The Impact of Settlement on Woodland Resources in Viking Age Iceland

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Abstract

The settlement of Iceland in the late 9th and early 10th centuries – the *landnám* – is associated with a large scale deforestation which resulted in significant and long-term consequences for the island's fragile environment. The *landnám* deforestation has been the focus of academic research for more than a century, but its process and reasons remain poorly understood. The size of the pre-*landnám* forests has not been established and it remains unclear whether the deforestation was an unavoidable effect of human colonisation, whether it was the result of a deliberate strategy or whether it was a case of mismanagement.

The aim of this dissertation is to throw light on these issues. It establishes an estimate of the extent of the pre-*landnám* forests and shows that even the most generous estimates for the settlers' requirements for fuel and building material would not have made an appreciable impact on the woodlands. Rather it was clearance for pastures and home-fields which was the cause of the large scale deforestation. The deforestation process is explored through four possible scenarios of available manpower and social relations. The scenarios are processed through a series of spatially explicit agent-based models of three sample study areas: Vestur-Eyjafjallahreppur, Mývatn and Borgarfjörður. The outcomes of those models suggest that the deforestation was the result of a deliberate strategy to establish and develop an economy based on animal husbandry. This strategy was however applied without a full awareness of the potential and the fragility of the local environments. Very early on, the newly created pastures began to suffer degradation and their grazing potential declined. The decline was caused by a combination of overgrazing, the spread of grazing-tolerant vegetation, and to a lesser degree, by woodland regrowth. As a result, the initial extent of cleared pastures proved insufficient, requiring repeated re-initiation of clearance at many locations. The model outcomes also suggest that the deforestation was neither as drastic nor as rapid as it has commonly been portrayed. Although most of the deforestation had taken place already before the end of the 9th century, it was a drawn-out process which lasted throughout the 10th century and most likely continued well into the post-*landnám* periods.

Ágrip

Landnám Íslands seint á 9. öld og í byrjun 10. aldar hafði í för með sér stórfellda skógareyðingu með víðtæk og langvarandi áhrif á viðkvæma náttúru landsins. Skógareyðing landnámsaldar hefur verið rannsökuð í meira en öld en ekki hefur verið skýrt hvernig skógareyðingin átti sér stað né hvað olli henni. Stærð skóglendis fyrir landnám er ekki þekkt og óljóst er hvort skógareyðingin var óhjákvæmileg aukaverkun landnáms manna og dýra, hvort hún var afleiðing af meðvitaðri stefnu eða ofnýtingu.

Markmið ritgerðarinnar er að varpa ljósi á þetta mál. Lagt er mat á stærð skóglendisins fyrir landnám og sýnt fram á að þörf landnámsmanna fyrir eldsneyti og byggingarefni ein og sér, jafnvel ef mjög rúmt er áætlað, hefði ekki getað haft þessi miklu neikvæðu áhrif á skóglendið. Skógarhögg í þeim tilgangi að rýma fyrir túnum og skapa víðfeðm beitilönd var ástæða hinnar stórfelldu skógareyðingar. Til að rannsaka framgang skógareyðingarinnar eru skilgreindar fjórar sviðsmyndir sem byggja á mismunandi forsendum með tilliti til tiltæks mannafla og félagslegra tengsla. Til að kanna sviðsmyndirnar eru „agent-based“ tölvulíkön keyrð fyrir þrjú rannsóknarsvæði: Vestur-Eyjafjallahrepp, Mývatn og Borgarfjörð. Niðurstöður tölvulíkananna sýndu að skógareyðingin var afleiðing vísvitandi stefnu sem hafði það að markmiði að stofna og þróa samfélag byggt á búfjárrækt. Þessari stefnu var hins vegar framfylgt án fulls skilnings á þolmörkum umhverfisins á hverjum stað. Mjög fljótlega fór að bera á hnignun landgæða á hinum nýju beitilöndum og afrakstur þeirra minnkaði. Þessi hnignun orsakaðist af ofbeit, útbreiðslu beitarþolins gróðurs og einnig, þó í minna mæli, af endurvexti skóga. Upphaflegt umfang af ruddum svæðum reyndist ekki nægjanlegt og því varð víða nauðsynlegt að hefja aftur skógarruðning fyrir nýju beitilandi. Niðurstöður tölvulíkananna gefa einnig til kynna að skógareyðingin hafi hvorki verið eins stórfelld né eins hröð og oft hefur verið haldið fram. Þó svo að skógareyðingin hafi að stærstum hluta átt sér stað fyrir lok 9. aldar, náði heildarferlið yfir mun lengra tímabil sem stóð yfir alla 10. öldina og hélt að öllum líkindum áfram löngu eftir landnám.

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Appendices

This dissertation is accompanied by two appendices. Appendix 1contains the most important results of this study – the outcomes of the agent-based simulation runs presented in the form of charts. Appendix 2 is placed on the accompanying DVD and consists of complete codes for the NetLogo-based series of agent-based models, corresponding GIS-based material and brief instructions about the use of the models (available upon request).

1 Introduction

1.1 The subject of the study

Deforestation is recognised, by the general public as well as scholars of different disciplines, if not as the most significant then at least as the most visible way of modifying landscapes. Since prehistoric times humans have intentionally cleared forests, leaving behind open landscapes. Those have often been farmed landscapes of fields and meadows, but sometimes deforestation has set in motion soil erosion and desertification that has resulted in desolation and depopulation.

Intentional deforestation can be seen to serve two ends: the wood itself can be a valuable resource and deforestation then only results if the cutting is not managed to allow for regeneration and woods may be cleared to make space for other, more productive or valuable, uses of the land. Both can be significant factors in the establishment, subsistence and development of any society. The constant need for greater space that accompanies urban and industrial expansion worldwide is met through large-scale clearance of forests. Deforestation therefore can appear as a sign of growth and progress.

Deforestation also has various negative consequences: the loss of valuable resources and dangerous interference with the environment. Today, for instance, it is being recognised that deforestation drives climate change through the release of large amounts of greenhouse gases that fuel global warming; it reduces the bio-productivity of ecosystems by disrupting the habitats of thousands of species, and often transforms forest lands into barren deserts. It also opens the way to soil erosion, thus making the entire ecosystem unstable. Consequently, by impoverishing our natural environments, in the long run deforestation affects our lives and economy negatively (Martin *et al.* (eds.) 2012).

Forest clearance has been practiced by humans since prehistory (Williams 2000, p. 29). Examples can be found, on scales ranging from small to massive, in many different parts of the world in relation to various types of cultures. Deforestation associated with the origins and spread of farming worldwide is usually seen in a positive light as a measure of human development, when people are harnessing resources and acquiring space to build complex societies and civilizations. However, there is also a growing appreciation that deforestation has come at a cost to the natural environment with long-term consequences on local and regional scales as is the case in the present. Many recent studies suggest that deforestation caused by man has resulted in serious consequences for local and regional hydrology and climate (e.g. Kaplan *et al.* 2009).

Despite obvious negative consequences in the past, deforestation continues and has now more than ever become an issue affecting our future. There are well-known examples from the past, it is much in evidence as an ongoing activity in the present and will remain so, at least in the near future. It therefore represents an important aspect of our lives. For these and many others reasons, deforestation deserves particular attention and study. Involving social, economic and biological aspects of development in the modern world, it presents a research field of particular importance for society, science and our environment. The need to investigate deforestation, its causes, development and consequences is therefore obvious and should be addressed seriously.

In the past, it looks as if woodlands were seen as an almost inexhaustible resource and that there was no environmental awareness of the consequences of the long-term exploitation and clearance activities. This can be seen in terms of „careless utilisation“ of resources. It is however also reasonable to assume that clearance activities were simply made to meet the requirements of the human population and the development of its economy – in other words, it was an „unavoidable necessity“. This dichotomy is clearly echoed in debates in the present, couched in terms of development versus conservation, and the past is often viewed from the perspective of that debate, as a question of either one or the other.

However, the issue of early utilisation of woodlands is not a simple one and should not be discussed solely within the frame of the mentioned dichotomy. Thus, there are numerous examples from the past which also suggest obvious appreciation of woodlands and attempts to exploit them in a way that would preserve not just their own bio-diversity but also the bio-diversity of other environmental categories. There, the best-known example would be the ancient Roman system *ager-saltus-silva* („field-pasture-forest“) that implied practising of farming, animal husbandry and forestry on non-overlapping landscape cells (Blondel and Aronson 1995, p. 65) and that can be seen as one of the reasons for more or less succesful management of complex Mediteranean agroecosystems.

Furthermore, there are examples from both distant and very recent past about woodlands being protected from utilisation, primarily because of religious factors. Thus, for a long period of time stands of woodlands have been worshipped as shelters of gods and spirits and were protected in order to please the gods in ancient Greece, Rome and pre-Columbian America (Mosley 2010, p. 34). Sacred groves were and still are an important feature in the culture and religion of African nations where they are associated with for instance, rain-making and burial grounds (Niamir 1990).

In reality, deforestation was therefore a complex issue – not only that it frequently entailed different modes of utilisation of resources but it was also shaped by the concept of sustainability and was restricted by the cultural traditions. Needless to say, it was also limited by environmental potential and was influenced by its reaction to deterioration.

Icelandic history provides a case of comprehensive deforestation with long-term negative consequences. Although once forested to a considerable extent, during the period of colonisation Iceland experienced significant human-induced deforestation, a process which started in response to the needs of a newly established society at the end of the 9th century AD. We now know that large areas of Iceland completely lost their woodland cover in a matter of decades after the arrival of the first settlers. Even though deforestation, probably at different rates and from different causes, continued to change Icelandic landscapes during the following centuries, the woodland loss during the settlement period is with little doubt the most rapid and far-reaching change that the natural environment of Iceland underwent during the Holocene. The story of the Icelandic settlement deforestation is a complex one, as is the case with all interactions between humans and their environment. Not only did Iceland's natural environment change, but this change and the consequences that followed also shaped the development of the economy of the settlement population and important aspects of the culture of the emerging society.

What is of primary importance, however, is that although a slight natural decline in the forest cover was underway when humans arrived in the Icelandic ecosystem, the settlement deforestation was overwhelmingly human-induced. It is traditionally seen to have been induced by the new society's requirements for space, building material, firewood, pastures, and probably also, though only on a small scale, cereal cultivation, but also by unrestricted/ uncontrolled livestock browsing which was a direct consequence of the animal husbandry economy. In addition to this, it is necessary to recognise that other causes than those which can be related to subsistence requirements may have contributed, to a greater or lesser degree, to the deforestation. Bad management, accidental fires, the effects of volcanic eruptions, climatic variations and impact by parasites also need to be brought into connection with this environmental change.

