SAUÐFÉ | SHEEP
Í LANDI ELDS OG ÍSA | IN THE LAND OF FIRE & ICE

Sheep in the Land of Fire and Ice

Sauðfé í landi elds og ísa

COURSE NOTES v0

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Part 1. Course introduction

Section 1.1 Sheep in the Land of Fire and Ice

About this course

Sheep in the Land of Fire and Ice is a short Massive Open Online Course (MOOC) about sheep grazing in Iceland.

As humans, we use natural resources to sustain our daily lives. How much of these resources we use and how we obtain them will determine how long they will last. Sustainable management practices aim at ensuring that natural resources are not depleted for us and for future generations. Unsustainable land uses can lead to environmental degradation, which compromises the future use of resources. The aim of this short course is to provide you with an overview of the impacts of an important land use in many regions of the world, sheep grazing.

In this course we use Iceland as a case study because here, traditional sheep grazing has been associated with extensive environmental degradation. Sheep grazing is an important economic activity in Iceland today, mainly for meat but also for wool products, and it is also an important part of Icelandic culture. However, the sustainability of sheep grazing has been questioned, because it has been linked to vegetation degradation and soil erosion. To assess the sustainability of sheep grazing in Iceland it is necessary to understand how history has shaped the culture, ecology and management of sheep grazing. In this course you will gain an understanding of basic ecological principles that underlie sheep grazing systems, their complexity and their dynamics. We will discuss the cultural, historical and economic relevance of sheep grazing in Iceland, as well as current issues, initiatives and approaches. We will also explore some of the theory that has shaped the application and management of grazing resources.

Course goals

The aim of this short course is to raise awareness of the environmental risks associated with inadequate management of natural resources. We use Iceland as a case study because here traditional land uses, like sheep grazing, have been associated with extensive environmental degradation. In this course you will learn about:

- The cultural, historical and economic relevance of sheep grazing in Iceland
- Current issues, initiatives and approaches to sheep grazing management in Iceland
- Basic ecological principles that drive grazing systems, their complexity and dynamics

Course structure

The course is divided into five parts (**Figure 1**). **Part 1** provides a general overview of the course and explains why sheep grazing in Iceland can be used to illustrate common challenges in sustainable management of natural resources. **Part 2** covers some general concepts about grazing in northern ecosystems, the particular conditions of Iceland and one of the main problems associated with sheep grazing in Iceland, soil erosion. As we will see, the impacts of grazing are not the same everywhere, so we need to understand the environmental conditions in which the interaction takes place. **Part 3** provides an overview of the historical influences of sheep grazing in Iceland since the human settlement to the present. We can use paleoenvironmental approaches to infer what Icelandic landscapes looked like before sheep were introduced by the first settlers and modelling approaches to understand the drivers of change between different ecosystem states. The history of sheep grazing however, is not only about sheep; it is the history of different socioeconomic conditions in Iceland that determined how natural resources were used, from subsistence economy to production-oriented exploitation allowed by the availability of new technologies, and finally to a concern for environmental sustainability once degradation became a widespread problem. **Part 4** focuses on the present and the future of sheep grazing in Iceland. We discuss current grazing practices in Iceland and the laws regulating them,

current research efforts aimed at understanding the ecological impacts of sheep grazing and the sustainability of sheep grazing. Finally, **Part 5** brings sheep grazing back to a broader picture, in the context of natural resource management in a changing Arctic and a changing world.

Each part of the course contains one or more sections that are built around short videos that provide an overview of the topics. For each of the sections, you can find more information and additional reading materials in the Course Notes (this document). The Course Notes are organized following the same outline as the online course but expand on and reinforce some of the concepts presented in the videos. The Course Notes can be used as a standalone teaching material.

In the online course, at the end of each section you will find knowledge checks, to assess your understanding of the main concepts. Feedback is provided for correct and incorrect answers to reinforce and clarify the main ideas. You can take these knowledge checks as many times as you need. At the end of the course there will be a final quiz.

Figure 1. *Course contents. The course is divided into five parts, each containing one or more sections.*

Course grading

Because this is a course, there has to be some grading for you to pass (or not pass). Evaluation of the online course is based on participation (completing the knowledge checks for 60% of the final grade) and the final quiz (40% of the final grade). Participation in discussions is not graded, but we strongly encourage you to contribute to the discussion boards because they will let you get to know other course participants, ask questions, and get help. To pass the course you need at least 60% overall. You can find more information about the grading policy in the Course Syllabus.

Special thanks

Developing this MOOC has been a long and exciting process. The project has been possible thanks to the support of the Teaching Innovation Fund of the University of Iceland (Kennslumálasjóður) and a lot of friends and colleagues that patiently offered their assistance. The University of Iceland, the Agricultural University of Iceland, Simon Fraser University, the United Nations University Land Restoration Training Programme and the Soil Conservation Service of Iceland have contributed to this project in various ways. Sticks & Stones designed the course logo and all the animations and helped with production.

Meet the experts

ISABEL C BARRIO, AGRICULTURAL UNIVERSITY OF ICELAND
Isabel is an Associate Professor at the Agricultural University of Iceland where she teaches a course in Rangeland Ecology and Management. Her research focuses on the ecological impacts of sheep grazing in Iceland.

DAVID HIK, SIMON FRASER UNIVERSITY
David is a Professor of Ecology at Simon Fraser University, Canada. He has been studying plant-herbivore interactions in the North for several decades, including snow geese in La Pérouse Bay and collared pikas in the Yukon.

INGIBJÖRG SVALA JÓNSDÓTTIR, UNIVERSITY OF ICELAND
Ingibjörg Svala is a Professor of Ecology at the University of Iceland. Her research addresses how ongoing environmental changes will affect tundra ecosystems, from the sub-arctic in Iceland to the High Arctic in Svalbard.

ÓLAFUR ARNALDS, AGRICULTURAL UNIVERSITY OF ICELAND
Ólafur is a soil scientist and Professor at the Agricultural University of Iceland. His work on soil erosion, dust storms and desertification in Iceland emphasizes the need to protect a vital resource for life on Earth: soils.

EGILL ERLENDSSON, UNIVERSITY OF ICELAND
Egill is a Professor at the University of Iceland. He is a palaeoecologist and thanks to his work we know better what the landscapes of Iceland looked like in the past, before humans (and sheep) arrived to Iceland.

ÞÓRUNN PÉTURSDÓTTIR, SOIL CONSERVATION SERVICE OF ICELAND
Þórunn is a restoration ecologist working for the Soil Conservation Service of Iceland. Her research deals with the implementation of participatory approaches in Iceland and how to evaluate the socioecological effects of restoring natural capital of degraded ecosystems.

