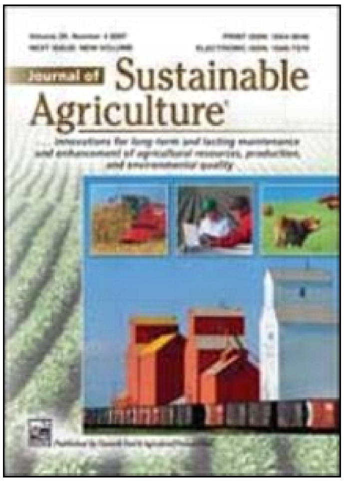

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Potential and Challenges of Soil Carbon Sequestration in Iceland

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Potential and Challenges of Soil Carbon Sequestration in Iceland

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Soils of Iceland are severely degraded and land resources desertified due to anthropogenic perturbations since AD. 875. Of the total area of 10.3 million hectares (Mha), the land area is 10.0 Mha. Land cover, at the time of settlement 1100 years ago comprised 6.5 Mha of vegetation cover, of which 3.0 Mha was birch (Betula pubescene) woodland and 3.5 Mha other vegetation. At present, the land area under some vegetation cover is only 2.8 Mha, of which highly productive birch cover is only 0.125 Mha. There are 3.7 Mha of severely eroded and barren lands in Iceland. The fossil fuel emission was 0.7 Tg C yr^{-1} in 1990, 0.82 Tg C yr^{-1} in 2000, and is projected to be 0.9 Tg C yr^{-1} in 2010 and 0.95 Tg C yr^{-1} in 2020. Afforestation and adoption of recommended management practices (RMPs) can lead to terrestrial C sequestration at the rate of 0.01 to 0.05 Mg C ha^{-1} yr^{-1} (1 Mg = megagram = 10^6 g = 1 tonne) in degraded rangeland soils by establishing native lyme grass (Leymus arenarius) and soil organic carbon (SOC) sequestration at the rate of 0.7 to 0.8 Mg C ha^{-1} yr^{-1} through N fertilization. Effective erosion control can lead to emission avoidance of 0.01 to 0.02 Tg C yr^{-1}, and restoration of eroded soils to C sequestration of about 1 Tg C yr^{-1}. Potential of terrestrial C sequestration in Iceland is 1.2 to 1.6 Tg C yr^{-1}, which can effectively offset fossil fuel emission by 2025 and beyond, and make Iceland an emission-free nation.

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KEYWORDS afforestation, deforestation, soil C sequestration, soil conservation, soil erosion

LAND USE IN ICELAND

Iceland, situated in the North Atlantic Ocean between 63° and 66° N, has a total area of 10.3 million hectares (Mha). The climate, affected by the Gulf Stream, is maritime cold temperate to sub-artic (Wastl et al., 2001) with annual rainfall ranging from 500 mm north of Vatnajokull glacier to over 2000 mm in South Iceland. Precipitation is adequate for vegetation growth in most parts of the country except in the Northeast region, which receives about 500 mm. Human settlement began around AD 874, when about two-thirds of the island may have been covered by vegetation (Karlsson, 2000). The initial vegetation cover, estimated at 6.5 Mha, comprised 3.0 Mha of birch woodland (*Betula pubescene*) and 3.5 Mha of other vegetation, including a native lyme grass (*Leymus arenarius*) (Magnusson, 1997; Hallsdottir and Caseldine, 2005). At present, only 2.8 Mha of the island have some vegetation cover, of which high productivity birch occupies 0.125 Mha and low productivity vegetation about 2.4 Mha. Barren deserts occupy about 3.7 Mha of Iceland (Magnusson, 1997).

Volcanic soils of Iceland are developed under high-latitude climates (Johannesson, 1960; Ó. Arnalds, 2003; Ó. Arnalds et al., 2000), and are highly sensitive to land degradation processes (A. Arnalds, 2000) and to climate change (Oskarsson et al., 2004; Gislason, 2005). Consequently, the soils and vegetation resources of Iceland have been severely degraded and desertified due to anthropogenic perturbations (Sigurdardottir, 2000; Gisladottir, 2001; Arnalds et al., 2001; Olafsdottir and Gudmundsson, 2002; Kardjilov et al., 2006). Degraded and desertified soils of Iceland are severely depleted of their Soil Organic Carbon (SOC) pool (Oskarsson et al., 2004), and there is a strong interest in restoring degraded soils and ecosystems. The objective of this manuscript is to collate, review, and synthesize the available research information on the extent and severity of soil degradation in Iceland, and assess the impact of restorative measures on potential of C sequestration in the terrestrial ecosystems in general, and soils of Iceland in particular.

POPULATION GROWTH AND FOSSIL FUEL EMISSION IN ICELAND

The population of Iceland has fluctuated widely throughout the history (Demarée et al., 2001), and was 255,000 in 1990, 282,000 in 2000 and 294,000 in 2005. It is projected to be 303,000 in 2010, 311,000 in 2015, 318,000 in 2020, 325,000 in 2025, and to stabilize at 330,000 by 2030 (FAO, 2000). The data on fossil fuel emissions in Iceland are shown in Table 1. The CO_2-C emission was 0.20 Tg in 1950, and 0.60 Tg in 2000 (Tg – teragram = 10^{12} g = 1 million Mg or tonne) (Ministry for the Environment, 1992; 2000). The per capita emission was 1.41 Mg yr^{-1} in 1950 and 2.10 Mg C yr^{-1} in 2002 (Table 1). In comparison, the per capita emission in the U.S. is 5 Mg yr^{-1} (Figure 1). Future emissions are expected to be 0.90 Tg in 2010 and 0.95 Tg in 2020. In comparison with 1990, baseline year for the Kyoto Treaty, CO_2-C emission increased by 16% in 2000 and are projected to increase by 26% in 2010 and by 35% in 2020. Of the total CO_2-C emission of 0.57 Tg in 1998,

