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THE NATURE AND RESTORATION OF DENUDED AREAS IN ICELAND

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ABSTRACT

Denuded areas in Iceland can be divided into the following categories: glacial deposits, sandy areas, postglacial lavas, alluvial and colluvial materials, and areas covered with pumice. Of these, glacial deposits are most extensive. The paper describes the nature of the denuded areas with emphasis on the glacial deposits. The denuded glacial deposits generally have sparse plant cover ($<5\%$) and suffer from wind abrasion and cryoturbation. The soils are deficient in organic matter (about 1%). The texture is sand and loamy sand. Despite the lack of organic materials and the coarse texture, the sum of exchangeable cations ranges from 5 to 15 meq 100 g^{-1} dry soil.

Revegetation with agronomic grasses and fertilization under subarctic conditions in the Icelandic highlands has increased the vegetative cover to over 50% after 5 yr of fertilization. Little increase in soil organic matter is apparent after 5 yr.

Objectives for revegetation in Iceland include (1) reclamation of disturbed areas; (2) stabilization of moving sand; (3) prevention of soil erosion; (4) forage production; (5) aesthetic reasons; and (6) restoration. Slow natural restoration is attributed to grazing, low temperatures, freeze-thaw cycles and needle ice, abrasion due to wind erosion, desiccation, lack of seed sources, low biological activity, low nutrient status, and leaching of nutrients.

INTRODUCTION

Few areas in the circumpolar regions have suffered as severe ecosystem disturbance as Iceland. It is estimated that when Iceland was settled in 874 about 65% of the country was vegetated, but vegetative cover is now about 25% (Thorsteinsson, 1978). This decline is a result of accelerated erosion that began shortly after the settlement (Thórarinsson, 1961) and is still destroying valuable rangelands.

Farming in Iceland is mostly confined to the lowlands, while highlands are communal grazing areas. Extensive vegetative cover has been lost both in the lowlands and in the highlands due to erosion. Most severe losses have been in the highlands within the active volcanic regions. Highlands are defined here as areas above 400 m in southern Iceland and above 300 m in northern Iceland. The climate is mostly maritime, cold-temperate in the lowlands, but is classified as low arctic in the highlands and in some parts of the lowlands in northern Iceland (M. Einarsson, 1976).

Thorsteinsson et al. (1971) and A. Arnalds (1987, this volume) have reviewed the causes and the extent of soil erosion in Iceland. This paper describes some of the characteristics of the denuded areas and revegetation efforts; several aspects of revegetation and restoration in Iceland will also be discussed.

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Icelandic soils can be divided into dryland (Andic) and wetland (Organic) soils, the dryland soils being more susceptible to soil erosion. The soils are silty, the mineral fraction of most soils being deposited by eolian processes. The profile is often characterized by many and sometimes thick ashlayers which can erode very easily (O. Arnalds, 1984).

We consider the interaction of livestock grazing, vulnerable soils, cold climate, and volcanic ashfall events to be the main reason for the extensive erosion in Iceland. Heavy livestock grazing, mainly by sheep, reduces the ability of the vegetation to withstand environmental hazards, such as cold spells and ashfall events, which have resulted in accelerated erosion (O. Arnalds, 1981).

Water erosion in Iceland occurs primarily on sloping landscapes, where gullies are formed. There are two main processes of wind erosion in the country. During the first process, eolian materials, commonly volcanic ash from ashfall events or soils from erosion, are deposited rapidly on vegetation. The resulting abrasion and burial eventually kills the vegetation. Subsequently, the soil surface becomes unstable and exposed to erosion, and the soil materials that formerly were under the vegetation are added to the pool of materials that the wind can use for further erosion. Once the vegetation has been destroyed, the soils are most often removed right down to bedrock. The fronts formed during this process can be several kilometers long, and movement of up to 100 m in a year has been observed. The second process is the removal of soil materials by wind from erosion banks, enhanced by saltation movement of soil grains, often tephra. These erosion banks are the Icelandic "rofabards," where the whole vertical soil profile is exposed to the wind and is removed with erosion down to the underlying bedrock which often is glacial material. Because all these soil erosion processes strip the surface of soil materials, the denuded surface is almost devoid of belowground plant tissue and subsequent vegetation succession can be considered primary.