JÓHANN ÞÓRSSON, SOIL CONSERVATION SERVICE OF ICELAND
Jóhann is a senior research scientist and project manager at the Soil Conservation Service of Iceland. Johann's research interests include land degradation processes, land use issues, land management and land condition monitoring.

BJÖRN HELGI BARKARSON, MINISTRY FOR ENVIRONMENT AND NATURAL RESOURCES
Björn works at the Ministry for Environment and Natural Resources, where he is responsible for issues in the field of sustainable land management, including forestry, soil conservation and ecosystem restoration.

BRYNDÍS MARTEINSDÓTTIR, SOIL CONSERVATION SERVICE OF ICELAND
Bryndís works at the Soil Conservation Service of Iceland, where she is coordinating GróLind, a pioneering monitoring program for sustainable management of grazing resources in Iceland.

TARA MULLOY, SIMON FRASER UNIVERSITY
Tara is a MSc student at Simon Fraser University and the Agricultural University of Iceland. She spends her summers in the highland rangelands of Iceland looking at the combined effect of fertilizers and grazing on vegetation.

UNNSTEINN SNORRASON, SHEEP FARMERS' ASSOCIATION
Unnsteinn is the director of the Sheep Farmers' Association of Iceland and is a sheep farmer himself. He has a background as a farm technician and has worked for the National Farmers' Association and the Icelandic Agricultural Advisory Centre.

ANJA MAGER, AGRICULTURAL UNIVERSITY OF ICELAND
Anja is a sheep farmer and student at the Agricultural University of Iceland. She is from Germany but she has been living in Iceland for more than 10 years. She has a very interesting perspective about the sustainability of sheep grazing in Iceland.

Navigating the course

The online course is built in the edX edge platform of the University of Iceland. You will be able to access the course through a unique URL that is available in the course website. To enroll the course, you will need to create an edX edge account if you do not already have one. The layout of the courses in this platform is pretty intuitive but if you need more information on how to navigate an edX course you can enroll in DemoX, the edX demonstration course.

Throughout the course you will find two types of interactive activities: knowledge checks and discussion boards. Knowledge checks aim at assessing your understanding of the main concepts. Discussion boards will allow you to get to know other course participants, ask questions, and get help. We kindly ask you to follow the Discussion Guidelines when contributing to discussions in this course. A few key points you should remember:

1. When adding a post, please mark it as a question or a discussion post: questions raise issues that need answers, whereas discussions share ideas and start conversations.
2. Before posting a new question, check if the question has already been asked by looking for keywords.
3. Use descriptive titles in your posts. Please write in complete sentences, avoid typing in ALL CAPS, unnecessary symbols, abbreviated words, or shorthand.
4. Be polite and considerate when posting in discussions - treat others how you would like to be treated!

Part 2. Sheep grazing in the North

Section 2.1 Sheep grazing in the North

Grazing in Nordic regions

Sheep grazing is a main cultural and economic activity in Nordic regions, but also one with important environmental impacts[1]. At the end of the day, sheep are herbivores, animals that eat plants. As such, they influence the plants they eat and have cascading impacts to the whole ecosystem. However, the impacts of herbivores on ecosystems are related to a complex set of factors, including the herbivore itself, the plants they eat, and the environmental conditions in which they live. In addition, the impacts of domestic herbivores like sheep will also depend on how we manage them: how many sheep we have, how early we bring them up to the mountains, and how long they stay on the rangelands.

Herbivores play important roles in processes that determine the functioning of both natural and managed ecosystems. By consuming plants and being food for predators, herbivores represent a central link in the flow of energy and cycling of nutrients in nature.

Herbivores can have negative impacts on plants the plants they eat. However, grazing rarely kills the plants, and plants can respond to being eaten. Some plants like grasses can even increase their growth rates in response to moderate levels of herbivory[2]. By selectively eating some plants and not others, herbivores often change the structure and composition of plant communities. These changes can have far-reaching consequences on the productivity and diversity of grazed ecosystems. As well, herbivores trample on plants and provide them with natural fertilizers. Trampling by large herbivores can disrupt vegetation cover, opening patches of bare ground where new plants can grow. And with their dung, herbivores transport nutrients and seeds across landscapes.

The impacts of herbivores will of course depend on the environmental conditions in which herbivory takes place. In colder regions, temperature limits plant growth and in these areas there is marked seasonality, essentially a cold winter and a mild summer. It is only during the relatively warmer summers that plants can grow and reproduce and this will determine how plants can respond to herbivory. As well, in northern regions there are marked seasonal patterns in the amount of light, a vital resource for plants to produce their food: to the North of the Arctic Circle summers have nearly 24-hour daylight, while winters have nearly 24-hour darkness.

Cold regions tend to have lower plant productivity and herbivores have a variety of adaptations to cope with these conditions. In wild populations, herbivores are regulated by the availability of plants, and by predators. The availability of food, which is usually most limited during winter, sets an upper limit to the number of herbivores we can have in an ecosystem – this is called the carrying capacity.

When we are talking about managed or domestic herbivore populations, the carrying capacity of an ecosystem can be easily exceeded. When herbivores are decoupled from natural resource availability, for example when they are supplemented with food throughout the winter, we may end up with unsustainably high numbers of herbivores in the system. This increases the likelihood of overgrazing, which can deplete plant resources and alter community structure. The chances of overgrazing will depend on the environmental conditions and how plants respond to grazing. Some places will be more sensitive than others to increased numbers of herbivores.

Studying herbivory in the North – the need for coordinated research efforts

Herbivory is a key interaction in northern ecosystems, but the effects of herbivory depend on many factors. In fact, the effects of herbivores vary widely between sites across the circumpolar North. For example, in some places reindeer grazing can reduce the abundance of shrubs, whereas in other places these changes are not as pronounced. Understanding what drives this heterogeneity is critical if we want to manage these ecosystems in a sustainable way, and requires coordinated research efforts across sites. Coordinated research networks can address this need by

serving as platforms for scientific cooperation. One example of such an initiative is the Herbivory Network[3], which started in 2013 as a grass-roots initiative to bring together researchers interested in studying plant-herbivore interactions in arctic and alpine ecosystems.

Other examples of coordinated research networks are the International Tundra Experiment (ITEX), which uses the same simple experiment at many sites to investigate the responses of tundra vegetation to warming, and ShrubHub, which coordinates research on shrub expansion in the Arctic.

Section 2.2 Sheep grazing in Iceland

The effects of herbivores depend to a large extent on the environmental conditions in which the interaction takes place, that is, the biotic and abiotic factors that characterize the environment where plants and herbivores interact. Thus, to try to understand the effects of impacts of sheep grazing on Icelandic ecosystems, we first need to look at the conditions in Iceland: its climate, geology and biodiversity.

