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Assessing the Ecological Impacts of Extensive Sheep Grazing in Iceland

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ABSTRACT

The sustainability of sheep grazing in Iceland has been repeatedly questioned as in some areas high stocking rates have been associated with extensive soil erosion and ecosystem degradation. We synthesized all available information on the effects of sheep grazing on vegetation, soil properties and other organisms in the rangelands of Iceland, with special focus on the grey literature. We compiled 347 documents, but only 44 contained extractable data, reporting on 16 studies. The scarcity of studies prevented us from drawing general conclusions for most ecological variables across environmental conditions, but some consistent trends were found. The extent of bare ground was significantly higher in grazed areas and grazing affected plant community structure. The potential for increased soil erosion in grazed areas remains a problem in Icelandic rangelands. A better understanding of the ecological impacts of sheep grazing is required to inform sustainable grazing practices adapted to the local conditions of this region.

Keywords: extensive grazing, rangeland, soil erosion, sustainable management, tundra

YFIRLIT

Áhrif sauðfjárbeitar á íslensk vistkerfi

Sjálfbærni sauðfjárbeitar á Íslandi hefur oft verið dregin í efa enda tengja margir beit við mikla jarðvegseyðingu og hnignun vistkerfa. Hér tökum við saman þær rannsóknir sem birtar hafa verið um áhrif sauðfjárbeitar á vistkerfi íslenskra úthaga. Alls fundust 16 rannsóknir, birtar í 44 skjölum, flest á skýrsluformi. Fyrir flestar vistfræðibreytur voru rannsóknirnar of fáar til að draga mætti almennar ályktanir útfrá þeim. Safngreining (e. meta analysis) sýndi þó að beit hefur áhrif á uppbyggingu plöntusamfélaga og eykur rof í gróðurþekjunni. Úthaginn verður þar af leiðandi viðkvæmari fyrir jarðvegsrofi. Ljóst er að afla þarf betri þekkingar á áhrifum beitar á vistkerfi íslenskra úthaga svo tryggja megi sjálfbæra sauðfjárbeit sem hæfa aðstæðum á hverju svæði fyrir sig.

INTRODUCTION

For centuries, sheep grazing has been a major component of agricultural systems in the North Atlantic region, and has strongly shaped landscapes and biodiversity (Ross et al. 2016). The environmental impact of sheep grazing varies within the region due to differences in climate, ecosystem properties and, to a lesser extent, grazing management (Ross et al. 2016).

Land degradation (i.e. overgrazing sensu Mysterud 2006) and soil erosion have been associated with sheep grazing and recognised as a serious problem in Scotland (Hulme et al. 1999), the Faroe Islands (Dahl et al. 2013) and, particularly, in Iceland (Arnalds 2015). To meet the demands for sustainability by ensuring long-term productivity potentials of the land and maintaining its environmental function (SDG 2017) it is urgent to halt degradation processes in Iceland, restore degraded land and manage sheep grazing in a sustainable way. This requires detailed knowledge of the characteristics of the ecosystems and how they respond to grazing.

Volcanism and the relatively recent introduction of mammalian herbivores have been proposed as the two main reasons for why ecosystem degradation has been so severe in Iceland. Icelandic vegetation developed since the last deglaciation without the selective pressure of large herbivores. The first large herbivores were introduced into Iceland by the Norse settlers in the late ninth century (*landnám*), who brought with them various livestock, including sheep (Þórhallsdóttir et al. 2013). In high densities, large mammalian herbivores can disrupt vegetation cover by selectively consuming aboveground plant parts and trampling, which causes plant damage and soil compaction. Once bare ground is exposed, the volcanic soils of Iceland (andosols) are particularly prone to water and wind erosion: subsequent aeolian deposition further enhances the erosion process (Arnalds 2015). Palaeo- and archeological records provide evidence for dramatic human environmental impact shortly after the *landnám* in some areas (Streeter et al. 2015, Eddudóttir et al. 2016). The impact was probably most intense in the lowlands, involving extensive clearance of mountain birch woodlands (*Betula pubescens*) in combination with livestock grazing, resulting in a rapid transition to open grasslands and dwarf-shrub heathlands that were less resilient to natural catastrophes (Dugmore et al. 2005, Vickers et al. 2011).

Sheep became the dominant livestock in Iceland shortly after the *landnám* (Dugmore et al. 2005), and for centuries sheep farming was the main provider of meat in Iceland, in addition to other products like wool, skin and milk (Dýrmundsson 2006, Þórhallsdóttir et al. 2013). Access to winter grazing and fields for haymaking in combination with diseases, adverse climatic conditions and natural catastrophes controlled the number of livestock, and sheep stocks fluctuated between 50,000 and 300,000 until the mid-19th century (Arnalds & Barkarson 2003). Following technological progress, access to commercial fertiliser and better access to markets, the number of sheep increased by the end of the 19th century (Þórhallsdóttir et al. 2013). Sheep numbers reached a peak of 900,000 sheep in 1977, leading to overgrazing in many districts and grazing commons (Arnalds 1987, Arnalds & Barkarson 2003). Sheep grazing became so extensive that nowadays it is hard to find an area in Iceland that has not been impacted (Olsen & Klanderud 2014). Land degradation and soil erosion became particularly severe within the volcanically active zone and in the highlands where the ecosystems are more vulnerable (Arnalds 2015). When livestock quotas were introduced in 1985 (Act on Production and Sale of Agricultural Products, no. 46/1985), the number of sheep dropped to around 450,000 and are still around that level today, a relatively high number given the historical context (Arnalds & Barkarson 2003). By the time the stocking rates were reduced after the historical maximum, the ecosystems in many districts and grazing commons had shifted to a severely degraded state in terms of productivity and resilience to disturbance, and their recovery has been very slow (Arnalds 2015). Sheep production on the highland ranges is high and comes at a low cost to farmers that usually utilize the rangelands at no cost. This has therefore traditionally been regarded as a profitable grazing system (Guðmundsson & Þórhallsdóttir 1999). Today, most sheep are grazed without herding during summer in extensive rangeland commons, including the highlands, from late June to early September (Guðmundsson 2001). However, due to the limited knowlegde of the ecological consequences of grazing (Petursdottir et al. 2017), areas in poor condition, with degraded and even collapsed ecosystems (due to extensive soil erosion), are still being grazed today (Arnalds 2015).

