of cohesive clay minerals contributes to the high wind erosion susceptibility of the sandy surfaces in Iceland (see Arnalds et al. 2001a). Clays which are characteristic of Andosols, such as allophane, ferrihydrite and imogolite form in Icelandic soils, but their physical behavior is that of silt-sized particles and further increase the susceptibility of such soils to wind erosion (see Dahlgren et al. 2004).

In this paper three units for aeolian processes are used: 1) surface transport (flux) is measured as the mass crossing a 1 m wide line with unspecified height (kg m^{-1}), most often with a year as the time reference (kg m^{-1} yr^{-1}), but also per storm or day; 2) amount of dust emitted into suspension from a unit area (kg m^{-2}), both on a storm basis and per year; and 3) deposition of materials from suspension on a unit area per year (g m^{-2} yr^{-1}).

MATERIALS AND METHODS

There are several sources of data and information that are considered in the attempt to build an overview of aeolian activity in Iceland. These include 1) a geographic information database of sandy deserts in Iceland, 2) direct measurements of sand transport (flux)
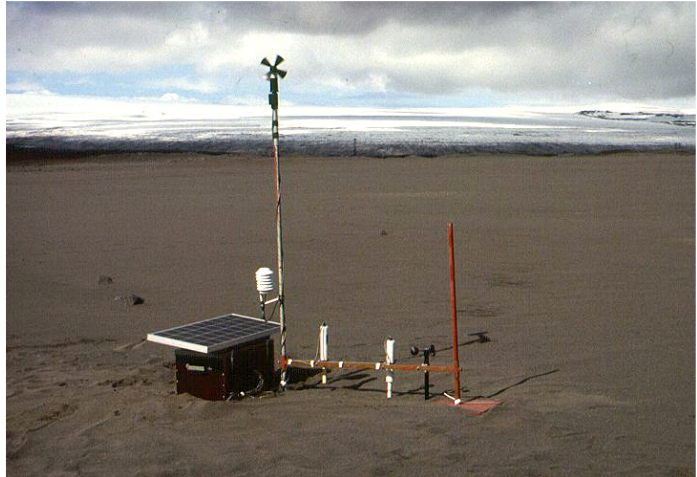

Figure 1. Sandur south of Langjökull Glacier. Stability class (erosion severity) 5. This sandy surface is near Hagavatn (P1 area in text). The photo shows automated sensors (Sensit) and instruments to measure weather parameters. Photo: Ó. Arnalds.

Figure 2. Sandy lag-gravel west of Mýrdalsjökull. Stability (erosion severity) class 4. Sand is being deposited on top of gravelly surface by aeolian processes and volcanic activity. Part of the gravel surface is pushed up by frost each winter and there is a sandy layer below the surface. Photo: Ó. Arnalds.

on the ground, 3) soil map and geographical variation in soil parameters that give an indication of rates of aeolian deposition, 4) satellite images of active dust storms, 5) measured soil thickening rates, and 6) field experience, which includes visual observations of storm events from dust source areas for identification of major dust source areas. An attempt is made to consider only recent or present-day conditions for aeolian sources.

Figure 3. Sandy lava near Mt. Hekla. Stability (erosion severity) class 4. BSNE sediment traps being emptied. Photo: Ó. Arnalds.

Geographical information database for sandy deserts in Iceland

Soil erosion in Iceland has been surveyed in the field at the scale of 1:100 000. (Arnalds et al. 2001b). This survey included Icelandic desert surfaces. The sandy desert surfaces were divided into three major surface types: i) sandur, which is a sandy and relatively even surface without much gravel (Figure 1), ii) sandy lag-gravel surfaces which are sandy surfaces with a partly gravelly surface (Figure 2), and iii) sandy lava surfaces, which are Holocene lavas that have various amounts of loose sand in depressions (Figure 3). The sand is being accumulated into the sandy lava and sandy lag-gravel surfaces from a nearby sand-source or the sand is being deposited as tephra during eruptions. A more comprehensive overview of sandy surfaces in Iceland was provided by Arnalds et al. (2001a).

While mapping of erosion in Iceland, the stability of the surfaces was divided into five erosion severity classes which reflect surface stability. The severity classes of interest are 3 (considerable erosion), 4 (severe erosion) and 5 (very severe erosion). The resulting map of the sandy deserts in Iceland is presented in Figure 4, dividing the sandy areas into major geographical regions (S1-S7). The extent of the sandy areas separated by stability classes is shown in Table 1. Areas in erosion classes 4

and 5 can be considered unstable and contribute to aeolian processes in Iceland during dry storms.

Measurements of erosion rates in the field

There have been several attempts to measure erosion rates on sandy surfaces in Iceland. These measurements help clarify the aeolian processes within the source areas discussed in this paper. Measurements were obtained using BSNE (Fryrear) traps and piezoelectric saltation sensors (Sensit) with simultaneous measurements of weather parameters. Measurements include three 5 month-long field measurements at the Hólsfjöll highland area, Northeast Iceland (silty soils) (Arnalds & Gísladóttir 2009), 3-year continuous BSNE trap measurements at Geitasandur, South Iceland (Arnalds & Orradóttir 2010), current large scale measurements in the Hekla volcanic region (Thórarinsdóttir & Arnalds 2010), measurements near a dust-plume source at Hagavatn, South Iceland (Gísladóttir et al. 2005), and at various other sandur unstable saltation surfaces (Sigurjónsson et al. 1999, Arnalds et al. 2001a). Attempts have been made to model aeolian flux of Icelandic soils in relation to possible flux of sediments from the shores of the newly formed Hálslón hydroelectric reservoir (see Kjaran et al. 2006). Kjaran & Sigurjónsson

Table 1. Extent of sandy surfaces in Iceland. Sandy surfaces in all three classes cover nearly 22 000 km², with nearly 15 000 km² in the more unstable classes 4 and 5.

Surface type	Stability Class			Total
	3	4	5	
	km²			
Sandur	318	1087	2828	4233
Sandy lag-gravel	5407	6217	1286	12910
Sandy lava	1366	1757	1620	4743
Total	**7091**	**9061**	**5734**	**21886**
Total 4+5	**14795**			

(2004) also modeled possible dust emission from the Hálslón shores, which is utilized to estimate possible emissions from dust-plume areas in this work.