TABLE 1 Total and Per Capita CO_2-C Emission in Iceland (Marland and Andres, 2004)

Year	Emission (Tg C yr^{-1})	Per capita emission (Mg C yr^{-1})
1950	0.20	1.41
1955	0.25	1.57
1960	0.33	1.88
1965	0.38	1.99
1970	0.38	1.86
1975	0.44	2.02
1980	0.51	2.23
1985	0.45	1.85
1990	0.55	2.16
1995	0.53	1.99
2000	0.59	2.10
2002	0.60	2.10

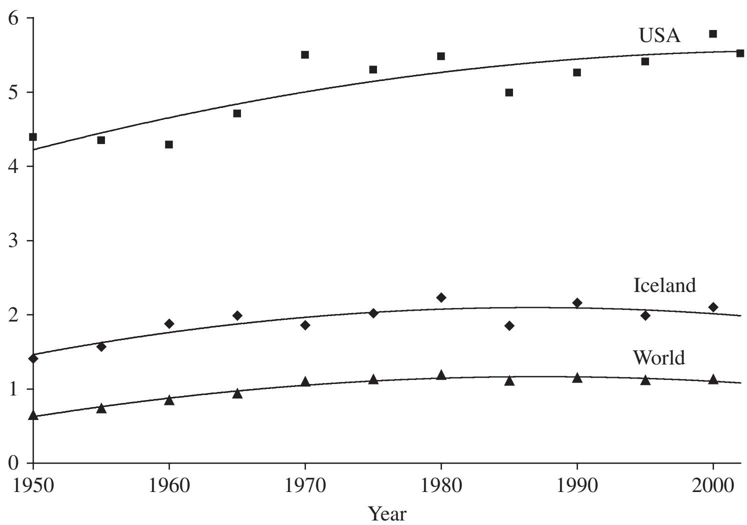

FIGURE 1 Per capita CO_2 emissions for Iceland, the U.S., and the World (EIA, 2004a,b; Marland and Andres, 2004).

86% was from liquid fuels, 12% from solid fuels, and 2% from gaseous fuels and other industry (Marland and Andres, 2004).

SOIL EROSION AND DESERTIFICATION IN ICELAND

Accelerated soil erosion is a serious problem in Iceland (Óskarsson et al., 2004; Ó. Arnalds, 1999; 2000; Ó. Arnalds et al., 2001). When Vikings settled in Iceland around AD 874 about 1132 years ago, they brought domestic animals with them (e.g., sheep, cows, horses), which are not native to Iceland. Rapid population growth of both people and animals following settlement caused large-scale deforestation and denudation of landscape. Animal grazing can cause severe ecological perturbation in harsh climate of Iceland (Gisladottir; 1995; 1998; 2001). It is estimated that 3.7 Mha are barren deserts and that an additional 1.0 to 1.5 Mha are strongly disturbed with limited plant production. At the time of settlement in AD 874, Iceland's deserts covered only 0.5 to 1.5 Mha. Thus, human induced desertification over the last 1132 years is estimated at 3.7 to 4.2 Mha. The barren surfaces are generally sandy and gravelly, and devoid of plant nutrients. The drastic disturbance of the fragile ecosystem (A. Arnalds, 1987) caused severe soil erosion (Figure 2). The extent and severity of soil erosion are illustrated in Table 2.

A special form of erosion in Iceland is called "Rofabards," (O. Arnalds, 2000). The term, Rofabards is a synthesis of two Icelandic words: "Ruf" means erosion and "bard" implies a distinctive form of erosion escarpments. Andosols are cohesionless and severely prone to erosion (O. Arlands, 2003; 2005; O. Arnalds et al., 1995). The erosion begins with disturbance caused by grazing and removal of vegetation cover. As it progresses, escarpments are formed with a resistant root mat on top and resistant material at the base under the Andosol mantle. The escarpment height ranges from 0.2 m to 3 m. Erosion progresses by retreat of the front, and the "Rofabards" retain the escarpment form as they retreat (Ó. Arnalds, 2000). Rofabards or escarpments are attributed to wind erosion processes. Saltation is the predominant process in relatively dry areas in northeast Iceland and escarpments are generally > 1.5 m high. Water erosion causes escarpments in the humid southwest. Sheep commonly use the escarpments for shelter and the trampling exacerbates the hazard, and sheep population has been an important factor (Table 3). Erosion rates can be expressed in terms of the rate of retreat or loss of Andosol. The rate of retreat ranges from 1 to 10 cm yr^{-1} and loss of Andosol from 0.02 to 0.60 ha km^{-2} yr^{-1} (Ó. Arnalds, 2000). Rofabards have denuded 1.5 to 3.0 Mha of land that was previously fully vegetated and is now mostly desert. Estimated losses of Andosols in Rofabard areas are about 230 ha yr^{-1} (Ó. Arnalds, 2000).