Environmental conditions in Iceland

Iceland is a small island in the North Atlantic Ocean. It is 103,000 km^2 and it is sparsely populated. According to the national statistics office (Hagstofa Íslands), in 2018 the population was 348,450 inhabitants. Most of the population (60%) lives in the capital area in the southwest of the island, which includes the capital city, Reykjavík. The rest of the population lives in towns or isolated farms, in the lowland areas relatively close to the coast.

The interior of the island, about 75% of the land area, is comprised by a high elevation plateau, the Highlands (**Figure 2**). The Highlands are usually defined as areas at elevations above 400 m[4], and most of this plateau lies between 500 and 700 m, with the highest mountains raising 1000-1100 m above the plateau. Most of the plateau is an undulating plain with till and glaciofluvial deposits. These areas are dominated by tree-less heathlands and wetlands, much like the tundra ecosystems we find further north in the Arctic. As well, there are extensive, sparsely vegetated deserts in the Highlands. Some of these deserts are naturally formed by volcanic activity, but others are consequence of human activities. The main human use of the Highlands is as an extensive summer grazing land for sheep.

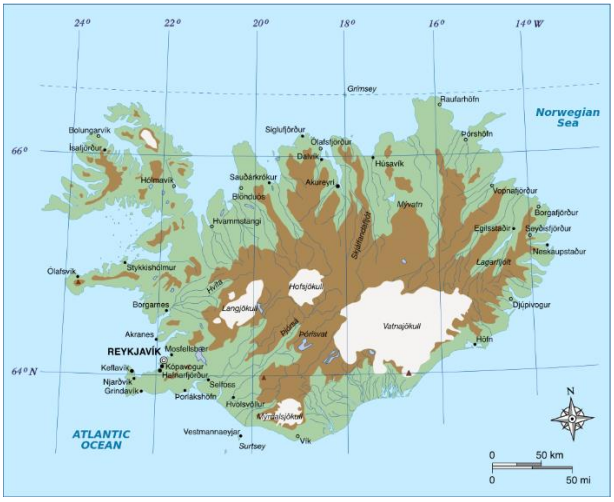

Figure 2. *Map of the Highlands of Iceland (source: Map_of_Iceland_highlands.svg by Pethrus). The Highlands are used as an extensive summer grazing land for sheep.*

Iceland lies just south of the Arctic Circle; only the small island of Grímsey, off the north shore of Iceland is crossed by the Arctic Circle. This means that there is no true midnight sun, because the sun sets for a few hours per day during

summer, although during the longest days there is effectively light for the whole 24-hour period. In midwinter, there are around 5 hours of effective daylight.

Despite its northern latitude, Iceland has a relatively mild climate thanks to the North Atlantic current, which brings warm waters from lower latitudes. The average temperatures of the coldest month of the year in the lowlands of Iceland range between -2.3 and -0.4 degrees. Summers are relatively cool, with average temperatures of the warmest month ranging between 7.6 and 12 degrees. The climate of Iceland can be classified as oceanic. There is a marked gradient in precipitation from the north (400-700 mm yr^{-1}) to the south (700-1600 mm yr^{-1}).

Actually, there are only a few permafrost areas (i.e. areas of frozen ground) in Iceland, confined to palsas in the highland plateau. Palsas are mounds or small hills created by frost heaving in areas of discontinuous permafrost, formed when an ice lense shifts the overlaying ground. Palsas in Iceland are of relatively low relief. The largest palsa area in Iceland is Þjórsárver[4], south of the Hofsjökull ice cap. Palsa areas are characterized by mire vegetation (mainly the grass *Calamagrostis stricta* and sedges of the genus *Carex*) and species that can survive the habitat changes that follow the rise of the palsa, like willows (*Salix arctica* and *S. herbacea*).

As well, Iceland is very windy, because it lies at a latitude where air masses coming from the poles move from the surface of the planet higher up in the atmosphere. In the global atmospheric circulation models this is called the polar cell. At 60° latitude, the relatively warm and moist air at the surface of the Earth rises in the troposphere and moves poleward, cooling off on its way North. When the air reaches the polar areas, it has cooled and is considerably denser than the underlying air, so it descends to the surface, creating a cold, dry high-pressure area. At the polar surface level, the mass of air is driven toward the 60th parallel, replacing the air that rose there, and the polar circulation cell is complete. The polar cell creates nearly constant movement of air over Iceland. Iceland is rather windy which can be explained both by its position within the polar cell of the global circulation.

As well, weather in Iceland is largely determined by the presence of a large semi-permanent low-pressure centre between Iceland and South Greenland, called the Icelandic low. The Icelandic low is a main centre of action in the atmosphere circulation of the Northern Hemisphere, as it forms one pole of the North Atlantic Oscillation (NAO), the other being the Azores High. Through fluctuations in the strength of the Icelandic low and the Azores high, the NAO controls the strength and direction of westerly winds and the location of storm tracks across the North Atlantic.

Iceland is well known by its volcanism. Iceland lies on the mid-Atlantic Ocean ridge, the divergent boundary between the Eurasian and North American continental plates. The mid-Atlantic Ocean ridge has an average spreading rate of about 2.5 centimetres per year. Iceland lies above a hotspot, a volcanic region thought to be fed by underlying mantle that is anomalously hot compared with the surrounding mantle. This hotspot is called the Icelandic plume. The volcanism of Iceland is attributed to this plume, which is believed to have caused the formation of Iceland itself, when it appeared over the ocean surface about 16 to 18 million years ago. The consequences are repeated volcanic eruptions and high geothermal activity. Most of the active volcanoes in Iceland are concentrated within what is called the volcanic active zone. This area is geologically young, so its soils are less well developed, and it is generally more sparsely vegetated than elsewhere.

The volcanic nature of the island also makes its soils quite special. Soils of volcanic origin are called Andosols and have particular characteristics: they have low bulk density, high water retention, and their mineralogy is dominated by amorphous materials; andosols are therefore highly friable and extremely susceptible to erosion by wind and water.

Another consequence of volcanic activity is the presence of volcanic ash (tephra). Tephra damages vegetation while moving around with winds through abrasion and sandblasting. As well, accumulation of tephra can suffocate vegetation.

Glaciers have played a major role in shaping both landscapes and biodiversity in Iceland. During the Pleistocene an ice sheet repeatedly covered land areas and retreated again. The glaciers caved the landmasses and formed valleys and fjords, disrupted the terrestrial ecosystems and contracted the areas where plants and animals could survive, wiping

out most of the biota. It is about 10 000 years since the end of the Ice Age and today glaciers cover about 11% of the land area in Iceland.

