REVIEW

Sheep grazing in the North Atlantic region: A long-term perspective on environmental sustainability

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Abstract Sheep grazing is an important part of agriculture in the North Atlantic region, defined here as the Faroe Islands, Greenland, Iceland, Norway and Scotland. This process has played a key role in shaping the landscape and biodiversity of the region, sometimes with major environmental consequences, and has also been instrumental in the development of its rural economy and culture. In this review, we present results of the first interdisciplinary study taking a long-term perspective on sheep management, resource economy and the ecological impacts of sheep grazing, showing that sustainability boundaries are most likely to be exceeded in fragile environments where financial support is linked to the number of sheep produced. The sustainability of sheep grazing can be enhanced by a management regime that promotes grazing densities appropriate to the site and supported by area-based subsidy systems, thus minimizing environmental degradation, encouraging biodiversity and preserving the integrity of ecosystem processes.

Keywords Atlantic region · Management · Nordic agriculture · Rural economy · Sheep grazing · Sustainability

INTRODUCTION

Sheep (*Ovis aries*) grazing is an important agricultural practice affecting landscapes and biodiversity in all major regions of the world (Milchunas and Lauenroth 1993). In the North Atlantic region, defined here as the Faroe Islands, Greenland, Iceland, Norway and Scotland (Fig. 1), sheep husbandry has been important for human survival for thousands of years, especially in Scotland and Norway (Dýrmundsson 2006). Since the colonization of the Faroe

Islands, Iceland and Greenland some 1800–1000 years BP, it has also been important there, although in Greenland the practice has been more intermittent (Church et al. 2013). Throughout the twentieth century and into the twenty-first, ‘overgrazing’ has been seen as a serious problem in Scotland (Thompson et al. 1995; Albon et al. 2007), the Faroe Islands and Iceland, especially in the Icelandic highlands (Arnalds and Barkarson 2003). Generally, high sheep densities have been a less serious problem in Norway, although there is overgrazing in some alpine areas (Austrheim et al. 2007; Mysterud et al. 2014). Here, we define overgrazing as situations when “forage species are not able to maintain themselves over time due to an excess of herbivory or related processes” (Mysterud 2006). The severity of a given overgrazing situation will depend on several factors, such as the extent of the affected area, the temporal scale of overgrazing and the number of fodder plants affected. Herbivores may be regulated at carrying capacity (K) with no overgrazing, but overgrazing may occur below K, e.g. if rare preferred plant species with little effect on K are declining. Overgrazing is believed to have resulted in the degradation of vegetation and soils across much of the North Atlantic region (Hulme et al. 1999, Thórhallsdóttir et al. 2013).

Today, sheep are still the most numerous free-roaming livestock animal in the North Atlantic countries (Nordic Council of Ministers 2007; Scottish Government 2014), which are today part of a post-industrial economy where livestock management is a significantly smaller component than in the past. Both spatially and temporally, impacts of grazing on plants, animals and ecosystems, as well as interactions between sheep grazing, other herbivore species and environmental change drivers, have been highly variable (Hartley and Mitchell 2005; DeGabriel et al. 2011). Nevertheless, sheep grazing has been maintained by state

Fig. 1 Map of North Atlantic countries

subsidies and remains, from an ecological perspective, an important land use with marked effects on biodiversity, ecosystem function, plant biomass quantity and quality and soil stability, with important implications for the economy of rural communities where sheep grazing is locally important (van der Wal et al. 2011).

An assessment of sustainability is generally based on a broad range of environmental, social and economic elements, of which socioeconomic development is limited by environmental boundaries (Steffen et al. 2015). The sustainability of sheep grazing is questionable in cases where high stocking rates exceed the carrying capacity of the land (Thompson and Miles 1995; Olsen et al. 2014). Here, we define sustainable grazing management not just in terms of maintenance of vegetation, soil and animal components of these grazing systems, but also the delivery of socioeconomic benefits while maintaining the environment. It has been argued that sustainable development should meet the needs of the current generation without undermining the ability of future generations to meet their own needs (WCED 1987). In that case, the economic and societal importance of sheep grazing should be balanced against the environmental impacts in order to avoid overgrazing and to be sustainable.

Although sustainable grazing that is environmentally sound is a desirable management aim, defining such regimes presents a major challenge, and there are different opinions around grazing in the countries of the region (Thompson and Miles 1995; Myrsetrud 2006). This is a complex issue, 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 and Lauenroth 1993). There is also a lack of common understanding on defining the critical levels of sheep grazing across northern Europe, where extreme events such as harsh winters, diseases and volcanic eruptions have mediated the sheep grazing effects, and where economic factors (e.g. changing market demands and prices) have also been important. These economic factors are influenced by socioeconomic and nature conservation objectives, including policies, subsidies, EC directives and other statutory regulations, with the overall result that the definition and application of sustainable sheep grazing regimes in the region is challenging. The fundamental importance and long-term management of sheep grazing in the North Atlantic region therefore provides a uniquely important

opportunity to examine the environmental effects of sheep grazing and to discuss sustainable management practices from an ecosystem perspective.

In this paper, we bring together relevant findings and expert opinion from the countries of this region in order to provide a synthesis of status and trends in sheep grazing, and to elucidate some of the key, measurable factors of sustainability in this context.