Few attempts have been made to classify eroded surfaces in Iceland. The following is a simple classification

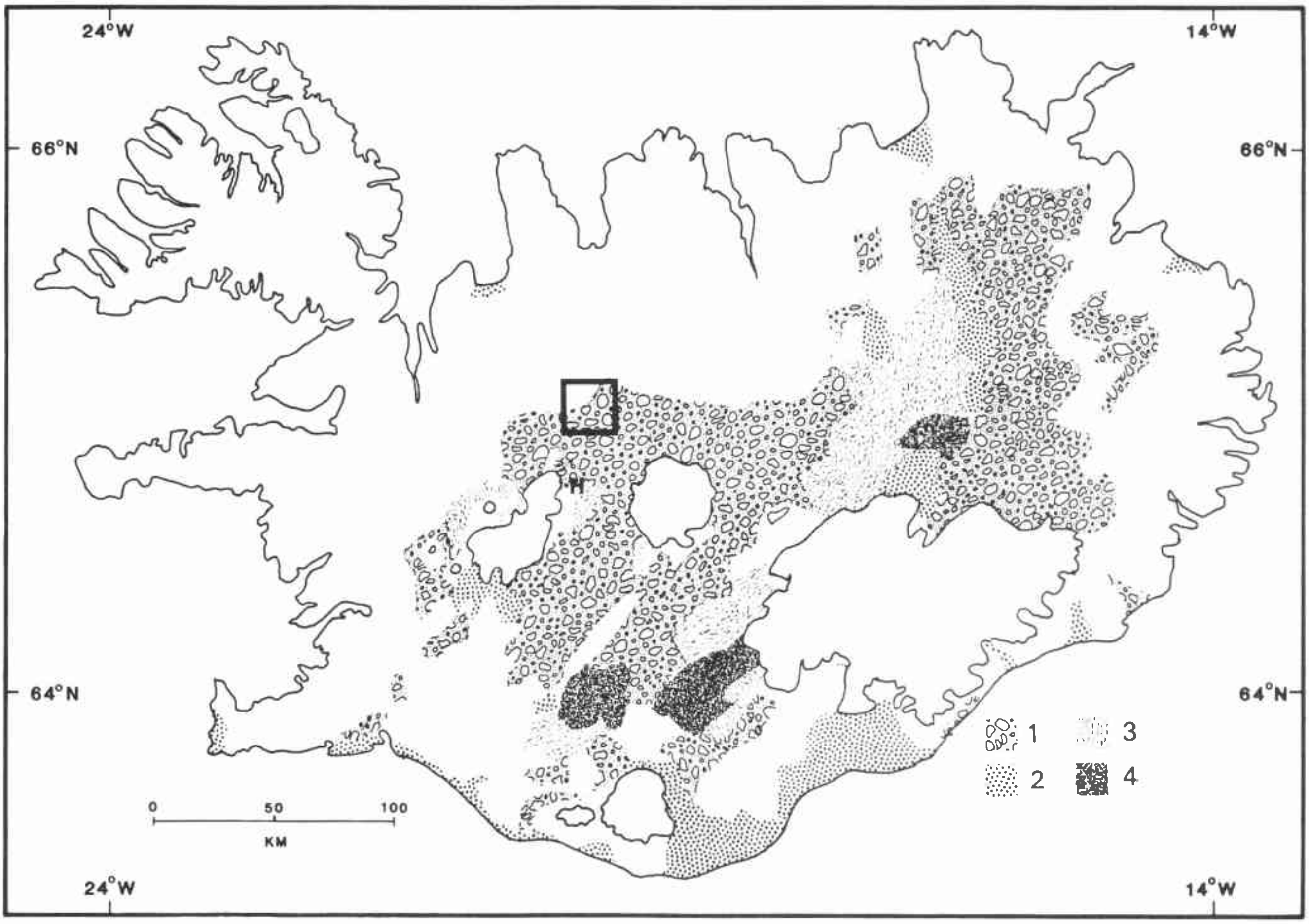

FIGURE 1. Denuded areas in Iceland. 1—Glacial deposits; 2—Sandy areas; 3—Postglacial lavas; 4—Pumice; H—Hveravellir weather station; Square—The Blanda area.

of the denuded areas:

(1) Glacial deposits.
(2) Sandy areas.
(3) Postglacial lavas.
(4) Alluvial and colluvial materials.
(5) Areas covered with pumice.