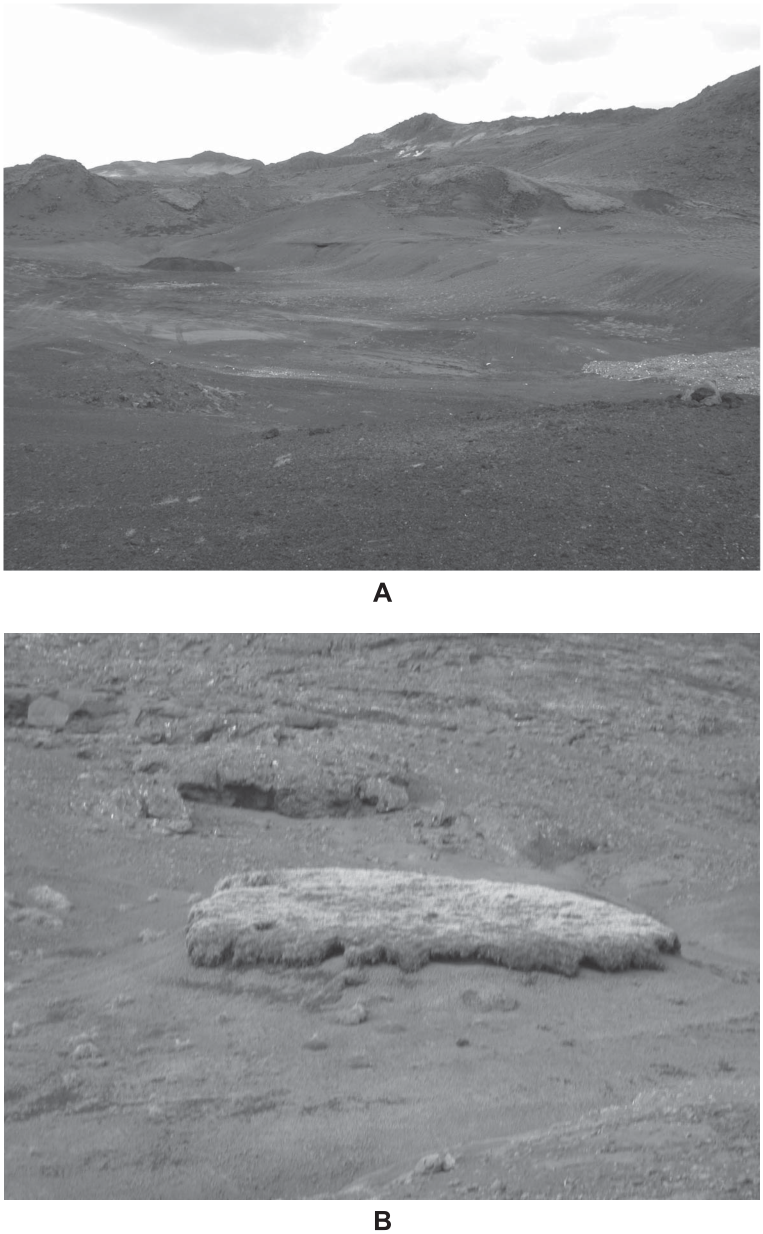

FIGURE 2 A and B Severe problem of accelerated soil erosion in Iceland.

SOIL EROSION AND CARBON DYNAMICS IN ICELAND

The average value of the SOC pool in the dominant soil types of Iceland ranges from 320 Mg ha^{-1} to 1500 Mg ha^{-1} (1 Mg = megagram = 1×10^6 g = 1

TABLE 2 Extent and Severity of Soil Erosion in Iceland (Adapted from Ó. Arnalds and E. Gretarsson, 2000)

Severity of soil erosion	Class	Land area (Mha)	% of Total land area
None	0	0.41	4.0
Little	1	0.75	7.3
Slight	2	2.67	26.0
Considerable	3	2.31	22.5
Severe	4	1.13	11.0
Extreme	5	0.64	6.2
Mountains		0.98	9.5
Glaciers		1.14	11.1
Rivers and Lakes		0.14	1.4
Others		0.10	1.0
Total		10.27	100.0

TABLE 3 Sheep Populationin Iceland Between 1990 and 2005 (FAO, 2005)

Year	Sheep Population (10^3)
1990	549
1992	487
1994	499
1996	464
1998	490
2000	466
2002	469
2004	455
2005	454

tonne) for untruncated soils and only 20 Mg ha^{-1} for severely truncated soils (Tables 4 and 5). Total C pool in soils of Iceland is estimated at 2.1 Pg (Pg = petagram = 1×10^{15} g = 1 billion tonnes). Intact and fully vegetated soils have large SOC pool and denuded soils are severely depleted of their SOC reserves. Óskarsson et al. (2004) estimated that the historic C loss due to anthropogenic erosion is 120 to 500 Tg C over the past millennium, based on the following assumptions:

TABLE 4 Soil Organic Carbon Pool in Four Dominant Soils of Iceland (Recalculated From Óskarsson et al., 2004)

Soil type	SOC concentration	Depth (m)	Bulk density (Mg m^{-3})	SOC pool (Mg ha^{-1})
Brown Andosol	33	1.41	0.69	321
Gleyic Andosol	75	1.52	0.52	593
Histic Andosol	175	2.20	0.39	1501
Vitrisol	3.9	0.44	1.20	21

TABLE 5 The Present Carbon Pool in Soils of Iceland (Recalculated from Óskarsson et al., 2004)

Soil type	SOC pool (Mg ha^{-1})	Area (Mha)	Total SOC pool (Tg)
Brown Andosol (BA)	227	1.34	303
Gleyic Andosol (WA)	460	0.24	110
Histic Andosol (Ha)	891	0.49	438
Histosol (H)	1975	0.11	215
Cambic Vitrisol (MV)	45	1.76	79
Sandy Vitrisol (SV)	20	0.46	9
Leptosol	0	0.73	0
Cryosol-WA Complex	460	0.014	6
BA-WA Complex	340	2.81	955
MV-SV Complex	32	0.60	19
SV-L Complex	10	0.48	5
Total			2100

Denuded land area = 0.8 to 2.4 Mha
Loss of SOC by erosion = 150 to 210 Mg C ha^{-1}
Total C loss by erosion = 120 to 500 Tg
Assuming 20% emission (Lal, 2003) = 24 to 100 Tg

The current rate of soil erosion by Rofabards and the associated displacement of SOC is as follows: (Óskarsson et al., 2004):

Land use affected by Rofabards = 232 ha yr^{-1}
Soil thickness = 1 to 2 m
SOC concentration = 33 g Kg^{-1}
SOC loss by Rofabards = 50 to 100 × 10^3 Mg yr^{-1}

Dynamics of C by the current rate of soil erosion in Iceland is shown in Figure 2. Of the 2.1 Pg C pool, accelerated erosion annually displaces 50 to 100 thousand Mg by erosion. Assuming that 20% is mineralized (Lal, 2003), erosion-induced emission is estimated at 10 to 20 × 10^3 Mg yr^{-1}. In contrast, 5 to 10 × 10^3 Mg yr^{-1} is carried into the ocean and 35 to 70 × 10^3 Mg yr^{-1} is redistributed in the depressional sites over the landscape (Figure 2).