OBJECTIVES

In this review paper, we have synthesized information from studies on aspects of sheep grazing management, both past and present, from the countries of the North Atlantic region: the natural environment; sheep numbers, density and habitat use; breeds; grazing seasons, predation and supplementary feeding and products. We review the effects of sheep grazing using a set of available measures reflecting environmentally and socioeconomically sustainable agricultural production: biodiversity, the sustainable production of forage plants, ecosystem function and socioeconomic sustainability. Together with expert opinion on grazing in the countries of this region, we explore lessons from past and present grazing regimes in order to ascertain, where possible, where and how sustainability boundaries are being exceeded, so as to inform future sustainable grazing management plans for the North Atlantic region.

SHEEP GRAZING MANAGEMENT IN THE NORTH ATLANTIC REGION: PAST AND PRESENT

Natural environment of the North Atlantic region

The climate of the North Atlantic region is highly oceanic in coastal areas, characterized by cool summers and relatively mild winters, often with high precipitation. Inland, the climate is more continental in character, with warmer summers and colder winters. The oceanic heat transport provided by the warm North Atlantic Drift gives rise to a changeable and windy climate (Seager et al. 2002). In Iceland, volcanism (ash deposition, soil erosion, dust storms, bedrock permeability) is an important factor (Arnalds 2015). The current vegetation of the North Atlantic region is dominated by semi-natural dwarf-shrub heath and grassland communities, whose composition, structure and extent are all strongly influenced by livestock grazing (Averis et al. 2004).

Land use patterns are broadly similar in the countries of the North Atlantic region. Historically, most of the outfield areas (unenclosed marginal land, often grazed as commons) were grazed by mixtures of cattle, sheep, horses and

goats, but today sheep (mainly ewes and lambs) are the most common grazing animal in almost all upland areas (Albon et al. 2007), although in Iceland the number of horses has doubled in the lowlands since the 1970s, and semi-domestic reindeer are the dominant herbivore in northern Norway (Austrheim et al. 2008b). The traditional and current grazing systems, and trends relating to the grazing lands, vary between countries, although common patterns and issues are also evident (Table 1). In addition to sheep grazing, the main land uses in the Scottish outfield in recent decades have been deer forest, grouse moor, cattle grazing, water abstraction, recreation and afforestation, primarily with non-native conifers (Averis et al. 2004). Native woodland regeneration is increasing, and tree planting with both native and introduced trees to create new woodlands is ongoing in Scotland, the Faroes and Iceland, much of this influenced by recent reductions in sheep grazing pressure as well as a drive to increase carbon storage by tree planting. In Norway, the encroachment of woodland and scrub in semi-natural grasslands and heathlands is evaluated as problematic in some areas where grazing pressure has been reduced (Speed et al. 2010).

Sheep numbers, density and habitat use

Grazing by sheep in the outfield mainly takes place in alpine and northern boreal vegetation in the North Atlantic region (Fig. 2). Winters are long and can be harsh, and there is a very limited amount of fodder for 5–7 months of the year. Sheep in this region generally graze large areas of open heathland and grassland, including vegetation of variable productivity, as for example in Scotland, where grazing ranges from intensively utilized *Festuca–Agrostis* grassland, through *Calluna vulgaris* and *Vaccinium* heath, to less “desirable” blanket bog and raised mire (Smith et al. 2003). Wet areas are avoided for as long as possible, so are typically grazed in the autumn. Spatial patterns of grazing vary greatly according to the distribution of vegetation types, with selection of less preferred dwarf shrubs made more likely by proximity to the small patches of grass preferred by sheep (Hester and Baillie 1998). Sheep are moderately selective feeders and tend to favour herbs over graminoids (grasses, sedges and rushes), and graminoids over woody plants (Mobæk et al. 2012), although the relative proportions of these plant functional groups in the diet vary seasonally and between breeds. Total sheep numbers vary between and within the countries of the North Atlantic region, as well as on a temporal scale (Table 2). They are necessarily limited by the carrying capacity of the vegetation, i.e. the forage quantity and quality, but can also vary as the result of events in the physical environment, changing economic conditions, and the state of agricultural subsidy systems (van der Wal et al.

Table 1 Overview of the environmental characteristics, traditional and current livestock systems and the main trends associated with the grazing lands in the countries of the North Atlantic region (taken from Austrheim et al. 2008b and Averis et al. 2004 for Scotland)

Country	Key environmental characteristics	Traditional and current sheep grazing systems	Trends in the sheep grazing lands
Faroe Islands	Strongly oceanic climate, relatively steep slopes, few plains, acidic and wet soils	The current system is the same as the traditional, with continuous grazing in the outfields and winter grazing in the infields. Around 20 % of the sheep have access to the infield pastures during winter. Few farmers have agriculture as their main profession	Increased land degradation has been observed as sheep biomass has increased and losses due to disease, etc. have declined
Greenland	Short growing season with limited production	Traditional (1920–85): Free-ranging sheep in outlying land during summer and winter. Current (1985–2014): Free-ranging sheep in outlying land during summer. Sheep housed and fed indoors during winter	Loss of <i>Vaccinium/Empetrum</i> heathland and <i>Betula</i> forest stands associated with sheep grazing. Increase in generalist graminoids and semi-natural alpine plants
Iceland	Oceanic coastal areas, highlands with short growing season and limited production. Volcanic soils susceptible to erosion	Traditional: sheep free-ranging in summer, year-round grazing in coastal areas, otherwise housed. Current: 6 months outdoor grazing with 2–3 months on rangeland commons in summer, and on lowland pastures in spring and autumn	Dominance of unpalatable plant species (<i>Juncus trifidus</i> , <i>Kobresia myosuroides</i> , <i>Empetrum nigrum</i>) in heavily grazed area. Decline of <i>Salix</i> shrubs in highlands and mountain birch in lowlands reduced moss layer thickness
Norway	Short growing season with limited production	Traditional: Free-ranging cattle and sheep in outlying land during summer. In winter, housed and fed (upland) or free-ranging in coastal areas. Current: Uplands still managed for extensive sheep grazing in summer. Winter grazing with ancient breeds in coastal areas	Grazing-resistant <i>Nardus stricta</i> dominates in overgrazed uplands. Sheep also limits tree-line expansion in alpine areas, and promotes semi-natural and alpine plants to the detriment of woodland species and lichen vegetation
Scotland	Strongly oceanic, short growing season, mostly acidic soils	Traditional: Transhumance (seasonal movement of people with their livestock between summer and winter pastures). Current: Upland grasslands and <i>Calluna</i> moorlands managed for extensive sheep grazing. Winter grazing on infields	Overgrazing associated with loss of <i>Calluna</i> heathland, the dominance of <i>Nardus stricta</i> and other generalist graminoids, declines in lichen cover and the prevention of native woodland regeneration