Soil map of Iceland and geographical distribution of major soil properties
The soil map in the scale of 1:250 000 (Arnalds et al. 2009) is based on an Icelandic soil classification scheme that considers the effect of aeolian materials and soil drainage as major factors influencing the characteristics and properties of Icelandic Andosols under vegetation (Arnalds & Óskarsson 2009). The estimated aeolian deposition is compared with the soil classes on the map and general distribution of soil properties. The Agricultural University of Iceland (AUI) soil database (Ýmir) was used to compare aeolian deposition and the geographical variation in major soil properties such as carbon content, clay content and soil pH.

Field experience and satellite imagery showing active dust plumes and plume directions
Evidence of dust-plumes is often prominent in the field, and photographs exist of active plume formation for all the dust plume areas discussed in this paper. Field observations combined with satellite imagery provided relatively reliable information about most of the major dust-plume sources.

A survey of recent satellite images was made to identify or confirm the existence of major plume areas. The Moderate Resolution Imaging Spectroradiometer (MODIS), which is part of the Terra and Aqua NASA satellites, acquires images of Iceland each day. The 3 year period of 2007 - 2009 for the months May through October was explored and 20 images which showed plume activity were identified. Four older MODIS images that had already been acquired were also used in identifying plume activity. Observed plume activity in the field does not necessarily show up on images from a given day as the activity may have been before or after the pass of the satellite. Furthermore, plume activity can take place unnoticed during cloudy days. Images are therefore not indicative of the frequency of the activity but are references to pinpoint sources and to verify the general direction of aeolian transport.

Deposition rates in dryland soils and other information sources
Tephrochronology has been widely employed in Iceland to study rates of aeolian deposition or soil thickening rates for various purposes, such as to deduce past environmental conditions. This method was pioneered by Thórarinsson (1961) and colleagues and used early on by Sigbjarnarson (1969) and Guðbergsson (1975) and more recently by many researchers such as Dougmore et al. (2009), Gísladóttir et al. (e.g. 2010) and others (see review by Larsen & Eiríksson 2008).

The rate of thickening of the soils (mm yr⁻¹) can be used to calculate aeolian deposition in g m⁻² yr⁻¹ if the bulk density of the soils and the proportion of mineral matter are known (or the organic content). The bulk density of Icelandic soils varies considerably, but is commonly near 0.7 g cm⁻³ for freely drained Andosols (Arnalds 2004), with the organic carbon content generally varying between 2 and 6%. However, thickening rates can vary considerably within an area depending on various landscape factors such as slope and the roughness of the terrain. Therefore, only general and recent trends in thickening rates in Iceland (expressed by surface horizons) are considered in this report. Various existing sources for thickening rates

were used and are indicated with the respective results.

Satellite images, both SPOT and Landsat, were used for a closer look at the plume areas. Data from dust monitoring equipment in East Iceland (Björnsson 2006, Guðmundsdóttir 2007, 2008, 2009) were used in relation to considerations for the Dyngjusandur dust-plume area.

RESULTS AND DISCUSSION
Sources and deposition areas
Sandy areas
The sandy areas in Iceland are separated into geographic zones in Figure 4. These zones act as a group of dust sources with similar dry wind directions and aeolian drift in the same direction. Their general characteristics, including texture and wind erosion parameters, were described by Arnalds et al. (2001a). Mean grain-size generally ranges between 0.1 and 1 mm, but density of the grains range from < 1 g cm^{-3} for pumice grains to nearly 3 g cm^{-3} for dense basaltic glass. Saltation material is the dominant aeolian component during storm events in these areas, but 10-30% of the material may become suspended and travel long distances and impact air quality. The areas that are most likely influenced by aeolian deposition from the different zones of sandy areas are indicated in Figure 5.

In order to improve our understanding of aeolian dynamics in Iceland, a summary of quantitative measurements and modeling is presented in Table 2. There is a remarkable range difference in the erosion magnitude that can be expected in storms on sandy surfaces in Iceland, or up to >500 to 6,000 kg m^{-1}. This is a general range for single storms under a variety of conditions which produce aeolian dust and deposition far from the sandy surfaces. The surfaces vary in nature, as do weather conditions and length of the storms.

It is known from field experience that these surfaces have extremely variable threshold velocities (wind measured at 2 m height), ranging from < 5 m s^{-1} (e.g. sandur surfaces; Gísladóttir et al. 2005) to > 15 m s^{-1} on rough and partly gravelly surfaces (Sigurjónsson et al. 1999; Arnalds et al. 2001a). These threshold velocities are in good agreement with values reported in the literature, such as for typical unvegetated sandy surface in West Texas (5.5 m s^{-1}; wind speed at 2m height, Stout 2007) but are often lower than seen in agricultural fields (14 m s^{-1} reported by Stout & Zobeck 1996b).

No model is available for estimating dust production for these various sources in g m^{-2}, but it can be assumed that it is an order of magnitude less than for plume areas, judging from the difference in the activity of these surfaces. Results from Hagen at al. (2010) in exploring methods to estimate saltation and suspension components from field erosion show a ratio between suspension and saltation of 0.16 to 0.48 for several US wind erosion research sites, which is in agreement with the general wind erosion literature and assumptions made for the sandy areas in Iceland. Kjaran and Sigurjónsson (2004) calculated a 1 to 5 kg m^{-2} possible discharge from the

Table 2. Aeolian transport (kg m^{-1}) in storms on sandy deserts in Iceland.

