



# Icelandic Inland Wetlands: Characteristics and Extent of Draining

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**Abstract** Iceland has inland wetland areas with soils exhibiting both Andosol and Histosol properties which are uncommon elsewhere on Earth. They are generally fertile, with higher bird-nest densities than in similar wetlands in the neighboring countries, with nutrients released by rapid weathering of aeolian materials of basaltic nature. Icelandic inland wetlands cover about 9000 km<sup>2</sup> constituting 19.4 % of the vegetated surfaces of the island. The wetland soils are often 1–3 m thick and store 33 to >100 kg C m<sup>-2</sup>. They have been subjected to broad-scale subsidy-driven draining for agricultural purposes. About 47 % of Icelandic inland wetlands are impacted by drainage. The ditch network extends about 30,000 km, mainly in lowland areas, where about 70 % of the wetland areas are impacted. There are >1 million wetland patches, most of them <1 ha. Much of the wetlands impacted from drainage are not used for intensive agriculture such as hay-making, however some are used for grazing. There is a need to prioritize the protection of undrained wetlands and their restoration based on a broad range of factors.

**Keywords** Wetland draining · Andosols · Wetland patch size · Gleyic

## Introduction

High latitude wetlands with an elevated organic content make up a large proportion of Earth's wetlands (e.g., Mitsch and Gosselink 2007). Iceland, an island in the North-Atlantic Ocean, has diverse wetlands ranging from the coast to the interior highland, including marshes, estuaries, ponds, lakes and rivers. The wetlands addressed in this paper are the inland palustrine wetlands, mostly fens with both organic or inorganic soils (see definitions in Cowardin et al. 1979), which we here also term 'inland fen wetlands' or simply 'inland wetlands'. They were termed "mires" ("mýrar" in Icelandic) in an overview by Gardarsson (1998). Sloping fens are a common feature of the fiords and valleys formed during the last glaciation which cut into the Tertiary basalts whereas the greatest extent of topogenous fens are found within the gently sloping lowlands of west and south Iceland. Alluvial fens are located along some of the larger rivers, particularly in north and east Iceland. Palsa wetlands are found in isolated areas in the central highlands. Intertidal flats and inland marshes are not covered in this paper (559 km<sup>2</sup> and 387 km<sup>2</sup>, respectively, numbers based on the CORINE cover for Iceland).

The Icelandic wetlands are strongly influenced by the volcanic nature of the island and by intense aeolian deposition ("volcanic loess"), which separate Icelandic wetlands from most other wetlands on the globe. The volcanic and aeolian (loess) influences make these inland wetlands fertile with a relatively high pH and favorable nutrient availability (Arnalds 2004, 2015 Ch 8; Oskarsson et al. 2004). The fertility is reflected by high breeding bird densities, which often are >10 times higher in Iceland than for the same species in the UK and >2 times that of The Netherlands (Johannesdottir et al. 2014; Gunnarsson et al. 2015). The inland fen wetlands are important habitat for many bird populations in Iceland (Gunnarsson et al. 2006) with some of them important

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internationally (Einarsson et al. 2002). There have been extensive studies on changes in species composition of plants following drainage impacts (Magnusson 1998). Thorhallsdottir et al. (1998) found that the occurrence of rare wetland plant species was higher in areas with limited drainage disturbance. The extensive draining of Icelandic wetlands (addressed below) has had significant influence on both the distribution and overall abundance of Icelandic birds (Thorleifsson 1998; Skarphedinsson and Thorleifsson 1998). The wetland draining, along with the introduction of the American mink (*Mustela vison*), are considered to be the main reasons for the local extinction of the water rail (*Rallus aquaticus*), Iceland's only rail species (Skarphedinsson and Thorleifsson 1998).

Icelandic inland fen wetlands were subjected to widespread drainage during the twentieth century for agricultural purposes, with a large proportion of the wetlands being disturbed. Drainage for various purposes is still a threat to the remaining undisturbed wetlands. The Agricultural University of Iceland has generated nationwide geographical databases for land cover, including wetlands, and has surveyed the extent and impact of wetland drainage. The estimate of the extent and impact of drainage has been carried out in relation to the Icelandic national reporting to the UN Framework Convention on Climate Change (Hellsing et al. 2016). The main goal of this paper is to provide a general overview of the soils of the inland wetlands in Iceland and present an estimate of their extent, disturbance by drainage and the patch size of the remaining undrained wetlands based on relatively high resolution data.

## Background and General Characteristics of the Wetlands

Iceland, a 103,000 km<sup>2</sup> volcanic island, is located just south of the Arctic Circle, between 63° and 66° north latitude, and 13° to 24° west longitude. The climate is relatively mild in spite of the high geographic latitude, the reason being the oceanic climate and the effect of the Gulf Stream that brings warm waters to the shores of Iceland. It is worth noting that continental areas at the same latitudes, in Siberia and Canada for example, experience much colder climates than Iceland, particularly in winter.