CARBON BUDGET IN ICELAND

Chemical weathering of silicate minerals is another mechanism of C sequestration, especially in volcanic rocks in which case the rate of weathering is fast. The chemical denudation rate of Icelandic rocks is 0.19 to 1.46 Mg ha^{-1} yr^{-1} (Gislason, 2005; Ólafson, 1979; Gislason et al., 1998). The denudation rate under tree cover is 3 to 4 times than that in bare soils. Being an island nation, it is relatively simple to prepare a national C budget. Gislason (2005)

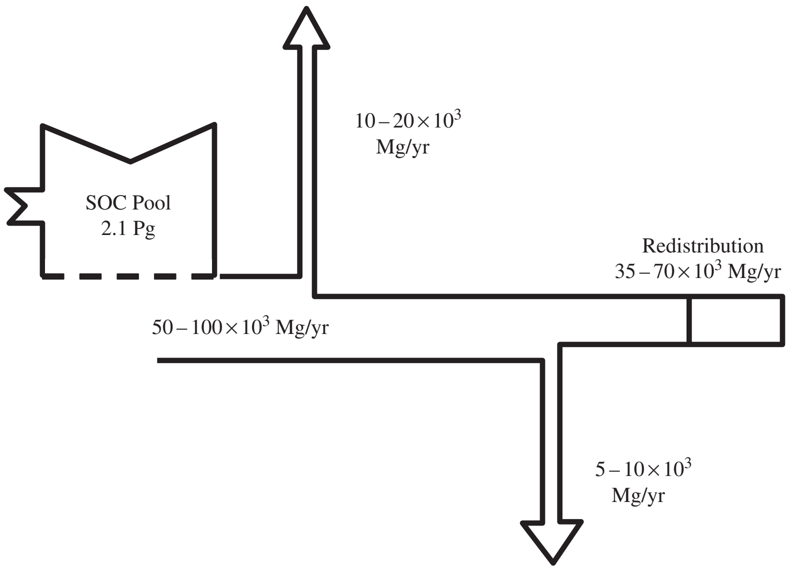

FIGURE 3 Fate of carbon transported by soil erosion in Iceland (recalculated from Oskarsson et al., 2004).

used a chemical weathering and denudation approach to compute a C budget for Iceland, and estimated that the average rate of dissolved inorganic carbon (DIC) flux of Iceland is 82 Kg C ha^{-1} yr^{-1}. The total source of CO_2 – C is estimated at 1.03 to 1.33 Tg C yr^{-1} and permanent sink at 0.42 Tg C yr^{-1}. Thus, there is a net emission of 0.61 to 0.911 Tg C yr^{-1} (Table 6). The assessment by Gislason is comprehensive and thorough with detailed assessment of all transient and permanent sources and sinks. However, Gislason did not include detailed assessment of C sequestration in terrestrial ecosystems, which is the theme of this manuscript.

TABLE 6 Icelandic C Budget Using Chemical Weathering and Denudation Approach (Modified From Gíslason, 2005)

Process	Quantity (Tg C yr^{-1})
I. Sources	
1. Degassing from volcanoes	0.33–0.60
2. Anthropogenic emissions in 2000	0.77
Total Sources	1.03–1.33
II. Sinks	
1. Transient chemical weathering	0.85
2. Uptake by Ca^{+2} and Mg^{+2}	0.29
3. Uptake by vegetation	0.13
Total Sinks	1.27
Permanent Sinks	0.42
III. Net emission	0.61–0.91

CARBON SEQUESTRATION IN TERRESTRIAL ECOSYSTEMS

There is a long history of soil conservation and rehabilitation and restoration of eroded and denuded lands in Iceland (O. Arnalds, 2005). Because of a severe problem of soil erosion at the end of the 19th century, the Soil Conservation Service (SCS) of Iceland was founded in 1907 and is one of the oldest services in the world (O. Arlands et al., 2001). There is also an Icelandic Forest Service (IFS), which has also been in place for a long time.

Restoration of degraded/denuded lands is a high priority in Iceland, and it leads to C sequestration (Ó. Arnalds et al., 2000). At the time of settlement in AD 874, 65% of the country was vegetated. At present, only 25% of Iceland is covered with vegetation (A. Arnalds, 1987; Standard Bureau of Iceland, 1984). Furthermore, the present vegetation is devoid of trees and comprises only low density grasses, forbes, willows, and low-growing non-palatable shrubs, sedges and rushes with low annual biomass production.