This thesis will investigate the complexity of this kind of process and will demonstrate that the deforestation was the result of complex processes involving the most important economic requirements and social factors, limited by environmental potential and influenced by its response to degradation. Furthermore, it will be demonstrated that the deforestation cannot be accounted for in terms of single causes or only by considering requirements of settlement economy and structure of its society. Also, it should not be seen as uniform – it varied over time and the process differed from one region of Iceland to another. Such variations also raise the issues of choices and strategies, that is, decisions made by people on the ground.

Given its obvious significance for later developments, it is little wonder that the settlement deforestation has received considerable scholarly attention. However this has mainly been directed towards reconstructing the original extent of the woodlands and identifying single causes which could account for their demise. So far there has been no systematic attempt to explain the process of deforestation in detail; where it first started and in response to what particular requirements, the rate of exploitation, the part played by each of the requirements in the overall process and how the needs, interests, aims and concerns of individual settlers overlapped and affected the state of the woodlands during this period. The present study primarily attempts to answer questions such as how and why the deforestation process began, whether it was a matter of unavoidable necessity, deliberate strategy or unintended consequences of other activities and what impact this largely anthropogenic destruction of the environment had on the woodlands themselves, but also how this environmental change affected the settlement economy and society.

1.2 The study period

The period discussed in this dissertation is the Settlement period of Iceland (in Icelandic *landnámsöld*)[1], in the late 9th and 10th centuries, when the island was colonised.

The starting point of the study period is the year AD 871, which we may assume as the initiation of the settlement of Iceland, based upon the existing archaeological records. They suggest that most of the settlements were established just above the *landnám* tephra layer which has been successfully dated with a margin of error of less than four years on the basis of the study of ice-cores from the Greenland ice cap (Grönvold *et al.* 1995). Since the establishment of the first settlements would obviously have marked the start of human impact on the environment, this date is taken as the starting point for the time-scale of this research project. We cannot exclude the possibility that there were settlements in Iceland earlier than AD 871±2, in the early to mid- 9th century, and some archaeological results indicate that this was the case[2]. Nevertheless, the vast majority of available archaeological studies, and also research in various other disciplines, indicate that the large-scale arrival of permanent settlers in Iceland took place in the first two to three decades after the fall of the *landnám* tephra in AD 871 ± 2. The closing point on the time-scale of this research is the year AD 1000, as the end of the 10th century and a year which will be used to roughly denote the end of the settlement in Iceland.

The idea is therefore to recreate the process of deforestation during the entire period of settlement. However, a particular focus will be on the initial three decades of this period during which most of the country was claimed and occupied. It is one of the assumptions behind this project, based on existing hypotheses of the settlement process, that most of the deforestation occurred with (or soon after) the arrival of the first major wave of settlers. Although a recent study has confirmed that immigration to Iceland continued in the subsequent decades (Price and Gestsdóttir 2006), it was most probably not of a scale comparable to that of the initial stage (Vésteinsson and Gestsdóttir forthcoming) and we may assume that deforestation in the mid to late 10th century was not as drastic as in the initial phase. Nevertheless, reduction of forest cover during those later stages of the Settlement period will also be given considerable attention.

1.3 Objectives of the study

Explaining the process of the *landnám* deforestation will be achieved in several steps. These are:

a) to propose a solid estimate of the distribution of pre-*landnám* forests,
b) to offer quantifiable estimates of the impact on the woodlands caused by different types of utilisation, and on this basis, to assess the relative contribution of different kinds of requirements of the settlement population on the process of deforestation.

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[1] The term *landnám* translates literally as „land-taking“, i.e. the process when people arrived and took possession of the land and established settlements.

[2] See disscussion on that issue in Vésteinsson and McGovern 2012.

c) to investigate the process of deforestation through the examination of different scenarios of available manpower and of social relations,
d) where possible, to compare the outcomes of the abovementioned scenarios with available empirical research results, and on this basis, to verify and/or refute our assumptions about the process of deforestation,
e) finally, to discuss and clarify whether it was unavoidable necessity, deliberate strategy or unintended consequences that best explain the deforestation. In the areas where deforestation was obviously drastic, was it inevitable? Was it (mis)management or other circumstances that caused a more gradual decline in the birch woodland cover in other parts of Iceland?

In general, the aim is to establish a more detailed and realistic picture of this momentous environmental change.

1.4 Thesis outline

In addition to this introduction, this thesis consists of the following chapters:

Chapter 2. This chapter presents a survey of previous research, including a critical analysis of available studies from the research disciplines which have addressed the issue of *landnám* deforestation in Iceland.

Chapter 3. The main part of this chapter presents all the data used in the research and explains the methodological approach of the dissertation. It also gives an account of the theoretical framework, and discusses its potential and limitations.

Chapter 4. This chapter describes the density, distribution and previous estimates of the extent of the pre-*landnám* woodlands, the *landnám* vegetation map made by the Icelandic Institute of Natural History (*Náttúrufræðistofnun Íslands*) and corrections proposed by the present author.

Chapter 5. This chapter presents estimates of the different degrees to which particular subsistence requirements of the settlement population required woodland clearance. The first part of this chapter gives an account of the possible impact on the woodlands due to needs for space, building material and firewood. The second part explains the degree of impact on woodlands due to needs for pastures.

Chapter 6. This chapter defines a number of scenarios of the deforestation process, and explains the rationale behind them and their historical context.

Chapter 7. This chapter explains the structure of the computational agent-based models which were constructed in order to test the proposed scenarios.

Chapter 8. This chapter discusses validity of the series of models and presents and discusses their outcomes.

Chapter 9. The final chapter presents the conclusions of the thesis. It further discusses the outcomes of the series of models and offers a final interpretation of the nature of the human impact on the woodlands which resulted in their long-term loss.

2 Present state of knowledge on the *landnám* deforestation

2.1 Introduction

The density and distribution of pre-*landnám* woodlands and in particular the nature of woodland exploitation associated with the *landnám* have been the subject of interest for a long period of time. The present state of knowledge on the *landnám* deforestation process derives initially from medieval written sources but has been substantially complemented by modern research initiated at the beginning of the 20th century. A large amount of research results within several disciplines has been produced and different kinds of interpretations of this environmental change have been proposed. An analysis and overview of the field reveal that in spite of considerable efforts and important results, there are still many gaps in our understanding and many questions remain to be addressed. Nevertheless the available research forms the basis of the present effort to explain the process of deforestation during the *landnám* period.

Caveat

It is important to stress that the idea behind this dissertation was to rely primarily on modern academic research studies since they provide data of sufficient quality and resolution that can be used for investigation of the period under discussion. Additionally, the work on this project also entailed the use of written sources, but only to a lesser degree. This is firstly because many of the early written sources that provide information about the Icelandic *landnám* deforestation (e.g. Ari fróði‘s *Book of Icelanders*, mentioned below) are written at least more than 200 years after the events they describe and therefore cannot be regarded as entirely appropriate. Secondly, and more importantly, many of those offer only generalised and/or exaggerated descriptions of the state of the Icelandic environment and the changes it underwent during the *landnám* – those were therefore only used to obtain hints about this environmental change and not the accurate, verifiable data that had to be used for this research study. Still, a minor number of written sources (e.g. *Jarðabók*: Magnússon and Vídalín 1980, mentioned below) that provide relevant and thorough documentary evidence valuable for this research project were extensively used throughout the work. Therefore, because of the higher degree of quality and relevance of modern academic research studies over historical sources, the latter were reviewed in the following sections only briefly. On the other hand, modern academic, empirical studies on the subject are presented through an exhaustive analysis. A qualitative analysis of the data and particular studies used for this research project is presented in Chapter 3.

2.2 The written sources

Ever since the 12th century, remarks on and descriptions of the deforestation and its consequences appeared in various writings, including sagas, annals and law codes. Until recently, these written records were the principal source of knowledge on this drastic environmental change, and although new research methods have been brought to bear on the subject, the written records remain influential for general perceptions of the deforestation.

An awareness of the woodland situation in the Settlement period appears already in early 12th century texts, in the work of Ari fróði Þorgilsson. In his *Book of Icelanders,* he states that forests once stretched „between the mountain sides and the shore“ (Benediktsson (ed.) 1968, p. 5). The *Book of Settlements,* which derives some of its material from Ari but survives only in late 13th century and later versions, offers descriptions which connote the scale of changes as well as possible methods of forest clearance: for instance, Blund-Ketill, a very rich man, is said to have „had the forests cleared and established the settlements there“ (Benediktsson (ed.), 1968, p. 84). Although records like these reveal an early awareness of the extent of pre-*landnám* forests and processes of deforestation they may still be regarded as exaggerations and over-generalisations. Thus, with regards to defining the spatial distribution of woodland cover, as noted in the *Book of Settlements*, it is hard to believe that all the lowlands, which stretch up to 300 m and account for less than 35 % of the land area, were completely covered in woodlands with no space for other types of vegetation. In fact, many of the existing empirical studies suggest that this was not the case (see discussion on this issue in Chapter 4). Furthermore, it also seems conceivable that at many locations woodlands were cleared and settlements established by low-ranking, poor settlers and not only by wealthy landowners which is a conclusion that can easily be inferred from the writing about Blund-Ketill. It is therefore more plausible that the whole process of settlement and accompanying environmental alteration was much more complex than indicated by the abovementioned written sources. Nevertheless, it is important to stress that these records influenced later writers and created literary trope which, surprisingly or not, still shapes popular perceptions of this environmental change.

Some of the sources indicate that deforestation was seen to have resulted from unfortunate events. *Hrafnkels saga* for instance has descriptions of charcoal burning triggering accidental fires with serious consequences for the local woodlands (Pálsson 1987, p. 82). While there is no doubt that accidental fires like that may have happened at many locations and at many occasions, it seems highly unlikely that they affected the woodland cover on a significant scale, although the opposite is widely accepted by the general public.

An awareness of the expendability of natural resources is also reflected in the other written sources. In *Grágás*, the law code dating in its preserved form to the 13th century, the provisions on the use of driftwood and the importing of wood reflect an awareness of the importance and high value of wood. Thus, provisions such as:

> *„...if a man finds driftwood on his foreshore, he may, even though it is Sunday, roll it above high water mark. If he cannot get it up, he may put his mark of ownership on the wood. He is not to cut it in pieces. It becomes his, wherever it comes ashore, if he puts his lawful mark on it...“*
>
> (Dennis *et al.* (transl.) 1980, *Grágás* I, p. 41)

or

> *„...Icelanders have the right to make use of water and wood in Norway, but they have the right to cut all the wood they want only where the forest belongs to the king...“*
>
> (Dennis *et al.* (transl.) 1980, *Grágás* II, p. 211)

indicate that wood was a highly valued commodity, which is consistent with the view that the native woodlands were seriously depleted when these provisions were enacted, presumably in the 11th to 13th centuries.