Being a young island that has been repeatedly glaciated, Iceland has a relatively low biodiversity. For example, there are no native mammalian herbivores. The two species of large herbivores that are present nowadays in Iceland, sheep and reindeer, are both introduced species. Sheep were introduced as livestock by the Norse settlers in the 9th century; reindeer were introduced from Norway in the 1700s and are now restricted to some parts of East Iceland. The only native herbivores in Iceland are birds (ptarmigan, migratory geese and swans) and invertebrates. Several species of migratory geese use Iceland as a stopover in their migration to their breeding areas in the Arctic, but several species breed in Iceland. This includes the pink-footed goose (*Anser brachyrhynchus*) that breeds in large colonies in the Highlands.

The only native mammal in Iceland is the Arctic fox (*Alopes lagopus*). The mink (*Mustela vison*) was brought to Iceland in the early 1930s for mink farming; escaped animals established in the wild and are now present mainly in the lowlands. In contrast to other terrestrial systems at high latitudes, Iceland has no native small mammalian herbivores either, like lemmings or voles, except for the introduced wood mouse (*Apodemus sylvaticus*) mostly in lowland areas.

How do these conditions influence the impacts of grazing?

In Iceland the effects of grazing are compounded by the climatic conditions and the geological forces that have shaped the island. First, northern climates imply that growing seasons are short, so vegetation does not have much time to develop. This is particularly true for sites at higher elevations, like the Highlands where most of the extensive grazing commons are located. Second, the volcanic origin of Icelandic soils means that they are very sensitive to erosion, especially within the volcanic active zone. Further, volcanic activity and ash deposition can suffocate and kill vegetation, opening more patches of bare ground. All these conditions together have led to the association of sheep grazing and extensive soil erosion in Iceland.

Section 2.3 Sheep grazing can lead to soil erosion

Soil erosion is an environmental problem not unique to Iceland. In many parts of the world inadequate land use and excessive grazing pressures have been associated with rangeland degradation and soil erosion. However, the particular ecological conditions of Iceland make Icelandic ecosystems particularly sensitive to sheep grazing.

Soils in Iceland, Andosols, are of volcanic origin, which means that they are fertile but not very cohesive. Vegetation protects soils and keeps them in place, but once vegetation is removed soils are easily blown or washed away. This is one of the reasons why Icelandic ecosystems can be particularly sensitive to grazing by large herbivores, because trampling by large herbivores can disrupt vegetation cover, opening patches of bare ground that are exposed to the erosive forces of wind and water. But of course, different parts of Iceland will be differently sensitive: areas closer to the active volcanic zone with less developed soils, and areas at higher elevations, like the Highlands, with a colder climate, will be more sensitive to grazing.

Grazing by sheep prevents the regeneration of birch forests and willows, which once provided many of the most fragile soils with protective cover. Further heavy grazing can contribute to the formation of bare ground patches that accelerate soil erosion. In fact; soil erosion has caused large scale ecosystem degradation in Iceland and it is still one of the most pressing environmental issues of the country. The condition of many Icelandic ecosystems is often poor, with large areas being barren deserts, in spite of the moist climate.

Many landscapes in Iceland are dominated by active erosion processes. One of the most distinctive erosion forms in Iceland is the rofabard, an erosion escarpment that is typical of areas near the active volcanic zone[5]. Rofabards are erosion escarpments formed in thick but non-cohesive Andosols that overlie more cohesive materials. As erosion

progresses, the relatively loose Andosols are undermined and escarpments are formed. Rofabards can also be perceived as remnants of the previously vegetated surfaces, because they keep a turf of vegetation on top while the sides of the escarpment are eroded (**Figure 3**). Rofabards can have various shapes, with heights ranging from about 20 cm to more than 3 m. The height of a rofabard however, is affected by the eroded material in the surroundings that are trapped in the remaining vegetation on top, so it does not reflect the thickness of the original soils. An important characteristic of rofabards is that they retain the escarpment form as they retreat as active erosion progresses.

Figure 2. *Rofabards are active erosion forms typical of the volcanic active zone. They form in thick andosols that overlie more cohesive materials, like lava or glacial till. They keep a turf of vegetation on top, while the sides of the escarpments erode away (Photo: Rofabard in Myvatnsveit, N Iceland; Áskell Þórisson)*

The nature of Icelandic deserts varies immensely. There are naturally occurring deserts, at high elevations, and those formed by glacial river outbursts and volcanic eruptions, but many deserts are a consequence of human use, for example as a result of clear-cutting and intensive grazing. Ecosystem degradation is often aided by unfavorable climate events or volcanic eruptions, after the resilience of the ecosystems has been reduced by long-lasting land use.

Bare soils and desert surfaces in Iceland are also unstable because of the action of frost. With sub-zero temperatures the water in the soil freezes. The formation of ice crystals called “needle-ice” on the ground is especially detrimental to plant establishment, as seedlings are pushed out of the soil by the ice-needles. The unstable surface is thus a hostile environment for new plants to colonize.

Further, grazing of poorly vegetated areas can completely halt plant establishment and soil development. Trampling also impedes the formation of biological crusts, which are essential to prevent needle-ice formation and to provide nutrients and safe sites for new plants to establish.

Part 3. Historical perspective of sheep grazing in Iceland

Section 3.1 Iceland before sheep

Human settlement in Iceland, *landnám* in Icelandic, only happened a bit over a thousand years ago, in the 9th century. Farming was an important part of Norse societies, so the first settlers brought with them sheep and other livestock.

Human activities soon started to have an impact on Icelandic landscapes, through wood-cutting and clearing land for grazing. In addition, it is important to keep in mind that humans and sheep are not native to Iceland. Before human settlement, there were no humans and no large herbivores in Iceland, so vegetation had developed since the last glaciation without the influence of large herbivores.

What Iceland could have looked like before human settlement

To reconstruct past environmental processes, we can use sediment cores from peatlands and lakes. As sediments accumulate, they become characterised by the environment in which they formed. Through different proxies we can analyse changes in the environment over time. For example, the abundance of pollen and spores of different species can inform about how plant communities have changed, and sedimentary proxies can be used to reflect changes in landscape stability. For instance, soil erosion can be estimated by measuring the rate of soil thickening (soil accumulation rates).

One way of identifying the time when changes take place is the use of layers of volcanic ash (tephra). Tephra is deposited on the ground and forms deposits or layers that can be used as markers in the stratigraphy. Tephra layers bear their own unique chemistry and character and their age is usually known. Just about the time of human settlement (c. AD 871) two large eruptions took place in southern Iceland. The eruptions deposited a tephra layer over almost the whole country. This layer, usually called the landnám tephra, provides a marker horizon, indicating when humans arrived. By looking at changes in the *paleoenvironmental record* before and after human settlement (below and above the landnám tephra), we can assess the influence of humans and past land uses in shaping the ecosystems we see today.