Carbon Sequestration in Vegetation

Re-vegetation of eroded areas is an important strategy of C sequestration in terrestrial ecosystems. Several studies have documented the impact of afforestation on terrestrial C sequestration in Iceland (Snorrason et al., 2000; Þórardotir, 1984). The importance of re-establishing birch forests was recognized more than a century ago. The first forest plantation was established in 1899 (Sigurdsson and Snorrason, 2000). However, systematic tree planting started in 1946. The rate of afforestation was < 1 million trees yr^{-1} until 1980, and it increased to 4 to 5 million trees yr^{-1} during 1990s. By 2000, about 84 million trees were planted in Iceland. Five tree species grown in Iceland are Russian larch (*Larix sukaczewii*), birch, lodgepole pine (*Pinus conoria*), sitka spruce (*Picea sitchensis*) and Norway spruce (*Picea abies*). In 1997, the Iceland Government launched a special program for increasing the terrestrial C sequestration by 100,000 Mg CO_2 (27,273 Mg C) in the year 2000 compared with the 1990 baseline. Denuded areas are characterized by lower pool of biomass and soil C than their potential capacity. Thus, reforestation would enhance the terrestrial C pool in both soil and biota. Therefore, several studies have been conducted to measure the rates of C sequestration in revegetated plots. Expectedly, the measured rates are highly variable and reportedly range from 0.01 to 0.5 Mg C ha^{-1} yr^{-1} (Aradóttir et al., 2000). Another study showed that the mean C sequestration rate of mature forest stands in Iceland is 1.7 Mg C ha^{-1} yr^{-1} in the above ground biomass and coarse roots (Óskarsson, 2000). Arnalds et al. (2000) reported the sequestration rate of 0.3 to 0.6 Mg C ha^{-1} yr^{-1}. Measurements of net primary productivity (NPP) in young birch forests show the C sequestration rates of 1.0 Mg C ha-1 yr^{-1} to 3.52 Mg C ha^{-1} yr^{-1} (Sigurdardottir, 2000; Snorrason et al., 2002). The mean rate of C sequestration in vegetation

TABLE 7 Measured Rates of Carbon Sequestration in Vegetation and Soils of Iceland

Ecosystem	Rate (Mg C ha^{-1} yr^{-1})	Reference
I. Vegetation		
Above ground biomass	0.04–1.5	?
Biomass	0.01–0.5	Aradóttir et al. (2000)
Above ground carbon	0.3–0.6	Ó. Arnalds et al. (2000)
Above ground vegetation	0.5	Ó. Arnalds et al. (2000)
Afforestation	1.7	Oskarsson (2000)
Re-vegetation	0.75	Aradóttir et al. (2000) Ó Arnalds et al. (2000)
II. Soil		
Soil organic carbon	0.6	Ó. Arnalds et al. (2000)
Effect of fertilizer use	0.6–1.0	Gudmundsson et al. (2004)

ranges from 0.01 to 1.7 Mg C ha $^{-1}$ yr^{-1} (Table 7). Wetlands are also a net C sink (Gisladottir, 1998).

Carbon Sequestration in Soil

Some field studies have shown that the terrestrial C sequestration occurs mostly in soils of Iceland, and the rate of SOC sequestration ranges from 0 Kg m^{-2} in Leptosol to 197.5 Kg m^{-2} in Histosols (Ó. Arnalds et al., 2000; Oskarsson et al., 2004; Gudmundsson et al., 2004). High potential of SOC sequestration exists in eroded soils of Iceland. Systematic attempts to control soil erosion and restore degraded soils started at the turn of the 20^{th} century (Runólfsson, 1987; Arnalds, 2000). Early attempts at controlling drifting sands involved establishing lyme grass and erecting barriers of stones and timber (Magnússon, 1997). In addition to establishing the native lyme grass and other species (*D. caespitosa* and *F. richardsonii*) some exotic species used to improve rangelands include *Deschampsia beringensis* and *Festuca rubra* (var. Leix). Some annual grasses (e. g., *Lolium multiflorum*) are also used. Establishment of exotic nootka lupin (*Lupinus nootkatensis*) for reclamation was started in mid-1980s (Aradótir et al., 2000). In addition, use of fertilizers and manures to improve rangelands (25 – 50 Kg N ha^{-1}) is also practiced (A. Arnalds, 2000). Tree species grown to control soil erosion are birch, *Salix* shrubs and legumes such as *Lathyrus japonicus* and *Trifolium repens*. The rates of SOC sequestration through restoration of eroded soils are estimated 0.6 to 1.0 Mg C ha^{-1} yr^{-1} (Table 7).

ICELANDIC C BUDGET INCLUSIVE OF TERRESTRIAL CARBON SEQUESTRATION

The updated Icelandic C budget including terrestrial C sequestration is shown in Table 8. There are three principal components of the data presented in

TABLE 8 Estimated Icelandic C Budget Using Natural and Anthropogenic Sources and Sinks

Process	Quantity (Tg C yr^{-1})
I. Sources	
1. Degassing from volcanoes	0.33–0.60
2. Anthropogenic emissions in 1990	0.55–0.70
3. Erosion-induced emissions	0.01–0.02
Total Sources	0.94–1.42
II. Sinks	
1. Permanent uptake by Ca^{+2} and Mg^{+1}	0.29
2. SOC sequestration in restoring eroded soils	1.0
3. Above ground biomass C in vegetation	0.2–0.6
4. Emission avoidance from erosion control	0.01–0.02
Total Sink	1.50–1.9

Table 8 which have long-term implications to C sequestration in terrestrial ecosystems and in off-setting anthropogenic fossil fuel emissions.

Erosion-Induced Emission

Assuming that 20% of the SOC displaced annually by soil erosion is emitted into the atmosphere (Lal, 1995; 2004) erosion-related emission in Iceland is estimated at 0.01 to 0.02 Tg C yr^{-1}. Implementation of conservation-effective measures can avoid erosion-caused emission.

SOC Sequestration by Restoration of Eroded Soils

This is a long-term strategy and its positive effect on SOC sequestration may continue for a long time. Total area affected by historic erosion in Iceland is 0.8 to 2.4 Mha, and the cumulative SOC lost by erosional processes is about 310 Tg. Assuming that attainable potential is only two-thirds of the SOC pool depleted, an estimated 200 Tg C can be sequestered over the next 200 years (2000 to 2200) at an average rate of 1 Tg C yr^{-1} (Figure 4). This accumulation would occur at an average sequestration rate of 0.4 to 1.25 Mg C ha^{-1} yr^{-1} over 0.8 to 2.4 Mha for 200 years.

Carbon Sequestration in Biomass

The potential annual rate of C sequestration in biomass is estimated at 0.2 to 0.6 Tg C yr^{-1}. These rates of C sequestration in biomass are more by 0.13 Tg C yr^{-1} than that estimated by Gislason (2005). Thus, restoring vegetation cover with NPP of 0.8 to 2.4 Mg C ha^{-1} yr^{-1} would have a total potential sequestration of 0.2 to 0.6 Tg C yr^{-1}.