In addition to this, it is important to recognise written records from later periods, which have information about the extent of post-*landnám* woodlands, especially woodlands surviving into early modern times. They suggest what kind of areas could have been forested at the time of *landnám* and also in what kind of areas woodlands could have been preserved during and after the *landnám* period. The most comprehensive of these sources is undoubtedly the land register made by Árni Magnússon and Páll Vídalín between 1702 and 1714 (Magnússon and Vídalín 1980) which, even though it does not cover the entire country and showing only partial extent of woodland in the 18th century, is one of the most frequently quoted sources on the environmental history of the country.

These, and many other written records as well as place names, complementing the written sources, have been used by many authors to illustrate the extent and decline of the *landnám* woodlands. Even though their reliability has been questioned, they provide useful indications about the environmental history of early Iceland.

2.3 Modern research and the major disciplines involved

Modern studies on this subject have produced a significant amount of valuable research results and provide a basis for an interpretation of the extent of the original woodlands as well as various aspects of the process of deforestation. They have been conducted by biologists, geologists, geographers, historians, archaeologists as well as other scholars.

Early to Mid-20th century: Initiation and establishment of modern academic research

The starting point of modern research was the work of Þorvaldur Thoroddsen, geologist and geographer, one of the pioneers of the study of Iceland’s environment. He explored the island’s desolate and remote areas at the end of the 19th century (e.g. Thoroddsen 1884; 1891) and is the author of the first geological map of Iceland (Thoroddsen 1901). Thoroddsen was the first scholar to discuss the *landnám* vegetation systematically, in an academic way, arguing about the possible extent of vegetation cover and the processes of deforestation. Thus, while stressing winter grazing as a key variable which resulted in seriously damaged woodlands and dwarf shrub heaths (Thoroddsen 1933), he also pointed out different opinions regarding the extent of woodlands in the settlement period, explaining that for a long time it was believed that only 3,000 – 5,000 km² had been covered with woodland before the *landnám* (Thoroddsen 1912, p. 298; 1933, p. 437). The work of Þorvaldur Thoroddsen provided a solid foundation for academic research in the following decades.

The essential step forward was made in the middle of the 20th century with the work of geologist Sigurður Þórarinsson. His doctoral thesis *Tefrokronologiska studier på Island*, which was published in 1944, engaged palynology and tephrochronology and suggested that charcoal remains could be fruitfully studied. It was a „break-through“ in terms of professionalization of research. In particular, Þórarinsson's pollen diagrams from Þjórsárdalur mark the beginning of palynological research in Iceland. Since this study, palynology has proved crucial in recognising and reconstructing the past vegetation of the country. Not least, it has become established as a vital research tool in studies of the *landnám* deforestation process. The principles of tephrochronology, which has since become established as the principal dating method in archaeological and palaeoenvironmental studies in Iceland, were first clearly laid down and defined in the same study. Finally, Þórarinsson studied charcoal remains which he interpreted as evidence for the burning of woodlands near farmsteads (Þórarinsson 1944, p. 192), heralding the later significance of charcoal analyses for the study of human-induced deforestation. *Tout ensemble*, the work of Sigurður Þórarinsson undoubtedly raised the standards of the overall research by applying empirical methodologies although Þórarinsson also freely used other evidence like place-names.

Second half of the 20th century: Increased multidisciplinarity

The following decades saw major advances in this field. The overall frequency of research and the interest of various kinds of scholars increased considerably, resulting in a significant amount of new research results. Also, disciplines such as palaeoentomology and historical demography became involved while the importance of archaeological research finally started to be appreciated. The use of written sources and historical records continued to be common, although it was in this period that critical attitudes to their relevance as a research tool began to be asserted. Written sources were used by different kinds of scholars to a greater or lesser degree and this was reflected in the different estimates of the extent of woodlands which were produced during the 1970s.

The palynological research of scholars such as Þorleifur Einarsson in the 1950s and particularly '60s (e.g. Einarsson 1957, 1962) and Margrét Hallsdóttir in the '80s and '90s (e.g. Hallsdóttir 1984; 1987; 1995; 1996), apart from describing vegetational changes during the *landnám* period, also contributed to the modern interpretation of the pre- and post-settlement vegetation. This was very significant since the clarification of the scale of woodland cover in the pre- and post-*landnám* periods directed the spot-light towards what happened during the *landnám* period itself. Mostly thanks to Einarsson and Hallsdóttir, the overall picture of the Early Holocene vegetation has been clarified. Of particular importance is the suggestion that birch was the only tree-species capable of forming woodlands before the arrival of the first settlers (Hallsdóttir 1987, p. 7). However, the most significant aspect of these studies, based on research mostly from the south and south-western parts of the country was that they suggested rapid and drastic deforestation at the very beginning of the settlement period (e.g. Einarsson 1962; Hallsdóttir 1987). Although it is based on studies of a very small number of localities, this idea of rapid, large-scale clearance of woodlands underpins the prevailing view of the *landnám* deforestation.

The idea of exploitation of woodlands for charcoal production was further developed and presented by Þórarinn Þórarinsson in 1974. His study „The nation lived, but the forests died“ („*Þjóðin lifði en skógurinn dó*“: Þórarinsson 1974) constituted a turning point in the approach to the topic, since it presented for the first time a quantitative estimate of the impact of resource utilisation on the woodlands. Þórarinsson based his study on the assumption that up to the mid-15th century, all the iron used in the country was locally made, requiring the production of about 45 metric tons per year (Þórarinsson 1974, p. 28). Judging upon Norwegian references and the iron content of the local bog-iron, Þórarinsson suggested that „the minimum annual amount of charcoal needed to smelt 45 tons of iron was about 25,000 barrels“ (each equivalent to 25 kg of charcoal; Þórarinsson 1974, p. 28, 29). Þórarinsson suggested that the total amount of charcoal needed for the first 500 years of settlement was about 65,000 barrels annually. This result, converted into birch forests, suggested that around 1,000 ha, or at least 10 km² of woodlands, must have been cleared annually (Þórarinsson 1974, p. 29). Based on this assumption and changes in the rate of iron production, and taking into account the beginning of iron imports at a later date, Þórarinsson reached the conclusion that in the first 1,000 years of settlement, Icelanders must have felled „at least 8,200 km² of woodland just to obtain the bare essentials for livelihood“ (Þórarinsson 1974, p. 29). These were important results, not least in that they offered a clear and measurable perspective on the process and reasons for the woodland destruction. Many aspects of Þórarinson’s estimates are unclear however. Thus, the minumum annual production figure of 45 tons of iron (Þórarinson 1974, p. 28) is not supported by appropriate documentary evidence, nor is it completely clear how he calculated the average amount of wood needed for charcoal production. Further, there are no data on the type of forests exploited and it remains unclear what density the author had in mind. Nevertheless, this was a pioneer comparative and quantitative study which has had significant impact on subsequent research. Charcoal production continued to be a subject of interest, although only indirectly, of many other scholars. Therefore, some have suggested that charcoal required for smelting processes could only have been partially obtained by other sources such as driftwood (McGovern *et al.* 1988, p. 230), while others have emphasized the idea that the initial assault on the woodlands was motivated, among other needs, by the need for fuel for iron production (Smith 1995, p. 336).

With respect to clearance for pastures, an important contribution was made, albeit obliquely, in the study of McGovern and others (McGovern *et al.* 1988) where they suggested estimates for the possible extent of pasture areas belonging to the low- and high-ranking farms of Gjáskógar and Stöng. This represented the first step towards estimating the possible extent of clearance for pastures.

The first detailed studies on modern utilisation of rangeland resources and significance of livestock grazing and browsing of wooded areas were carried out by Ingvi Þorsteinsson in the 1970s and 1980s (e.g. Thorsteinsson *et al.* 1971; Thorsteinsson 1980). Probably the most important aspect of those studies was that they provided the data on average annual yield and carrying capacity of different types of vegetation in the rangelands of modern Iceland. Þorsteinsson's work was used in the following decades, to a greater or lesser degree, to illustrate the environmental potential of the wooded rangelands during the age of Settlement and its capacity or inability to sustain uncontrolled livestock grazing and browsing (e.g. Thomson 2003).

The application of tephrochronological techniques was improved in Sigurður Þórarinsson's study of farm abandonment in North and North-East Iceland (Þórarinsson 1977). The work of several other scholars by the end of the 20th century such as Andrew Dugmore and Guðrún Larsen (e.g. Dugmore *et al.* 2000; Dugmore and Buckland 1991; Larsen 1993) further improved on Þórarinsson's method and strengthened the role of tephrochronology in the study of different kinds of past environmental changes. This has produced results that are useful for reconstructing the extent of primary forests and tracing their loss. A very significant contribution of Dugmore's studies is the emphasis on tephrochronology as one of the very few methods available for assessing the spatial variation in sediment accumulation and helping to infer the shapes of past land surfaces (Dugmore *et al.* 2000, p. 32), but also as a highly useful research tool in studies of soil erosion (e.g. Dugmore and Buckland 1991; Dugmore and Erskine 1994) which are frequently related to the issue of deforestation.

Even though entomological research intensified in the 1970s after the establishment of the Department of Biology at the University of Iceland (Gíslason and Ólafsson 1989, pp. 11, 13), studies of past insect fauna from the settlement period were not undertaken until the 1980s. These, conducted mainly in association with archaeological research, confirmed among other things increased species diversity immediately after the *landnám*, indirectly reflecting changes in the vegetation (Buckland *et al.* 1991b, p. 135). In addition, studies of the fossil record by scholars such as Buckland and others have indicated that the intensity of the changes in the beetle fauna were related to those noted in the flora (Buckland *et al.* 1991b, p. 141), supporting the general impression of a large scale and rapid impact on woodlands.

Historical demography has also made important contributions with estimates of the size of the settler population providing a base to assess its impact on the vegetation. The work of Vésteinsson and McGovern (2012) provides a considered estimate of population pressure during the *landnám*, delimiting parametres for investigating population dynamics of the period. Vésteinsson and McGovern, based on a variety of archaeological research results, suggested 24,000 as the minimum number of people necessary to establish all the settlements in the late 9th century (Vésteinsson and McGovern 2012, p. 216). The work of Sturla Friðriksson (e.g. Friðriksson, S. 1967; 1972) who estimated a population of approximately 77,000 people at the end of the settlement period, can also be used to assess the likely impact of *landnám* population pressure on the woodlands, although due to an absence of persuasive empirical evidence, its reliability may be brought into question.

In addition to research relating to Iceland, important knowledge has been gained from studies in its neighbouring countries, particularly Greenland (e.g. Fredskild 1978, Fredskild

1992, Jakobsen 1991), which have provided valuable comparative data in view of the similar context of Norse settlement, its environmental impact and woodland exploitation.