The ecological impacts of sheep grazing outside Iceland have been well-documented. In general, even moderate sheep grazing has strong effects on ecosystem structure and function, as well as biodiversity. In grazed areas, graminoids become dominant while woody species and grazing and trampling-intolerant forbs and mosses decline (Pakeman & Nolan 2009, Austrheim et al. 2014,). However, the impacts of sheep grazing depend on grazing pressure (Austrheim et al. 2016) and environmental conditions (de Bello et al. 2006), such as climate, and the presence of other herbivores (Albon et al. 2007). For instance, grazing is generally more harmful (enhancing erosion) in alpine areas than in lowlands (Dahl et al. 2013). A number of grazing studies have also been conducted in Iceland (Guðmundsson 1996), but most of them have only been published as internal reports, in local journals or as abstracts of conferences and meetings, mostly in Icelandic (grey literature), or remain unpublished. Only a handful of peer-reviewed papers with extractable data is accessible to a wider, international research community. Published studies point to some general trends in heavily grazed ecosystems, such as increases in dominance of unpalatable plant species, decreases in the abundance of mosses, shrubs (Jónsdóttir 1984) and trees (Valdimarsdóttir & Magnússon 2013), reductions in moss layer thickness (Jónsdóttir 1991, Hecht et al. 2007) and more extensive soil erosion (Jónsdóttir 1984). In addition, grazing has been found to prevent restoration of denuded areas (Arnalds et al. 1987, Magnússon & Svavarsdóttir 2007). However, there is high uncertainty associated with these trends, particularly as to how different environmental conditions affect ecosystem responses.

The aim of this study is to compile and synthesize data on the ecological impacts of sheep grazing on Icelandic rangelands to allow generalization of the environmental impacts of this practice, and guide future research by identifying knowledge gaps. We collated all documents reporting on the impacts of sheep grazing on plant communities, soils, and other animals, including the grey literature. A systematic search in international and local databases was complemented with expert knowledge and references cited in the documents. Available data were extracted and synthesized using meta-analyses. In addition, where possible, we explored whether the impacts of grazing differed between sites within and outside the volcanic zone.

METHODS

We compiled a list of relevant documents by searching in national and international databases. A search in SCOPUS and Web of Knowledge in October 2016 using the search terms “Iceland*” AND “graz*” AND “sheep” retrieved 18 and 16 documents, respectively (Table 1). A search in Icelandic databases, one compiling agricultural papers in journals, magazines, proceedings and reports (http://www.landbunadur.is) and another compiling BSc, MSc and PhD theses (http://www.skemman.is) in October 2016 using Icelandic (“beit” AND “sauðfé”) and English search terms (“grazing” AND “sheep”) retrieved 188 results. We expanded this list by including potentially relevant references found within the original documents and asking Icelandic experts in the field for references that might had been overlooked during our search. In total, our search resulted in 347 documents. Documents were classified according to type (international publication, national publication, book or book chapter, report, conference proceedings, publication series or magazine, newspaper article or other) and language in which they were published (English or Icelandic). From this initial list, 28 documents could not be physically found and 47 were unsuitable document types, e.g. tables of contents or raw reference lists. Of the remaining documents, 162 were discarded because they did not deal specifically with sheep grazing, were not conducted in Iceland, did not focus on rangelands or did not report on ecological impacts (see Appendix S1); these

Table 1. Number of documents retrieved from bibliographic searches in October 2016 in different databases, including English and Icelandic search terms.

Database	Search terms	Documents retrieved
International		
SCOPUS	“Iceland*”, “graz*” and “sheep”	18
Web of Knowledge	“Iceland*”, “graz*” and “sheep”	16
Icelandic		
landbunadur.is	‘beit’ and ‘sauðfé’	134
	‘úthagi’ and ‘sauðfé’	29
	‘grazing’ and ‘sheep’	59
	‘grazing’, ‘sheep’ and ‘rangeland’	16
skemman.is	‘beit’ and ‘sauðfé’	5
	‘grazing’ and ‘sheep’	7

documents reported variables related to sheep production (e.g. lamb weight), sheep behaviour, sheep health and grazing management. In total, 110 documents focused on the ecological impacts of sheep grazing on rangelands in Iceland; however, 66 of these had to be excluded from our analyses because sheep grazing was confounded with that of other livestock (5) or did not report extractable data (61). Out of the 61 studies not reporting extractable data, 39 were opinion pieces discussing the topic of sheep grazing.