Considering these three inputs, the data in Table 8 show the total CO_2-C source in Iceland of 0.94 to 1.42 Tg C yr^{-1} Tg C yr^{-1}. In contrast, total sink

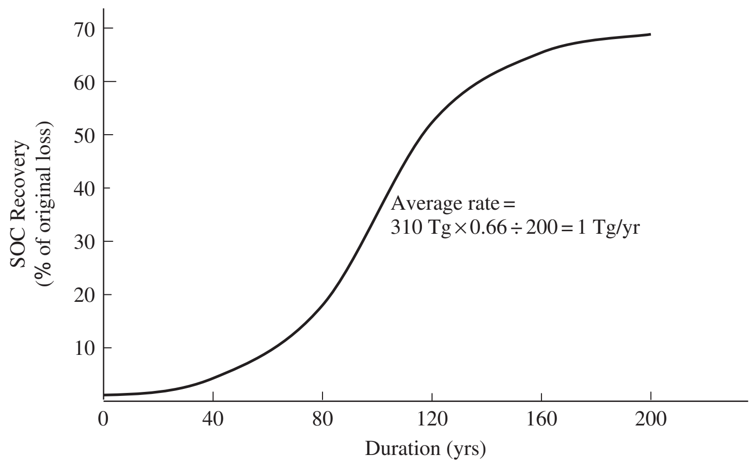

FIGURE 4 Rate of SOC sequestration by restoration of desertified and eroded soils.

capacity is 1.5 to 1.9 Tg C yr^{-1}. Thus, net C sink capacity of the terrestrial ecosystems in Iceland is about 0.5 to 0.6 Tg C yr^{-1}.

POLICY CONSIDERATIONS

Increase in atmospheric concentration of greenhouse gases (WMO, 2006), has enhanced interest in strategies for CO_2 sequestration in terrestrial ecosystems. Iceland ratified the UNFCC in 1993 and officially communicated with the Secretariat of the Kyoto Treaty in 1996, 1997 and 2001 (Sigurdsson and Snorrason, 2000). Iceland can use the provisions of Article 3.4 and obtain credit for C sequestration in the terrestrial ecosystems.

Sigurdsson and Snorrason (2000) estimated C sequestration in biomass under the so-called "Kyoto forests" or forests established since 1990. Estimates of C sequestration by "Afforestation" since 1990 was estimated at 26,727 Mg C in 1995 and 89,182 Mg C in 1999 (Ministry for the Environment, 1992; 2000). These estimates were based on mean sequestration rate of 1.7 Mg C ha^{-1} yr^{-1} (Oskarsson, 2000). In addition, revegetation since 1990 included 28,636 Mg C in 1995 and 95,455 Mg C in 1999. These estimates were based on mean rates of C sequestration of 0.75 Mg C ha^{-1} yr^{-1} for re-vegetated lands (Aradóttir et al., 2000). Total afforested and reforested re-vegetated area in Iceland since 1990 was 17,5000 ha in 1995 and 36,400 ha in 1999.

With a large potential of aforestation and reforestation, identifying policies and developing programs which facilitate establishing vegetation on eroded/denuded lands remains a high priority. The strong tradition of aforestation going back to more than 100 years needs to be continued, enhanced, and sustained.

ANCILLARY BENEFITS: A WIN-WIN STRATEGY

The SOC pool is an important component of earth's biogeochemical cycles (Figure 5), and the largest component of the terrestrial C pool (Lettens et al., 2004). It is essential to the maintenance of numerous ecosystem services and functions (Lal, 2004). Thus, there are numerous ancillary benefits of restoring degraded and desertified soils. Important among these are: sequestration of SOC to offset fossil fuel emissions, improvement of soil quality, increase in agronomic productivity, improvement of soil biodiversity, reduction in soil erosion, and decrease in non-point source pollution. There is a strong and a positive correlation between SOC concentration and agronomic/biomass productivity leading to synergistic effects on nutrient cycling, water conservation, bioturbation, and the overall improvements in the environment. Increasing the SOC pool, creating a positive nutrient balance and favorable soil moisture and temperature regimes, and improvement in soil structure set in motion the restorative trends. Amelioration of soil structure improves water infiltration capacity, decreases runoff, increases soil water retention and improves NPP. The SOC pool is an important determinant of soil quality, NPP, and long-term sustainability of agricultural and forestry land uses. It is essential to restoring ecosystem services of degraded/desertified soils, reducing risks of runoff and erosion, and improving the environment.

It is because of these ancillary benefits of SOC sequestration with regards to increase in biomass production, improvement in water quality, increase in biodiversity and desertification control that Iceland must work very closely with the Kyoto Secretariat, FAO, UNEP, UNU, EU and other organizations to promote C sequestration in terrestrial ecosystems. Terrestrial/soil C sequestration is a common thread which links the three United Nations (UN) conventions: UN Framework Convention for Climate Change (UNFCC), UN Framework Convention for Desertification Control (UNFCDC) and UN Framework Convention for Biodiversity (UNFCBD).

FIGURE 5 Linking U.N. Millennium Development Goals and those of three framework conventions with carbon sequestration in terrestrial ecosystems.

This linkage may also be critical to achieving the U.N. Millennium Development goals.

If the Kyoto Treaty were to give the credit for the terrestrial C sequestration under Article 3.4, then the Net C sink capacity of 0.5 to 0.6 Tg C yr^{-1} would make Iceland an emission-free nation, because the total annual emission was 0.6 Tg C in 2002 (Table 1). If accepted by the Kyoto Treaty and E.U. countries, the concept of Iceland being an emission-free nation would be an historical landmark of global significance. Adoption of the same concept could be the driving force to restore degraded/desertified soils of Africa, Asia, South America and The Caribbeans. Furthermore, improvement in soil quality through SOC sequestration would also be crucial to achieving global food security because of the attendant increase in food production (Lal, 2006). Thus, terrestrial C sequestration is a truly win-win strategy.