The fact that the written sources are not contemporary with the *landnám* and that the first two centuries of Icelandic history are essentially prehistoric, suggests that archaeology, together with palaeoecology, are the only research tools that can be used to properly investigate and offer reconstructions of the vegetation cover in the *landnám* period. Archaeological investigations have been the vehicle for much of the palynological, archaeobotanical, palaeoentomological and tephrochronological research carried out but it has also led to the development of theories about the settlement, illuminating the nature and structure of the *landnám* society, its economy and its utilisation of environmental and thus woodland resources. In particular, the size and location of the first Norse farms can now be reconstructed enabling assessments of their initial impact on vegetation. In other words, archaeology has helped us to understand better the consumer-side of this impact and its effect on woodland resources. While the work of Sigurður Þórarinsson (1977) heralded things to come, it was not until the last two decades of the 20th century that archaeological data began to be applied systematically to the sort of questions considered here. Thanks to the work of several scholars (e.g. McGovern *et al*. 1988, Vésteinsson 1998), attention was drawn to the potential of archaeological research to provide detailed answers about the *landnám* period. Thus, today we are aware of a strategic positioning of the initial settlements in coastal locations or in river valleys, based on the availability of wetland fodder resources to feed livestock over the winter period, with the clearing of woodland areas being seen as occurring in a secondary phase of settlement (Vésteinsson, 1998; Vésteinsson *et al.* 2002; Mairs *et al.* 2006). This hypothesis which involves an idea of a phased clearance of woodlands throughout Iceland, and has been supported by different kinds of empirical research in particular locations, can be used as a framework to study *landnám* deforestation.

The use of written sources and place names has a long tradition in Icelandic academia. It permeates Icelandic studies of the Viking Age and middle ages throughout the 20th century and has played an important role even in the most recent studies (Gunnarsdóttir 2001). As an example of the influence written sources and place names have continued to exert on the research under discussion, a series of estimates of pre-*landnám* woodland cover produced in the highly productive periods of the 1970s and 1980s can be mentioned. As a result of an interdisciplinary approach, these estimates indicated that between (approximately) 18 and 40 % of Iceland was covered with woodland (Friðriksson 1987; Bjarnason 1971). Drawing on different kinds of research results, and frequently relying on Þórarinsson's (1944) and Einarsson's (1962) work, these estimates were mainly based on information about modern birch growth limits and conditions in other countries, although it seems that they were also influenced by the authors' different political and professional backgrounds.[3] However, it is also obvious that the authors used, in different ways, knowledge gained from written sources. For instance, Hákon Bjarnason, one of the first scholars to advance estimates about the approximate

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[3] A detailed description of published estimates of distribution of pre-*landnám* woodlands is given in Chapter 4.

extent of woodlands at the time of settlement, and who used written sources, in particular the land register made by Árni Magnússon and Páll Vídalín (*Jarðabók*) for making his estimate, suggested a figure of about 40,000 km² (Bjarnason 1974, p. 41; see also Chapter 4), which is the highest so far. Scholars such as Ingvi Þorsteinsson explained that there is no reason to doubt Ari *fróði*'s descriptions of the pre-*landnám* woodlands, which would imply a large extent of woodland cover, perhaps corresponding to the high estimate of Hákon Bjarnason. Surprisingly, Þorsteinsson settled for a somewhat „low" estimate of c. 25,000 km² of pre-*landnám* woodlands (Þorsteinsson 1972, p. 12; for further explanation see Chapter 4). Some of the authors however questioned reliance on written sources. Thus, scholars such as Þórarinn Þórarinsson discussed the possibility that the use of historical records in this kind of research might result in exaggerated estimates, pointing on the idea that the aboriginal woodlands „were merely brushwood and of limited use" (Þórarinsson 1974, p. 28). In any case, although interpreted and used differently and occasionally being questioned and/or criticized, written sources had significant influence on 20th century research in this field.

Late 20th century research has contributed enormously to the present state of knowledge, not just by increasing the frequency of research and producing new data, but also by introducing new disciplines and methods, creating the multi-disciplinary field that environmental history is today.

21st century: New results and new ideas

The most recent period is characterised by more extensive research than ever before. A series of visual estimates of the extent of woodlands have been produced and the research results of a variety of empirical disciplines have produced very important data. Nevertheless, the influence of written sources remains significant. The most important aspect of 21st century research is that new palynological and archaeobotanical results have paved the way for substantially different interpretations of the process of deforestation then those which shaped the prevailing view during the 20th century.

New maps of the extent of the pre-*landnám* woodlands have been published. Among the most influential is the one produced by the Icelandic Institute of Natural History (2001) based in large part on a variety of written sources. That the use of written sources continued to be of considerable importance was also reflected in another estimate, made by Björg Gunnarsdóttir (Gunnarsdóttir 2001). Here, the distribution of woodlands was estimated through comparisons of saga-descriptions of vegetation with actual vegetation in the same places. In contrast, other scholars made their estimates by relying on scientific data. For instance, the estimate proposed by Ólafsdóttir and others (Ólafsdóttir *et al.* 2001; explained in Chapter 4) was based on the vegetation growth potential and estimated temperature limits.

Other types of research have produced important data which need to be taken into consideration when interpreting this environmental change. Thus, the work of scholars like Thomson and Simpson (Thomson 2003, Thomson and Simpson 2007) on modelling farm management and vegetation degradation in pre-modern Iceland, Edwards and others (Edwards *et al.* 2005) on differences between Icelandic and Faroe Islands' Viking Age landscapes and their transformation, but also the work of Sigurðsson and others (Sigurðsson *et al.* 2005) on biomass of understorey vegetation of modern Icelandic forests, represent significant advances and today appear as almost *sine qua non* for any detailed study on the Icelandic *landnám* deforestation.

The palynological and archaeobotanical studies carried out in the last decade are particularly significant for our understanding of this environmental change. The palynological study of Lawson and others (Lawson *et al.* 2007) in the Mývatn region introduced new ideas by suggesting the possibility of a long-term gradual loss of woodland cover in some of the northern parts of the country, opening up the possibility of different regional trajectories within the processes of woodland clearance. It is important also to highlight the first pollen diagrams produced within the context of archaeological excavations in Reykjavík (Guðmundsson 2001) and Hofstaðir (Chepstow-Lusty 2001). Also, the most recent work of scholars such as Erlendsson and others (e.g. Erlendsson 2007; Erlendsson and Edwards 2009; Erlendsson *et al.* 2009) have further strengthened the importance of palynology in this context by offering high-quality data. With respect to the archaeobotanical work, recent studies by scholars such as Michael Church (Church *et al.* 2006, 2007) analysing charcoal production pits in the areas of Mývatn in the north-east and Eyjafjallahreppur in the south, have resulted in more accurate dates for the deforestation processes. The research results from a series of pits that were excavated and sampled in these regions, suggested a phased process of forest clearance. This also indicated possible local management of woodlands which is an idea first introduced by Vésteinsson and Simpson (Vésteinsson and Simpson 2004) and supported by other scholars (Dugmore *et al.* 2006, p. 337; Edwards *et al.* 2005, p. 75).

It can be claimed that research in the 21st century has already transformed our understanding of this environmental change, in particular by bringing fresh ideas onto the scene. Most important is the increased appreciation of and interest in complexity and the emphasis on detailed understanding of local processes as a basis for generalisations as prompted forcefully in Dugmore's work. Even though research has increased in volume, enriched by new ideas and its multi-disciplinary aspect has been further strengthened, there are still considerable weaknesses and gaps in the overall picture.

2.4 Gaps and limitations of the existing research

Despite more than a century of academic research on the subject and a very respectable volume of work carried out so far, many questions remain to be addressed. An overview and analysis reveal several problems such as lack of data, an absence of detailed estimates of the density and distribution of the pre-*landnám* woodlands, a lack of quantification of the impact on woodlands and in the end a detailed interpretation of the deforestation process.

Firstly it may be said that there is still a need for more empirical research and the lack of basic data is still an obstacle. Despite recent advances, pollen analyses still do not have sufficient geographical coverage to make detailed assessments of the process of forest clearance on a country-wide scale. Pollen analyses are obviously of crucial importance, but so far the palynological evidence originates from a fairly limited number of locations (Erlendsson 2007, p. 2, Fig. 1.1). To further exacerbate the situation, most of it is based on samples taken from peat sediments, thus reflecting only very local changes in vegetation during the *landnám* period and giving only isolated hints of what happened to vegetation. Furthermore, it could be said that palynology has generally been applied in a „patchy“ way, giving excessive prominence to certain regions (i.e. the north and south-west of the country) and thereby creating a regional imbalance in research. While research done in these two regions has produced much high-quality data, other regions have been either less adequately covered or even completely neglected. Further research is still needed in the north-west, far north-east, in the fjords of eastern Iceland and in the highlands. This restricted regional coverage has been recognised as one of the major drawbacks in Icelandic palynological research both in the mid-1990s and in very recent times (e.g. Hallsdóttir 1995, p. 18; Erlendsson 2007, p. 1). Also, among the pollen analyses, only three, made in Reykjavík (Guðmundsson 2001), Hofstaðir (Chepstow-Lusty 2001) and Sveigakot (Tisdall and Verill 2009) are on samples taken in the context of archaeological excavations. The other analyses to date originate from continuously accumulated deposits that are spatially separate from the *landnám* farmsteads. The fact that the farmsteads themselves must have contributed significantly to the deforestation, means that sample locations far from the farmsteads are not sufficient to illustrate the dynamics of the exploitation and the decline of the wooded areas with adequate sensitivity. This fact complicates the interpretation of the rate of deforestation. In general, the application of palynology has not been the subject of sufficent questioning and there is still too much reliance on it as an ultimate research tool while other disciplines have almost been neglected. It is, however, well known that palynology has its own weaknesses and that occasionally primary attention should be given to other research disciplines – some of the prominent studies have recognised that for instance macrofossil analysis is a more reliable research tool than palynology mostly because of the higher spatial and taxonomic resolution than is possible in pollen studies (e.g. Tinner 2007, p. 2376). Last but not least, uncertainties about the estimates of the extent of relevant pollen source areas (see discussion on this issue in section 8.2.2.1.) raise scepticism about the actual potential of palynology when reconstrucing the past environments in different geographical contexts. Finally, the scarcity of other empirical evidence gained through e.g. archaeology (only 24 Viking Age dwellings have been fully excavated so far), archaeobotanical and/or palaeoentomological studies (only very few produced so far) places limits on how detailed the interpretation of deforestation on a country-wide scale can be.