A map of denuded areas (Figure 1), although incomplete, gives an indication of the extent of denuded areas in Iceland. Alluvial and colluvial materials are mostly included with glacial deposits on the map, but these areas often occur in smaller sections within the other areas. The map is largely based on a soil map prepared by the University Research Institute and Nygaard (1959), together with the aid of vegetation maps and our own observations.

Glacial deposits constitute the largest area of denuded land. These areas are characterized by gently rolling landscape and a wide range of grain size on the surface, from silty materials to large boulders. The sandy areas include glaciofluvial materials at the margins of the glaciers, beach dunes, and on recent lavas. Many of the postglacial lavas have become denuded since the settlement, but there are also extensive recent lavas that are not yet vegetated. Alluvial and colluvial materials refer to materials coarser than sand, such as alluvial gravel at valley bottoms and colluvial at footslopes. Large areas within the volcanic zone in Iceland are covered with pumice, especially west of Vatnajökull glacier, and the areas around the volcanoes Hekla and Askja.

NATURE OF DENUDED AREAS

Surface Characteristics

Vegetation cover of denuded areas is commonly less than 5%, and often about 1%, especially on sand and pumice. Vegetation cover on denuded glacial deposits and on colluvial and alluvial materials usually does not exceed 10%, and is commonly around 1 to 2%. Common plant species are *Armeria vulgaris, Arenaria norvegica, Cardaminopsis petraea, Cerastium alpinum, Festuca rubra, Festuca vivipara, Poa alpina, Poa glauca,* and *Silene maritima.* These plant species are hardy perennials and often deep rooted.

The surface of denuded glacial deposits is gravelly and sandy and has a desert pavement concentration of boulders on the surface. The surface characteristics of other denuded areas is diverse. The sandy and alluvial areas commonly have textural properties similar to those of the denuded glacial areas, but more soil movement by wind occurs on the surface of the sandy areas. Denuded lavas are mostly devoid of loose materials on the surface but sand drift is common in unvegetated lavas.

Soils

Soils on denuded glacial deposits have thin A/Bw profiles. At the top is a coarse textured A horizon, low in organic matter (0.5 to 1.0 %C), often about 4 cm thick (Table 1). Below the surface layer is a horizon which is tentatively designated Bw. This horizon is finer grained than the A horizon. At the bottom is glacial till. The Bw horizon has on average slightly higher organic matter content and higher sum of cations than the A horizon. The same pattern has been recorded for many other profiles elsewhere on denuded glacial deposits in Iceland (O. Arnalds, unpublished data). Some of the plant species mentioned earlier have root systems that extend into the

Table 1

Soil properties of denuded land in the Blanda area[a]

Horizon	Depth (cm)	pH	C (%)	N (%)	C/N	CEC (meq 100 g^{-1}) K	Na	Ca	Mg	Sum
Site 4 (revegetated, level land)										
A	0– 4	6.2	1.0			0.1	0.2	5.5	1.8	7.7
Bw	4–14	6.8	1.4			0.7	0.2	9.1	3.7	13.2
BC	14–		0.2							
Site 6 (revegetated, exposed hill)										
A	0– 4	6.9	0.5			0.2	0.2	6.8	3.4	10.6
Bw	4– 7	6.8	1.7			0.1	0.3	11.8	4.5	16.8
Site 6 (revegetated, depression)										
A	0– 5	5.5	0.9	0.07	12.9	0.2	0.2	4.8	1.4	6.6
Bw	5–45	6.5	1.6	0.12	13.3	0.2	0.4	13.1	5.4	19.4
C	45–	6.5	0.1			0.3	0.2	9.9	0.5	11.0

[a]pH was measured in saturated paste, organic C by Walkley-Black (Nelson and Sommers, 1982), nitrogen by Kjeldahl, cations by ammonium acetate exchange at pH 7 (Thomas, 1982).

B horizon, which forms an environment more favorable for root growth than the A horizon. Potassium content of the soil is relatively low (0.1 to 1 meq 100 g^{-1}), as are both nitrogen and phosphorus contents. The soils are coarse and the textural class is sand or loamy sand, with total silt and clay generally less than 10%.