CONCLUSIONS

Soil degradation and desertification are serious problems in Iceland. The Soil Conservation Service and other institutions have initiated long-term programs of erosion control and soil restoration through aforestation and establishment of vegetation cover on denuded lands. Erosion-induced emission of CO_2 - C is 10 to 20 × 10^3 Mg C yr^{-1}. The rate of C sequestration in biomass ranges from 0.01 to 1.7 Mg C ha^{-1} yr^{-1}. In comparison, the rate of SOC sequestration ranges from 0.6 to 1.0 Mg C ha^{-1} yr^{-1}. Restoration of eroded soils covering a land area of 0.8 to 2.4 Mha would sequester C at the rate of 1 Tg yr^{-1}. Total CO_2 - C source of Iceland is 0.94 to 1.42 Tg C yr^{-1} and total sink of 1.5 to 1.9 Tg C yr^{-1}. Thus, net C sink capacity of 0.5 to 6 Tg C yr^{-1} would make Iceland an emission-free nation.

REFERENCES

Aber, J.D., and J.M. Melillo. 1991. *Terrestrial ecosystems*. Saunders College Publishing, Philadelphia, PA.

Aradóttir, A.L., K. Savarsdottir, Th. H. Jónsson, and G. Gudbergsson. 2000. Carbon accumulation in vegetation and soils by reclamation of degraded areas. *Icel. Agri. Sci.* 13: 99–113.

Arnalds, A. 1987. Ecosystem disturbance in Iceland. *Arctic and Alpine Research* 19: 508–513.

Arnalds, A. 2000. Evaluation of rangeland conservation strategies. In: Ó. Arnalds and S. Archer (eds.) *Rangeland desertification*. Kluwer Academic Publishers, Dordrecht: 153–163.

Arnalds, Ó. 1999. Soils and soil erosion in Iceland. In: H. Armannsson (ed.) '*Geochemistry of earth's surfaces*'. Rotterdam, Balkema: 135–138.

Arnalds, Ó. 2000. The Icelandic Rofabard soil erosion features. *Earth Surface Processes and Landforms* 25: 17–28.

Arnalds, Ó. 2003. *Volcanic soils of Iceland*. Ó. Arnalds and K. Stahr (Eds.) 'Volcanic soil resources: occurrence, development and properties'. *Catena Special Issue*.

Arnalds, Ó. 2005. Icelandic Soils. In: C. Caseldine, A. Russell, J. Hardardottir, and O. Knudsen (eds.) '*Iceland: Modern Processes and Part Environments*', *Developments in Quaternary Science 5*. Elsevier, Amsterdam: 309–318.

Arnalds, Ó., C.T. Hallmark and L.P. Wilding. 1995. Andisols from four different regions of Iceland. *SSSA J.* 58: 161–169.

Arnalds, Ó., A.L. Aradottir, and G. Guobergsson. 2000. Organic carbon sequestration by restoration of severely degraded areas in Iceland. In: R. Lal, J. Kimble, R. Follett and B.A. Stewart (eds) '*Methods for assessment of soil carbon*', CRC Press, Boca Raton, FL.

Arnalds, Ó., G. Gudbergsson, and J. Gudmundsson. 2000. Carbon sequestration and reclamation of severely degraded soils in Iceland, *Icel. Agr. Su.* 13: 87–97.

Arnalds, Ó. and E. Gretarsson, 2001. Soil Map of Iceland, 2nd Edition, www.rala.is/desert.

Arnalds, Ó., F.O. Gisladottir and H. Sigurjonsson. 2001. Sandy deserts of Iceland: an overview. *J. Arid Env.* 47: 359–371.

Arnalds, Ó., E.F. Porarinsdotir, S. Metusalemsson, A. Jonsson, E. Gretarsson, and A. Arnason. 2001. *Soil erosion in Iceland*. Soil Conservation Service and Agricultural Research Institute, Reykjavik, Iceland (translated from original publication in 1997 in Icelandic).

Demarée, G.R. and A.E.J. Ogilvie. 2001. Bans Baisers d'Islande: Climatic, Environmental, and Human Dimensions Impacts of the Lakagigar eruption. In: P.D. Jones, A.E.J. Ogilvie, T.D. Davies, and K.R. Briffa (eds) '*History and climate: Memories of the future*'. Kluwer Academic/Plenum Publishers, New York: 219–246.

EIA (Energy Information Administration). 2004a. *Annual energy outlook: with projections to 2025*. Washington, D.C., USA.

EIA (Energy Information Administration). 2004b. International Energy Outlook. http://www.eia.doe.gov/pub/international/iealf/tableel.xls

FAO, 2000. *Production yearbook*, FAO, Rome, Italy.

FAO, 2005. *Production yearbook*, FAO, Rome Italy.

Gisladóttir, G. 1995. Ecological effects of grazing on sub-alpine common in southwestern Iceland. Latin America in the World: Environment, Society and Development. *Regional Conference of Latin American and Caribbean Countries*. IGU, Havanna, 156 pp.

Gisladóttir, G. 1998. Environmental characterization and change in south-western Iceland. *Dissertation #10. Stockholm Univ. Dissertation Series*, Stockholm.

Gisladóttir, G. 2001. Ecological disturbance and soil erosion on grazing land in Southwest Iceland. In: A. Conacher (ed.) *Land degradation*. Dordrecht, Kluwer: 109–126.

Gislason, S.R. 2005. Chemical weathering, chemical denudation and the CO_2 budget for Iceland. In: C. Caseldine, A. Russell, J. Hardardottir, and O. Knudsen (eds.) *Iceland: Modern processes and past environments'*, *Developments in Quaternary Science 5*. Elsevier, Amsterdam: 289–307.