The 44 documents from which data could be extracted reported on 16 studies, comprising a total of 53 study sites (Figure 1). In some cases, studies reported several comparisons of areas with different grazing treatments, for example if comparisons were made at different sites within the same study; these studies thus contributed several data points (independent comparisons) to the analyses (Table 2). We distinguished three main types of study approaches depending on how the grazing treatments were defined (Table 2): 1) those that compared grazed and non-grazed areas (here non-grazed is defined as areas that have been fenced off for at least 3 years or that have never been grazed); 2) studies that

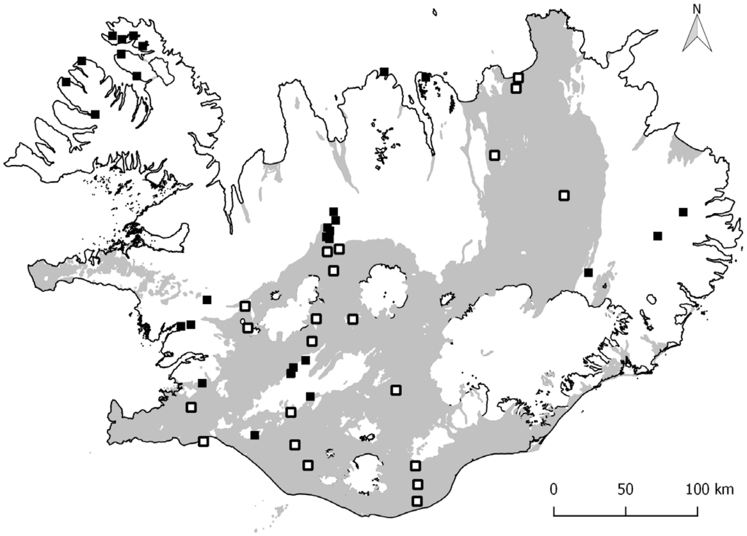

Figure 1. Map of Iceland indicating the location of study sites for sheep grazing studies in Iceland. The volcanically active zone is indicated in light grey; sites within the volcanic zone (open symbols) and outside the volcanic zone (solid symbols) are shown. Map adapted from Jóhannesson (2014).

Table 2. Summary of grazing studies conducted in Iceland from which data could be extracted, indicating the number of independent comparisons reported in each study. Three types of study approaches were identified: those comparing grazed and non-grazed areas (non/grazed), studies that compared different grazing intensities (intensity) and studies that assessed the effect of grazing cessation (protection) without grazed controls. The number of years of protection from grazing and number of study sites are indicated; for studies where non-grazed areas have never been grazed years of protection are indicated as >100. Studies reported data on vegetation, other organisms and soil variables. Vegetation data include percent cover of at least one growth form of plants, diversity (mainly reported as species richness), and other characteristics of vegetation, such as vegetation height, standing crop, moss depth or information for particular plant species. Soils were mostly characterized in terms of pH and % content of C, N.

				Vegetation				
Sheep grazing studies in Iceland	**type**	**years of protection**	**No. independent comparisons**	**percent cover**	**diversity**	**other**	**Soils**	**Other organisms**
Biskupstungaafrétt	non/grazed	3	4	3		3		
Mosfellsheiði	non/grazed	3	1	1				
RANGE - Borgarfjörður	non/grazed	5-24	1	1				
Lómatjarnin	non/grazed	>100	1	4	4		1	
Hallormstaður A	non/grazed	30	1	1	1			
Hallormstaður C	non/grazed	82	1			1		
Hnausheiði og Auðkúluheiði	non/grazed	5-14	2	2		1		
Örfoka	non/grazed	17-60	13	13	13		13	
Tundra diversity	non/grazed	60	6		1	1		
Auðkúluheiði og Eyvindastaðaheiði	non/grazed	10	7	1	2		4	4
Hálslón	non/grazed	6	1	1			1	
Blöndulón	non/grazed	33	1		1			
Viðey	non/grazed	>100	1	1	1	1	1	
Utilization and Conservation of Grassland	intensity	NA	9			7		
Húsafellsskógur	protection	>25	1			1		
Hornstrandafriðland	protection	19-58	5			5		

compared areas subjected to different grazing intensities; and 3) studies that assessed changes (mostly in plant community composition) before and after, or only after, an area had been protected from grazing.

Data analysis

Data were extracted from values directly reported in the text or from tables and figures (see Appendix S2 for more details on data extraction and processing). To extract data from figures we used the image processing software ImageJ (Schneider et al. 2012); the figures in the original papers were scanned and scaled according to the measurement units in the figure axes. The values of the data points in the figures were then extracted based on their relative position on the figure axes. When studies reported data from the same plots over several years, we extracted data from the longest time period possible, or the year for which most data were available. Studies reported on a variety of measures, mainly on vegetation, but also on other organisms and soil variables (Table 2). Vegetation variables included percent cover of different plant groups (grasses, other graminoids, shrubs, forbs, moss, lichen, moss and lichen combined and total percent cover of vascular plants), cover of bare ground, litter cover, vegetation height, herbage production, species richness and moss depth; soil variables included pH, C and N content, C:N ratios and abundance of soil-dwelling collembolans.

We synthesized the results from the different study approaches separately (Table 2). Meta-analysis was used to synthesize data from studies comparing grazed and non-grazed sites, and to summarize the data from the only study comparing areas with different grazing intensities. Data from the two studies assessing the changes after protection from grazing are only treated qualitatively in the discussion.

In the meta-analysis of studies comparing grazed and non-grazed areas (13 studies, 39 independent comparisons), variables were included if data from at least three independent comparisons from one or more studies were reported. To make results from different studies comparable, the effect sizes of grazing on each of the response variables were calculated. Studies reported data either as measures (average, sample size and a measure of variation) for grazed and non-grazed plots separately, or reported only average values of grazed and non-grazed plots that were paired due to an additional treatment (e.g. pairs of grazed and non-grazed plots that received different levels of fertilisation or were seeded with different grass species). In the first case ('independent groups') we calculated the unbiased estimate of the standardized mean difference, Hedges' g (Hedges 1981) as a measure of the effect size of grazing (Appendix S2). In the second case ('matched pairs'), the differences between paired grazed and non-grazed plots were computed, and the average, standard deviation and sample size of these change scores across levels of the additional treatment were used to calculate the standardized mean change (grazed vs non-grazed) as a measure of effect size (Appendix S2). In both cases, effect sizes indicate the effect of grazing, by comparing grazed to non-grazed areas. Effect sizes are unitless measurements that indicate the strength of an experimental manipulation (Borenstein et al. 2009). It is important to note that comparisons here reflect the effect of grazing as inferred from the exclusion of grazing, because experimental manipulations generally involved fencing off areas that had previously been grazed.