There are several possible explanations for the formation and nature of the Bw horizon in denuded glacial deposits, such as (1) roots may have contributed organic matter to the horizon; (2) frostheaving of gravel may explain the textural differences between the A and the B horizons; and (3) the organic content of the B horizon may in places be remnants of an A or AC horizon of the soil that covered the area before it became eroded. The last is possible if the lowest part of the previous existing A/C profile has been protected by gravel that was heaved by frost action up into the soil from the underlying till. All of these explanations may apply to some extent.

In contrast to the soils of denuded areas, the CEC of Icelandic dryland soils is commonly between 30 and 50 meq 100 g^{-1} dry soil. This high cation exchange capacity is related to high organic content (6 to 10 %C), which extends from the top of the soils down to bedrock (Helgason, 1968). Tu (1960) found allophane or allophane-like materials in Icelandic soils, which may partly explain the high exchange capacities.

Jóhannesson (1960) and Gunnlaugsdóttir (1982) presented soil data for sandy areas of both alluvial and eolian origin. Although the Bw horizon is usually not present, chemical properties are similar to the soil of glacial deposits described here.

REVEGETATION

The denuded areas recover slowly by natural means, especially at higher elevations. There are areas that apparently became denuded relatively early after the settlement, 1100 yr ago, and still have little vegetative cover, whereas natural vegetation establishment has taken only some decades in other areas (Iceland Ministry of Agriculture, 1986; Runólfsson, 1987, this volume). No attempt has been made to compare different "recovery rates" of the different environments in Iceland.

Large areas in the south Icelandic lowlands have been reclaimed with commercial grasses and fertilization and are now being used for grazing and haymaking. Revegetation experiments with commercial grass seed and fertilizer at higher elevations have also been successful. Fridriksson and Pálsson (1970) showed that seeding with *Festuca rubra* and fertilization, and sometimes fertilization alone, increased vegetative cover of denuded plots up to 70 to 80% in the highlands of central Iceland. They concluded that the vegetation mat would increase the water retention of the soil and halt movement of erosive sand, and that the vegetation might also be used as a summer pasture for sheep. The study indicated that the vegetative cover would be retained for at least a few years without continued fertilization. Other studies by Fridriksson in south-central Iceland (1969) and in central Iceland (1960) gave similar results.

The Blanda Revegetation Program

Based on these and other earlier experiments, revegetation on a large scale was conducted in the Blanda area in north-central Iceland. A dam for hydroelectrical purposes is being built in the area, and extensive rangelands will be submerged by the reservoir. Denuded glacial deposits in the neighborhood of the reservoir were selected for revegetation. This revegetation program is an example of such efforts in the Icelandic highlands. More detailed descriptions of this revegetation research is found in Arnalds and Pálmason (1986), Thorsteinsson et al. (1986), and Aradóttir et al. (1987). There are two main objectives for the revegetation program in the Blanda area: (1) Forage production as a compensation for the loss of rangelands; (2) Study of the effects of various factors on the success of revegetation, such as different grass varieties, fertilizer application rates, and environmental factors like soils, elevation, existing vegetation, and grazing pressure (Thorgeirsson et al., 1982).

The revegetation was started in 1981 at six sites, 17 to 35 ha each, for a total of 142 ha. Five of the sites were seeded with grasses and fertilized, but site 4 was only fertilized to promote the growth of the existing vegetation. The grasses used were varieties of *Festuca rubra* and *Poa pratensis,* the fertilizer used was 23-23 N-P_2O_5, and the annual application was 400 kg ha^{-1}. The seeds and fertilizer were applied by an aircraft.

When selecting species for revegetation in Iceland, especially in the highlands, winter hardiness and ability to complete the life cycle during a short and cold growing season are among the most important factors that need to be considered. Many different grass species have been tested in field-plot experiments adjacent to the revegetation sites, and some results have already been published (e.g., Helgadóttir and Tómasson, 1983).

The surface of the denuded land in the Blanda area is dominated by glacial deposits. The elevation of the study sites ranges from 470 to 620 m. The closest weather station is at Hveravellir (Figure 1, Table 2). The mean monthly temperature in June, July, and August, which is approximately the growing season, was about 6°C in 1981 to 1985, the mean monthly precipitation was 55 to 83 mm for the same months. However, there is large year to year variability in the climate (Table 2). The sites have been grazed by sheep and horses during the summer, but 5-ha exclosures were fenced off within each area. Vegetation cover of the sites has been monitored throughout the study period.