2011). In Iceland, sheep numbers have fluctuated considerably due to diseases (1761, 1855, 1878, 1932) and volcanic eruption (1783) (Thórhallsdóttir 2003). Sheep numbers here were greatest in the 1970s–1980s, but when quotas were introduced in the 1980s following overgrazing, the population was reduced by 50 % (Arnalds and Barkarson 2003). Sheep numbers in Scotland began to increase at the end of the eighteenth century, and indeed the year 1792 became known in Scottish Gaelic as *Bliadhna nan Caorach* (“Year of the Sheep”) to mark the transition from cattle-dominated grazing systems to larger farming operations using larger sheep breeds during the Highland Clearances (Hunter 2016). Numbers then increased considerably between 1950 and the 1980s, mainly as a response to EU subsidies based on headage payments (fixed subsidy payment per animal), and were highest around the turn of the twenty-first century (Scottish Government Website 2014). Sheep are currently in decline as a result of a combination of factors, including a downturn in the economic viability of sheep farming, the foot-and-mouth disease outbreak in 2001, livestock reductions

related to agri-environment schemes and changes in the way that sheep farmers are subsidized through the European Common Agricultural Policy (Pollock et al. 2013). In Norway, sheep numbers also increased during the twentieth century, with a small reduction in the last decade. In Greenland, there was a 50 % reduction in the number of ewes during the harsh winter of 1966/1967, followed in subsequent decades by a stabilization of sheep numbers and a gradual intensification of farming methods, with more supplementary feeding and higher fodder production on Greenlandic fields (Greenland Agricultural Consulting Services website 2014).

Sheep density is more difficult to assess as it varies between areas and historical data are often unavailable. A large proportion of the land area is available for grazing, and large areas are used for grazing in each country (Table 2). Grazing at high density is generally believed to correspond with times when the total numbers of sheep were highest in any particular country. The density of sheep relative to resource levels is a fundamental biophysical variable for assessing the sustainability of grazed

Fig. 2 **a** Faroe Islands (Erla Olsen), **b** Iceland (Borgthor Magnusson), **c** Norway (Gunnar Austrheim), **d** Greenland (Jon Feilberg) and **e** Scotland (Louise Ross)

ecosystems (Austrheim et al. 2016). A sustainable grazing regime in this respect must ultimately be defined by the number of sheep recommended to graze at upper and lower density limits within a specific grazing area at a given productivity. However, appropriate stocking rates are fundamentally dependent on the productivity and quality of the vegetation present and so will vary

considerably between sites. For example, current densities are considered to exceed upper limits in the Faroe Islands at 57 ewes per km² throughout the year (Austrheim et al. 2008b), in some low-productive mountain areas in Southern Norway at 70–88 ewes and lambs per km² during the summer season of 2006 (Rekdal and Angeloff 2007), and in upland Scotland at 40–60 ewes per km²

Table 2 Approximate area of grazing land for each country. Percent of the total land area is given in brackets. Total number of sheep (*1000) in the North Atlantic countries from the beginning of the 18th century to the present day

	Approx area of grazing land (km ²)	c. 1700	c. 1800	c. 1900	c. 2000	c. 2014
Faroe Islands ^a	1231.5 (88 %)	200	75–100	100	70	70
Greenland ^b	242 937 (11 %)	n/a	n/a	0.250	17.0	16.3
Iceland ^c	37 000 (43 %)	280	304	595	458.5	484
Norway ^d	266 631 (87 %)	n/a	1000	1400	2500	2200
Scotland ^e	41 000 (52 %)	n/a	n/a	2900	3200	2600

^a Based on four different estimates: Bjørk (1956/57), Svabo (1976), Patursson (1919) and Bjarnason (2004). For references see Austrheim et al. 2008b

^b Greenland Agricultural Consulting Services website

^c Arnalds and Barkarson 2003, Statistics Iceland 2013, unpublished data from land use database, Agricultural University of Iceland

^d Total number of sheep is based on Statistics Norway 2014. Estimations of grazeable area are based on Arnoldussen et al. (2014)

^e Scottish Government (2014)

(Scottish Agricultural College 2007). Densities in Greenland were estimated to be between 23 and 33 ewes per km² during the summer season (Austrheim et al. 2008b), which is evaluated as uncertain in relation to some environmental elements of sustainability. Note, however, that the actual metabolic biomass of sheep varies in these examples, as live weights and litter size of breeds differed between countries (Table 3).