Research / area	Ref[§]	kg m^{-1}	Comments
Sandy areas in general	1	5000	> 10 hr, active sandur areas
Hólsfjöll, NE Iceland, sandy soil	2	2500-5000	20 m s^{-1} part of day
Geitasandur (sandy lag-gravel)	3	>500	One day, partly >20 m s^{-1}
Hekla area, sand and pumice	4	500 - >1200	Single storms (various length)
Advancing front at Blanda reservoir	5	2000-3000	Wind > 20 m s^{-1}
Erosion Model, Hálslón reservoir	6	350-1150	July 2000 storm event
Erosion Model, Hálslón reservoir	7	6000	Max movement per day

[§]: References. 1: General AUI datasets from many locations; 2: Arnalds & Gísladóttir 2009; 3: Arnalds & Orradóttir 2010; 4: Thórarinsdóttir & Arnalds 2010; 5: Vilmundardóttir et al. 2009; 6: Kjaran & Sigurjónsson 2004; 7: Kjaran et al. 2006.

Hálslón reservoir shores in single large storms (total of 1200 kg m^{-1} surface transport in the storm). This site has a large component of fine silt deposits and is more similar to Icelandic plume areas than the typical more coarse grained sandy surfaces. Judging from these models and considering the great variety of the sandy surfaces, a discharge range between 0.01 to 1 kg m^{-2} can be expected in storms with discharge values > 0.5 kg m^{-2} in localized areas during major storm events. These numbers are higher than reported on a continental scale for the US (Gillette & Hanson 1989), but the Icelandic deserts are often more barren with extensive areas highly susceptible to wind erosion. Below is a description of the deserts (Figure 4 and 5).

S1 - Northeast sandy deserts comprise some of the largest continuous sandy deserts in Iceland, extending about 5000 km^2 from the Vatnajökull Glacier in the south and up to 130 km to the north at Hólsfjöll, and > 80 km wide (east-west) in places. The Vatnajökull is the main source for the sandy materials, mostly as glacio-fluvial deposits at the ice margin and along the major river Jökulsá á Fjöllum and its tributary Kreppa, but also along the Jökulsá á Brú and Skjálfandafljót glacial rivers. Volcanic eruptions have contributed to the sand with tephra deposition and have also resulted in large scale floods which have left unstable sandy materials along the Jökulsá á Fjöllum floodplains. The largest and the most active dust-plume area, labeled below as P1-Dyngjusandur (see plume areas), lies within this area. Large scale dust redistribution is experienced in much of Northeast Iceland from this sandy area (and the Dyngjusandur plume area), blocking the view on windy days tens of km away from the area, as shown in Figure 6.

S2 - Central-North sandy areas are the sandy areas between the Vatnajökull and Hofsjökull glaciers and north of Hofsjökull. These areas do not appear to be as active as the S1 area,
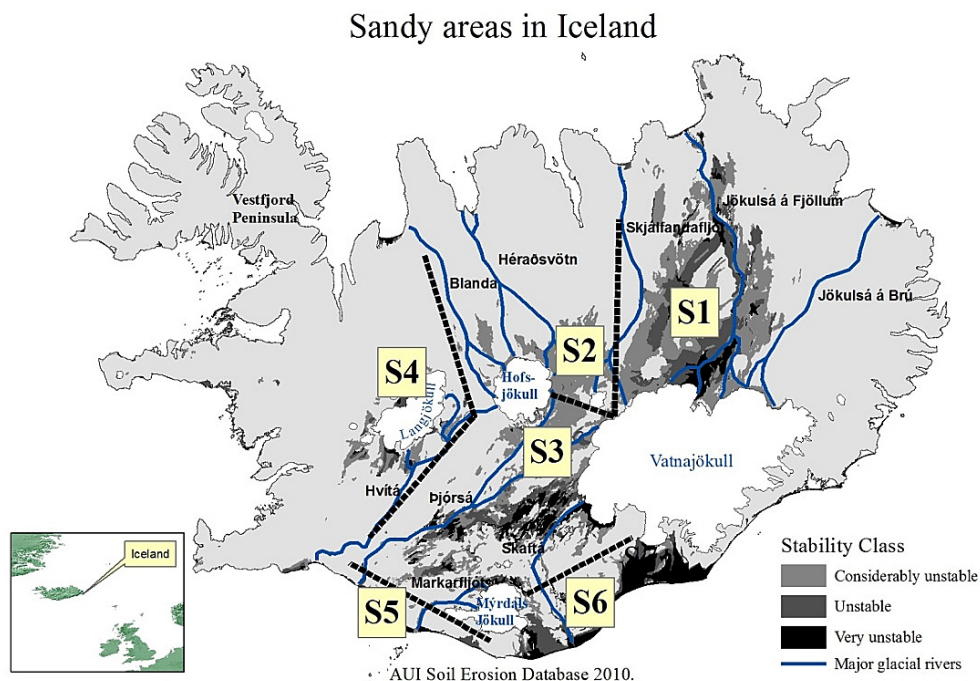
Sandy areas in Iceland

Figure 4. Sandy areas in Iceland divided into 6 major geographic units, but the S7 and S8 areas along the southeastern shoreline are not shown. Glaciers and major glacial rivers mentioned in the text are also shown.

with less large scale glacio-fluvial flooding and less tephra deposition. Main dry winds are from the south, causing redistribution of materials to the north.

S3- Central-South Iceland. This sandy area comprises a variety of surfaces, such as sandy lag-gravel surfaces in the northern part of the area, tephra (including pumice) dominated surfaces in the Veiðivötn area west of the Vatna-
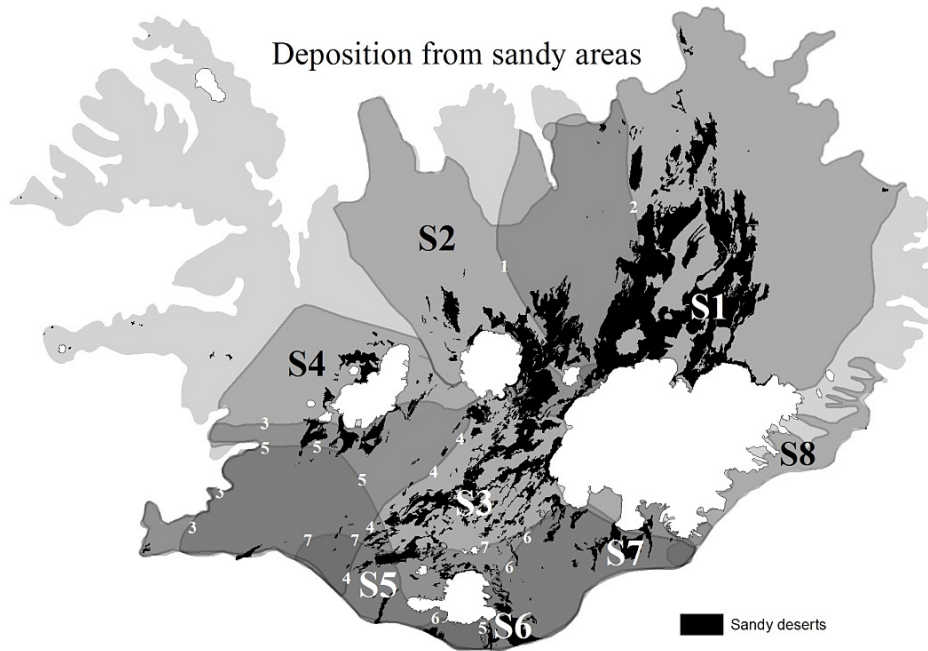