In this paper, results are presented from two of the revegetated sites in the Blanda area, sites 3 and 4. The elevation of site 3 is 500 to 520 m, and its initial plant cover

TABLE 2

Mean temperature and precipitation at Hveravellir, Iceland during 1981–1985 (elevation 641 m)

	May	June	July	Aug.	Sept.	Year
Temperature (°C)						
Mean	0.4	5.4	6.8	6.0	1.8	-1.4
Min.	-0.6	3.6	5.6	5.2	0.4	-2.0
Max.	1.6	6.7	9.0	7.1	3.0	-0.7
Precipitation (mm)						
Mean	20	55	59	83	33	719
Min.	1	40	33	44	15	559
Max.	26	68	94	111	40	813

Source: Vedurstofa Islands: Vedráttan 1981–1985. Monthly and annual climatological summaries.

was 10%. It was both seeded and fertilized in 1981. Site 4 is at 470 to 510 m, and it had an initial plant cover of 28%. Because of the relatively high initial plant cover, site 4 was not seeded, only fertilized from 1981 to enhance the growth of native species. Growing conditions are similar for the two sites, except that site 4 has a slight south-facing aspect, and more favorable soil conditions. Site 4 is also closer to vegetated areas, hence more natural seed rain can be expected.

Vegetative cover increased at both sites for the 5 yr of the study (Figure 2). Cover increased from 10 to 57% at site 3, and from 28 to 70% at site 4. The increase was more rapid on the protected areas, and resulted in 84 and 88% cover on sites 3 and 4, respectively. The increase in cover is largely due to increase in grass cover and to the accumulation of standing dead material, especialy on the protected areas (Table 3). The increase in grass cover is very similar at the two sites, even though site 3 was seeded in the beginning and site 4 was not. However, there is more standing dead material at site 3, because of more winter kill at that site, especially in the protected area, where the seeded *Poa pratensis* suffered serious winter kill during the winter of 1984/85. Most important native grass species at both sites are *Poa glauca, P. alpina,* and *Festuca rubra,* together with *F. vivipara* and *Agrostis canina* at site 4.

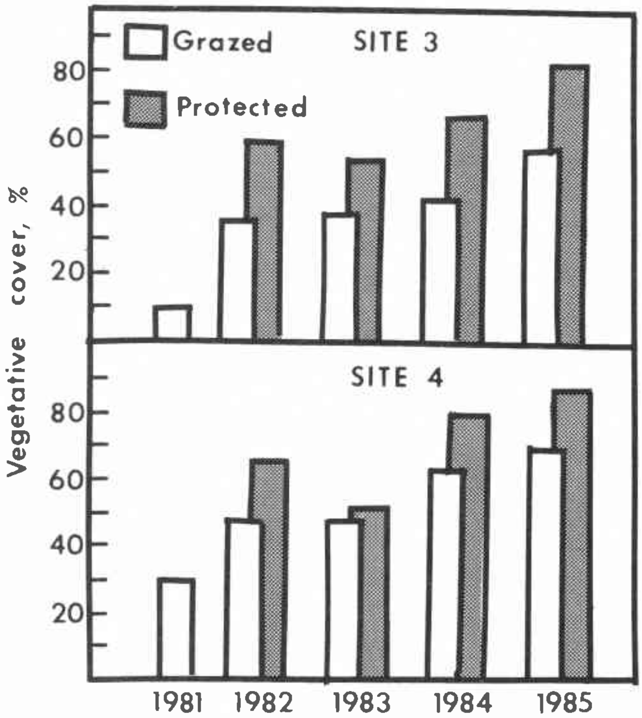

FIGURE 2. Changes in total vegetation cover at revegetated sites in the Blanda area from 1981 to 1985.

There has been a slight, but statistically insignificant, increase in the organic content of the soil on the revegetated areas (Table 4). This indicates that buildup of organic matter to natural levels (6 to 10 %C) will take a long time, especially on heavily grazed areas.