For each of the response variables, we built a random effects meta-analysis, that is, a model that assumes that effect sizes observed by the different studies represent a random sample normally distributed about a mean. Heterogeneity in the effect sizes of studies around that mean can be attributed to identifiable sources of variation (i.e. moderator variables) and their influence quantified using mixed-effects meta-analysis, which provides a statistical test analogous to ANOVA (Viechtbauer 2010). When at least two studies or three independent comparisons were available for sites within and outside the volcanically active zone (Figure 1), we built mixed-effects meta-analyses including study location as a moderator. Assignment to the volcanic zone was based on bedrocks younger than 0.7 million years old (Jóhannesson 2014, Figure 1). Unless otherwise indicated, summary effect sizes (ES) and standard errors are reported.

A similar meta-analytical approach was used to synthesize the results from the single study assessing the impacts of grazing intensity. In most cases mean values were presented without an associated measure of variation; we could therefore only include in our analyses data from sites reporting 2 replicate plots per site that allowed calculation of an effect size and the associated variation that could then be synthesized across sites in a random-effects meta-analysis. We computed effect sizes for independent groups using Hedges' g, comparing high vs. low and high vs. medium sheep densities. As both comparisons yielded qualitatively the same results, we only present here the results using high vs. low densities.

For variables that could not be included in the meta-analyses due to insufficient sample size, for example where the authors reported quantitative data for areas with different grazing treatments just for a single site (single independent comparison), we assessed the differences between areas with different grazing treatments (either different grazing pressure or grazed vs. non-grazed areas) using t-tests (Appendix S3).

All analyses were conducted in R (R Development Core Team 2014) using the *metafor* package (Viechtbauer 2010).

RESULTS

Data availability

Our search retrieved 347 documents, mainly in Icelandic (266; 76.7%). Most of the documents were conference proceedings (118) or reports

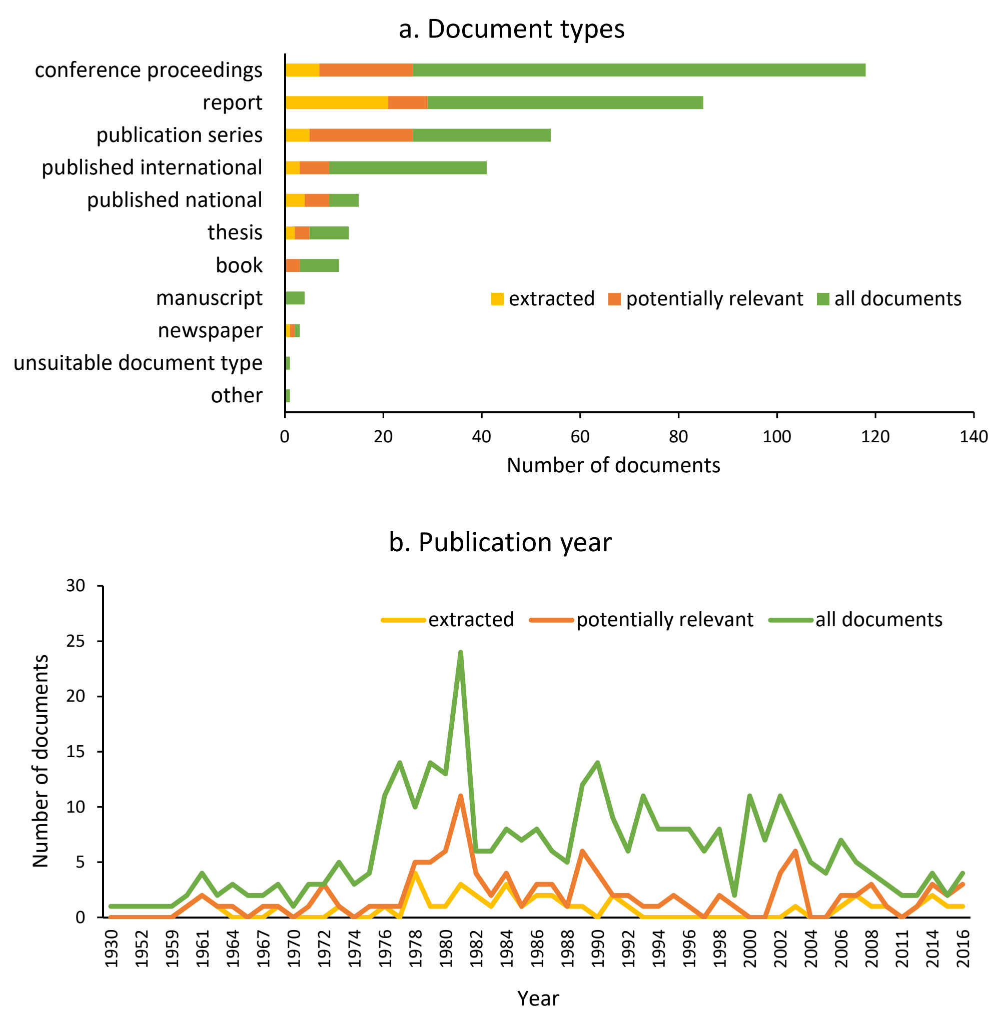

Figure 2. Types of documents (a) and publication year (b) for all documents found in the literature search for the ecological impacts of sheep grazing in Iceland (green) and for the potentially relevant documents (orange) and for those from which data could be extracted (yellow).