Sheep breeds

The use of different sheep breeds results in varying impacts on the grazing system, both in terms of amount and selectivity of forage (Steinheim et al. 2005). The modern breeds are generally less hardy and require additional housing and feeding in the winter months. In Scotland, the distribution of sheep breeds is stratified, with particular breeds occupying the environments to which they are

adapted. Hardy breeds in the uplands are purebred, but older animals and lambs not required to maintain flock numbers move down the hill for breeding with longwool varieties or for fattening. Female lambs of these crosses are then bred in the lowlands with lowland breeds to produce fast-growing lambs (UK Agriculture website 2015).

DNA analyses have shown Icelandic, Faroese and Greenlandic sheep to be variants of the North European short-tailed sheep, and genetically more similar to the smaller Scottish and Norwegian breeds, which were more common before the nineteenth century (Tapio et al. 2005). These traditional breeds take longer to mature and are less profitable than the main breeds today: the Scottish Blackface, North-Country Cheviot and South-Country Cheviot in Scotland and the Norwegian White Sheep (NWS) in Norway, all of which are heavier and more fertile (Table 3). Ewes of NWS are also heavier than the other key Norwegian breed, the Norwegian Spel, and although litter size

Table 3 Life history parameters for domestic sheep breeds in the North Atlantic region (Austrheim et al. 2008b, Milne et al. 1998 for Scotland)

Country	Main sheep breed(s)	Live weight of ewes (kg)	Mean litter size at birth	Mean carcass weight of lambs at 5 months (kg)	Predators (which scavenge as well as kill sheep)
Faroe Islands	Faroese variant of the North European short-tailed sheep	40–50	0.8	12.5	Raptors, especially ravens
Greenland	Greenlandic variant of the North European short-tailed sheep	60–70	1.5	15	White-tailed eagle, arctic fox, raven
Iceland	Icelandic sheep	60–70	1–1.8	15.5	Arctic fox Raven White-tailed eagle
Norway	Norwegian White Sheep = 80%, Norwegian Spel = 13.1%	NWS = 83, NS = 65	NWS = 1.5–2.0, NS = 1.5–2.0	NWS = 19.2, NS = 17.8	Brown bear, lynx, wolverine, wolf, red fox, golden eagle, white-tailed eagle
Scotland	Scottish Blackface North-Country Cheviot South-Country Cheviot	SB = 50–56, NCC = 49–53, SCC = 56–59	1–2	SB = 15–19, NCC = 16–21, SCC = 17	White-tailed eagle, golden eagle, raven, fox

does not differ, NWS seem more dependent on graminoid fodder, while Norwegian Spel selects a higher percentage of woody species in the diet (30–50 % compared with 26 % for NWS). Increasing the numbers of sheep breeds that forage extensively on woody plant species may thus be a useful management tool in areas where woody plant encroachment an issue (Steinheim et al. 2005), and would also create an important beneficial externality: maintaining the open cultural landscapes which are important in a tourism and recreation context (Bryn 2011).

Grazing season, predation and supplementary feeding

Food availability, relating to the length of the grazing season and the amount of supplementary feeding, is a third factor which affects the actual grazing ‘intensity’ (i.e. the total grazing pressure exerted in a given landscape). Schematic representations of the present-day grazing year on typical sheep farms in each country are shown in Fig. 3 (historically the grazing season has varied). The timing varies, but generally ewes and their offspring are let out on spring pastures and then may move on to graze in mountains or extensive rangelands, depending on access (Vatn 2009). During the outdoor grazing season, the weight gain of lambs is limited by the available grazing resources, and determined by the vegetation quality/consumption per animal (Skonhøft et al. 2010). Predation can be an issue over the summer months, particularly in Norway—in 2008, 130 000 ewes and lambs were lost (Vatn 2009). Up to 40 % of the sheep, or ca. 50 000 sheep, have supposedly been killed by wolverines, lynx, wolves and bears in recent years (Mabille et al. 2015). Additional losses to the golden eagle as well as the red fox make up to roughly half the losses supposedly killed by protected predators. Widespread winter grazing is only practised in Scotland today (mainly on infields), where sheep are also fed on silage, turnips and occasionally concentrates, and in the Faroe Islands both on infields and outfields, and at some farms they are provided with some supplementary fodder especially in the spring. Sheep in Iceland, Greenland and Norway are generally housed and fed indoors over winter (due to harsh weather conditions), mainly on hay/silage, grains and concentrates, especially during the breeding season. Lack of suitable agricultural land for growing these crops in these countries does not necessarily limit the number of sheep that can be supported by supplementary feeding, as much of the feed stuff for concentrates can be, and is, imported. In the North Atlantic countries, a great deal of cultivated land is used for winter forage production (hay/silage), for example, 58 and 95 % in Norway and Iceland, respectively (Nordic Council of Ministers 2007). However, winter grazing outdoors can potentially lead to a greater degree of environmental degradation, as it

takes place when the vegetation is dormant and unable to recover as easily (Thompson 2009). Conversely, winter grazing, particularly of traditional breeds, may be an effective management practice if the prevention of woody plant encroachment is the objective.

Products

Wool and milk were the main products from sheep farming up until the twentieth century, but the importance of meat production gradually increased in all countries, and today meat is the main product in the North Atlantic region. For example, in Norway 80 % of the yearly income is from the sale of meat, while the rest is from wool (Skonhøft et al. 2010). Increasing the use of the old Nordic type Spel breed will influence the marketing potential of the wool, as this double-fleeced breed combine fine inner wool with a coarse outer fleece. While being sought after for some arts, crafts and other niche products, this type of wool is difficult to treat in large-scale industrial mechanical handling systems and generally obtains lower prices than the cross-bred homogeneous wool (Steinheim et al. 2005).