The revegetated areas have attracted large numbers of sheep and have consequently been heavily grazed throughout the 5-yr study period. This has resulted in reduced grazing pressure on nearby vegetation, which should improve the condition of the latter and decrease erosion susceptibility.

TABLE 3

Composition of vegetative cover (%) at the revegetation sites

	Site 3			Site 4		
	1981[a]	1985[b] Grazed	1985[b] Protected	1981[a]	1985[b] Grazed	1985[b] Protected
Monocotelydons	5	34	19	10	38	27
Dicotelydons	5	7	7	15	22	11
Bryophytes and lichens	—	4	5	3	5	12
Standing dead material	—	12	53	—	5	38
Total	10	57	84	28	70	88
Number of quadrats	102	354	38	153	255	39

[a]Cover estimates in 0.25-m² quadrats.
[b]Cover estimates in 0.1-m² quadrats.

Goals of Revegetation

Johnson and Van Cleve (1976) defined revegetation as to reestablish vegetative cover over disturbed lands but restoration as bringing back to former condition. Bradshaw and Chadwick (1980) defined restoration as when land is returned to its former use. They used the term to describe activities which seek to upgrade or recreate damaged or destroyed land and bring it back to beneficial use, in a form in which the biological potential is restored.

There can be many objectives for revegetation of an area. The objectives, with reference to Icelandic conditions, can broadly be divided into the following categories:

(1) To reclaim severely disturbed areas.
(2) To stabilize moving sand.
(3) To prevent soil erosion.
(4) To increase forage production.
(5) To promote aesthetics.
(6) To contribute to restoration.

Before revegetation programs are started, it is necessary to define the goals of each operation. As stressed by Johnson and Van Cleve (1976), the most important reason for clarifying objectives, however often overlooked, is that these may dictate what revegetation techniques should be used. They further stated that revegetation can simultaneously accomplish a number of objectives, but one must recognize that some of the objectives may conflict.

Stabilizing moving sand and preventing soil erosion have been the most important objectives of revegetation in Iceland in order to prevent further destruction of Icelandic ecosystems. Revegetation in Iceland has primarily been conducted with agronomic grasses and fertilization, while native *Elymus arenarius* has been used to stabilize moving sand (Runólfsson, 1987, this volume). Forage production has been an increasingly important goal of revegetation. A conflict between aesthetic values and forage production may rise in the future in Iceland, as artificial seeding and continuous fertilizing sustains a vegetative system that may be questioned from the aesthetic point of view. Where a conflict may arise, it is important to differentiate between forage production on one hand and aesthetic objectives and restoration on the other.

Restoration Perspectives

Restoration is often the ultimate goal of revegetation. Natural restoration, without human influence, does occur in the Icelandic lowlands, especially in areas that are protected from grazing (Iceland Ministry of Agriculture, 1986). This kind of restoration has, however, not been well documented nor studied. Revegetation in the lowlands can accelerate restoration by stabilizing the surface and providing seedbed for native species. Fertilization aids rapid establishment of plant cover on the nutrient deficient denuded areas. Little is known of fertilizer requirements of native species in Iceland, and fertilizer rates have been suited to the needs of introduced agronomic grasses. Chapin (1983) pointed out that revegetation of nutrient deficient sites by agronomic grasses and other rapidly growing species may not lead to rapid community recovery and a self-sustaining plant community, due to their inherently high nutrient requirement. He suggested that restoration might be accomplished more successfully with the use of native grasses with low relative growth rates and nutrient requirements. Suitable native species for use in Iceland have not been identified yet.

Table 4
Organic C in top 10 cm of soil in the Blanda area

Treatment	%C	n	S.D.
Revegetated, protected	1.14	5	0.42
Revegetated, grazed	0.94	5	0.40
Denuded	0.83	5	0.46

The vast acreage of the denuded areas is an important factor to consider when restoration efforts are planned. The total area of denuded areas in Iceland is at least 40,000 km² (4.0 million ha) (Thorsteinsson, 1978). For comparison, the land that was disturbed by construction of the trans-Alaska pipeline is about 78,500 ha (Johnson, 1981), which gives an indication of the extent of the disturbance of Icelandic ecosystems during 1100 yr of settlement. Intensive restoration efforts are possible only on a small scale, but may be feasible to provide seed sources.