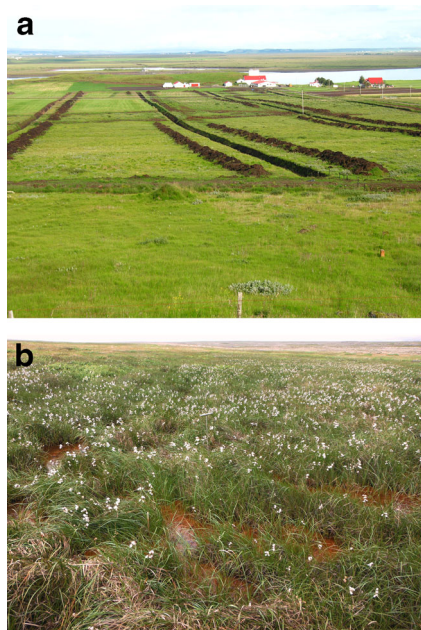
Iceland has about 30 active volcanic systems, fed by a volcanic mantle plume under the island (hotspot), with eruptions occurring every 3–5 years (Thordarson and Höskuldsson 2008). The oldest rocks are from the late Tertiary, but much of the surface is covered by rocks <3 million years old, with widespread Holocene lava and tephra deposits. Glaciers cover about 11 % of the country and many active volcanoes are located under ice. The volcanism provides the parent materials of Icelandic soils through tephra deposition and aeolian redistribution of volcanic materials, resulting in the formation of Andosols. The volcanic materials are primarily poorly

crystalline basalt grains with rapid weathering rates, which results in the formation of allophane, ferrihydrite and imogolite (Arnalds 2015 Ch. 9). Areas outside the active volcanic regions are primarily made up of Tertiary basalt piles, but the Quaternary glaciation has cut deep valleys into the Tertiary rock formation. The porosity of the Tertiary rocks has been partially plugged by secondary minerals such as calcite, silica minerals, zeolites and clays by chemical weathering (e.g. Ehlmann et al. 2012), resulting in slow hydraulic conductivity and higher water tables with more frequent occurrence of wetlands within the Tertiary Formation than in the active volcanic regions (Arnalds and Oskarsson 2009).

For centuries, the fen wetlands were used for grazing by livestock and harvested for hay. The wetland sward also provided sod for house construction (Sigurdardottir 2007). Intermittently flooded wetlands were important sources of hay in many parts of the country and often shared within the community. The more organic soils provided peat for fuel (Thorsteinsson 1975).

Draining the wetlands primarily took place during the latter part of the twentieth century and was subsidized by the government. The draining was part of the effort to enhance agricultural production and “food safety” in the post-World-War II era, but also an effort to reduce the migration of people from rural sections to fast growing urban areas (see Helgadóttir et al. 2013). The drainage efforts were sustained for almost 50 years in spite of substantial overproduction of meat and dairy products. Dairy and lamb meat production constitute the major proportion of Icelandic agriculture (data from Statistics Iceland February 2013; [www.statice.is](http://www.statice.is)) and characterize the rural landscape (Fig. 1a). Currently there are about 26,000 dairy cows and 75,000 head of cattle in all, 460,000 winterfed sheep (> 1.3 million grazing sheep in summer) and about 80,000 horses. Sheep and cattle rearing is highly dependent on hay making in the summer as the cold winter means that animals are kept indoors in winter (see Helgadóttir et al. 2013). Approximately half of the hayfields are on drained wetland soils (Wöll et al. 2014).

Previous estimations of the extent of wetlands include the soil map prepared by Johannesson (1960; see explanations by Arnalds 2015 Ch. 7), yielding 9–10,000 km<sup>2</sup> of what he termed ‘peatlands’. However, *wetlands of various organic content* are a more appropriate term as is explained in the section on soils below. This mapping was a noteworthy attempt, yet with relatively high uncertainty as the map is highly generalized with a very coarse scale (1:750,000). Other complete overviews include a vegetation map with the scale of 1:500,000 by the Icelandic Museum of Natural History (Gudjonsson and Gislason 1998) and the CORINE coverage, which is in large part a simplified version of the Agricultural University of Iceland (AUI) data presented here.



**Fig. 1** **a** Typical Icelandic agricultural landscape. Hay fields are located between the ditches (photo A.L. Aradóttir); **b** Undisturbed wetland patch. Vegetation dominated by *Eriophorum angustifolium*. Reduced iron (blue) and bog iron (reddish brown) present in the water. Many of the wetlands have frequently occurring gradients from wet to dry. *Salix* is present at the edge of this patch (upper left) in damp wetland. Typical highland landscape with mosaic of vegetation and soil types, including barren areas (deserts, upper right)

## Materials and Methods

The geographical data applied for the spatial analyses were derived from three main sources: the Agricultural University of Iceland (AUI) Nytjaland and IGLUD databases and the AUI soil map and soil databases. The AUI hosts several national geographical databases which include a soil database and a map, a database for broadly defined vegetation classes (Icelandic Farmland Database, Nytjaland in Icelandic) and the IGLUD (Icelandic Geographical Land Use Database), which was constructed in response to Iceland's commitments to the UN Framework Convention on Climate Change (UN FCCC; Gudmundsson et al. 2013). The Nytjaland database was made from supervised classification of Landsat 7 and Spot 5 satellite images, covering all of Iceland. Most of the work entailed separating the land into 10 vegetation classes, in addition to ice/glaciers and water/sea, but for a proportion of the country, 6 vegetation classes were used. The database was described in detail by Gísladóttir et al. (2014) in Icelandic, but also in part in English by Arnalds and Barkarson (2003). The IGLUD database land use map of Iceland is compiled annually from a large number of available map layers, including the Nytjaland classification. The ditch network was digitized at the AUI manually using aerial and satellite photographs. Data on cultivated land (hay fields) were also assembled by digitizing the areas. The IGLUD database and its preparation was

described by Gudmundsson et al. (2013) and Wöll et al. (2014). The soil map was constructed by combining soil meta-data housed by the AUI (Ymir database) and the Nytjaland land cover database (Arnalds and Oskarsson 2009). This is a rather broad scale map (1:250,000) for general overview of the soils of Iceland.