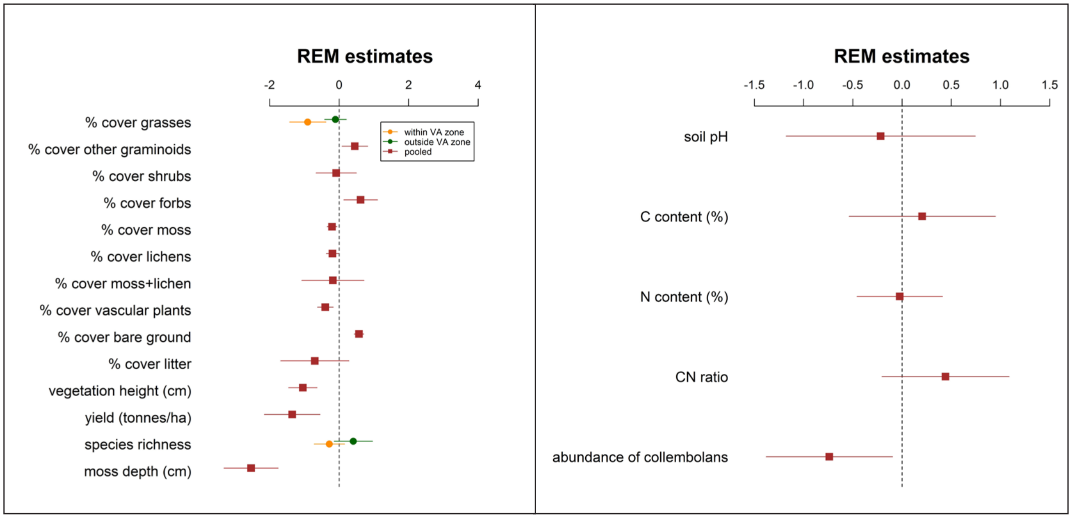

Figure 3. Estimates of effect sizes of sheep grazing on vegetation (a) and soil variables (b) across studies that compared grazed and non-grazed areas. When the effect of a site being located within the volcanically active zone had a significant influence on the effect of sheep grazing, separate analyses were run by zone: within (yellow circles) or outside (green circles) the volcanically active (VA) zone; otherwise data for the two zones are pooled together (red squares). Effect sizes estimated with a Random Effects Model (REM) and their 95% confidence intervals are shown. The direction of the effect indicates the effect of grazing (comparison grazed vs. non-grazed areas). Effect sizes to the right of the zero line (vertical dashed) indicate a higher value of the variable in grazed vs non-grazed areas, whereas values to the left represent higher values of the variable in non-grazed areas.

(85; Figure 2a) and only 16% of the documents (57) were publications in national or international scientific journals. Of the 44 documents with extractable data, most were written in Icelandic (76.7%) and 21 were reports; 2 documents were published in peer-reviewed and 2 in non-peer-reviewed national scientific journals, and 3 in peer-reviewed international scientific journals. A quarter of the documents were published over just 6 years in the late 1970s into the early 1980s (Figure 2b), and half of the documents with extractable data were published between 1978 and 1987.

Effects of sheep grazing on ecosystems

According to the meta-analyses of studies comparing grazed and non-grazed areas, differences were found for 10 of the 14 vegetation variables tested (Figure 3a), but only one of the 5 soil variables investigated (Figure 3b; for more details see Appendix S4). The percentage cover of grasses (ES=-0.312±0.157, z=-1.996, p=0.046), mosses (ES=-0.206±0.071, z=-2.889, p=0.004), lichens (ES=-0.191±0.093, z=-2.052, p=0.040) and vascular plants (ES=-0.398±0.116, z=-3.435, p<0.001) was lower in grazed than non-grazed areas. There was also reduced vegetation height (ES=-1.046±0.210, z=-4.984, p<0.001), herbage production (ES=-1.353±0.411, z=-3.300, p=0.001) and moss depth (ES=-2.535±0.398, z=-6.371, p<0.001) in grazed areas. However, there was higher cover of graminoids other than grasses (ES=0.451±0.190, z=2.377, p=0.018), forbs (ES=0.617±0.248, z=2.491, p=0.013), and the percent cover of bare ground (ES=0.573±0.071, z=8.029, p<0.001) in grazed areas. There were no differences in the percent cover of shrubs (ES=-0.085±0.298, z=-0.284, p=0.777), lichens and moss combined (0.182±0.467, z=-0.397, p=0.691), litter cover (ES=-0.700±0.501, z=-1.398, p=0.162) or plant species richness (ES=-

0.006±0.182, z=-0.032, p=0.162) between grazed and non-grazed areas. Excluding sheep grazing did not have a significant effect on any of the soil chemical parameters analysed (soil pH: ES=-0.218±0.490, z=-0.444, p=0.657; C content: ES=0.205±0.380, z=0.539, p=0.590; N content: ES=-0.024±0.222, z=-0.107, p=0.915; soil C:N ratios: ES=0.441±0.330, z=1.337, p=0.181), but soil collembolans were more abundant in non-grazed areas (ES=-0.739±0.328, z=-2.255, p=0.024; Figure 3b).

Some studies reported variables in grazed and non-grazed areas that could not be included in the meta-analyses (see Appendix S3). One study found higher values for Shannon's diversity index for vascular plants (t = 3.603, df = 7, p-value = 0.009) and evenness (t = 2.661, df = 7, p = 0.032) in grazed plots. Another study found no differences in the cover (paired t test; t = -0.310, df = 3, p = 0.777) or height (paired t test; t = 0.154, df = 3, p = 0.888) of planted willows between grazed and non-grazed areas that had received different fertilisation treatments. One study reported no differences in percent water content of soils (t = -2.3593, df = 1.835, p = 0.1535) and percent content of organic matter (t = -1.626, df = 4.05, p = 0.178) between grazed areas and areas that had never been grazed.