There is still too much uncertainty about the extent of the pre-*landnám* woodland cover. An overview of the available estimates (see Chapter 4) shows how scholars have used similar data to arrive at quite different interpretations. The lack of consensus and/or refinement is a significant obstacle to progress. The estimates have been presented in broad terms, for instance most often without clear reference to the distinction between different species of birch or between birch and willows. The lack of appropriate comparative data from modern Icelandic forestry research is also a drawback.

At present there is no research which has attempted to describe the possible rate of deforestation expressed in actual numbers, or quantify the human-induced, intentional, impact on the woodlands. Thus, apart from the generalised estimate of the extent of woodlands that could have been cut for charcoal requirements for iron production which has not been explained in detail (see above: Þórarinsson 1974), we still have no estimates of, for instance, how much wood could have been cut in order to meet the need for firewood to heat Viking Age houses or what area of woodland could have been cleared to obtain home-fields or new pastures to meet the growing needs of *landnám* animal husbandry. What is clear, however, is that if we are to understand this environmental change in close detail, a number-based interpretation is a necessary step.

Finally, the deforestation has not been studied as a process enfolding in real-time, involving actual people making actual decisions based on actual and perceived needs. Only through an appreciation of what was really happening on the ground can we begin to assess whether it is more likely that the deforestation was a matter of deliberate strategy or the unintended consequence of other activities.

Nevertheless, the extant research does provide us with sufficient data to answer some of these questions and give a more detailed explanation of the process of deforestation. Precisely how this can be done is described in the following chapter which explains the methodological approach of this project.

3 Data used and methodology

3.1 Introduction

This research project consisted of four stages. This chapter describes the data and methods which were used to accomplish them. Each of the stages is presented in the sections below and corresponds to the previously described major goals of this study. By accomplishing them, it was possible to comprehend the course of the overall process of deforestation and finally, to reach an answer on the principal question of this study.

The four stages were as follows.

***Stage I* - Mapping the original woodlands (further described in section 3.2.1. below)**

The initial task was to determine the extent of woodland cover before the arrival of the first settlers in the late 9th century. Obviously, prior to examining the human impact on woodlands it was necessary to define their location.

***Stage II* - Estimating the degree of impact on woodlands (section 3.2.2. below)**

The next step was to estimate, in a numerically explicit way, the possible rates of exploitation and possible range of impacts on woodlands due to the requirements of the settlement population for space, building material, firewood and pastures. Quantification of the overall impact on woodlands was the precondition for the subsequent stages – which involved defining scenarios of deforestation and building a series of spatially explicit agent-based models.

***Stage III* - Defining scenarios of deforestation (section 3.2.3. below)**

The abovementioned estimates and the results of studies already made suggested that there is no simple and single explanation of the process of deforestation. Instead, they indicated that they could have involved different scenarios. To define those scenarios was the next stage of the project.

***Stage IV* - Agent-based modelling of the process of deforestation (section 3.2.4. below)**

The abovementioned scenarios, supported by the estimates of the degree of impact on woodlands, were processed through spatially explicit agent-based models of three sample study areas. Analysis of the outcomes of those models enabled the recreation of the entire process of deforestation and the achievement of the final goal of this research project.

3.2 Data used and methodology applied

3.2.1 Mapping the forests

With respect to mapping the extent of original woodlands, the baseline of the work was the map of the Icelandic Institute of Natural History (2001), which was in turn based largely on diverse written sources. Although the most detailed so far, this map is still only a conjectural representation of the pre-*landnám* vegetation. A careful analysis of it indicates evident weaknesses and inaccuracies in its picture of the forest cover.[4] This map was corrected mainly by using data from modern forestry research. The corrected map, representing a more sophisticated picture of the original woodland cover, was used as a base for a series of agent-based models.

It is important to stress that notwithstanding the considerable improvements it includes, the newly produced map is still only a hypothetical and simplified representation of the vegetation cover for the period under discussion. Given the incompleteness of the extant empirical data, the paucity of conclusive results, and the limitations of modern research tools, even the most considered picture of the extent and composition/structure of the original Icelandic forests is bound to be inaccurate.

The data used to correct/upgrade the map made by the Icelandic Institute of Natural History with the aid of the Geographic Information System (ArcGIS 9.3), were derived from research findings of various types including the results of published and unpublished studies and estimates of the limits of birch growth provided by specialists of the Iceland Forest Service (*Skógrækt rikisins*), as follows:

a) Published data:

- data obtained from palynology, geography, environmental reconstructions and forestry, indicating the altitude limit of birch growth, at present and at the time of settlement (600 m a.s.l) (Guðbergsson 1996; Guðbergsson and Einarsson 1996; Hallsdóttir 1995, Wöll 2008);
- data which indicate the absence of birch woodland cover on the island of Heimaey (Hallsdóttir 1984).

b) Unpublished (official) data:

- data on tree density, stem volume and tree biomass of the modern Icelandic birch woodlands (Þorbergur Hjalti Jónsson at the Iceland Forest Service – pers. comm.);
- modern network of rivers and lakes (provided by the Icelandic Institute of Natural History).

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[4] The map and its gaps, as well as the corrections, which suggest why this map should be seen as a fairly reliable representation of the pristine vegetation cover, are described in Chapter 4 of this dissertation.

c) Unpublished (unofficial) estimates:

- assumptions regarding the maximum incline of steeply sloping ground which allows birch growth (40° of slope);
- assumptions regarding the absence of effect of north-facing slopes on birch growth, and
- assumptions regarding the extent of treeless areas in the immediate vicinity of the coast, rivers and glaciers (10 – 100 m: Þröstur Eysteinsson at the Iceland Forest Service – pers. comm.).

The map of woodland cover was produced for the following sample study areas:

1. Vestur-Eyjafjallahrepur, in the south of Iceland.
2. Borgarfjörður, in the west of Iceland.
3. Mývatn, in the north of Iceland.

The subsequent modelling part of this project focused on the process of deforestation in those three areas.

3.2.1.1 Sample study areas. Farms' settings

Sample study areas

The lack of research data that can be used for building and validating models precludes developing a model of deforestation on a country-wide scale. Therefore, sensitive modelling of this environmental change can only be done through analyses of sample study areas where large amounts of various types of data exist. The areas of Vestur-Eyjafjallahreppur, Borgarfjörður and Mývatn were selected because sufficient data exist to create the models and, up to certain degree, to validate their outcomes. Those areas were also chosen since they represent different types of environment (coastal plain, valley and highland) which, together with the fjord environment, can be seen as the most characteristic types of Iceland‘s inhabited areas (Vésteinsson 2006, p. 92, refering to Vésteinsson 2000a, pp. 12 – 15). Natural boundaries, or in some cases property boundaries, were adopted as the limits of the areas modelled.

The first prerequisite for constructing the models was to have sufficient information about the number, size and type of settlements. It was important to know how many farms, and what kinds of farms (low-, mid- or high-ranking) had been inhabited in each particular area, and also the nature of their inter-relationships (client or independent status). However, the extant archaeological research is simply insufficient – a survey of it reveals a substantial lack of information regarding the exact number and inter-relationships between the farms during the relevant period. Most of the information crucial for setting up this part of a model was therefore derived from the written records.

Even though it may be disputed whether the later written sources can be used for investigation of the period under discussion, arguments have been developed that settlement patterns, including hierarchical relations between farms, underwent no substantial changes from the settlement period onwards, allowing later records (on e.g. property values and livestock numbers) to be used to inform on the situation during the *landnám* period. This indicates i.a. that the medieval land division and tenancy, i.e. cliency system, may have originated at least to some extent in the Settlement land-taking processes (Vésteinsson 1998, 2007). Data gained from the extant archaeological research were used to supplement the information from the written records. This was done to a greater degree for the region of Mývatn, where substantial archaeological research in the last two decades has provided data on a large number of farms not mentioned in the written sources (primarily *Jarðabók* and the Old Icelandic Land Register). On the other side of the spectrum, due to the paucity of archaeologically documented data on the position of early farms in Vestur-Eyjafjallahreppur and Borgarfjörður[5], the model was based on information extracted from those written records.

When choosing the sample study areas it was also important to have access to empirical evidence that could be used to validate the outcomes of the agent-based models. Thus, with respect to the issue of reduction of woodland cover, it was important to operate with results from for instance, palynological and, where applicable, archaeobotanical and palaeoentomological research. With regard to the issues of overgrazing and soil erosion, it was of crucial importance to be able to rely on data gained from soil-erosion studies and studies of changes in sediment-accumulation rates. This requirement narrowed down the selection to the three sample study areas.

Where applicable, the natural boundaries[6] of the regions were used as the limits of the areas modelled. At locations where there were no natural boundaries to define the area modelled, boundaries were used from the property boundary map made by the Agricultural Research Institute of Iceland (*Rannsóknastofnunar landbúnaðarins*; abbrev. RALA[7]) in 2005.

Farms, their rank, location and status/inter-relationships

Farms assumed to have been in existence during the age of Settlement and therefore considered in the accompanying series of models as the main subjects of the deforestation process, are the farms mentioned as *lögbýli* (permanent farms) in the 1695 Icelandic Land Register (Lárusson 1967)[8] but also those described as *hjáleigur* (cottages) in *Jarðabók* which were inhabited then (described as being of long standing or having no comment about their age) and which were also farmed in 1847 (Johnsen 1847), therefore representing the most permanent of the cottage- (*hjáleigur*) type of settlements. With regards to the region of Mývatn, farms are also those archaeological sites where evidence for permanent settlement in the middle ages has been found but also other uninvestigated sites of the same character

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[5] Shieling seasonal sites were not taken into the account.

[6] A combination of water bodies and boundaries of different environmental categories (types of vegetation cover).

[7] Now Agricultural University of Iceland (*Landbúnaðarháskóli íslands*).

[8] Except those farms which are clearly identified as *nýbýli* (new farms) in *Jarðabók*, for instance Svangi and Grafardalur in Borgarfjörður.

(Orri Vésteinsson – pers. comm.)[9]. Each of the farms is characterised by its own rank, location, status and where applicable, inter-relationship with other farms.

The rank of the farms was defined based upon their tax value as suggested by the Old Icelandic Land Register (Lárusson 1967). Farms with tax values of 1 – 24 hundreds[10] were defined as low-ranking, those with tax value of 25 – 36 hundreds were defined as mid-ranking and those with tax value of 37 and more were defined as high-ranking. The rank of the farms in Mývatn which have unknown tax values (i.e. archaeological sites) was defined based on a variety of information presented in research reports and studies associated with those sites.