The extent of wetlands and drainage was estimated using the AUI Nytjaland and IGLUD databases. Two main classes of the Nytjaland classification encompass wetlands: “saturated wetlands” and “damp wetlands”. The IGLUD map layer of areas affected by drainage represent areas with average drawdown of the water table of >15 cm, which is, however, subjected to seasonal and annual differences. The preparation of the map layer of drained soils is based on a maximum 200 m distance from ditches. Other vegetation classes closer to 200 m distance from ditches are excluded, as well as areas of more than 10° slope. Areas <200 m from a ditch but isolated from it by a body of water are excluded from affected areas. The 200 m distance is based on considerable efforts by AUI to categorize drainage impacts (mostly unpublished data, see also Oskarsson 1998; Gísladóttir et al. 2007, 2010; Gísladóttir and Oskarsson 2011). The preparation of the map layer for drained soils has been further described by Wöll et al. (2014). Map layers for croplands (mostly hay fields) on wetland soils were made separately based on surveys of croplands and time series of land use conversions as described by Wöll et al. (2014). All data layers were combined to prevent overlapping or double counting of areas.

The impacts range from subtle changes in water flow, habitat diversity and nutrient and greenhouse gas dynamics (lowest density) to substantial lowering of the water table with pronounced releases of greenhouse gasses and vegetation changes, but many of the areas are also subjected to plowing (hay-making) and intensive grazing that cause ecosystem changes on top of changes caused by the drainage.

Levels of disturbance were estimated by using a kernel density method to calculate accumulated ditch density for areas closer than 200 m from a ditch. Then the impacted area was grouped into the following density intervals: 0.1–5, 5–10, 10–15, 15–20, and >20 km km<sup>-2</sup>. Areas of slopes >10°, poorly vegetated land and road beds were excluded in the process. In addition, the size distribution of the inland wetlands in the AUI databases was determined, using the following size categories: <1, 1–5, 5–50, 50–100, 100–500 and >500 ha.

## The Inland Wetlands: Soils, Vegetation and Birds

### Soils

Most circumpolar areas of similar latitudes, such as in Finland, Russia, Alaska and Canada, have extensive wetlands of high organic content (peat), often dominated by permafrost (Jones et al. 2010). The mixture of poorly crystalline basaltic volcanic

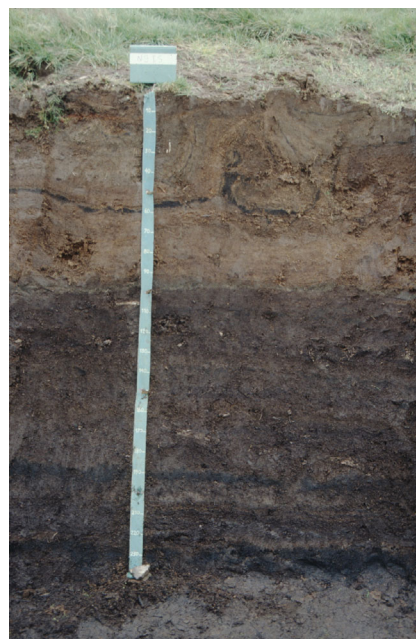
materials and peat, which dominates Icelandic wetland soils, is uncommon in the world, judging from our literature search. They differ from the paramo Histic Andosols of Ecuador (Buytaert et al. 2005, 2007) and the Azores (Madeira et al. 2007) in having a lower content of metal-humus complexes and a higher proportion of vitric materials deposited by continuous re-distribution of volcanic ash materials. The Icelandic wetland soils rarely exhibit hydric soil properties (>100 % water content at 15 bar tension) in contrast to more developed Hydric Andosols of warmer climates. Aquic Andosols have been reported in many areas such as Japan (e.g., Shoji and Ono 1978), however usually much more developed and lacking the frequent volcanic additions and continuous aeolian deposition of volcanic ash which give the Icelandic soils their distinctive young and vitric character.

The soils of Icelandic inland wetlands have a wide range of organic content in the surface horizons that determine the classification of the soils. The C content is most often <25 %, considerably lower than the 36–54% C averages reported by Loisel et al. (2014) for northern peatlands. The soils of palsa areas (permafrost mounds) also have low organic content in surface horizons in contrast to most other Arctic palsa areas (Saemundsson et al. 2012). Carbon accumulation in the Icelandic soils, based on data from Oskarsson et al. (2004) and averaging total carbon stocks over 8000 yrs. indicates accumulation from  $4 \text{ g m}^{-2} \text{ yr}^{-1}$  (Gleyic Andosols) to  $25 \text{ g m}^{-2} \text{ yr}^{-1}$  (Histosols). The accumulation in Histosols is of the same order as  $23 \text{ g m}^{-2} \text{ yr}^{-1}$  reported for northern peatlands by Loisel et al. (2014). Gudmundsson (2008) studied reported carbon accumulation between tephra-layers of known age for a Histosol in NW Iceland. The accumulation ranged between  $9$  and  $20 \text{ g m}^{-2} \text{ yr}^{-1}$  during the Holocene (4 periods) with the average rate of about  $15 \text{ g m}^{-2} \text{ yr}^{-1}$ .