Influence of site location relative to the volcanically active zone

Owing to the small sample sizes it was only possible to assess the effect of study location on the ecosystem effects of sheep grazing for 8 variables (see Appendix S4). Although overall there was a lower percent cover of grasses in grazed areas than non- grazed areas, this difference was stronger within (ES=-0.905±0.265, z=-3.410, p<0.001) than outside the volcanic zones (ES=-0.108±0.160, z=-0.672, p=0.251; Figure 3a). Furthermore, although not significantly, sheep grazing appeared to have the opposite effect on species richness, within and outside the volcanic zone (ES=-0.690±0.361, z=-1.913, p=0.056). Species richness tended to be lower in grazed areas within the volcanic zones (ES=-0.282±0.225, z=-1.251, p=0.105), but higher in grazed areas outside the volcanic zone (ES=0.408±0.282, z=1.449, p=0.926; Figure 3a) as compared to non-grazed areas. There were no differences inside and outside the volcanic zones for the other six variables for which study location could be included in the mixed-effects meta-analysis (percentage cover of mosses, lichens, vascular plants and bare ground cover, or soil pH and C content) Figure 3.

Intensity of grazing

Increased grazing pressure decreased herbage production (ES=-1.434±0.458, z=-3.134, p=0.002; Figure 4), but had no effect on characteristics of vascular plant: crude protein content (ES=0.497±0.463, z=1.074, p=0.283), content of magnesium (ES=0.272±0.460, z=0.593, p=0.553), potassium (ES=0.540±0.485, z=1.115, p=0.265), phosphorus (ES=0.674±0.467, z=1.444, p=0.149), calcium (ES=-0.528±0.924, z=0.571, p=0.568), ash content (ES=0.428±0.536, z=0.799, p=0.424) or digestibility (ES=0.145±0.388, z=0.374, p=0.709) of herbage.

For one of the sites (see Appendix S3), one study manipulated sheep densities for 12 years and used fertilised and unfertilised plots. The study reported higher soil C (t = 2.432, df = 15.44, p = 0.028), soil N (t = 2.480, df = 15.06, p = 0.025) and soil potassium (t = 2.420, df = 13.52, p-value = 0.030) content in plots receiving higher sheep densities compared to low densities. No differences were found between high and low sheep density areas in the percentage of bare ground (t = 0.239, df =21.53, p-value = 0.813), soil pH (t = -1.563, df = 16.46, p-value = 0.137), or how uneven the terrain was (estimated as differences in hummock height, measured from troughs to the highest part of the hummocks, t = -1.636, df = 16.86, p-value = 0.120).

DISCUSSION

Sustainability of sheep grazing in Iceland has been debated for over half a century. It is well-established that human impact on the ecosystems after the *landnám* has been extensive and that

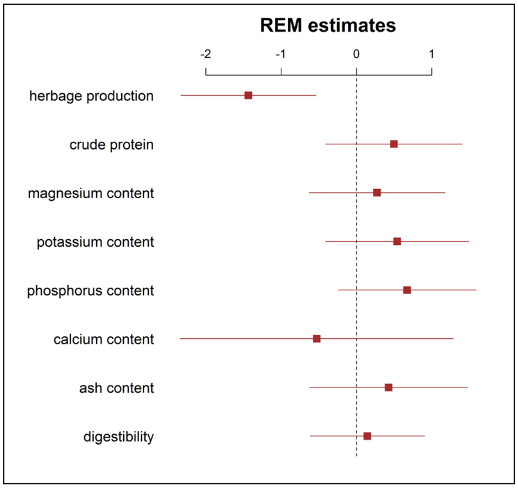

Figure 4. Effect of increased sheep grazing intensity on forage quality. Effect sizes estimated with a Random Effects Model (REM) and their 95% confidence intervals are shown. The direction of the effect indicates the effect of sheep density (comparison high vs. low sheep density). Effect sizes to the right of the zero line (vertical dashed) indicate a higher value of the variable in grazed vs. non-grazed areas, whereas values to the left represent higher values of the variable in non-grazed areas.

livestock grazing has played an important role (Streeter et al. 2015). The ecological data we extracted from published and grey literature provide further support for the importance of sheep grazing in shaping Icelandic ecosystems and add important details to that picture. Few studies reported data in a format that could be used in the meta-analyses, which limited both the type of ecological variables that could be explored and the inferences on how environmental conditions modulate the impacts of grazing. This literature review and meta-analyses also identify the main knowledge gaps and will hopefully guide research needed to inform farming policy and sustainable land management at all levels (i.e. governmental, community, individual farms).

Ecological impacts of sheep grazing in Iceland

Sheep grazing affected the structure and composition of vegetation in rangelands of Iceland. Overall, structural differences between grazed and non-grazed areas were greater than differences in plant community composition. Due to direct removal of plant biomass by grazers, vegetation structure is likely to show more immediate responses to different grazing regimes than plant community composition and functional diversity (Pakeman 2004, Díaz et al. 2007). For example, in a 10-year experiment in the upland moorlands of the UK, vegetation structure, but not diversity, was significantly affected by livestock grazing (Evans et al. 2015). Similarly, the species richness of vascular plants did not change in response to grazing after 5 years of exclusion at an alpine site in Norway, while plant height significantly increased when sheep were excluded (Austrheim et al. 2007). Many of the studies comparing grazed and non-grazed areas in our synthesis were also based on relatively short term grazing protection.