Sheep meat consumption varies between countries, being around 20.5 kg per capita in Iceland (Iceland Statistics, 2013) (halved since 1978), 29 kg in the Faroes (of which only 17 kg are produced in-country, Olsen et al. 2014), but only 5.8 kg in Norway (Dýrmundsson 2006). Sheep meat consumption per capita in the EU has been fairly stable over the last 40 years. In sustainability terms, there is a trade-off between high total meat production and high production per lamb, which decreases from high to low sheep densities (Mobæk et al. 2012). In future, climate warming could increase productivity of the system, increasing lamb weight, the number of lambs available for slaughter and the likelihood of being able to maintain a higher stocking rate (Johannesen et al. 2013). If policy changes to improve domestic food security were made, grazing higher densities of livestock, including sheep, in order to fulfil the demand for meat could result (Reed et al. 2009).

ASPECTS OF SUSTAINABILITY IN SHEEP GRAZING MANAGEMENT

Biodiversity

Changes in herbivore densities can lead to both positive and negative effects on biodiversity, depending on grazing history and intensity, size of species pool, site productivity and elevation (Hester et al. 2005; Speed et al. 2013). Sheep grazing has a profound effect on vegetation, with important knock-on effects on animal communities and ecosystems (Evans et al. 2015). Longer term effects of grazing on

Fig. 3 Typical year on a sheep grazing farm in the five countries of the region (data from the Faroes, Greenland, Iceland and Norway are taken from Austrheim et al. 2008b, Scotland by J. Milne, pers. comm.)

biodiversity differ from short-term effects, and the ensuing biodiversity depends on the trajectory taken by the ecosystem. The complex nature of the environmental conditions in the North Atlantic region, and the grazing management systems within these, makes it difficult to directly compare between countries. However, there are common themes from the results of studies on sheep grazing and biodiversity across the region, which we distil below.

Heavy grazing generally causes an increase of graminoids (grasses, sedges and rushes) (Pakeman and Nolan 2009), with a decline in the cover of some herbs and most woody species (Austrheim et al. 2008a). Continued overgrazing of heathland can lead to its conversion to grassland in many cases, facilitating the dominance of graminoids that can sustain higher levels of offtake. This creates a positive feedback loop for grazing, as more grazing leads to more resources becoming available (Thompson et al. 1995; van der Wal et al. 2003). Furthermore, sheep grazing may change bryophyte community composition (Jónsdóttir 1984; Austrheim et al. 2007) and reduce abundance of mosses (Jónsdóttir 1991; Magnússon and Magnússon 1992; Fosaa 2015) and also, in some cases, lichens (Mysterud and Austrheim 2008). In the Icelandic highlands, for example, heavy grazing has eliminated palatable, grazing-intolerant species (Jónsdóttir 1984) in extensive areas, causing slow responses to cessation of grazing (Jónsdóttir et al. 2005). Similarly, many upland areas in Scotland have become dominated by the unpalatable grasses *Nardus stricta* and *Molinia caerulea* at the expense of more productive *Agrostis capillaris*–*Festuca ovina* grassland (Hulme et al. 1999). Within areas that would naturally support forest, heavy grazing by sheep has maintained these areas as open heath and eventually grassland. However, where sheep numbers have declined, natural succession back to forest and scrub is increasingly evident, for example in Norway (Speed et al. 2010, 2014). This is a process that is expected to accelerate further, due to the influence of climate warming in the future. Other effects of reduced grazing are still emerging, but may include reduced structural heterogeneity and extent of grasslands (Pollock et al. 2013). The degree of plants' tolerance to grazing, which is subject to environmental conditions, trampling, time of year, competitive ability and dung deposition, will contribute to the ultimate effect of sheep grazing on plant species composition (Hartley and Mitchell 2005).

Sheep grazing also indirectly affects invertebrates, mammals and birds, but the responses reported in the literature differ between the group studied, the location/temporal duration of the study and the intensity of grazing. High grazing pressure, for example, has been shown to have a positive short-term effect on the diversity of nesting birds (Loe et al. 2007), but is thought to be linked to declines in the number of upland birds in the longer term (Fuller and Gough 1999). There is also experimental evidence that intermediate

grazing pressure can be of benefit to some bird species in the uplands (Evans et al. 2006b). Sheep have also been shown to have a negative effect on the diversity of plant-eating beetles at high densities (Mysterud et al. 2010). Arthropod abundance and diversity can be affected by grazing through changes in vegetation structure; for example, taller swards created by reducing grazing intensity have been shown to favour beetle (Coleoptera) species (Dennis et al. 2004) and foliar arthropods (Dennis et al. 2008).

Sheep have been associated with the largest increase in grazing impact of all herbivores (Albon et al. 2007), yet their effects can interact with those of other herbivore species in different ways. Red deer (*Cervus elaphus*), for example, were found to graze less frequently on grasslands on lower slopes when in the presence of sheep; conversely, sheep grazing was shown to improve foraging conditions for rabbits (*Oryctolagus cuniculus*) by creating shorter swards (Milne et al. 1998). The intensity of sheep grazing has also been shown to affect rodent population growth, indicating facilitation at low sheep densities which became a competitive effect at high densities (Steen et al. 2005). The reduction in sheep numbers as a result of agricultural policy reform in the European Union may lead to increases in deer densities, with greater potential impacts on heathland habitats (Albon et al. 2007). However, many studies point to overall benefits to biodiversity from a reduction in sheep grazing intensity. Low-intensity mixed grazing by sheep and cattle (equivalent to 0.91 ewes ha⁻¹) was identified as providing optimal biodiversity benefits in the Scottish uplands by maintaining vole populations, a key prey species for raptors and other vole-eating invertebrates (Evans et al. 2006a, 2015). Similarly, low-intensity mixed grazing by sheep and deer can increase both alpha and beta diversity and minimize damage to *Calluna*, thereby enhancing habitat quality (DeGabriel et al. 2011).