Figure 5. Main aeolian deposition areas from sandy deserts. Each of these is discussed in the text. Numbers mark deposition contour lines where deposition areas overlap.

Figure 6. Dust pollution over Eyjafjörður, North Iceland in September. The dust is coming from various sources in the highlands (Plume area P1, and S1 and S2 in Figure 4). Photo: Ó. Arnalds.

jökull Glacier, the tephra areas around Mt. Hekla and glacio-fluvial plains at the margins of the Vatnajökull and Mýrdalsjökull glaciers and on the floodplains of the Þjórsá, Tungnaá and Skaftá rivers. Distribution of aeolian materials is mainly to the south and southwest with dry north and northeasterly winds (NW winds not as common).

S4 - Langjökull sandy deserts, are the sandy desert areas in the vicinity of the Langjökull Glacier. They are mostly widespread south of the glacier where there is often intense aeolian activity (see Gísladóttir et al. 2005). The main distribution of material is to the south and southwest.

S5 - South coast sandy areas. There is a continuous area of unstable sands along the south coast, from the Reykjanes Peninsula to the southeast coastline. S5 represents the western part of this area, but there are very active sandstorms coming off the Landeyjasandur area (also noted as a plume area in the section on plume areas). Most of this sand is blown to the

south to the ocean during dry northerly winds, but occasionally strong southeasterly winds drive this sand to the northwest over the southwest lowland areas.

S6-Mýrdalssandur. Mýrdalssandur is a large unstable sandy area formed by catastrophic flooding events (jökulhlaup) during volcanic eruptions of the Katla volcano, which is within a large caldera under the glacier (see Björnsson 2009). Active glacial rivers also contribute steadily to the sandy deposits. Mýrdalssandur has frequent sandstorms, mostly blowing to the south with dry northerly winds (see Arnalds & Metúsalemsson, 2004 for an example of a massive erosion event). The area also includes plume areas (labeled Leirá/Múlakvísl below).

S7 - Skeiðarársandur. Skeiðarársandur is Iceland's largest sandy floodplain, about 1000 km^2 in area (Björnsson 2009). Like Mýrdalssandur (S6), it has been largely formed during catastrophic floods during volcanic eruptions under the Vatnajökull Glacier. Again, sandy materials mostly blow to the south, but
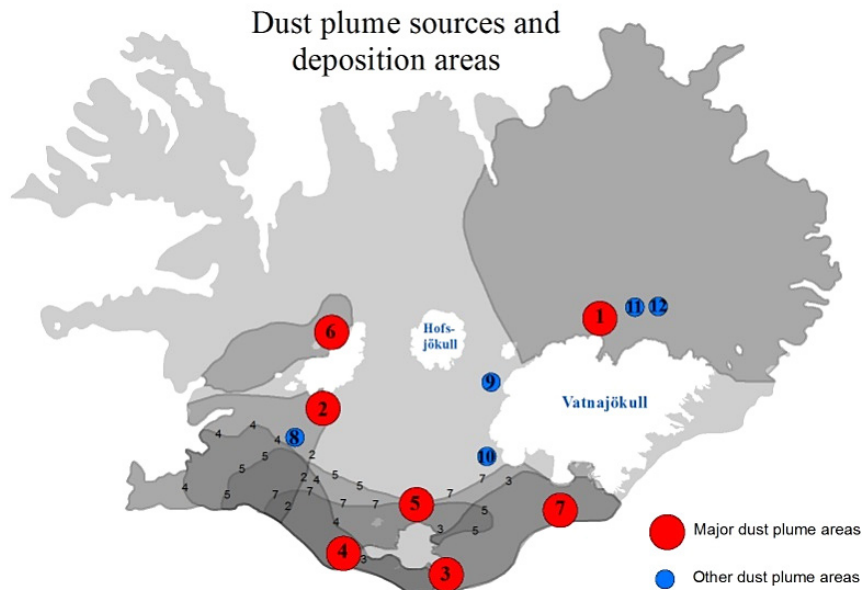