An Icelandic soil classification system (Arnalds and Oskarsson 2009) separates the inland wetland soils based on carbon content in the top 30 cm into *Gleyic Andosols* (<12 % C), *Histic Andosols* (12–20 % C) and *Histosols* (>20 % C). Andosols, by nature, accumulate higher organic content than other mineral soils and are differentiated from Histosols according to the US Soil Taxonomy (Soil Survey Staff 1999) and the WRB (IUSS Working Group WRB 2014) at the 25 % C level (not 12–16 % as for the difference between Histosols and other mineral soils). These soils differ from the highly peaty Arctic soils, as they have a higher pH (often >5) and C/N ratio of 13–25, noticeably lower than the 34–77 average range reported for northern and Arctic peatlands (Loisel et al. 2014). Considerable amounts of nitrogen become readily available upon drainage. Part of the organic matter in all the wetland soils is in the form of organo-mineral complexes, which are characteristic of volcanic soils in general (see Arnalds 2015 Ch. 8). The variability in carbon content of Icelandic wetland soils is in large part due to differences in aeolian and tephra deposition contributing mineral matter to the soils, with substantially lower organic content close to volcanoes and the major dust sources. Variability in organic content is also caused by differences in drainage, flooding

regimes and landscape positions (Arnalds 2004; Arnalds and Oskarsson 2009). Gleyic Andosols (Fig. 2) with relatively low organic content (often 2–6 %) are dominant within the active volcanic zone, but there is a gradient with carbon content gradually becoming higher with distance from active dust sources and volcanoes. Highly organic soils are therefore mostly found far away from active dust sources such as in West, Northwest and North Iceland. The main characteristic of the organic matter in the soils is that it is poorly decomposed and the Histosols would classify as Fibrists (Borofibrists and Cryofibrists) under Soil Taxonomy. They show considerable shrinkage when they are completely dried in the laboratory (often less than 1/2 of the original volume when dry), but limited or very slow shrinkage in the field when drained, which is in part attributed to the volcanic ash materials in the matrix (Bartoli and Burtin 2007).

The Gleyic Andosols contain 10–20 % clays (allophane and ferrihydrite) on average, while the Histosols do not contain appreciable amounts of clays with Histic Andosols being intermediate. There is a gradient in pH from Gleyic Andosols (6–7) through Histic Andosols (5–6) to Histosols (4–5) attributable to decreasing aeolian input and increased organic content (Arnalds 2015 Ch. 8). Bulk density ranges from 0.2 in organic horizons to about  $0.7 \text{ g cm}^{-3}$  in mineral horizons in Gleyic Andosols. The organic horizons have higher water retention than would be expected, but so do also the mineral horizons due to their andic soil properties (see Arnalds 2004,



**Fig. 2** Typical Gleyic Andosol, showing distinct tephra layers and signs of cryoturbation in the upper horizons. The boundary between the lighter colored upper part and darker colored lower part of the profile marks the settlement of Iceland about 1200 yrs. ago. Increased aeolian activity consisting in part of re-distribution of light colored tephra fragments influences the soil color. The lower part is more organic (>13–20% C) while the upper part has about 10% C; see Arnalds 2015 Ch. 8)

2015 Ch. 7). The depth of the Icelandic inland wetland soils is quite variable, ranging from a few cm to several meters, but commonly 1–3 m.

## Vegetation

The vegetation of Icelandic wetlands was described by Steindorsson (1964), but Magnusson (1998) specifically addressed the plants of drained wetlands. The overarching characteristic of Icelandic wetland vegetation is the predominance of vascular plants and virtual absence of *Sphagnum* moss dominated wetlands. This can most likely be ascribed to the general fertility of these systems arising both from the widespread aeolian deposition of mineral matter and the fact that there are almost no truly ombrotrophic inland wetlands in Iceland, most being minerotrophic or only partially ombrotrophic (Steindorsson 1964). Drainage changes the systems from minerotrophic to ombrotrophic in areas closest to the ditch.

The subsequent discussion takes note of the Agricultural University databases which separate the wetlands into “saturated wetlands” and “damp wetlands”. Other divisions of Icelandic wetlands are discussed in Olafsson (1998). The plant species characteristic of the “saturated wetland” class include various *Carex* spp., such as *Carex bigelowii*, *C. lyngbyei*, *C. rostrata*, *C. chordorrhiza*, and *Equisetum* spp. Cotton grass (*Eriophorum angustifolium*) is quite common as are some heathland species such as dwarf-birch (*Betula nana*), blueberries (*Vaccinium uliginosum*), crowberries (*Empetrum nigrum*), common heather (*Calluna vulgaris*) and *Arctostaphylos uva-ursi*, but also willow species (*Salix phylicifolia*, *S. arctica* and *S. lanata*). Moss species of the genera *Hypnum*, *Philonotis*, *Mnium* and *Racomitrium* are widespread. Species characteristic of damp wetlands include many of the same species found in saturated wetlands, with lower dominance of *Carex* spp. and more frequent occurrence of woody species.