However, the complete cessation of grazing, which can contribute to scrub and tree expansion in former semi-natural habitats and the loss of species-rich grasslands and heathlands, may also have negative impacts on biodiversity. Most open-ground species in semi-natural habitats depend on grazing and/or other land uses to limit scrub and tree encroachment. In Iceland, lowland areas that are no longer grazed by sheep have been increasingly invaded by introduced species, e.g. *Lupinus nootkatensis* and *Anthriscus sylvestris*, replacing the species-rich heathland vegetation with very species-poor stands. The original habitats cannot be maintained without continued grazing (Magnússon et al. 2006).

There is an apparent biodiversity trade-off, then, between higher stocking densities and the maintenance of heathlands and semi-natural grasslands, and lower stocking densities and the encroachment of scrub and/or invasive

species. Such encroachment is not necessarily a negative process, however, and whether vegetation with a more open character should take preference over scrub and woodland is a value-laden management decision, depending on which landscapes and resources are preferred (Austrheim et al. 2016).

Sustainable production of forage plants

The status of forage plants in grazing systems is important, as sheep farming can be more sensitive to changes in pasture quality and productivity than changes in economic conditions (Skonhoft et al. 2010). Income through meat production should therefore be generated from grazing densities that are low enough to sustain the production of forage plants (Mysterud 2006). High sheep densities increase the abundance of grazing-resistant species, for example *Nardus stricta* on low-productivity sites (Pakeman 2004; Fosaa and Olsen 2007). This is to the detriment of more palatable/less grazing-resistant forage plants (Austrheim et al. 2007; Speed et al. 2014; Welch and Scott 1995), although many commonly grazed forage plants are highly grazing tolerant (e.g. *Agrostis capillaris*, *Carex bigelowii*) (Jónsdóttir 1991). This reflects not only selectivity by sheep but also the relative resistance of different plant functional groups: woody species are generally less tolerant to grazing than herbaceous species, and grasses are usually the most tolerant group (Austrheim et al. 2008a). Setting densities of different breeds to ensure no net loss of forage plants may need to be carried out on a site-specific basis, but it is clear that such plants are a limited resource in the North Atlantic region, and must be managed with care to ensure sustainable production not only of their own populations, but also of sheep meat production (Mysterud et al. 2014).

Ecosystem function

Sheep grazing can have fundamental effects on ecosystem structure and function, primarily through changes in plant quality, structure and biomass (Austrheim et al. 2014). Achieving sustainable sheep grazing regimes is particularly important in mountainous areas, where steep slopes, thin soils and the slow rate of biological processes limit resilience to grazing and trampling. Studies have shown that erosion events correlate with high-intensity grazing in the Faroe Islands (higher altitudes) (Dahl et al. 2013), Greenland (mainly one site) (Massa et al. 2012) and most notably on Iceland, where erosion of varying severity has been recorded on 70 % of the land area and, although erosion is reported to have decreased, some degraded areas are still grazed (Arnalds 2015; Arnalds and Barkarson 2003). The condition of some parts of the summer grazing land in Iceland has improved considerably in recent years; however,

due to lower densities of sheep, shorter grazing seasons and a warmer climate (Thórhallsdóttir 2003), this is still a serious problem in other parts, especially within the volcanic active zone (OECD 2014). Recovery of grazing ranges is often slow (decades) even after total exclusion of grazing. The grazing effects on soil properties are probably the main reason for the slow recovery of grazed ecosystems after excluding grazing, but lack of viable propagules of grazing-sensitive species may also play a role. More studies are needed to examine the specific effects of grazing on erosion. In general terms, higher densities of sheep are likely to exacerbate erosion, particularly through interactions with other factors as discussed (e.g. extreme weather events) and in areas with more easily erodible soils.

Grazing can have varying effects of ecosystem services, depending on the level of intensity. In an alpine region of Norway, biodiversity and regulating services, including habitat openness and carbon storage, were particularly favoured by low sheep densities (25 sheep per km²). Other services, such as run-off water quality, plant productivity and carbon storage, declined when grazing intensity increased (80 sheep km²) (Austrheim et al. 2016). It has been suggested that a reduction in grazing by hill sheep would decrease greenhouse gas emissions by 3.6 tonnes of carbon per km² per year, both directly through the removal of animals, and indirectly through effects on soil carbon budgets (Worrall et al. 2009). However, the carbon cost of raising sheep is not equal in all areas. Carbon storage will peak at low to moderate sheep densities, but high nitrogen deposition rates are found to reduce carbon storage in grazed land (Smith et al. 2015).

The habitats in which grazing takes place are invariably vulnerable to multiple pressures aside from grazing itself. Grazing and faster nutrient turnover, for example, are known to have interacting effects on vegetation dynamics (e.g. Alonso et al. 2001). In addition to effects on the growth and performance of plants, increased nutrient availability can cause chemical changes in plants, which can influence their relative palatability to herbivores and therefore the outcome of plant competition (Hartley and Mitchell 2005). Although grazing has been a driver of vegetation change for far longer than nitrogen deposition, at the time of writing the combined effect of the two processes provides the best explanation for the increase of graminoids in both dwarf-shrub heath (Alonso et al. 2001) and moss communities in the UK (van der Wal et al. 2003).