Figure 7. Dust plume sources and estimated main deposition areas. Each of the major sources is explained in the text. The map is based on field observations and verified by MODIS satellite images.
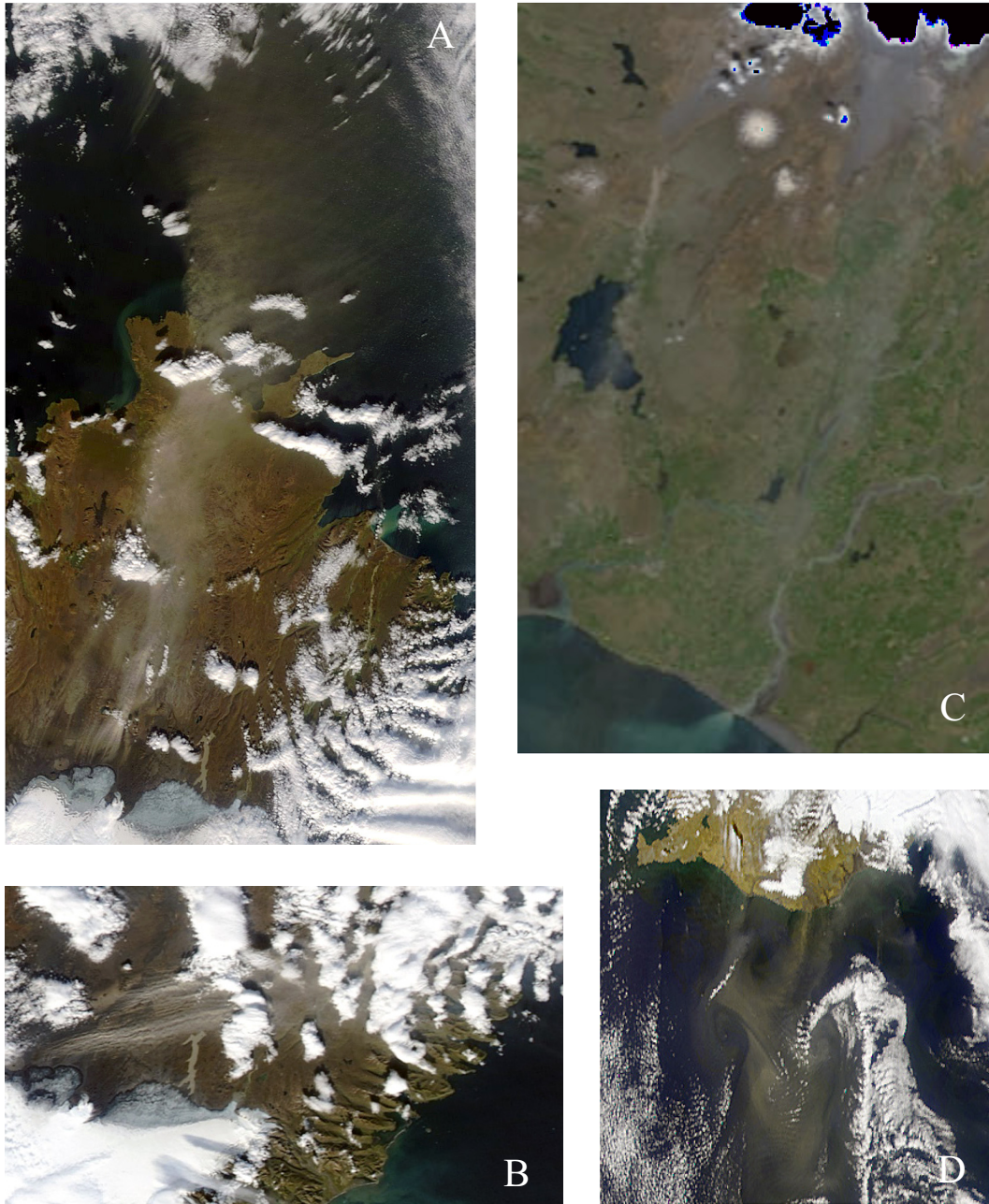
Figure 8. MODIS satellite images of dust plumes in Iceland (NASA/MODIS). a. Dust plume from Dyngjusandur sand field (plume area) September 17, 2008. Dust is blown from Dyngjusandur NNE out to the ocean in the north at about 200 km from the source. b. Dust plume towards the east coast from Dyngjusandur, September 15, 2009. Gusts at Hálslón reservoir (large cloudy lake on image) are up to 28 m s^{-1} during this day, and in such high intensity storms other sources north of Dyngjusandur are also quite active (sandy areas). c. Dust plumes from Hagavatn (P2) and Sandkluftavatn (P8), June 23, 2002. d. Dust from the south coast of Iceland October 5, 2004. The dust plumes are extending > 400 km from various plume areas (such as P3, P4, and P7, see numbers on Figure 7) and sandy areas (S3, S5, S5, S6, and S7 (Figure 4 and 5).

both Skeiðarársandur and Mýrdalssandur are a source for occasional sediment deposition inland from these deserts.

The map (Figure 5) also shows influence from sandy areas along the southeast coast (area S8).

Plume areas
The following identification and presentation of dust-plume areas is mostly based on observations of active dust emission events from certain areas during fieldwork and travel in Iceland over the past 30 years. These areas are further confirmed by a survey of MODIS satellite imagery, mostly from 2007 through 2009. These areas are more confined than the sandy deserts described above. The reason for the intense activity of these areas can be related to the fine silty texture of the sediments, as explained by Prospero et al. (2002) for other globally active plume areas. The continued plume activity is dependent on continuous supply of fine grained glacial and glacio-fluvi-

al sediments. The mean grain size is commonly 0.05 to 0.1 mm, however with larger sand grains that enhance saltation movement. The plume areas are shown on Figure 7, and selected satellite images showing plume activity at several of these areas are shown in Figure 8 a-d. Major areas are marked 1-7, but other less active plume areas as 8-12, and these correspond to areas described as P1-P12 in the following text.

P1 - Dyngjusandur (NE Iceland). Dyngjusandur is the largest plume area in Iceland. The reason is partly the dry climate in the rain shadow north of the Vatnajökull and geomorphic conditions that cause the streams that come from underneath the Vatnajökull to flood over a large flat area during peak flow in summer, with large daily fluctuations. The streams carry a heavy load of sediments that is partly deposited on this extensive glacial floodplain. Some of the water seeps into the porous bedrock leaving sediments on the surface

Figure 9. Dust source at Dyngjusandur (P1). Area recently flooded by glacial meltwater in July with fine silty materials on the surface. Dust plumes beginning to form on relatively calm day (< 8 m s^{-1} at 2 m height). Photo: Sveinn Runólfsson.

Figure 10. Dust bowl over the Hagavatn plume area (P2). The photograph taken from a 40 km distance from the source, showing intense dust emissions. MODIS satellite images did not capture the activity this particular day (July 23, 2009). Photo: Ása L Aradóttir.