Gislason, S.R. B.T. Guomundsson and E.S. Ericksdottir. 1998. *Chemistry of River Ellioaar 1997–98*. Reykjavik Science Institute, Univ. of Iceland, RH–19–98.

Gudmundsson, T., H. Bjornsson and G. Thorvaldsson. 2004. Organic carbon accumulation and pH changes in an Andic Gleysol under a long-term fertilizer experiment in Iceland. *Catena* 56: 231–224.

Hallsdottir, M. and C. J. Caseldine. 2005. The Holocene vegetation history of Iceland, state of-the-art and future research. In: C. Caseldine, A. Russell, J. Hardardottir and O. Knudsen (eds.) *Iceland: Modern processes and past environments, Developments in Quaternary Science 5*. Elsevier, Amsterdam: 319–334.

Johannesson, B. 1960. *The soils of Iceland*. Dept. of Agric., Reports Series B – #13, University Research Institute, Prentsmiojan Edda h.f., Reykjavik, Iceland, 140 pp.

Karlsson, G. 2000. *The history of Iceland*. University of Minnesota Press, Minneapolis, MN 418 pp.

Kardjilov, M.M., G. Gisladottir, and S.R. Gislason. 2006. Land degradation in northeastern Iceland: Present and past carbon fluxes. *Land Degrad. & Develop.* 17: 401–417.

Lal, R. 1995. Global soil erosion by water and the carbon dynamics. In: R. Lal, J. Kinmble. E. Levine and B. A., Stewart (eds.) '*Soils and global change*, *Adv. Soil Sci.*, Lewis Publishers, Chelsea, MI: 131–142.

Lal, R. 2003. Soil erosion and the global carbon budget. *Env. Intl.* 29: 437–45.

Lal, R. 2004. Soil carbon sequestration impacts on global climate change and food security. *Science* 304: 1623–1627.

Lal, R. 2006. Enhancing crop yields in developing countries through restoration of the soil organic carbon pool in agricultural lands. *Land Degrad. & Develop.* 17: 197–209.

Lettens, S., J. Vanorshoven, B. Van Wsemael, Vos B. De, and B. Buys. 2004. Stocks and fluxes of soil organic carbon for landscape unites in Belgium derived from homogenous data sets for 1990 and 2000. *Geoderma*, 127: 11–23.

Magnusson, S.H. 1997. Restoration of eroded areas in Iceland. In: K.M. Urbanska, N.R. Webb and PJ. Edwards (eds.) *Restoration Ecology and Sustainable Development*. Cambridge University Press, Cambridge, U.K.: 188–211.

Marland, G., and R. Andres. 2004. Global CO_2 emissions from fossil fuel burning, cement manufacture and gas flaring: 1751–2003. *ORNL*, Oakridge, TN.

Ministry for the Environment 2000. Land Use, Land Use Change and the Forestry: Submission by Iceland. *Special Report to SBSTA*. Reykjaik, Ministry for the Environment, 13 p.

Ministry of the Environment, Iceland. 1992. Release of greenhouse gases from Iceland in the year 1990. Reykjavik, Ministry of the Environment, May 1982.

Ólafson, J. 1979. The chemistry of Lake Myvatin and the River Laxa. *Oikos* 32: 82–112.

Olafsdottir, R., and H.J. Gudmundsson, 2002. Holocene land degradation and climate change in northeastern Iceland. *The Holocene* 12: 159–167.

Oskarsson, H., Ó. Arnalds, J. Gudmundssonn, and G. Gudbergsson. 2004. Organic carbon in Icelandic Andosols: geographical variation and impact of erosion. *Catena* 56: 225–238.

Oskarsson, U. 2000. C-sequestration in vegetation and soil. Verkefnisst-jorn ataks i landgraedslu og Skograekt 1997–2000. *Reykjavik*, 31 p.

Þórardóttir, P. 1984. Primary production of North Iceland in relation to water masses in May-June 1970–80. Council of the Exploration of the Sea, C.M. 1984/ L20:1–17.

Runólfsson, S. 1987. Land reclamation in Iceland. *Arctic and Alpine Res*. 19: 514–517.

Sigurdardottir, R.S. 2000. *Effects of different forest types on total ecosystem carbon sequestration in Hallormsstadur Forest, Eastern Iceland*. Faculty of the Graduate School, Yale University, Yale, USA.

Sigurdsson, B.D. and A. Snorrason. 2000. Carbon sequestration by afforestation and revegetation as a means of lifting net CO_2 emission in Iceland. *Biotechnology, Agronomy Society and Environment* 4: 303–307.

Snorrason, A., T.H. Jónsson, K. Svavarsdóttir, G. Gudbergsson, and T. Traustason. 2000. Carbon sequestration in afforestaion in Iceland. *Arsrit Skogroektarfelags Islands*. 2000 (1): 71–89.

Snorrason, A., B.D. Sigurdsson, G. Gudbergsson, K. Svavardottir, and T. H. Jonsson. 2002. Carbon sequestration in forest plantations in Iceland. *Icelandic Agric. Sciences* 15: 79–91.

Standard Bureau of Iceland (The), 1984. Handbook of statistics, 1984. The Statistical Bureau of Iceland, Reykjavik (Iceland).

Wastl, M.J. Sotter, and C.J. Caseldine. 2001. Sea-ice-climate-glacier relationships in northern Iceland since the 19th century: possible analogues for the Holocene. In: P.D. Jones, A.E.J. Ogilvie, T.D. Davies and K.R. Briffa (eds.) '*History and climate: Memories of the future* Kluwer Academic/Plenum Publishers, New York: 187–200.

WMO 2006. *Greenhouse gas bulletin: The state of greenhouse gases in the atmosphere using global observations up to December 2004*. WMO, Env. Div., Geneva, Switzerland