Socioeconomic sustainability

For centuries, sheep farming contributed substantially to agricultural production in the North Atlantic region (Dýrmondsson 2006). Income comes from the sale of lambs, ewes as breeding stock or for mutton and wool and, to a lesser

extent, the sale of rams (Thompson 2009). In Norway, the value of the annual feed intake from outfield grazing was estimated to be slightly less than NOK 800 million in 2004, with roughly two-thirds of the feed grazed by sheep (Hegrenes and Asheim 2006). However, the economic importance of both the agricultural sector as well as sheep farming has declined significantly in recent years (Thompson 2009; Vatn 2009). In Norway for example, the total agricultural industry only contributed to 0.5 % of the GDP in 2007, as opposed to over 3 % in 1970 (Statistics Norway 2009). Sheep farming across Europe also faces increasing international competition, primarily due to cheap lamb imports.

Regulations concerning sheep grazing have probably been in place in the countries of the North Atlantic region since the oldest laws were implemented (Nedkvitne et al. 1995; Thórhallsdóttir et al. 2013). In the Faroes, management today is still based on these early laws, yet no formal regulation of grazing pressure has been introduced, leaving the farmers to decide the density of sheep in a given area. Iceland gained stricter regulations in 2000, when each farm was given a production quota linked to subsidies, subject to quality control through voluntary management of animal health and sustainable land use. In spite of these measures, overgrazing to the point of environmental degradation still exists in some mountainous areas (Arnalds and Barkarson 2003).

Government support for farming in upland areas in Scotland through a variety of price support and headage payment schemes existed through the second half of the twentieth century, supported by the EC Common Agricultural Policy (CAP) from 1974 (Condliffe 2009), resulting in a substantial increase in stocking densities. However, sheep numbers have declined since the recent CAP reform in 2002 (Thompson 2009), whereby the conversion of sheep headage payments to a land area basis by the UK government reduced stock numbers. This “single farm payment” is dependent on the maintenance of good agricultural and environmental conditions. Farmers in upland areas can also apply for the Scottish Upland Sheep Support Scheme launched in 2015 to help maintain sheep flocks on poorer quality rough grazing land (Scottish Government Rural Payments and Services website 2016). In Norway, the herders’ income increases with the number of sheep in some areas, but the subsidy package also has other support where the ‘multifunctional’ argument of agricultural production is important (Romstad and Skonhoft 2014). In Iceland, both dairy and sheep farming have received significant governmental subsidies ranked amongst the highest of the OECD countries in 2002 (Arnalds and Barkarson 2003). Payment of these is only partly tied to environmental cross-compliance requirements, including acceptable rangeland conditions, sustainable grazing management, livestock welfare obligations and sheep flock record keeping, resulting in a large number of grazing animals and subsequent negative environmental impact in some areas (OECD 2014). It is clear

that for sheep grazing to be sustainable, policies must discourage overgrazing by only linking financial support to sustainable carrying capacity, which must take account of the areal extent and productivity of the grazing land in question.

CONCLUSIONS: SUSTAINABLE MANAGEMENT OF SHEEP GRAZING

In the unproductive, oceanic environment of this region, the legacy of centuries of sheep grazing is apparent in the vegetation and landscape. Sustainability should arguably be the main objective for sheep grazing management in all North Atlantic countries at the present time. As indicated before, this includes not just biophysical impacts but also economic, social and cultural factors. The current paradigm shift in the grazing lands, from managing for agricultural production to increasing emphasis on the protection of biodiversity and ecosystem services, means that an understanding of sustainable sheep grazing is more important than ever. We have attempted to bring this concept into clearer focus by exploring, within the available data, what sustainable sheep grazing management could entail in practice. General rules may be devised for managers to follow based on current understanding, but fine-tuning of stocking rate decisions will inevitably need to be site specific. The factors relevant to grazing management discussed here—sheep breeds and stocking density, grazing season, supplementary feeding, products and policies—can be manipulated to improve sustainability within the limitations of data and understanding already outlined. A balance must be struck between economic gain and preventing ecological and environmental degradation, through the use of carefully defined sustainable grazing densities. This is most likely to be achieved by a management regime that can adequately support sufficient sheep densities through the sustainable production of forage plants, possibly using smaller, more traditional breeds. A return to shepherding and summer-only grazing could in some areas reduce damage to vegetation, maintaining forage quantity and quality, but the economic implications of such change, including the cost of winter fodder, would also need to be calculated. Evidence for the positive effects of fewer sheep on ecosystem services strengthens the case for the removal of sheep from outfield/upland areas as part of the re-wilding of such areas, whereby natural processes are left to shape landscape and ecology (Monbiot 2013). The fate of ecosystem services under such a scenario is perceived negatively by upland stakeholders, particularly cultural services relating to socioeconomic impacts due to the loss of agriculture, although any losses could be offset by nature tourism and environmental stewardship management (Reed et al. 2009).