(Björnsson 2009). In addition, the dry winds from the Vatnajökull are katabatic (Ashwell 1986), a condition that enhances the dust storm effect (Figure 9). Mountney & Russell (2004) gave an overview of the sedimentology of the area including geomorphological characteristics. The Dyngjusandur floodplain is partly blocked by surrounding mountains. Arnalds and Metúsalemsson (unpublished data) estimated from satellite images that the combined plume area was 30 km², while the size of Dyngjusandur is about 270 km² (Mountney & Russell 2004). The more coarse saltating sand is mostly blown northeastwards, where huge piles are found at the northern part of the Dyngjusandur area. Some of the sandy materials from the northern edge of the Vatnajökull are blown northwards to form pathways that can be tens of km long, stretching far into the Ódáðahraun deserts (see Arnalds 1992). Examples of dust plumes from Dyngjusandur are shown on satellite images in Figure 8a-b, and the estimated area that receives dust from this plume area is marked on the map in Figure 7.

P2 - Hagavatn. South of the Langjökull Glacier are glacial lakes with unstable water levels and shores with unstable fine-silty materials that commonly cause the formation of noticeable dust plumes driven by strong northerly winds (Figure 10). The materials are both tephra and crystalline basalt, as the glacier has previously advanced over older Holocene lava though it is presently retreating. In addition,

some glacial meltwater infiltrates into the porous bedrock at the glacial margin, leaving loose deposits on the surface. Aeolian processes in this area were investigated by Gísladóttir et al. (2005). Saltating materials are carried along to the south and are trapped at the Rótarsandur depression. The main deposition area of the dust materials stretches towards the south and southwest. An example of plumes from the Hagavatn area is shown in Figure 8c.

P3 - Leirá/Múlakvísl glacial rivers. The Leirá and Múlakvísl are glacial rivers southeast of the Mýrdalsjökull glacier in South Iceland that carry heavy suspended loads which create floodplains of loose silty materials (see also S6 sandy area).

P4 - Landeyjasandur. This area is both a coastal area and a floodplain of the Markarfljót glacial river. Plumes from this area are common and in some SE winds, dust is carried inland. Examples of plumes from P3 and P4 areas are shown in Figure 8d.

P5 - Mælifellssandur. North of the Mýrdalsjökull Glacier is a glacio-fluvial plain that undergoes widespread flooding during peak summer melting of the glacier, leaving unstable silty materials behind. It is assumed that most of the dust is carried southeast from the area, but dry westerly winds (southwest to northwest) can also carry dust eastwards from the Mælifellssandur area.

Figure 11. Dust being emitted in Flosaskarð (P6), where glacial meltwater disappears into porous bedrock leaving fine silty sediments on the surface. Photo: Ó. Arnalds

P6 - Flosaskarð (Eiríksjökull) area. Glacial meltwater seeps into the porous bedrock in this area, leaving fine silty materials on the surface. Dust plumes from this area are common, especially during strong and dry easterly winds (Figure 11).

P7 - Skeiðarársandur. There are large plume areas in the extensive Skeiðarársandur flood-plain, mostly related to the ever-changing glacial meltwater channels in the sandur area (see also S7). Periodic large scale floods caused by sudden drainage of trapped melt-water under the glacier and floods caused by volcanic eruptions periodically contribute to the formation of plume source areas.

P8 - P12. Other plume source areas. There are notable source areas that have been observed in the field and on satellite images marked on Figure 7 (the smaller circles). Their impact area can be considered to add to deposition of the other sandy and plume areas. Plume areas 9 (Hágöngur) and 12 (Hálslón) are on the shores of hydroelectric reservoirs with large fluctuations in water levels.

Redistribution of soils
It is often assumed that much of the aeolian material deposited in Iceland are Brown Andosols being transported and re-deposited because of wind erosion of such soils in the neighborhood. This material would therefore originate from soils under vegetation that undergo various land degradation processes (see e.g. Dougmore et al. 2009). Investigation of the mineralogy of the deposition materials reveals that this is often true (Stoops et al. 2008, Guðbergsson 1975) where easily identifiable rhyolitic tephra grains from Hekla eruptions > 900 yrs old are found in younger surface horizons. Arnalds (2000) stressed that this redistribution may have been more effective during active erosion periods during the Middle Ages, especially in so-called 'rofabard' areas. The AUI Ýmir soil database confirms a more rapid erosion phase during the Middle Ages, resulting in much lower organic content in horizons that developed during that time (Óskarsson et al. 2004). This effect is, however, quite site-dependent and is not the subject of the investigation presented here.

Volcanic eruptions
Volcanic eruptions add considerable mineral matter to soil profiles throughout the country, but this effect is most pronounced near the most active volcanoes, such as Hekla, Katla and Grímsvötn. Volcanic eruptions are responsible for large quantities of loose surface materials in many areas, which again are sources for aeolian redistribution, and these areas are

part of the sandy areas shown on the maps in this paper. The recent Eyjafjallajökull eruption (May 2010) has resulted in huge dust emissions while the volcanic ash has been still unstable after the eruption, causing poor air quality in the capital Reykjavik >100 km away in dust events during May 2010.

Effect of season

A large proportion of Iceland is covered with snow in wintertime, however with great variability between and within years. Inland areas are in general expected to be covered with snow or to be moist (thaw events) during winter, for example in the important Dyngjusandur area. There is, however, a possibility of dust events throughout the year from the southern coastal areas. This affects the total amount of aeolian deposition to be expected, with less winter deposition in all other areas except the south. Some inland areas, such as Dyngjusandur, make up for it by the high frequency of storms during summer. This is considered in outline the overall map for aeolian deposition in this paper.