## Birds

Icelandic wetlands in general are particularly important for birds with approximately 75 % of Icelandic bird species relying in part or fully on various types of wetlands as a habitat (Gudmundsson 1998). The Icelandic wetlands (including the inland fens) support about 20 internationally important bird species (Einarsson et al. 2002). They are of particular importance for waders (*Charadrii*) in the northern hemisphere (Gunnarsson et al. 2006). Wetland birds include golden plover (*Pluvialis apricaria*), dunlin (*Calidris alpina*), snipe (*Gallinago gallinago*), whimbrel (*Numenius phaeopus*), black-tailed godwit (*Limosa limosa*), red-shank (*Tringa totanus*), and meadow pipit (*Anthus pratensis*). Swans (*Cygnus cygnus*) and geese are also common, including the graylag goose (*Anser anser*) and pink-footed goose (*Anser brachyrhynchus*). Some of the highland wetlands are of

particular importance, e.g., the Thjorsarver RAMSAR area, the world’s largest breeding ground of pink-footed goose.

## History of the Drainage Effort

Draining wetlands facilitates oxidation of organic matter and release of nutrients, resulting in substantial increase in biomass production (Magnusson 1998), at least in the short-term. This prospect was of interest to the farming community during the early twentieth century. A law was passed in 1923 that initiated subsidies for draining. Minor areas were drained annually during the first few decades as ditches were excavated by hand. After World War II, with the arrival of large and effective machinery for excavation, a broad-scale draining of the wetlands was initiated. The drainage activity gained momentum relatively rapidly, expedited by the government subsidies (Fig. 3). The draining peaked in 1968, when 1633 km of ditches were excavated. The effort decreased considerably after 1987 (Bjarnason 1982; Snaebjörnsson et al. 2010), when subsidies were cut dramatically, but it can also be postulated that much of the easily drained land near the farmsteads had been drained by that time. About 15 % of the drained wetlands are used for hay-making. The drained areas are also used for grazing to some extent. However, some of the drained land is not used for agriculture; the draining disturbance of those areas has no practical purpose.

## Results

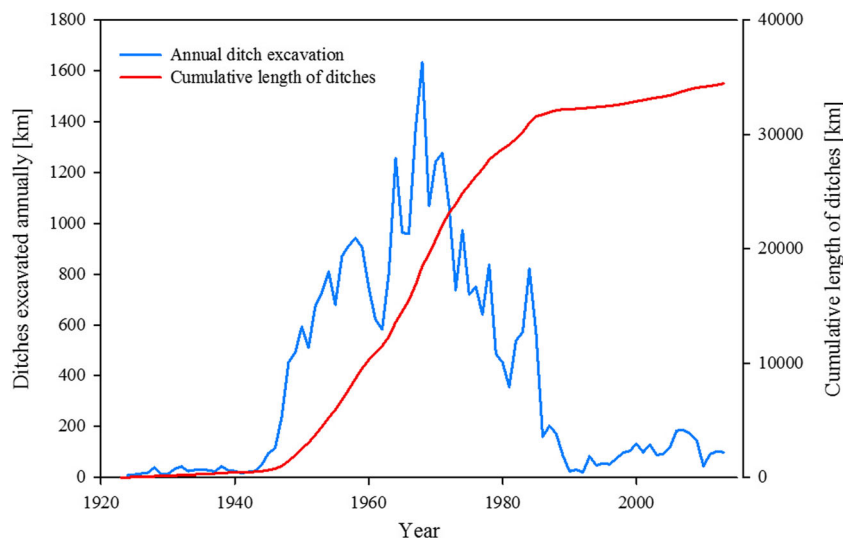
### The Extent of inland Wetlands

The wetlands, as represented in the AUI databases, consist of three classes: the saturated wetlands, damp wetlands and drained wetlands (partial to fully). The spatial distribution of these wetlands is presented in Fig. 4, and their altitudinal distribution is presented in Table 1.

The results of this GIS based analysis indicate that Icelandic inland wetlands cover about 9000 km<sup>2</sup>. This area is based on vegetation classification using satellite images, with open water reflectance signals to augment the classification. It is likely that soil-based classification reflecting the presence of shallow ground water would increase this extent. However, data are not available at this time.

Wetlands occur in all geographic regions of Iceland and extend into highland elevations. However, about two-thirds of the wetlands are found below 200 m elevation, or 5795 km<sup>2</sup>, which is equivalent to approximately 23 % of the lowland surface area and about 31 % of the vegetated land occurring below 200 m. About 20 % of wetlands are located between 200 and 400 m elevation, but their extent falls dramatically at higher elevations as does vegetation cover in general. Prominent inland fen wetlands occupy the southern lowlands (Fig. 4), with mostly

**Fig. 3** Cumulative and annual ditch excavation with time. The majority of ditches were excavated prior to 1987, with annual activity peaking in 1968 ( $> 1600 \text{ km yr.}^{-1}$ )



inorganic Gleyic Andosols in the eastern part where aeolian and volcanic ash inputs are relatively high, together with Histic Andosols and higher carbon content towards the western part of the southern lowlands (Fig. 4). Prominent inland wetlands also occupy western Iceland, mainly Histosols and Histic Andosols. Inland wetlands are also common within the deep valleys of the Tertiary Formation in North and West Iceland, harboring mostly Histic Andosols and Histosols. Widespread wetlands are found in the northwestern and eastern highlands (Fig. 4).