The exact location of the farms, in terms of GIS-based coordinates, was obtained from the extant archaeological survey (Ísleif, Institute of Archaeology, Iceland; *Fornleifastofnun Íslands*) and the map of the place names made by the National Land Survey of Iceland (*Landmælingar Íslands*).[11]

Farms denoted in this study as patron farms are *lögbýli*-type farms with probable clients, almost always the largest property in a cluster of (two or more) farms. Clusters are in turn defined by proximity, property relations (*hjáleigur* or farms owned by a church on a patron farm) and, where applicable, place-name indication of original unity (e.g. Dalur and Mörk in Vestur-Eyjafjallahreppur). Patrons should not necessarily be seen as landowners, but rather as operational managers of the properties, who could be either proprietors or tenants of other landowners residing at other locations or in other regions.

Client farms are in most cases smaller *lögbýli*-farms in a cluster of farms or occasionally *hjáleigur*-type of settlements located less than 2 km away from their patron farm.

Finally, independent farms are, in most cases, *lögbýli*-farms that probably had no client but also some *hjáleigur*-type of settlements which were located more than 2 km away from their patron farm (e.g. Hólmabæir group of farms, situated on the western site of Markarfljót in Vestur-Eyjafjallahreppur[12]).

Again, client or independent status are not necessarily consistent tenural categories. Although most client farms were no doubt rented, many independent farms could be so too (most were in later times). Rather the distinction is operational: the client operates under the direction of the patron for his or his farm cluster's benefit, while the independent farm operates for its own benefit.

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[9] Unfortunately, such sites are rare or absent altogether in the other two regions.

[10] Where hundred denotes the monetary unit which was equal to the price of one cow or 6 ewes.

[11] Available at: http://atlas.lmi.is/ornefnasja/. Last consulted on 23.09.2013.

[12] Consisting of the following farms: Tjarnir, Brúnir, Steinmóðarbær, Dalssel and Borgareyjar. Those farms are technically *hjáleigur*-type of farms. However, due to their distance from the patrons they are considered as independent farms.

3.2.2 Estimates of the impact on the woodlands

The following paragraphs give an account of the data used to create the estimates of the impact on the woodlands of clearance to meet four subsistence requirements of the Settlement population:

a) felling for building material,

b) felling for firewood,

c) clearance for home-fields (spatial requirements),

d) clearance for pastures.

Possible felling for ship-building material and clearance for cultivation were not taken into account since there is neither firm evidence nor agreement among scholars that such activities played any considerable role in the overall process of deforestation. With regards to ship building, it is likely that, although boats can be built from birch, birch was not a preferred building material and that in the case of total reliance on local materials, boat and ship builders used driftwood for this purpose. With regards to agricultural cultivation, it is reasonable to assume that it may have been practised only as a subset of subsequent, i.e. post-clearance, home-field activites that are not analysed in this dissertation and the accompanying simulation models.

Quantifying the clearance for spatial requirements is based on the following references:

a) plans of the *landnám* farms, obtained through the extant archaeological research, which indicate the possible range of extent of homefield areas (e.g. Gjáskógar: Eldjárn 1961; Granastaðir: Einarsson 1995),
b) modelling and studies of environmental reconstructions (e.g. Thomson 2003),
c) various written sources (e.g. *Túnakort* 1918).

Quantifying the felling for building requirements is based on the following references:

a) unpublished plans of the full-scale replica of a Viking Age hall at Eiríksstaðir, in the Haukadalur valley in the Dalabyggð district of western Iceland, indicating the amount of birch wood required for building a Viking Age longhouse (Argos ehf.),
b) research on durability and resistance to decay of birch as building material (e.g. Highley 1995; Trechsel 2001),
c) archaeological research indicating the size range of longhouses and other architectural structures in Viking Age Iceland and the frequency of reliance on birch as the main building material (e.g. Byock 2001; Milek 2006; Lucas, G. (ed.) 2009, Sveinbjarnardóttir *et al.* 2007),
d) both published (Aradóttir *et al.* 2001) and unpublished data on tree density, stem volume and tree biomass of modern natural birch woodlands (Þorbergur Hjalti Jónsson, Iceland Forest Service – pers. comm.),
e) ethno-archaeological experimental work from other countries (Edblom 2004).

Quantifying the felling for firewood is based on the following references:

a) original ethno-archaeological experimental work from Iceland (Trbojević *et al.* 2011),
b) ethno-archaeological experimental work from other countries (e.g. Edblom 2004; Skov *et al*. 2000),
c) extant archaeological research on the fuel resource utilisation (e.g. Simpson *et al.* 2003),
d) studies of calorific value of birch and other types of wood (e.g. Poole 2009),
e) studies which take into consideration climatic conditions (e.g. Tomasson 1980),
f) studies of charcoal production (Þórarinson 1974; Gjerløff and Sørensen 1997),
g) unpublished data on tree density, stem volume and tree biomass of the modern natural birch woodlands (provided by Þorbergur Hjalti Jónsson, Iceland Forest Service – pers. comm.).

Quantifying the clearance for pastures is based on the following references:

a) studies of animal husbandry and livestock population of the *landnám* period (e.g. McGovern *et al.* 2007, McGovern *et al.* 1988; Ólafsson *et al.* 2004),
b) studies of the carrying capacity of Icelandic vegetation types (Thorsteinsson *et al.* 1971),
c) studies of the ground vegetation biomass in modern Icelandic forests (Sigurðsson *et al.* 2005),
d) d) studies of the foliated biomass of modern Icelandic woodlands (Þ. H. Jónsson, Iceland Forest Service – pers. comm.),
e) studies of farm management and vegetation degradation in pre-modern Iceland – in particular the research results regarding livestock grassland and fodder requirements (Thomson 2003).
f) *Jarðabók* – data on livestock holdings from 1709 – 1712 (Magnússon and Vídalín 1980), which, although covering later historical periods of Iceland, still can be seen as relevant for the period under discussion (see section 3.2.1.1.).

Estimating the possible rates of woodland clearance is based on the following references:

a) studies of settlement population and its size (e.g. Vésteinsson and McGovern 2012),
b) experimental studies on woodland cutting (web-link 1 Last consulted on 09.10.2013.).
c) unpublished data on average density of tree units per ha (provided by Þ. H. Jónssson, Iceland Forest Service – pers. comm.)

Methods of forest clearance

Methods of forest clearance are discussed in Chapter 5, drawing on sources including experimental work (e.g. Rösch *et al.* 2004). There, it is demonstrated how beneficial, (in terms of profitable use of natural resources), it would have been for the settlers to cut or burn the woodlands and how these activities, in addition to animal grazing/browsing, determined the fate of the woodlands in particular regions and, in the end, in the entire country.

3.2.3 Defining possible scenarios of deforestation

The work on this stage of the project was guided by theories about the settlement process, the interests behind it and the aims and concerns of individual settlers (e.g. Vésteinsson 1998; Vésteinsson *et al*. 2002; Carter 2010; Steinberg 2006). Different scenarios were defined based on the examination of possible degree and pace of clearance, labour potential and labour engagement as well as patron-client relationship and also by taking into account the previously mentioned estimates of the impact on the woodlands. In total, four scenarios were defined. Those scenarios address the major aspects of the process of deforestation.

3.2.4 Agent-based modelling of the process of deforestation

Creating a visual simulation and a detailed explanation of the human impact on woodlands was achieved through the use of agent-based modelling (ABM). Agent-based modelling can be defined as a computational modelling technique that simulates behaviour and relations between individual agents and their effects on a certain system as a whole and, where applicable – vice versa, i.e. the effect of that system on those individual agents.

In this case, the actions of, and the interactions between individual agents of deforestation, were simulated and their effects on the woodlands were estimated. This was achieved with the use of NetLogo (ver. 4.1.3), a cross-platform multi-agent programmable modelling environment (Wilensky 1999), and through a series of spatially explicit simulation models of the three sample study areas. A concise description of the process of modelling follows below.

a) Through the import of GIS-based data (ASCII files), NetLogo recreates spatially explicit pre-*landnám* environments. Once imported into NetLogo, these environments consist of patches, i.e. cells, which represent various components of the original Icelandic landscapes.
b) Subsequently, a modeller sets a number of agents in the model where each agent represents a Norse farm, i.e. the household living on it. Those agents then move across the patches, i.e. the recreated environment, and change it in a way that is defined by the aforementioned different scenarios.

The series of simulation models was named ***ICELANDEF***[13], each model being constructed upon the well-known ***ODD*** protocol (Grimm *et al.* 2006 and Grimm *et al.* 2010; see below, section 3.2.4.1). Through the series of *ICELANDEF* simulation-models it was explained at which particular locations deforestation first started, what the rate, timing and spatial distribution of the deforestation was, what part each of the major requirements played in the process of deforestation and, what is particularly important for understanding the *landnám* economy and its impact on vegetation, how the needs, interests, aims and concerns of individual settlers overlapped and affected the state of the woodlands during this period.

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[13] Where ***ICELANDEF*** stands for **ICE**landic **LAN**dnám **DEF**orestation.

Caveat

It is important to stress that the idea behind the series of models was not to identify which particular scenario can explain the deforestation process in each of the regions and over particular localities. Rather, the aim was to obtain useful results by simulating each of those scenarios. Those results, in turn, threw light on the possible courses and consequences of this environmental change. In that sense, the *ICELANDEF* simulation models can be regarded as exploratory devices. Still, where possible (unfortunately only at minor number of locations), comparison between the empirical evidence (e.g. palynological and/or archaeobotanical data) and the outcomes of the model runs was used to suggest which were the most likely scenarios of the deforestation process and/or which scenarios had to be excluded from further consideration.

It may be said that, primarily due to lack of data, but also since this is the first ABM-related project in the field of archaeology and palaeoecology in Iceland, the potential of the models is unavoidably limited. Nevertheless, their structure is such that it allows for further improvements that will hopefully come into view along with the new research results produced in the coming years and/or decades.

3.2.4.1 The ODD protocol

Until very recently, one of the main weaknesses of agent-based models was the absence of a standard protocol that could be used to describe their main aspects – a protocol written in a way that would enable various users to understand them easily and, if necessary, replicate them. For a long time, many models have been designed without a uniform and clear description of equations, rules, schedules, agents' behaviours and other constituent elements of ABMs. This deficiency has been one of the main obstacles to a wide acceptance of ABMs as a standardised tool for research.

An international network of scholars has managed to remedy this situation and to establish the ODD[14] protocol, which is today recognised throughout academia as a prerequisite to the construction of almost every ABM. The ODD protocol was formally created upon the initiative of Grimm and Railsback (Grimm and Railsback 2005) and a series of discussions during the international workshop of agent-based modellers held at the University of Bergen, Norway, in 2004. It consists of seven elements that can be grouped into three blocks: Overview, Design concepts and Details.

The „Overview“ block provides a description of the overall purpose, state variables and scales, process overview and scheduling. The block „Design concepts“ describes the general design concepts and is intended to link model design to general concepts identified in the field of complex adaptive systems (Grimm and Railsback 2005; Railsback 2001). Finally, the third part of ODD, „Details“, contains details about the initialisation, input and sub-models.