In Iceland, the most consistent structural feature associated with sheep grazing was a greater extent of bare ground and reduced cover of vascular plants. This is in agreement with studies on the effect of wild and domestic herbivores on other sub-Arctic and low Arctic regions (Olofsson et al. 2001, Austrheim et al. 2007). Sheep grazing disrupts vegetation cover by trampling and selective grazing. By creating erosion spots, grazing accelerates subsequent erosion as exposed soil is more vulnerable to erosion by wind, rain and cryogenic processes than soils protected by a vegetation layer (Zuazo & Pleguezuelo 2008). Soil erosion has been associated with grazing in many rangelands worldwide, e.g. in North America (Neff et al. 2008), Northern Europe (Evans 1997, Humle et al. 1999, McHugh et al. 2001, Dahl et al. 2013) and China (Zhao et al. 2005). The effects of grazing animals on soil erosion depend on vegetation and soil type, climate and historical land uses (Olofsson et al. 2001, Austrheim et al. 2007). In tundra ecosystems recovery from soil disturbances when the organic layer has been removed occurs slowly, over timescales of hundreds of years (Forbes et al. 2001). Further, sheep grazing is assumed to prevent revegetation of bare ground patches in Iceland because sheep are thought to selectively consume the more palatable colonizing seedlings (Arnarson 2002).

Our meta-analyses also revealed some consistency across studies in the changes in plant community composition in Icelandic rangelands in response to sheep grazing. Large herbivores can drive transitions from moss-dominated vegetation to graminoid-dominated tundra (Van der Wal & Brooker 2004, Olofsson et al. 2001). An important change detected in Iceland was a consistent reduction in the percent cover of mosses and the depth of the moss layer with grazing. The effect of herbivores on mosses has been proposed as one of the main mechanisms by which herbivores influence plant abundance in arctic ecosystems (Van der Wal et al. 2001, Gornall et al. 2009, Van der Wal & Brooker 2004). By trampling and consuming mosses, herbivores reduce the thickness of the moss layer, increasing soil temperature and improving growth conditions for some vascular plant species, particularly grasses (Van der Wal & Brooker 2004). Generally, herbivore-driven transitions of vegetation into graminoid-dominated states are linked to increases in the abundance of grasses; however, data from Iceland suggest a decrease in grass abundance in response to grazing, especially within the volcanic zone, paralleled by an increase in the less palatable sedges and rushes. Reductions in the cover of grasses have also been reported in other northern alpine systems (Austrheim et al. 2007), with lower abundance of grasses, particularly *Deschampsia flexuosa*, outside grazing exclusions, than inside (Austrheim et al. 2007, but see Mysterud and Austrheim 2008). Increased abundance of some sedges, like *Carex bigelowii* under sheep grazing has been reported in Iceland (Jónsdóttir 1991) and elsewhere (Steen et al. 2005, Mysterud & Austrheim 2008). The mechanism proposed for the increased abundance of sedges is that trampling by sheep reduces competition from mosses by reducing the depth of the moss layer, and stimulates propagation of these plants by tillering (Jónsdóttir 1991).

The impacts of herbivory and the ability of different plants to tolerate or resist grazing depend in part on the evolutionary history of grazing (Milchunas & Lauenroth 1993). Grazing mammals were introduced to Iceland by Norse settlers in the ninth century. Given the short history of grazing, large ecological impacts of grazing may be expected (Cingolani et al. 2005). However, we did not find responses as strong as one might expect under these conditions. One possible explanation is the variety of studies included in our meta-analyses, which represented different environmental conditions (e.g. highlands vs. lowlands) and differences in the duration of grazing exclusion. For example, studies included in our meta-analysis covered comparisons of grazed areas within the whole range from relatively short-term grazing exclusion (3 yrs.) to areas that had never been grazed. When looking at studies that investigated the effects of grazing in areas that had never been grazed there were clear differences in species composition, with some species being more abundant in grazed areas (e.g. *Thymus praecox*, *Bistorta vivipara* and *Festuca vivipara*) and others less (e.g. *Geranium sylvaticum*, *Ranunculus acris* and *Rubus saxatilis;* Valdimarsdóttir & Magnússon 2013).

It is also important to keep in mind that most exclosure experiments in Iceland have been conducted in areas that had been previously grazed (i.e. grazing cessation *sensu* Austrheim et al. 2007). Responses to cessation of grazing may be less pronounced than responses to enhanced grazing (Evju et al. 2009), especially in grazing systems that have undergone irreversible transitions. For instance, no apparent plant community responses were detected in a dwarf-shrub heath after four years of grazing protection in the Icelandic Highlands that had been grazed by sheep during the summer for centuries (Jónsdóttir et al. 2005). According to the state-and-transition model (Westoby et al. 1989), rangelands may be found in one or several alternative states, whereby each state is relatively stable and resistant to change. Grazing can cause such shifts in vegetation that may not be reversible by adjusting grazing pressure alone (Van de Koppel et al. 1997).

An indication that the state-and-transition model could apply to Icelandic rangelands is, for example, the lack of differences found in a multi-scale study investigating changes in plant diversity in currently grazed areas and areas where grazing had been abandoned >60 years ago (Mörsdorf 2015). Similarly, a study assessing the responses of 13 common vascular plants to farm abandonment in Northern Iceland found that with increasing time since farm abandonment one species significantly increased (*Geranium sylvaticum*) and two decreased in cover (*Viola palustris* and *Leontodon autumnale*), while the abundance of other species did not change (Einarsdóttir 2006). Once the system has shifted into an alternative state, releasing grazing pressure alone is not sufficient to revert back to the previous state, and intensive management actions may be required. Another indication of these alternative states could be the lack of responses of shrub cover detected in our study following grazing cessation in areas where shrubs (and trees) had been eliminated from the system by grazing in the past and no sources of colonization exist. In contrast, in places where some shrubs and trees persist in the landscape and are able to expand and colonize adjacent areas, protection from grazing may favour reversal of the system to a shrub or tree-dominated state. For example, protection from grazing since 1964 of one of the relict native forests in Iceland, Húsafellsskógur (Þorsteinsson & Þórhallsdóttir 2003, Olsen et al. 2014), effectively enhanced shrub and tree cover. The effect of grazing on shrubs and trees are also evident when comparing grazed areas with areas that have never been grazed (Jónsdóttir 1984, Valdimarsdóttir & Magnússon 2013) and in the birch forest remnants found at locations that are by some reason isolated from sheep (Einarsson 1979, Kristinsson 1979, Magnússon 2003). The increase in birch cover in Iceland in past decades has among other things, been attributed to less grazing pressure (Snorrason et al. 2016) as natural regeneration of birch is slow under continuous grazing (Þórsson 2008).