Analyses of pre-settlement vegetation in Iceland are based on pollen assemblages preserved in lake sediments and peat, macrofossils and sediment analyses[6,7]. Pollen records from several lowland sites in Iceland show that birch (*Betula pubescens*) had a more widespread distribution before settlement. This reflects the wooded and stable environment before the settlement. The reduction of birch pollen around the time of settlement, suggests that land was cleared, likely to make space for farming. Increases in pollen from grasses and several weeds show the emergence of an altered plant community typical of open areas. The onset of grazing is also indicated by the spores of coprophilous fungi, which require herbivore droppings for germination. These environmental changes preceded the cooling episode of the Little Ice Age, which began around the middle of the 13th century. As a result, land use must be considered to be the primary driver behind this process.

Even though the spatial and temporal patterning of woodland retreat and landscape destabilization can be complex, and the underlying causes difficult to disentangle, the palaeoenvironmental record suggests that long-term unsustainable pastoralism has played a key role in the degradation of the Icelandic environment.

In addition, other sources of information can be used to reconstruct the dynamics of these past changes. After settlement, the history of land use and grazing practices is documented in different ways in historical documents. The old Icelandic sagas were written mainly in the 13th century but refer to events happening mostly during the 10th and 11th centuries. The sagas report extensive clearing, burning and cutting for fuel that reduced the extent of birch woodlands after settlement.

Section 3.2 Modelling the ecosystem

State and transition models

One way to summarize and describe the changes in dynamic landscapes and the drivers of these changes are State and Transition Models (STMs). STMs were proposed in the late 1980s by Mark Westoby and collaborators[8]. The basic idea here is that different ecosystem states can coexist in a landscape, each of them maintained by its own internal

feedbacks. In essence, these models are diagrams with boxes and arrows; each box represents a different ecosystem state in which an ecosystem can occur and the arrows linking the different boxes represent transitions between the different ecosystem states. Ecosystem states are broadly characterized by the structure and composition of their vegetation. The shifts between ecosystem states are called transitions. These transitions are not necessarily reversible, meaning that if we remove the pressure driving the shift, the original state may not be reverted. Transitions can be gradual or abrupt, and in some cases can cross ecological thresholds that determine irreversible transitions. By understanding and identifying these transitions and thresholds, state and transition models can guide management efforts and research.

If we think of Iceland before the influence of humans and large herbivores, that is before landnám, we can imagine a few possible ecosystem states[9]. Birch woodlands were common in Iceland before human settlement[10]. In the areas that were unsuitable for tree growth, heathlands and grasslands would have developed. Heathlands are dominated by small shrubs, and grasslands are dominated by grass-like plants. Wetlands, partly inundated or very moist areas, would have occurred in lower elevation areas and depressions. As well, some moss or lichen dominated areas may have occurred, as early colonizers of young substrates, like lava fields or on ridgetops. Of course, we would also have barren areas, the naturally occurring deserts.

During this time, transitions between the different ecosystem states would have been relatively slow, and mainly driven by changes in climate, or periodic events like volcanic eruptions or glacier outbursts. For example, from the paleoenvironmental record, we know that the extent of woodlands in Iceland during the Holocene tracked fluctuations in climate[10]. Birch forests were most dominant in warmer periods, while they retreated to lower elevations during colder periods. It has been estimated that at the time of settlement birch woodlands covered somewhere between 8 to 40% of the country, with the most recent estimate of 24%[11].

Later, the influence of humans in the ecosystems after settlement will create a new state, degraded areas, and will accelerate transitions towards barren and desertified lands. This new state represents a *transient state* leading, nearly always, from the well-vegetated states to barren areas[9]. High numbers of sheep could degrade vegetation and cause the occurrence of erosion spots in the landscape, that can coalesce and form larger patches of bare ground. Once this eroded state is established, it is maintained by positive feedbacks: bare ground areas are maintained by aeolian deposition that further suffocates vegetation, and processes like frost heaving that prevent establishment of vegetation in the exposed patches. Removing sheep alone may not be sufficient to revert the situation back to the original state.

STMs can help understand landscape changes brought about by human settlement and human activities relative to other drivers of change[9]. These models provide a framework to guide research efforts. For example, if we realize that we know little about what drives a specific transition, we can design an experiment to test our ideas. STMs can also help focus management efforts if we understand better the ecological processes behind those transitions.

Section 3.3 Then, sheep arrived

There were some profound changes in Icelandic landscapes after human settlement[7,12]. But of course, the influence of humans was not homogeneous across Iceland in space or over time. Human influence was more intense in some areas, like around farms and main settlements in the lowlands, and varied over time. Sheep numbers fluctuated in response to market interests, the availability of new technology and the occurrence of natural catastrophes. For example, there have been over 250 volcanic eruptions in Iceland since the time of settlement. The most destructive eruptions in historical times were the one from Hekla (1104), several eruptions during the 14th century, Mývatnseldar (1724-29) and Laki (1783); the eruption of Laki in 1783 caused much devastation, leading to a famine that killed approximately 25% of the island's human population. As well, from AD 1250 the onset of the Little Ice Age marked

the start of a cooling period in the North Atlantic that affected the productivity of ecosystems and the carrying capacity of the rangelands.

Sheep over time: from landnám to our days

Since the introduction of sheep by the Norse settlers, sheep farming has been the main provider of meat in Iceland, as well as other products like milk, wool and skin. Shifts in emphasis on the different products derived from sheep provide a deeper understanding of the history of sheep grazing in Iceland: from milk for subsistence farming in the early days, to wool for export, and finally, meat for national markets and export. In the 18th century the typical Icelandic sheep flock included more than 50% lactating ewes and about 30% wethers (castrated males). Wethers were kept for meat and wool production, and ewes for milk[13]. Because the ewes had to be milked twice a day, they were grazed in lowland pastures close to the farm, while the remaining flock was grazed on highland ranges; thus, at the beginning of the 18th century grazing pressure on highland ranges was relatively small[13].

From soon after the time of settlement the use of land for grazing was highly regulated. In the Icelandic law books from the 12th century *Grágás* and *Jónsbók* there were strict provisions for grazing management, which were still enforced in Iceland until 1969 when new grazing acts were passed. With an increased economic interest in sheep grazing, by the mid-18th century the Church gained ownership of grazing lands. Towards the end of the 19th century farming communities all over Iceland started buying grazing areas that would become common grazing areas. Many of these lands were farther into the Highlands, in areas that had not been under regulated grazing earlier.