Spatial distribution of aeolian materials and deposition rates

An attempt was made to combine maps of aeolian deposition from the sandy areas and plume areas in Figure 12. The sandy desert areas are also shown. The largest areas with low deposition rates are in Northwest Iceland and on the Vestfjord Peninsula. Other such areas are located at the northern and eastern tips of the country. North and West Iceland experience a medium level of dust deposition. The areas experiencing by far the most aeolian deposition are in South Iceland where there are both many plume areas, which are active most of the year, and extensive sandy deserts. The area also receives deposition from active volcanoes from time to time. Northeast Iceland receives large amounts of aeolian deposition from the Dyngjusandur plume area and other smaller plume areas. The Northeast sandy deserts also contribute to dust,
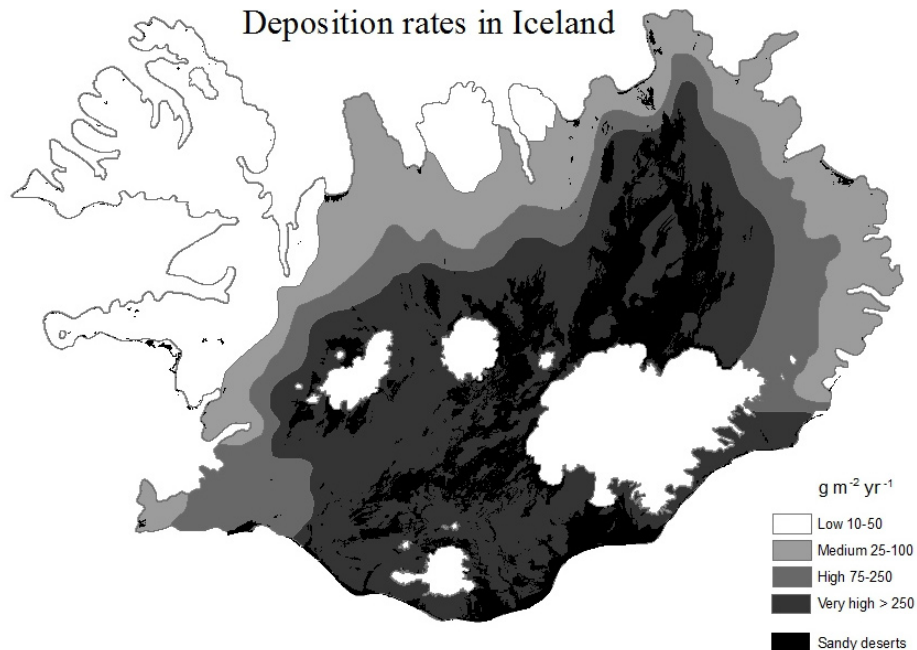

Figure 12. Aeolian deposition in Iceland. First approximation. The map is based on deposition rates and references presented in Table 3, distribution from plume areas (Figure 7) and sandy areas (Figure 5). Rate categories represent a range of deposition values, as factors such as topography and wind patterns affect the distribution.

as they are quite unstable in many locations, such as along the Jökulsá á Fjöllum river-bed, areas close to Dyngjusandur (P1) and along identified saltation pathways in the Ódáðahraun and Mývatnsöræfi areas (Arnalds 1992).

Using existing soil thickening rates, it is concluded that deposition rates on relatively level vegetated dryland areas varies from about 10 to 50 g m^{-2} yr^{-1} in areas far from aeolian sources, such as at the Vestfjord Peninsula, with an intermediate range of 25 to 100 g m^{-2} yr^{-1} relatively closer to aeolian sources, and rates of >75 g m^{-2} yr^{-1} close to source areas. The highest rates within the main deposition areas reach > 500 g m^{-2} yr^{-1} (Table 3).

Lawrence and Neff (2009) surveyed world plume areas and reported deposition rates from a variety of sources as 0.05 to 450 g m^{-2} yr^{-1} with 0.05 to 1 g m^{-2} yr^{-1} in areas > 1000 km from „primary and secondary source regions" and with global deposition rates under 1 g m^{-2} yr^{-1}. They further found that areas 10 to 1000 km located from regional dust sources experience dust inputs of 1 to 50 g m^{-2} yr^{-1} with 20 to 50 g m^{-2} yr^{-1} located near primary sources and

1 to 20 g m^{-2} yr^{-1} near secondary source regions. Deposition rates in Iceland exceed the highest number, 450 g m^{-2} yr^{-1} reported in their overview. This comparison highlights the fact that aeolian activity in Iceland is intense in terms of a global perspective, with more active redistribution of volcanic aeolian sediments than found elsewhere on Earth.

The Icelandic aeolian source areas are diverse in nature, considering the number of areas, their surface characteristics, seasonal snow cover, surface roughness and particle size. Kjaran and Sigurjónsson (2004) calculated about a 1 to 5 kg m^{-2} dust emission from an area similar to Dyngjusandur area (Plume P1), however in a major event. This emission rate is within a similar range Washington et al. (2006) reported for the Bodélé Depression in Chad which they consider 'the planet's largest single dust source', but in addition to rapid emission rates, the Chad source is about 200,000 km^2 in area (twice the size of Iceland). The plume area at Dyngjusandur is about 30 km^2. A range of 1 to 5 kg m^{-2} emissions (from Kjaran & Sigurjónsson 2004) in 5-20 plume events per year on average would result in 10 to 200 g m^{-2} dep-

Table 3. Typical deposition rates on Icelandic vegetated surfaces, excluding direct tephra deposition, for the last 500 years. Dryland soils (Brown Andosols) used as reference. Bulk density becomes lower with more organic content and finer particle size at a distance from the aeolian sources. Calculation of deposition rate considers both bulk density and organic content. Attempt made to adjust and/or exclude examples of thickening rates associated with wetlands (higher organic carbon) and at the edge of 'rofabards', which commonly give 1-2 mm yr^{-1} but overestimate thickening rates. Losses due to chemical weathering are not considered.