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[14] Where ***ODD*** stands for **O**verview, **D**esign concept and **D**etails

3.2.4.2 Validation

One of the most important aspects of agent-based modelling is validation of models. Validation is the process that compares outcomes of a certain model with data from a real-world environment – it actually informs us of the cogency of a model. Even though there is an increasing number of agent-based models that are not validated but instead serve as exploratory devices (e.g. Griffith *et al.* 2010), validation remains an integral part of most of the existing models, as a key to evaluating whether a certain model is a realistic representation of a certain process or a series of events.

However, the issue of validation is not a simple one. While some scholars suggest that validation of numerical models is simply not possible „because natural systems are never closed and because model results are always nonunique“ (Oreskes *et al.* 1994, p. 641), others suggest that it is possible „in the limited technical sense of simulation modelling“ (Rykiel 1996, p. 241). Castle and Crooks (Castle and Crooks 2006, p. 37) stressed that the validity of a certain model is not a matter of „either/or“ – a model cannot be treated as valid or invalid. Instead, there may be a question of whether a particular model is valid only up to a certain degree – depending mainly on a comparison of its outcomes with empirical data from a real-world system. Furthermore, the structure of validation varies from one discipline to another, depending equally on the type and quality of the validating data and on the context and focus of research. Last but not least, in many modelling studies, the process of validation is simply not clearly explained and sometimes different degrees of validation are considered as relevant. In general, throughout the ABM community, there are various interpretations of what validation actually is and agreement is still lacking about what it actually entails. Indeed, an overview of the existing studies suggests that it is a continuously developing branch of the agent-based modelling approach.

One of the most recent studies which pays particular attention to the issue of validation (Ngo and See 2012, refering to Zeigler 1976) points out what is probably the most efficient validation approach when it comes to building agent-based models. Ngo and See’s approach discusses the importance of 3 types of validation:

a) structural validation,
b) predictive validation, and
c) replicative validation.

Whereas predictive validation, „where the model is able to predict behaviour that it has not seen before and which might come from theories or which might occur in the future“ (Ngo and See 2012, p.182), obviously cannot be related to the project under discussion, structural and replicative validation must be taken into consideration here.

With respect to structural validation, „where the model not only reproduces the observed system behaviour, but truly reflects the way in which the real system operates to produce this behaviour“ (Ngo and See *ibid*), one needs to be aware of the following: the series of *ICELANDEF* models, their variables and parameters, were built and structured predominantly upon a variety of real-world, existing empirical data, and to a lesser extent upon written sources that indicate the structure and nature of the *landnám* society and use of natural resources during this period (e.g. *Jarðabók*). Taking into account that the previously mentioned scenarios, which are processed in the series of models, are also based on extant data which are widely accepted as giving a reasonable representation of the *landnám* economy, it may be regarded that the series of models is therefore structurally valid.

With respect to replicative validation, „where model outputs are compared to data acquired from the real world“ (Ngo and See *ibid*), in the case of the present series of models, the degree, or quality, of validation is determined, where possible, by the comparison of the empirical research results with the outcomes of the models.

3.2.5 Remarks on the use of Agent-Based Modelling

3.2.5.1 Reasons for using agent-based modelling

Why should we use agent-based modelling (which requires a knowledge of programming and is therefore highly demanding), and not some of the less complicated modelling options/tools? There are several reasons for this, including the capability of ABM to successfully examine the anthropogenic side of certain types of environmental change, the possibility of handling stochasticity and the capacity to deal successfully with the time-factor and complexity.

The allure of ABM lies in its power to investigate, in both qualitative and quantitative ways, the anthropogenic side of a particular environmental change. By replicating traits and activities of human communities and/or individual settlement units, we can clarify, for instance, why and under what circumstances exploitation of certain natural resource started and what course this exploitation followed. Agent-based modelling allows us to monitor adaptive, variable behavior of individual units and to study which system-level phenomena (for instance natural environment phenomena) truly emerge from those changes/variations and/or which are simply compulsory and/or expected (Grimm *et al.* 2006, p. 118). With regards to the *ICELANDEF* series of models, adaptation is depicted in a very simple way – agents adapt their movement and clearance activities (their duration and rate) in relation to the extent of land cover types, social relationships, and most importantly, environmental changes (see sections 7.5.2 and 7.5.3 for further descriptions of the emergence and adaptation). Some of the system level phenomena that emerge from the changes in behaviour of agents and natural environment are for instance phased forest clearance but also specific distribution of grazing-tolerant vegetation, overgrazing effect and, to a lesser degree, regrowth of birch cover.

Stochasticity is another aspect of ABM which can be noted as an advantage when comparing it to other modelling options. ABM allows us, randomly or with a carefully designed limited randomness, to choose the number of agents, their location and ways of acting within a certain model. This is an extremely important factor, for instance when a modeller deals with a broad range of values regarding the activities of an agent. There, through various kinds of options of random choices (e.g. Uniform, *Gaussian*, *Bernoulli*, *gamma* and *Poisson*) and in comparison with existing empirical research, the modeller can „sharpen the focus“ and calibrate a range of variations of the agent’s activities. Consequently, it becomes possible to reduce the number of possible outcomes or, in some cases, even to reach the sole and final one. The series of models built for this research project involved the application of stochastic processes when dealing with, among other things, timing of the establishment of settlements and rates and distribution of woodland clearance (see further description in Chapter 7).

Another advantage of ABM is its capability to successfully deal with time and/or permanent changes over certain period of time. By means of simulation and by using spatially explicit data, we can reconstruct the flow of the entire process of environmental change with respect to time-steps and with the option of introducing variations in the individual factors so as to explore outcomes based on different input values (Gilbert 2008, Gimblett 2002). The *ICELANDEF* models also incorporate this advantage. They investigate, among other things, possible changes in the vegetation cover over the course of 130 years during which occurences like for instance spread of grazing-tolerant vegetation (variation in its timing, degree and spatial distribution) are direct consequences of different input values (for further description see Chapter 7).

3.2.5.2 Necessity of combining deterministic and stochastic approaches

Some scholars stress that modelling of ancient history should be avoided if possible (e.g. Chattoe-Brown, lecture presentation[15]). This is because history and prehistory suffer from the lack of empirical and factual data, which are today recognised by modellers as the prerequisite for building appropriate and credible agent-based models. Furthermore, the occasional failure to use the ODD protocol, and the fact that some modellers apply validation of models while others do not, confuse regular ABM consumers and repel the public interested in simulations of historic/prehistoric processes. These and other drawbacks normally raise questions about whether it is really possible to make agent-based models that successfully recreate human-environment interactions in the past, and in general undermine confidence in the idea of ABM as a fully operational research tool. Nevertheless, in spite of occasional scepticism, simulating processes in the deep past is possible, and as has been demonstrated in several major projects (e.g. Kohler *et al.* 2005; Barton *et al.* 2011), it can be reasonably successful. However, one needs to be aware that successful simulations of the past, as is the case with the series of models presented in this dissertation, are forced to rely on a combination of stochastic and deterministic approaches due to the limited empirical datasets available.

With respect to this research project, on the one hand, the idea was to rely on empirical data when building and calibrating the models and as much as possible for validating their outcomes. For instance, the information used for setting initial locations of the agents (in this

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[15] Lecture presentation given at the ESSA summer school in social simulation: web-link 2, last consulted on 17.04.2013.

case, early farms and their households) and their hierarchical position (dependence on or independence of other farms) was based on available archaeological and historical studies, while the chronological frame of the models was partially based on tephrochronological studies. Validating outcomes of the models, where possible, was based on palynological, archaeobotanical and/or where applicable, palaeoentomological research and studies on sediment-accumulation rates.

On the other hand, stochasticity also plays an important role here – limited randomness was used to bridge the knowledge gaps of this environmental change. Thus, the timing of settlement was based on random choice from a time-scale previously defined by historical and archaeological sources as well as tephrochronology. Agents also chose the rate of clearance and size of home-fields in a random way, from a range of values defined through the experimental work and studies of the *landnám* environmental changes. Finally, random choice of areas which were supposed to be cleared for pastures, was based on the available distribution of woodlands.

4 The estimate of forest cover

4.1 Existing estimates of the extent of the pre-*landnám* woodlands

4.1.1 The initial estimates – 1970s and 1980s

The 1970s and 1980s were highly productive periods of research in the field of vegetation cover in Iceland, when a number of estimates of the extent of the pre-*landnám* woodland cover appeared. These estimates, which were unfortunately not the subjects of appropriate mapping and visualisation, indicated that between (approximately) 18 and 40 % of Iceland had been covered with woodland prior to Settlement. Drawing on different kinds of research results, and frequently relying on Þórarinsson's (1944) and Einarsson's (1962) work, these estimates were, among other things, based on data about modern birch growth limits and conditions, and also on insights from written sources.

An overview and analysis of the work from this period reveal that the major reason for such huge differences in estimates were scholars' disagreements about the altitude limit of the birch growth and its spatial variability. While some argued for the 550 m elevation as the upper limit of birch growth, thus supporting the idea of extensive woodland cover, others suggested that most of the forests would have grown in the lowlands thus arriving at considerably lower estimates.

4.1.1.1 The estimate of Hákon Bjarnason: 40,000 km²

So far, the highest estimate of the extent of the woodland cover is also the earliest – the one proposed by Hákon Bjarnason, suggesting that approximately 40,000 km² was covered with woodland (Bjarnason 1971, p. 15). Mainly using data from biology, geography and history, Bjarnason concluded that approximately half of the land had been vegetated, with 80 % of that consisting of birch woodlands of some description (Bjarnason 1974, p. 41).

The fact that he obviously included trees of less than 2 m in height, or even shrubland, in this estimate, is one of the reasons for such a high figure. In the period following Bjarnason's estimate, the issue of a clear definition of what constituted forest or woodland was one of the points of dispute among scholars, resulting in variations in their estimates of woodland cover. Thus, while some authors included birch shrub as woodland, without offering a clear definition of the types of vegetation involved and arguing for generally higher estimates, others defined woodlands as consisting only of trees of two metres in height or more, thereby arriving at lower estimates.

Another of Bjarnason's arguments supporting such a high estimate was the high altitude limit he ascribed to birch: up to 300 m in some parts of the country and even 550 m a.s.l. in others. This results in a high estimated extent of woodland area, corresponding to the greater surface area of land extending up to these altitude limits. Disagreement about the altitude limits of birch at the time of the Settlement was another point of interpretation resulting in differences in estimates.