In the early days and up to the late 18th century, sheep numbers were limited by access to food during winter. Harvesting of winter fodder was limited and most supplementary feed was used for dairy cattle. Sheep were grazed outdoors during winter, and in harsh winters the flock would collapse. Thus, grazing pressure on the land during this time was regulated by the number of animals that could survive the winter and the numbers of sheep was kept relatively low, fluctuating between 50 and 300 thousand animals. However, this relationship broke with the widespread cultivation of pastures, because the availability of winter fodder allowed keeping higher numbers of animals throughout the year. When numbers of herbivores are decoupled from natural resource availability, we can easily have too many animals for what the land would naturally support – that is, the *carrying capacity* of the system is exceeded, and this often leads to overgrazing.

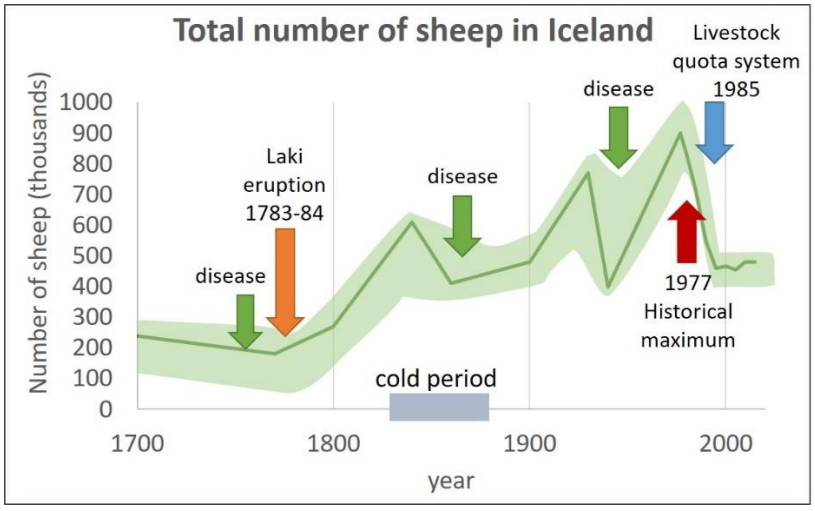

Figure 3. *The number of sheep in Iceland fluctuated since the early 18th century because of diseases, natural catastrophes and market interests. Changes in traditional*

grazing practices with more frequent use of the Highland ranges from the second half of the 19th century coincided with a cold period and led to environmental degradation in the Highlands.

The number of sheep began to increase in the 1820s, when foreign markets opened up for sheep products[13]. From the 1880s markets opened up in Great Britain for live sheep, and the expansion of cultivated hay meadows began. By the end of the 19th century, technological progress, the import of winter food and the use of fertilisers allowed the number of sheep to skyrocket. Along with a flourishing economy, the population of Iceland grew and moved away from the countryside to towns. From 300,000 sheep in 1800 to nearly 600,000 sheep by 1900[13].

In the second half of the 19th century, since the interest was no longer in sheep milk or milk products but in meat, good grazing areas for the lambs became more important. These grazing lands could be found in the extensive Highlands, which became increasingly used for extensive sheep grazing. In addition to the increased number of sheep and these changes in grazing practices, the climate in the second half of the 19th century was a particularly cold period, leading to extensive environmental degradation in the Highlands[13]. By the end of the 19th century environmental degradation was widespread in Iceland and became a nation-wide concern, leading to the establishment of the Soil Conservation Service of Iceland in 1907.

Still, in throughout the 20th century the numbers of sheep continued to increase, thanks to the introduction of artificial fertilizer, which was introduced to Iceland in 1910, and improved technology in hay-making. The number of sheep reached a historical maximum of nearly 900,000 animals in 1977. This peak in sheep numbers led to overgrazing in many districts and grazing commons, particularly within the volcanic active zone and in the Highlands. Sheep grazing became so extensive that nowadays it is hard to find an area that has not been impacted by sheep grazing.

In the 1980s the introduction of a livestock quota system reduced the number of sheep. Since then sheep numbers have decreased but are still relatively high when compared to historical abundances. Also, by the time that sheep numbers were reduced, the ecosystems in many rangelands had already shifted to a severely degraded state and their recovery has been slow. Nowadays, and probably due to the lack of common understanding on the ecological consequences of grazing, areas with degraded and even collapsed ecosystems are still being grazed.

Section 3.4 Efforts to mitigate environmental degradation

Land degradation at the beginning of the 20th century

From the perspective of land management and environmental protection, the onset of the 20th century implied great changes in Iceland[9]. By the end of the 19th century, environmental degradation was widespread and became a national concern. Accelerated soil erosion and sand storms forced the abandonment of many farms in the countryside. As well, the extent of native birch forests reached its minimum at 1% of the country at this time. In response to this, nation-wide efforts to halt soil erosion and to preserve the remaining birch forest began in the early 1900s. A legislation was passed in 1907, the Act on Forestry and Mitigation of Soil Erosion, and two state institutions were founded: the Soil Conservation Service of Iceland and the Icelandic Forestry Service. These institutions are pioneering initiatives in the world. The US Forest Service was established a little earlier, in 1905, but the US Soil Conservation Service (now called the Natural Resource Conservation Service) was established in 1932.

Organised measures to halt soil erosion and reclaim eroded land through controlled revegetation started in the early 1900s. Commonly used methods involved sowing of agronomic grasses or native species. Other reclamation activities involved fencing off areas to exclude grazing[14], using fertilizers or planting introduced species like the Alaska lupine (*Lupinus nootkatensis*), a species that is now considered invasive in Iceland[15]. During the early 1900s forestry efforts focused on preserving the remaining birch woodlands. The cover of birch woodlands during this period has been estimated to be 1% of the country[16]. Planting of exotic conifers started in the late 1930s and was continued and encouraged until the 1980s.

All these revegetation efforts paid-off and recent greening trends have been observed in Iceland during 1982-2010[17]. These changes can be observed using satellite observations of an index of vegetation growth called NDVI, and are likely related to a combination of factors including reductions in grazing, extensive revegetation and reforestation efforts, as well as climate warming and glacial retreat[17].

However, environmental degradation is still a big concern in Iceland. Tundra rangelands recover slowly. Some areas that have been protected from grazing have recovered to some extent, but active restoration is needed in many other places. Ideally, restoration programmes must involve local stakeholders to ensure their long-term effectiveness. In Iceland, the main stakeholders are sheep farmers; thus, restoration programmes have to be designed, implemented and maintained in partnership with farmers. , the people that actually use the land and have an interest in keeping it in good shape.