### Drainage Disturbance

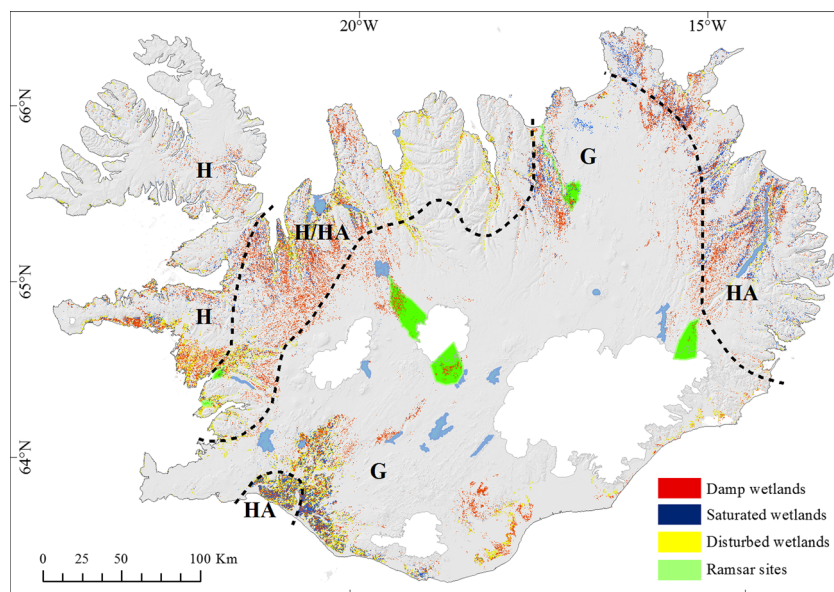
Our results show that  $4195 \text{ km}^2$  or 47 % of all Icelandic inland wetlands have been impacted by drainage (Table 1), ranging from full drainage to subtle changes in water levels. The table shows only areas affected by draining (see Materials and

Methods), but limited data are available for other wetland disturbances, except for hydro-electric reservoirs. The majority (70 %) of the lowland wetlands below 200 m elevation have been affected. Drainage of inland wetlands is rather limited above 200 m elevation, coinciding with the much limited agriculture at higher elevations.

### Ditches and Ditch Density

The digitization of the entire ditch system revealed a total of about 29,700 km of ditches (see also Gisladottir et al. 2010). Preliminary results from a survey on the accuracy of the digitization showed that 91 % of ditches mapped were confirmed as ditches and that 5 % of ditches had gone undetected by the mapping effort (Wöll et al. 2014). This estimate of the total length of ditches is slightly lower than the previous estimate of

**Fig. 4** Inland wetlands in Iceland. The most prominent areas are the southern and western lowlands together with the NW and NE highlands. Major wetland soil types dominating each region are indicated, enclosed by dotted lines. H: Histosols, HA: Histic Andosols, and G: Gleyic Andosols. Ramsar sites are indicated as green areas. The majority of the lowland wetlands have been impacted by drainage. Some impacted wetlands with altered vegetation cover and/or agricultural fields are not shown. Large water bodies are shown in blue. White areas on the map represent glaciers



**Table 1** A geographical summary for Icelandic inland fen wetlands, sorted by elevation intervals. Wetlands are separated into saturated and damp wetlands. Total vegetation cover is shown in the top row for comparison. Data from the IGLUD database which is based in part on the Nyttjaland database

	m.a.s.l.						Total
	0–200	200–400	400–600	600–800	800–1000	>1000	
	km <sup>2</sup>						
Total area	25,257	18,106	22,293	18,519	8345	10,163	102,683
Vegetated land	18,665	12,758	10,550	3932	385	41	46,331
Undisturbed wetlands <sup>s</sup>	1743	1611	1175	258	2	0	4789
<i>Saturated wetlands</i>	1112	1170	1010	236	2	0	3529
<i>Damp wetlands</i>	631	441	166	23	0	0	1260
Drained wetlands	4052	136	3	0	0	0	4191
Total wetlands	5795	1747	1178	258	2	0	8980
	%						
Impacted wetlands	69.9	7.8	0.3	0	0	0	46.7

<sup>s</sup> *Saturated wetlands + damp wetlands* in the table

Geirsson (1975), who estimated the total length of drainage ditches to be 32,700 km based on records of excavated volume obtained in relation to the subsidies rendered for making the ditches. The ditch system is further augmented by 61,600 km of sub-surface drainage made in 1961–1993, mostly in areas where ditches are in place (Geirsson 1975; Helgadóttir et al. 2013).

The majority of the impacted area has low accumulated ditch density (0.1–0.5 km km<sup>-2</sup>; Table 2) i.e. about 2300 km<sup>2</sup>, or 67 %. The highest densities of >10 km km<sup>-2</sup> make up 309 km<sup>2</sup> of the impacted area. The total extent of cultivated areas (hay-fields and other crops) in Iceland is about 1290 km<sup>2</sup>, of which about half is on drained wetland soils (Wöll et al. 2014; see also Helgadóttir et al. 2013).

An example of an area with extensive wetland draining in South Iceland is provided in Fig. 5. The figure shows that almost the entire area is influenced by the draining, which is in accordance with the results for areas <200 m elevation in general. The hayfields and other cultivated land are within the areas of the highest drainage densities next to the farms. Many areas shown as intact in the figure are encircled by a ditch system and are likely to be somewhat impacted. Undisturbed areas are found on the riverine floodplains. The impacts of low

ditch densities are also affected by landscape characteristics such as slope and bedrock hydrology. It is clear that a large proportion of the drained land is not used for such agricultural production. An undefined, but substantial proportion of the remaining drained wetlands is used for periodic grazing (data not available), and some are used for afforestation.