The revegetation studies that have been conducted so far indicate that areas at high elevations can be revegetated and that the vegetation can be maintained with continuous fertilization. Less is known about the duration of this vegetation if fertilization is discontinued. There are indications, however, that the vegetative cover will remain for at least a few years without fertilization (Fridriksson and Pálsson, 1970; Gunnlaugsdóttir, 1985). Succession and natural restoration in the highlands is very slow. A denuded area may still be in the first stages of succession, with low cover of vascular plants, several hundreds of years after the erosion took place. Little is known about succession in the highlands, but some succession studies have been conducted on recent lavas (e.g., Kristinsson, pers. comm., 1986) on a new volcanic island (Fridriksson, 1975; 1987, this volume), on nunataks (E. Einarsson, 1970), and on reclaimed areas (Gunnlaugsdóttir, 1985).

Some reasons for slow recovery of denuded areas at high elevations in Iceland are as follows:

(1) Grazing.
(2) Low temperature.
(3) Freeze-thaw cycles and formation of needle ice.
(4) Abrasion by blowing sand.
(5) Desiccation of the surface layer.
(6) Lack of seed bank and seed source.
(7) Low biological activity in the soil.

(8) Low nutrient status within the root zone.

(9) Leaching of nutrients.

Grazing undoubtedly prevents restoration, both in the lowlands and in the highlands and is perhaps the single most important factor that has prevented natural restoration. Protection from grazing is considered a prerequisite for successful reclamation (Runólfsson, 1987, this volume). As the vegetative cover is low and the areas are usually grazed, little seed rain is to be expected.

When areas become denuded, the microclimatic conditions become less favorable than on vegetated land. Natural restoration does take place in the lowlands, but to a much lesser extent in the highlands. Climate, primarily temperature, may play an important role in preventing natural restoration of the highlands. Some of the highlands have not recovered, even though they are not grazed. This leads to the possibility that vegetation establishment has occurred in the past under more favorable conditions than now exist. This hypothesis may be difficult to prove, but if it holds true, the vegetation remnants in the highlands are very valuable and must be preserved as a seed resource. A pilot study on the number of germinable seeds in soils of denuded glacial deposits indicated that the seed bank in the soil is very small (O. Arnalds, unpublished data).

The effect of temperature is both direct and indirect. Freeze-thaw cycles and needle-ice formation cause considerable soil movement, which is hazardous to seedlings and plants with shallow root systems. We expect the frequency of diurnal freeze-thaw cycles to decrease with increasing elevation (Fahey, 1973), but as the distance from the sea increases, decreasing oceanic effects could increase the number of freeze-thaw cycles in the highlands. Other effects of low temperature in the highlands are short growing season and slow rate of growth, which decrease seed production possibilities, little biological activity in the soil, and slow turnover rate due to slow decomposition.

Movement of soil materials by wind on the surface can be very destructive, especially on sandy surfaces but also on more stable denuded glacial deposits. This can prevent seedling establishment. The climate of Iceland is characterized by frequent winds, and desiccation of the surface is likely to be pronounced during dry periods as stressed by Brown et al. (1978) for alpine conditions.

No studies have been conducted on the biological activity of soils of denuded areas in Iceland. The data presented in Table 1 show that the soils contain little organic matter. The coarse nature of the soils undoubtedly results in leaching of nutrients as they become available, especially nitrate. All of the factors listed above need further research with regard to future revegetation and restoration.

CONCLUSION

Revegetation studies indicate that native species replace introduced grasses with time, even with continued fertilization (Fridriksson and Pálsson, 1970; Gunnlaugsdóttir, 1985). Potential seed sources are seed bank in the soil, vegetation remnants in each area, vegetation on denuded land, and seeds moved into the area with birds. The amount of seed rain from vegetations remnants is not known, nor is the extent of the seed rain. The vegetation remnants have species composition more similar to restored areas than does vegetation on denuded land. The remnants therefore may be an important source for the variety of species that enter the plant cover at later successional stages, and this makes these remnants all the more important to preserve. Fertilization alone may increase seed production if the plant cover is sufficient to respond.

We emphasize that more research is needed to clarify which factors inhibit natural succession of denuded areas in Iceland and how restoration of these areas can be enhanced in the most successful and economic way.

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