In the 1990s, inspired by the Landcare movement in Australia, the Soil Conservation of Iceland launched the Farmers Heal the Land (FHL) programme[18], aimed at involving farmers directly in land restoration. FHL is a state-funded, cost-shared programme, that builds on the voluntary participation of farmers that want to restore their own degraded rangelands, mainly in the lowlands. The initial objectives of the programme were: (i) to enhance trust, and ease cooperation between sheep farmers and relevant authorities; (ii) to encourage restoration of degraded lowland rangelands; (iii) to shorten the summer-grazing period in the highland commons; (iv) to raise awareness among participants on the importance of grazing management; and (v) to facilitate behavioural changes towards sustainable approaches to rangeland management. Currently 30% of Icelandic farmers participate in this programme.

A recent evaluation of the FHL programme has shown that it has facilitated restoration activities on extensive areas and has increased awareness among farmers of the potential of rangeland restoration and enhanced trust between officials of the Soil Conservation Service and sheep farmers. However, the programme has not entirely fulfilled its initial objectives. For example, the evaluation indicated that the programme has not facilitated other anticipated attitudinal and behavioural changes among its participants[18]. Furthermore, it seems that the direct incentives provided by the programme are pushing participating farmers towards favouring agronomic instead of ecological approaches in their restoration activities. This shows the importance of regular monitoring and evaluation; to verify if outcomes are consistent with the initial targets and apply adaptive management approaches whenever is needed to reset aims.

Part 4. The present and the future of sheep grazing in Iceland

Section 4.1 Sheep in Iceland today

Current grazing systems in Iceland

Sheep grazing is an important cultural and economic activity. Sheep products like wool, meat and milk are extensively used, and sheep farming supports rural livelihoods. This is true in Iceland, and across the North Atlantic region, which includes Norway, Greenland, the Faroe Islands and Scotland[1]. In this region, sheep grazing has shaped landscapes and biodiversity for centuries. However, the sustainability of this practice has been questioned because there are many examples of grazing associated with environmental degradation.

The Icelandic sheep breed is one of the Northern European short-tailed sheep. It is a traditional breed that is not as profitable as more modern breeds, but it is a hardy breed that can withstand the harsh climatic conditions of Iceland. The Icelandic sheep descends from the sheep that the first settlers brought with them from Norway, and it is a well-preserved breed. There are very strict rules about the import of livestock to Iceland, mostly because of diseases, so when a sheep leaves Iceland it cannot come back again. There were two diseases that came from abroad that

decimated the numbers of sheep in Iceland: the sheep scab came both in the 18th and the 19th century, and the maedi-visna disease in the 20th century (**Figure 4**). Both were eradicated by culling large part of the sheep population.

Land use patterns are broadly similar across the North Atlantic region[1]. Sheep grazing is practiced extensively, and without herding. The traditional and current grazing practices vary slightly between the different countries, but in general, they involve an indoor feeding period during winter, and an outdoor grazing season during summer (**Figure 5**). In the old days, before mechanisation, sheep were grazed in winter because there was not enough hay. This practice had damaging impacts on vegetation, especially on woody species. Nowadays, winter grazing has been abandoned and sheep are kept indoors during winter. In the spring, sheep are grazed on cultivated fields close to the farms until the adult females (ewes) and their lambs are released into their summer ranges, often in the highlands. Most local farming communities have grazing rights to the commons. The extent of the commons is very variable, from less than 100 km^2 to more than 5000 km^2. Commons are usually limited by natural boundaries, large rivers, glaciers or high mountains, but fences are also used.

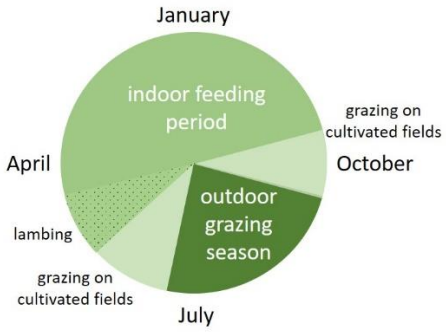

Figure 4. *Annual cycle in sheep farming practices in Iceland*

The sheep are grazed in the commons from late June to mid September. Summer grazing in the commons is a cost-effective practice. Lambs gain weight quickly, especially in early and mid summer. As fall approaches, the sheep are round up and are brought back from their summer ranges to the farms in what has become a hugely popular event all over Iceland, the réttir.

An important determinant of the impacts of grazing on the environment is management. How many sheep we have and how long they graze for are important considerations that define the grazing system. Current grazing practices in Iceland, including the length of the grazing period and stocking densities, vary between commons and are decided by the district councils. The summer rangeland condition is not properly assessed and little adjustments are made in terms of grazing pressure. In many cases, the rangelands have been utilized to their absolute limits. After decades and centuries of this management strategy, many rangelands are in poor condition. However, finding the right **stocking rates** – how many animals we have per unit area – and adjusting them within and between years is difficult. Ideally we should base our decisions on the *carrying capacity* of the rangelands, but that is equally hard to achieve because plant productivity varies widely between and within years. For example, the carrying capacity will be lower in a cold summer, because plant productivity will be lower. If we have several cold summers in a row, vegetation will not have time to recover and the carrying capacity will be severely reduced. The only way around this is to be very conservative when estimating stocking rates, so that the vegetation resource is not depleted. Given the current state of many rangelands in Iceland, it would be advisable to enforce regulations to prevent or at least strongly reduce sheep grazing in some areas, especially within the volcanic active zone[19].

Laws concerning grazing, vegetation and soil in Iceland, except some minor amendments, have not changed since 1965. A livestock quota was introduced in the 1980s and the number of sheep has since then reduced by half. However, sheep numbers were not reduced to the same extent everywhere in Iceland, and it is arguable that the current numbers of sheep might still be too high. Most farmers keep a low number of sheep, from 10 to 100 heads,

and the number of sheep farms decreased, but the proportion of larger farms, with more than 800 heads, has increased during the last years. This may have changed the grazing intensity in some areas. Many rangelands in Iceland still persist in poor condition after decades of overgrazing and extensive soil erosion. Just removing the grazing pressure might not be enough to recover the ecosystems, and active restoration is needed in some areas.

In the year 2000 sheep farmers and the government made a landmark agreement that tied production subsidies to quality management. Each farm was given a production quota linked to subsidies, subject to quality control through voluntary management of animal health and sustainable land use. Each farm is supposed to have enough grazing land in good condition available to his livestock. However, the rules allow grazing on land in bad condition if the farmer develops a land improvement plan. Generally, these plans include a land rehabilitation program and some management objectives, but still grazing of areas in poor condition is continued.

Sheep products today are mostly meat and wool. Domestic consumption of meat has been declining for a number of years, but the number of sheep is maintained by export. The last few years more than 30% of the total production has been exported. Agricultural subsidies are a substantial proportion of Iceland's national budget, and sheep farming cannot sustain itself without subsidies. Subsidies are provided as direct payments to the farmers and they represent about half of the income of the sheep production industry.