Deposition rating on map	Thickening rate[$]	Reference[$]	Bulk density	Organic matter	Depth[&]	Mineral matter	Deposition rate
	mm yr^{-1}		g cm^{-3}	%	mm	kg	g m^{-2} yr^{-1}
Very high	1	1,2b,3,5,6	0.85	5	500	403	807
Very high	0.8	1,2b,3,6	0.75	5	400	285	569
High	0.6	1,2ab,4,6,7,8,9	0.7	7	300	195	391
High	0.4	1,2a,4,6,7,8	0.7	8	200	128	256
Medium	0.2	2a,4,6,8	0.65	10	100	58	117
Medium	0.1	2a,6,8	0.65	10	50	27	54
Low	0.05	6	0.6	14	25	13	26
Low	0.025	6	0.6	14	12	7	13

[$]: dryland soils. [&]: depth accumulated over 500 yr deposition and soil development. References indicated in third column are 1: Thórarinsson 1961; 2: Guðbergsson 1975, a) northerly Skagafjörður, b) southerly Skagafjörður; 3: Sigbjarnason 1969; 4: Arnalds 1980; 5: Arnalds & Gísladóttir 2001; 6: AUI Soil Database (Ýmir); 7: Gísladóttir et al. 2010; 8: Dust trap measurements (Björnsson 2006, Guðmundsdóttir 2007-2009; 9: Strachan et al. 1998).

osition if evenly distributed within the 15,000 km^2 contour area shown on Figure 7 for the P1 area. The Northeast sandy area (S1) could potentially result in similar deposition (much larger area, much less dust emission per unit area). These computations are in good general agreement with the deposition rates presented in Table 3 and are supported by measured deposition rates adjusted to soil bulk density and organic matter, and dust trap measurements (references given with Table 3).

Aeolian processes, soil properties and the soil map

The rate of deposition together with grain size characteristics, which depend on distance from aeolian, sources are important factors that impact soil formation. The finer materials deposited far from aeolian sources and slower deposition rates lead to higher clay content in each soil horizon, in a relatively 'calm' soil environment in freely drained soils (Brown Andosols). The weathering of the basaltic tephra releases cations such as Ca^{++}, K$^+$, Na$^+$ and Mg^{++}, which influence soil pH. Soil pH is typically higher near aeolian sources than at a distance. A range for important soil properties within each of the deposition rate categories is presented in Table 4.

Areas receiving rapid rates of aeolian deposition tend to have low clay content (5 to 15%) and carbon content (1.5 to 4%) in freely drained soils under vegetation. Wetland soils that develop far from aeolian sources tend to have a relatively high organic content (Histosols with >20% C in surface horizons) with intermediate levels closer to sources (Histic Andosols, 12 to 20 %; Icelandic classification

scheme). Wetlands close to aeolian sources have low organic content in spite of their northerly global location (Gleyic Andosols, < 12% C; Icelandic classification scheme). Formation of allophane, the main clay constituent of Icelandic soils, is inhibited at a pH below 4.9, and is at optimum around pH 6. This results in the highest clay content with moderate aeolian inputs or drylands at a distance from aeolian sources. Soil reaction close to aeolian sources is commonly 6-7 while pH in the peatlands on the Vestfjord Peninsula has been measured as low as 4 (Arnalds 2008).

It should be noted that although absolute values for clays and/or carbon may be higher in soil horizons outside the major deposition areas, the total values (kg m^{-2}) for each profile or given time frame (e.g., 1000 years) may be higher within the main aeolian zones as the soils are becoming thicker at a more rapid rate, with faster burying of horizons.

CONCLUSIONS

Satellite images reveal dust plumes extend > 400 km into the ocean south of Iceland (Arnalds & Metúsalemsson 2004) and the effect of Icelandic dust is measured in Ireland (Ovadnevaite et al. 2009). Icelandic dust sources are normally not considered to be major global dust sources (e.g. Lawrence & Neff 2009) but undoubtedly belong there, as deposition rates in Iceland are comparable to or higher than those found in areas close to other Earth's active dust plumes. The dust plumes from Iceland carry large quantities of easily weathered volcanic materials over the ocean south of Iceland, possibly contributing several important nutrients to these ecosystems, but the influence of the aeolian dust on the oceanic systems is beyond the scope of this paper. The dust emissions from Iceland are noteworthy in the light of its sub-arctic location and moist climate. Dust emissions result from frequent high wind speeds combined with large sandy desert areas that are sus-

Table 4. Aeolian deposition rates and important soil properties. A general range is given for these properties, but large variation is expected. Numbers are based on the AUI soil database.

Deposition rate	Dryland soils %C	Wetland soils %C	Dryland soils % clay	Wetland soils pH
Low	6 - 9	>20	20 - 35	4 - 5
Medium	5 - 7	12 - 20	15 - 45	4.5 - 5.5
High	3 - 5	6 - 12	10 - 20	5 - 6.5
Very high	1.5 - 4	< 6	5 - 15	6 - 7

ceptible to wind erosion and numerous active plume areas.

The plume areas which are responsible for a large part of aeolian deposition in Iceland are in most cases a result of development at glacial margins or deposits of flooding rivers. The aerial extent of plume areas can be expected to increase with glacial retreat associated with global warming. This could increase atmospheric dust from Iceland substantially in the future.

Many of the plume areas occur at high elevations and are subjected to frequent flooding. They are not necessarily target areas of wind erosion control, especially if they do not threaten valuable ecosystems, human health and activities. However, some of the southern areas pose potential problems because of frequent dust emissions over populated areas.

The maps showing aeolian deposition do explain many of the main characteristics of soil formation in Iceland, stressing the importance of sandy areas and dust source areas in shaping Icelandic ecosystems. Basaltic tephra carried over Icelandic soils rejuvenate the systems with cations upon chemical weathering of the highly reactive basaltic glass (Gíslason 2008). This process helps maintain the favorable pH of Icelandic soils and their fertility, but only at a suitable distance from aeolian sources. On the other hand, coarse materials within the major deposition areas have a negative effect on the hydrology of soils. Rapid deposition slows the formation of allophane and ferrihydrate clay minerals that greatly enhance the fertility of Icelandic soils.

Dust formation and aeolian deposition in Iceland is often considered a result of anthropogenic disturbance of andic soil materials, considered the major component of the aeolian distribution. The importance of this factor is most likely overemphasized in present-day Iceland. However, it was undoubtedly more important during the Middle Ages (Arnalds 2000, Óskarsson et al. 2004). The formation of most major dust-plume areas is not or is only partly related to anthropogenic disturbance. On the other hand, the formation of some of the

sandy deserts, which also serve as a source of aeolian materials, is often associated with human-induced land degradation. The results imply that rates of aeolian deposition and rates of soil thickening need to be interpreted with caution.

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