Are sites within the volcanic zone more vulnerable to sheep grazing?

In general, rangelands within the volcanic zone are assumed to be more sensitive to grazing than outside the volcanically active zone (Arnalds & Barkarson 2003). In the volcanic zone, the soil has experienced much more severe erosion throughout historical times, as evidenced by poor current conditions (Arnalds 2015), and the zone frequently experiences catastrophic disturbances, including volcanic eruptions. If grazing weakens the resilience of the ecosystem to these disturbances, we would expect to have more severe effects of grazing within than outside the volcanic zone (Eddudóttir 2016). The availability of studies allowed only testing the effect of study location for eight response variables. The clearest difference in the effects of sheep grazing within and outside the volcanic zone was that percent cover of grasses was lower when grazed only within the volcanic zone. Sheep grazing also appeared to reduce species richness within the volcanic zone and to increase it outside. This indicates that rangelands of the volcanic zone are more severely degraded than others.

Future outlook – a management-driven research agenda

The use of outlying rangelands for domestic herbivore grazing is a controversial agricultural practice in many areas (Oesterheld et al. 1992, Simpson et al. 1998). Defining sustainable levels of grazing is complex, as livestock regimes (i.e. density, breeds, length of grazing season), habitat characteristics (productivity, vegetation type, land management) and spatio-temporal scale, all determine ecosystem impacts of livestock (Milchunas & Lauenroth 1993). In addition, extreme events such as harsh winters or volcanic eruptions can compound the effects of sheep grazing (Þórhallsdóttir 2003), together with economic factors and socio-political drivers (e.g. changing market demands Arnalds & Barkarson 2003). The sustainability of sheep grazing can be enhanced by management regimes that promote grazing densities adjusted to local conditions.

For efficient grazing management, research needs to focus on variables that are relevant to management, such as grazing intensity. With very few exceptions, grazing experiments typically examine the effects of livestock exclusion rather than gradients in grazing intensity. Exclosure experiments do not allow uncovering non-linear responses to grazing and may lead to conclusions that inform wrong management decisions. For instance, field experiments in Norway manipulating sheep densities showed non-linear effects of grazing on plant productivity; at low sheep densities the biomass of vascular plants increased, but at high densities plant biomass decreased (Austrheim et al. 2014). Similarly, other effects of grazing may be species-specific and only appear above certain threshold levels (Steen et al. 2005, Evans et al. 2015). For example, the negative impacts of sheep grazing on the populations of field vole (*Microtus agrestis*) were only detected when sheep densities were high (Steen et al. 2005). The only field study manipulating sheep densities across a number of sites in Iceland focused mostly on lamb production (Guðmundsson & Arnalds 1979) not on the environmental impacts of grazing. Identifying thresholds in the effects of grazing intensity is critical for effective grazing management and should be a priority in grazing research in Iceland.

Grazing does not only affect plants, but also other trophic levels and ecosystem processes. A long-term (10 yr.) experiment in the upland moorlands of the UK led to cascades across trophic levels, with fewer arthropods and small mammals, breeding bird territories and predator activities (Evans et al. 2015). In Iceland, very limited knowledge exists on the effect of sheep on parts of the ecosystem other than plants, even though the effects are probably considerable. For instance, sheep can affect bird communities (Loe et al. 2007, Evans et al. 2015). Anecdotal evidence from Iceland suggests that sheep can directly impact bird populations by eating eggs and chicks from nests (Pálsdóttir 1992, Gunnarsson 2000, Katrínardóttir 2012), or indirectly through changes in vegetation structure. We found only one study that looked at the influence of sheep grazing on organisms other than plants, and there grazing had a negative effect on the density of the soil *Collembola* (Þorsteinsson 1991). For adequate grazing management, these effects need to be known.

Up to 80% of Icelandic ecosystems can be classified as rangelands (Arnalds et al. 2001), and approximately 43% of the land area is used for grazing today (Agricultural University of Iceland, unpublished database, Ross et al. 2016); thus proper land management is of outmost importance. The long-standing debate about sheep grazing in Iceland is reflected by the vast number of opinion pieces written throughout the years. The currently generalized poor condition of land ecosystems and extensive soil erosion in Iceland have been linked to centuries of overgrazing (Arnalds et al. 2001). However, as we show in the present study, we are still lacking detailed knowledge on the effect of sheep grazing on Icelandic ecosystems and how they vary under different environmental conditions; the lack of knowledge hinders effective management. Establishing a scientifically sound monitoring programme is thus a key priority. This programme could benefit from revisiting some of the old grazing experiments that have been included in the present study. Our meta-analyses indicate that, in general, sheep grazing has a negative impact on vegetation cover; by increasing the proportion of bare ground, sheep grazing will contribute to soil erosion, which is already a main environmental concern in Iceland (Arnalds et al. 2001). Based on the outcome of our survey, we suggest that policymakers take a conservative approach and join efforts to achieve sustainable grazing practices. This would mean termination of grazing practices that contribute to soil erosion and an increased focus on research on the effect of different levels of sheep densities on the Icelandic ecosystem. Research efforts should be targeted towards enhancing knowledge that is useful to management with the aim of making all Icelandic sheep production sustainable.

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