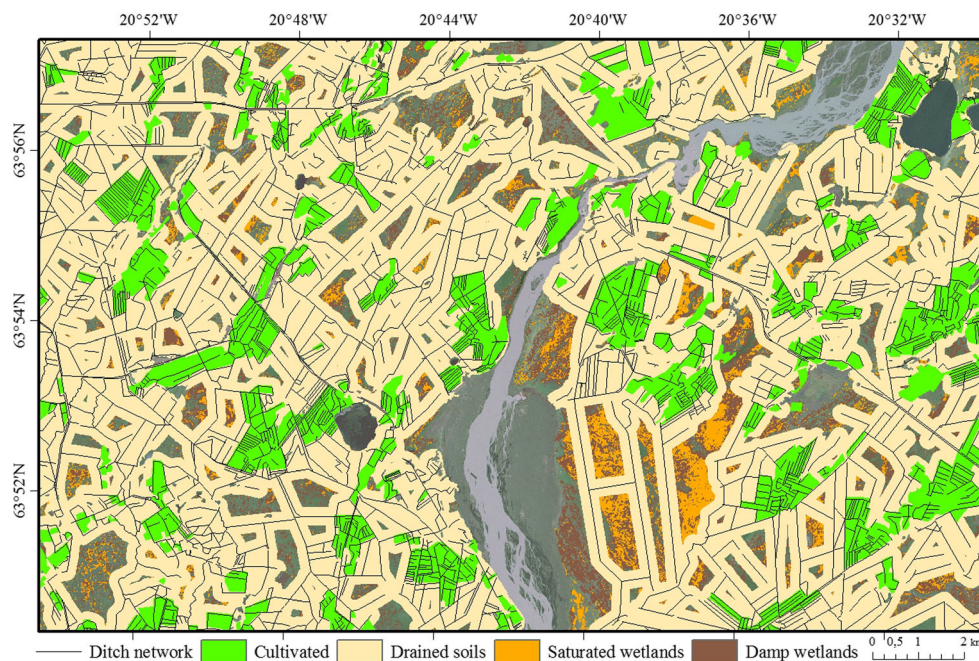
#### Wetland Patch Size

The majority of the fragmented wetland patches are small or below one ha in size (Table 3), with over one million such patches registered in our GIS Nyttjaland database and accounting for about 30 % of the wetland areas. Damp wetland patches are smaller on average than the saturated wetland patches (data not shown). Only 16 % of the wetlands occur as patches >100 ha (1 km<sup>2</sup>). Larger patches occur as saturated wetlands on average compared to damp wetlands, which indicates that there is a higher probability of saturated surface conditions within the larger wetland patches. Damp wetlands are often found at the periphery of the saturated wetlands and are therefore relatively smaller than continuous saturated wetland patches.

**Table 2** Wetland disturbance by drainage sorted by density of ditches

Density km km <sup>-2</sup>	Length of ditches km	Impacted areas km <sup>2</sup>	Proportion of ditches %	Proportion of total
0.1–5	1818	2300	6.1	66.6
5–10	11,462	858	38.6	24.7
10–15	8479	231	28.6	6.7
15–20	5337	63	18.0	1.8
>20	2585	15	8.7	0.4
Total	29,680	3468	100	100

**Fig. 5** Drained area in South Iceland. The river Thjórsá, partly in a gorge, runs through the center of the image. Undisturbed saturated and damp wetlands shown separately. The black lines display the ditch network. The map shows clearly that most of this area is less than 200 m from ditches, but a relatively small proportion of the area is cultivated (hay fields). Some areas marked undisturbed are surrounded by ditches but >200 m from them. These areas are mostly likely somewhat impacted by the drainage, but the numbers for impacted areas are not included



## Discussion

The soils of Icelandic wetlands are exceptional on a global scale for being a mixture of volcanic and organic soils, with extremely variable organic content. Their carbon content is usually much lower than in Arctic wetland soils (especially the Gleyic Andosols) and the C/N ratio is lower. They are more vitric in character than much of the Aquic and Hydric Andosols found in other volcanic areas. Their fertility is enhanced by a relatively favorable pH maintained by nutrient release from the rapid weathering of basaltic volcanic glass (see Arnalds 2008, 2015 Ch. 9). Their uniqueness is highlighted by their dissimilarity with other northern circumpolar soils, which mostly constitute peat soils (Histosols) and/or Cryosols (permafrost) (Jones et al. 2010), while Icelandic wetlands are dominated by Andosols (mineral soils with variable organic content) with a relatively small proportion of Histosols, which also are influenced by aeolian deposition of volcanic materials.

**Table 3** Number of wetland patches sorted by patch size for saturated wetlands and damp wetlands. Data from the Nyttjaland AUI database and includes some disturbed/impacted wetlands

Patch size (ha)	Number of areas	Combined area (km <sup>2</sup> )	%
<1	1,135,626	1631	29.6
1–5	61,859	1225	22.2
5–50	11,768	1446	26.2
50–100	486	334	6.1
100–500	318	588	10.7
>500	29	288	5.2

The results show that a substantial part of the Icelandic inland wetlands have been disturbed by drainage. About 47 % of Icelandic wetlands have been drained, mostly below 400 m elevation. The results show that 70 % of the inland wetlands below 200 m elevation have been impacted to some degree, which is in good accordance with research on the southern and western lowlands (Thorhallsdottir et al. 1998; Oskarsson 1998). We suggest that the motivations for many of the ditches of the lowest densities (< 10 km<sup>2</sup>) were subsidy driven rather than by need for agricultural land, but such claims are difficult to corroborate.