We have addressed several different elements of environmental sustainability and discussed the issues surrounding socioeconomic sustainability to give a fully rounded assessment of how to take this forward in the different countries, each of which has different management systems and sustainability challenges (Table 4). In the Faroe Islands, for example, where there is a high risk of exceeding sustainability boundaries, heavy grazing has caused environmental degradation and high pressure on forage plants. There is a need for appropriate regulation and a change in the subsidy system. In Greenland and Norway, subsidy payments are made for each slaughtered lamb and live breeding ewe, with similar premiums in all

areas. This is unlikely to be conducive to sustainability as it will encourage increasing flock sizes in order to increase animal production. However, whether production will increase in ‘overgrazed’ areas, such as the alpine region in south-west Norway, will also depend much on the economic situation in the region. In Iceland, the damage caused by heavy grazing on fragile soils has not yet been fully alleviated, and there is still a high risk of exceeding sustainability boundaries, so it may be preferable to enforce regulations to prevent or at least severely limit grazing in the active volcanic zone. In Norway, the spread of trees and shrubs as a result of reduced grazing pressure is a key challenge, which may be controlled by the use of

Table 4 Comparing elements of sustainability for each of the North Atlantic countries. Words in italics denote the level of risk for exceeding sustainability boundaries

	Faroe Islands	Greenland	Iceland	Norway	Scotland
Biodiversity	Loss of biodiversity and natural vegetation (Johansen 1985) <i>High risk</i>	Loss of forest and heath to grassland communities <i>Uncertainty/increasing risk</i>	Loss of grazing-sensitive species, increased landscape homogeneity (Jónsdóttir 1984), vegetation degradation (Arnalds 2015) <i>Uncertainty/increasing risk</i>	Reduction of grazing pressure leads to shrub invasion and decrease of semi-natural habitats. (Speed et al. 2010). Heavy grazing causes homogenization of plant and animal communities (Speed et al. 2012). <i>Uncertainty/increasing risk</i>	Heavy grazing causes invasion of graminoid species (Pakeman and Nolan 2009) that is exacerbated when combined with nutrient enrichment (Alonso et al. 2003) and has negative effects on invertebrate communities (e.g. Dennis et al. 2004). <i>High risk</i>
Forage plant production	Higher numbers of heavier sheep requiring higher volumes of forage plants. Species-poor <i>Nardus</i> grassland is widespread. <i>High risk</i>	Less biomass is produced under heavy grazing <i>Uncertainty/increasing risk</i>	Increasing cover of non-palatable species, e.g. <i>Juncus trifidus</i> , <i>Kobresia myosuroides</i> (Jónsdóttir 1984, B. Magnusson, pers. comm). <i>Uncertainty/increasing risk</i>	Increasing cover of non-palatable species, e.g. <i>Nardus stricta</i> at high densities. <i>Uncertainty/increasing risk</i>	Increasing cover of non-palatable species, e.g. <i>Nardus stricta</i> . <i>Uncertainty/increasing risk</i>
Ecosystem function	Erosion at higher altitudes (> 200 m a.s.l.) with high grazing pressure <i>High risk</i>	Erosion is a localized problem only <i>Uncertainty/increasing risk</i>	Heavy grazing on fragile soils has led to severe erosion, recovering in some areas <i>High risk</i>	Erosion is a localized problem only <i>Uncertainty/increasing risk</i>	Erosion is a localized problem only <i>Uncertainty/increasing risk</i>
Socioeconomic sustainability	No official regulations. Subsidy paid per kg meat. <i>High risk</i>	Subsidy paid per slaughtered lamb and per ewe. <i>High risk</i>	Subsidy system now partly encourages improved farming practice <i>Uncertainty/increasing risk</i>	Subsidies for each animal but reduces with flock size. <i>Uncertainty/increasing risk</i>	Subsidy paid per unit area of land, not per animal. <i>Low risk</i>
Conclusion	High densities are causing erosion at high altitudes and loss of biodiversity. Forage plant production is not sustainable	High densities cause overgrazing in some areas. Current incentives are promoting more sustainable moderate densities	Not sustainable within the volcanic zone, improved in other areas due to lighter grazing pressures and warmer climate.	Both high grazing pressure and grazing cessation are considered threats to sustainability. No general incentives are used for reaching max. and min. densities	Effects of overgrazing likely to persist for some time, even with recent reduction in sheep numbers and changes in subsidy

‘moderate’ sheep densities in the grazing lands, but the risk to sustainability is uncertain. In Scotland, where overgrazing has caused extensive damage to vegetation and landscapes, the change in subsidy system from payment per animal to per unit area of land should promote more sustainable grazing practices, although ‘overgrazing’ is still common and it may be many years before its effects can be alleviated; the risk to sustainability is still unknown. From the case histories of sheep grazing management in the countries of the North Atlantic region, it has been possible to establish that sustainability boundaries are most likely to be exceeded in particularly fragile environments where financial support is linked to the number of sheep ‘produced’. High grazing intensities have caused the impoverishment of ecological systems in terms of both biodiversity and ecosystem function, ultimately affecting their ability to support sheep grazing in the long term.

As the prominence of environmental concerns in policy-making increases, subsidy systems should be shaped to encourage grazing density to be maintained at a level that safeguards heterogeneity in the landscape, high levels of biodiversity and preserves the integrity of major processes important for the provision of ecosystem services, such as carbon sequestration, water quality and cultural services. Current evidence suggests that this is best achieved through low to moderate grazing pressures, as many services are traded off at high sheep densities. However, vegetation type and quality are critical, and must be taken into account when setting densities at the local scale. If subsidies for agricultural production are removed, these should be replaced with grants for environmental stewardship, to prevent ecosystem degradation and associated negative effects on society and economy. The results of this review have highlighted a need for further development of the evidence base on long-term grazing effects on biodiversity, fodder quality and quantity, and for many additional elements of environmental sustainability. In addition, improved communication between research and management to underpin the sustainable management of sheep grazing in the longer term is vital.

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