For sheep grazing to be sustainable, policies should link financial support to sustainable carrying capacity, which must take into account the extent and productivity of the grazing land[1]. As well, the development of sustainable grazing practices requires that we consider ecological, social and economic aspects.

Section 4.2 Current efforts in ecological research

Grazing research

Given the relevance of the topic, it is nor surprising that there has been a considerable amount lot of research about sheep in Iceland[20]. However, most research in the past has focused on sheep production and forage quality, and relatively little has addressed the environmental consequences of sheep grazing. But things are changing, and more research is now addressing the ecological impacts of sheep grazing.

For example, with the University of Iceland and the Soil Conservation Service of Iceland, we set up a field experiment in 2016 to assess the impact of sheep grazing on rangelands. The experiment was established in two locations, within and outside the volcanic active zone, and in two habitats with contrasting vegetation cover, a well vegetated heath and a sandy desert. These two habitats represent extreme situations in their susceptibility to soil erosion, and include areas that sheep commonly use when they are grazing in the highlands. We established fences that prevent access to sheep, and we are now monitoring changes in plots with and without sheep grazing. By comparing the responses of plants and other ecosystem components like soils and insects, within and outside the fenced areas we will be able to assess the influence of removing sheep grazing.

In addition, within this experimental set up we are also testing the effects of application of fertilizers as a restoration tool. Fertilisers have been commonly used to restore degraded lands in Iceland, because of their ability to stimulate quick vegetation growth. But in the rangelands this vegetation growth could actually attract more sheep, thus counteracting the effectiveness of the fertilisers. In a few growing seasons, these experiments can show the combined effects of sheep grazing and fertilizer applications, providing a possible management solution to land degradation in the rangelands of Iceland.

These experiments allow us target specific questions that can help advance our understanding of how the system works, and ultimately how to manage it better. By coordinating research efforts within national programmes, we can address some of the knowledge gaps more effectively. In 2017 sheep farmers signed an agreement with the

government to set up GróLind, a monitoring programme for the environmental impacts of sheep grazing. The Soil Conservation Service, the Farmers Association, the Icelandic National Association of Sheep Farmers, and the Ministry of Industry and Innovation, came to an agreement to set up a monitoring program to assess and monitor the condition of grazing resources in Iceland. The programme aims at understanding what the current land condition is, and how to manage grazing resources in a way that does not compromise the future use of the rangelands. The aim of GróLind is twofold: to assess changes over time in the vegetation and soil resources of Iceland, and to develop indicators of sustainable land use.

For this project to be successful it is critical that all parties involved are engaged and are able to talk to each other. It is therefore very important that everybody agrees on the questions being asked, the questions that will ultimately guide the monitoring programme.

GróLind will monitor land condition and rangeland health all over the country at different spatial and temporal scales. For example, satellite images will provide a frequent overview of the whole country, while specific sites will be tageted to have a detailed on-the-ground understanding of changes. Accurate site measurements are costly and time-consuming, so they will only be done every 5 or 10 years. However, each year land users will contribute simple standardized observations on the target sites. By linking analyses at different scales, GróLind will provide a more accurate picture of the state and changes in land condition in Iceland.

GróLind will also build on ongoing research and, where needed, will set up specific experiments to refine the monitoring programme. This is a long-term program that will evolve as more information and techniques become available. This type of monitoring approach is called adaptive monitoring. Adaptive monitoring results of applying the adaptive management framework to environmental monitoring[21]. This approach allows monitoring programs to evolve as we learn more about the system and new information becomes available. One of the challenges is that these changes and refinements of the research questions should not breach the integrity of past and ongoing data collection.

Section 4.3 Sustainable sheep grazing?

The future of sheep grazing

Sustainable sheep grazing should ensure the delivery of socioeconomic benefits while maintaining the environment[1]. A balance needs to be found between economic gain and preventing environmental degradation. From the ecological standpoint, sheep grazing can be enhanced by practices that minimize environmental degradation, encourage biodiversity and preserve the integrity of ecosystem processes[1].

At the same time, to be sustainable sheep farming needs to be profitable enough to sustain farmers' livelihoods. It is not easy times for sheep farmers, with declining prices and bad business environment, as well as raising voices that denounce unsustainable farming practices and animal welfare issues. But things are slowly changing. Over the last decades in Iceland there has been a general shift in the principles guiding grazing lands and rangeland management. From managing for animal production, to increasing the emphasis on preserving biodiversity and ecosystem services and an increasing understanding that rangelands should be maintained as functioning ecosystems and should be managed as a whole. This shift in focus is partly due to consumer demand, because consumers are now more concerned about food being produced in a sustainable way. The marketing of sheep products will also help in promoting sustainable management practices. As well, increased knowledge and better tools for rangeland management are facilitating this change.

Part 5. Summary and conclusions

Section 5.1 Summary and conclusions

Understanding how land uses affect biodiversity is key if we want to maintain ecosystem functioning and the ecosystem services we get from nature. Human land uses can have dramatic effects on the landscape and can lead to severe land degradation if management of natural resources is inappropriate. In this sense, the actions of humans in Iceland over a few centuries has been comparable to the forces of volcanoes and glaciers in shaping Icelandic landscapes over millennia. Iceland is in many ways a very special place, but there are many important lessons that we can learn from the Icelandic experiences that can be applied to other parts of the world.

In Iceland, harsh winters and volcanic activity can mediate the effects of sheep grazing, and economic factors, like changing market demands or fluctuations in prices, can also play an important role. We can devise general rules and guiding principles for management based on our current understanding but fine-tuning of stocking rate decisions will have to be site-specific. Ensuring the sustainability of today's management practices is important if we want to maintain the resources of tomorrow for the next generations.

Finally, it is important to keep in mind that we live in a time of change. We are witnessing accelerated changes in climate, especially in the North. Temperatures in the Arctic have rapidly increased in the last decades, at a faster rate than elsewhere in the globe[22]. It has been argued that increased temperatures may enhance growing conditions for plants at higher latitudes, and in fact, we are seeing "greening" trends in some parts of the Arctic[23]. But things are more complex: at the same time, we are detecting opposite trends, loss of vegetation or browning, in other parts of the Arctic. Therefore, we need to be cautious in our predictions of what the world may look like a few decades down the road.

Around the world, the continued co-existence of nature and people, and their cultural and economic activities requires good knowledge and thoughtful policy. Ongoing efforts to understand the effects of sheep grazing and develop sustainable management practices in Iceland will hopefully contribute to addressing this global issue.

Useful links

Course website: http://sheepfireice.org

EdX edge platform: https://edge.edx.org/dashboard

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