The areas of intense drainage most often go through a vegetation composition shift from wetland to grassland plant communities, with higher cover of *graminoids* with various amounts of *salix* species and herbaceous plants, but the shift is also dependent on land use, such as grazing and fertilizer use, which tend to increase the abundance of grasses (see Magnusson 1998). We recognize that our estimate based on the 200 m distance from a ditch has its limitations. This distance is an estimated average, but will vary from one area to the other. Areas beyond the 200 m range enclosed by ditches, a common scenario in South Iceland, are also most likely impacted, with altered water and nutrient flows. This methodology gives a good first appraisal of drainage impacts in Iceland.

A minor proportion of the drained land (15 %) is used for hay production, mostly of high density drainage. Grazing by horses on both drained and undrained lowland wetlands has caused damage to the vegetative cover in many places (Magnusson 1998). The highland ecosystems are not affected by drainage efforts. They often feed important salmon rivers that have a significant impact on the rural economy. However, some highland wetlands have been disturbed by hydropower



development, such as in the Blanda and Kárahnúkar areas in Northwest and East Iceland. There is widespread livestock grazing (mostly sheep) in the highlands, which has influence on wetlands, especially damp wetlands, which is likely to alter species composition, but research on these impacts is limited. Other disturbances have not been surveyed to date. It should also be noted that the nature of many of the inland wetlands, both highland and lowland, has been altered by increasing aeolian deposition rates after the Settlement of Iceland about 1200 years ago, with reduced carbon content per depth increment and often altered hydrology resulting from coarse sediments (silt and sand) being deposited on the areas.

The carbon dioxide emissions from drained wetlands outside cultivated areas are calculated as 5100–10,600 Gg CO<sub>2</sub> (data from Gudmundsson and Oskarsson 2014), or 7300 Gg CO<sub>2</sub> by applying the IPCC default emission factor for the area. The emissions of other greenhouse gasses (N<sub>2</sub>O, CH<sub>4</sub>) and off-site emissions are not included but add about 2300 Gg CO<sub>2</sub> equivalents to the greenhouse gas impact of drainage (Hellsing et al. 2016). These emissions exceed the sum of all Icelandic non-LULUCF emissions (including smelters and transportation) reported for the year 2014 for Iceland (4597 Gg CO<sub>2</sub> equivalents) (Hellsing et al. 2016).

Icelandic landscapes are characterized by a great variety of ecotypes over short distances and this is reflected by the large number of small wetland patches. Small patches are important in terms of ecological functions and biodiversity, with a wide range of habitats provided over relatively short distances, while the small wetland patches also provide improved hydrological characteristics such as water regulation during snow melt on a landscape level. Small-scale mosaics of different habitat types can better fulfill different requirements for birds during the breeding season (e.g. nesting, feeding) than larger homogenous areas (Gunnarsson et al. 2006; Pickett and Siriwardena 2011; Benton et al. 2003). Our results show that much of the inland wetland patches are <5 ha with about 30 % of wetland areas consisting of patches smaller than 1 ha. Only a proportion of the small damp wetland patches were created by the drainage activities in areas below 200 m elevation. The importance of patch size is reflected in the current law, stating that wetland areas >3 ha in size should not be disturbed. The 3 ha reference is based on much coarser mapping than presently available and potentially concealing the importance of smaller patches. The results presented here suggest that it is important to protect areas characterized by small wetland patches which give rise to the importance of the ecosystem mosaic rather than isolated habitat types and thus, small wetland patches are quite important. We argue that there should be adopted a smaller reference size than the current 3 ha (e.g. 0.5 ha) in light of the importance of the small wetland patches in the overall ecosystem mosaic. Further analysis of the 1–5 ha patch size shows that >40 % of wetland the area within this size class is between 1 and 2 ha. About 55 % of remaining wetlands are currently excluded from any protection.

## Conclusions

Icelandic inland wetlands are among the most important ecosystems of the country because of their role in biodiversity, water regulation and carbon budgets and they have an international value by supporting large populations of migratory bird species. There is a need for increased research on the hydrology of Icelandic wetland soils and the impact of draining. Furthermore, there is a need to analyze the relationship between drainage levels and impacts on various ecosystem factors and processes, such as fragmentation, GHG budgets, nutrient cycling and release, bird life, plant composition and other biotic factors. Research on biodiversity in relation to wetlands also needs more attention in future studies.

The remaining undisturbed inland wetlands are still being threatened by such factors as agriculture, with improved crop growing conditions with the current warming of the climate (see Helgadóttir et al. 2013), development and subdivision, land fragmentation (see Wald 2012), afforestation efforts and the generation of hydropower (large reservoirs). Some sectors, including the road authorities, have adopted strict policies to avoid wetland disturbance or restoring wetlands in place for wetland areas deemed necessary to disturb (Stefansdóttir 2011). We conclude that it is important to increase the level of protection of all wetlands in Iceland. Lists have been made of areas in need of protection based on the importance to bird ecology (Ferdinand et al. 1973). The databases presented here have been shown to be of value for predicting wetland bird species and densities (Johannesdóttir et al. 2014; Gunnarsson et al. 2015). Many wetlands are on a list proposed for nature protection (“Náttúruminjaskrá”, Icelandic Natural Features Database, kept by the Environmental Agency of Iceland). However, there is a need to strengthen work to systematically prioritize the protection and restoration of Icelandic wetlands, which considers a broad range of factors such as size, continuity, ecology, hydrology, geomorphology, and the uniqueness of the wetlands on national, regional and global scales.

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