4.1.1.2 The estimate of Snorri Sigurðsson: 28,000 km²

The second highest estimate came from Snorri Sigurðsson, who concluded that about 28,000 km² had been covered with woodlands (Sigurðsson 1990, p. 110). Like Bjarnason, Sigurðsson based his estimate on the work of Einarsson and Þórarinsson, which he supplemented by field observations of the modern altitude limits of birch around the country, and assumptions about the presence of birch at these levels at the time of the Settlement.

Through surveying, Sigurðsson confirmed a maximum birch altitude limit of 550 m a.s.l., with its actual presence in Skagafjarðarsýsla at this altitude (Sigurðsson 1990, p. 111). Furthermore, Sigurðsson also identified the areas where the large continuous spreads of birch woodlands are found. Thus, in S-Þingeyjarsýsla, where birch extends from 10 m to 400 m a.s.l. (Sigurðsson 1990, p. 112), he indirectly identified areas that could have had the largest woodlands at the time of the Settlement.

Sigurðsson took account of modern information about the temperature requirement for birch growth, applying these data to the potentially wooded areas at the time of the *landnám*. He stressed the idea that the average temperature in the period of 1931 – 1960 was similar to that at the beginning of the settlement period (Sigurðsson 1990, p. 110). By following this argument, and also the above-mentioned maximum potential extent of woodlands, based on the altitude limits for birch, and excluding wetlands, coastal sands and areas where average three-month summer temperature was less than 7.5 °C, Sigurðsson came to the conclusion that about 28,000 km² of Iceland had been covered with woodlands.

4.1.1.3 The estimate of Ingvi Þorsteinsson: 25,000 km²

Ingvi Þorsteinsson suggested that about 25,000 km² of Iceland had been covered with forests at *landnám* (Þorsteinsson 1972, p. 12). However, he stated this without a closer explanation of the data he used and without referring to particular regions.

Important elements in his estimate were studies of vegetation remains of heathland, place-names and written sources. By stressing the difficulty of determining past changes in climate and the significance of their effect on the vegetation cover, he also drew attention to the uncertainty regarding the presence of woodlands in the highlands of Iceland at the time of the Settlement.

However, while explaining that there is no reason to doubt Ari *fróði's* explanation that forests once stretched from the shore to the mountain sides (Þorsteinsson 1972, p. 12), as described in the *Íslendingabók* (Benediktsson (ed.) 1968, p. 5), which would imply a large extent of woodland cover, perhaps corresponding to the estimate of Hákon Bjarnason, he still settled for a somewhat „low“ estimate of c. 25,000 km² of pre-*landnám* woodlands, without going into detail about how he arrived at that figure.

Þorsteinsson assumed (in a very rough interpretation) that at the time of Settlement, the extent of the forest and other wooded land, combined, could have been 1/5 – 2/5 of the country, where it would not be too much to estimate that at least 1/4 of the country was covered with real forests (Þorsteinsson 1972, p. 12); in this, he was one of the first and few scholars who have drawn a clear distinction between the birch forests and the low birch vegetation cover.

Finally, like other writers, Þorsteinsson based his estimate mainly on Einarsson's palynological work when referring to the existence of birch in the areas he regarded as having been covered in woodland and also when explaining the rapid deforestation and transformation of woodland into grassland or heathland.

4.1.1.4 The estimate of Sturla Friðriksson: 18,000 km²

In 1987, Sturla Friðriksson suggested that about 18,000 km² of Iceland was covered with forests at the time just before the Settlement (Friðriksson 1987, p. 174). Referring to Þórarinsson's and Einarsson's work, like other scholars, and relying on written sources as well as examining modern conditions and limits of birch growth, Friðriksson assumed that about 40,000 km² of Iceland had been covered with continuous vegetation, while half of that, or even less, could have consisted of woodland, finally arriving at an estimate of 18,000 km² (Friðriksson 1987, p. 174).

Friðriksson supported his assumption about the extent of woodland cover by the idea that woodlands had thrived best in the lowlands and that about 2/3 of the woodlands would have grown under 200 m a.s.l. and only occasionally above this level, while low birch shrub extended up to 400 m a.s.l. or even higher (Friðriksson 1987, p. 175). Thus, in the north, according to Friðriksson, large forests were situated along the river Skjálfandafljót, in the valley Bárðardalur, in the innermost parts of the valleys by the Húnaflói bay, in the Skagafjörður region, Eyjafjörður and Fnjóskadalur; in the east, they grew in Fljótsdalshérað and the valleys of the East Fjords; in the south they were located between the sands and the glaciers (Friðriksson 1987, p. 176). Regarding the west of Iceland, Friðriksson (Friðriksson 1987, p. 176) proposed birch shrub vegetation for Mýrar, Snæfellsnes, Dalir, Barðaströnd districts and the western parts of West Fjords.

Explaining the processes of deforestation, Friðriksson stressed the possibility of deliberate burning of woodlands in order to clear new arable land and pasture (Friðriksson 1987, p. 173, 174); this corresponds with the interpretations of Sigurður Þórarinsson from the mid-20th century (Þórarinsson 1944, p. 192).

4.1.1.5 A note on the initial series of estimates

The estimates described above suggest that the general trend was towards higher resolution of research. Whereas Bjarnason's and Þorsteinsson's work offers only rough country-scale estimates, the research of Sigurðsson and Friðriksson also tackled the problematics of individual regions.

A political angle is another factor that caused differences in scholars' ideas. For instance, the reason why Bjarnason proposed such a high estimate could be his personal involvement in reforestation as director of the Iceland Forest Service. It is possible that he suggested the figure of 40,000 km^2 for the purpose of propaganda – to stress that large areas of Iceland could sustain forests. Sigurðsson likewise worked in forestry, while both Þorsteinsson and Friðriksson worked for the Agricultural Research Institute of Iceland and may have been under greater influence of the farming lobby. Nevertheless, all of these interpretations were made in earnest. Sigurðsson's and Friðriksson's work can be regarded as more realistic interpretations of the pre-*landnám* woodland cover because of their greater detail and reliance on empirical data. Unfortunately, even their work does not provide sufficient amount of high-quality data that can be used for appropriate mapping and visualisation of the country-wide scale pristine woodland cover.

4.1.2 Recent estimates – 21st century

The 21st century brought the first detailed visual estimates of the extent of the aboriginal birch forests of Iceland: the estimates of the Icelandic Institute of Natural History (2001), Ólafsdóttir and others (2001) and the Iceland Forest Service (2004). In addition to those, it is important to mention the work of Christoph Wöll (Wöll 2008).

4.1.2.1 The map of the Icelandic Institute of Natural History: 24 % forest cover

The most detailed map was compiled in 2001 by Eyþór Einarsson and Einar Gíslason at the Icelandic Institute of Natural History. This map suggests that almost ¼ of Iceland (24 %, i.e. 24,761 km²) was covered with woodland at the time of the Settlement (see Figure : dark green areas).

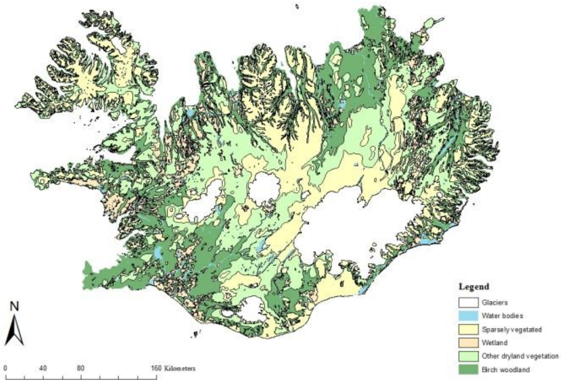

Figure 1. Map of estimated vegetation cover in Iceland at the time of the Settlement. (Icelandic Institute of Natural History 2001)

The map is based on a vegetation map of Iceland from 1998, diverse written sources and various expert opinions and consists of 6 different environmental categories: birch woodland, dryland vegetation, wetland, sparsely vegetated areas, rivers and lakes and finally glaciers. It is important to state that glaciers, valley terrain and outwash plains are shown in their present distribution, although it is known that they covered considerably smaller areas during this period. Also, the shoreline has changed, in particular the Southern coast of Iceland (Icelandic Institute of Natural History: unpublished material 2001). In addition to that, it is important to stress that there are different kinds of mistakes on this map – for instance the map suggests that there was woodland on the island of Heimaey, which is contradicted by the palaeobotanical research (Hallsdóttir 1984, p. 68). Other points also raise questions regarding the correctness of the map. Thus, mistakes are found on it regarding the existence of woodlands on steep slopes, i.e. slopes of more than 40° of inclination (today, we may assume that 40° slopes can be seen as the limit of birch growth – see the explanation in the pages below). Nevertheless, this map represents a major step forward from the numerical estimates discussed above and is undoubtedly of value for further studies.

4.1.2.2 The estimate of Ólafsdóttir and collaborators: 8 % of forest cover

The lowest estimate so far was proposed by Rannveig Ólafsdóttir and collaborators in 2001 (Ólafsdóttir *et al.* 2001)[16]. Through simulation of spatial relationships between temperature change and long-term potential vegetation cover dynamics, Ólafsdóttir and colleagues, estimating that the minimum temperature limit for birch growth[17] was 7.5 °C, suggested that the forest cover at the time of Settlement could not have exceeded 8,000 km^2.

The essence of the simulation was based on the idea that the major controlling factor for vegetation growth at high latitudes is the annual amount of heat (e.g. Woodward 1992), the heat being calculated from the length and the temperature of the growing season. In order to stress the importance of temperature, the authors also suggested that, in theory, a temperature limit for birch growth of 7.0 °C would result in 14,000 km^2 forest cover while if the limit was 6.0 °C, the forest cover would increase to 26,000 km^2.

The outcomes of the simulation were validated, i.e. they were compared with existing palynological data which strengthened this estimate's relevance. However, as the authors stress (Ólafsdóttir *et al.* 2001, p. 206), differences in latitude, microclimate and elevation limit of birch due to oceanic influence were not taken into consideration. Precisely those factors could be used to draw the pertinency of this estimate into question. As an addition to this, it remains unclear exactly which birch growth altitude/temperature limits the authors support/suggest. For instance, the 7.5 °C limit is based on research on birch in northern Scandinavia using June-August temperatures. In a more oceanic climate, it may be appropriate to use a limit based on May-September temperatures. Nevertheless, this estimate, being based on scientific data, is important in the long history of research of the aboriginal vegetation cover of Iceland.

4.1.2.3 The estimate of the Iceland Forest Service: Up to 40 % of birch woodlands

The map of the Iceland Forest Service (Eysteinsson 2004), which is less detailed than the one of the Icelandic Institute of Natural History, is based on the limits of birch growth potential in relation to mean summer temperature[18]. The map illustrates the extent of forests at present, but also the areas with average July temperature above 9 °C (c. 23 % of Iceland‘s teritorry), and finally, the areas with mean three-month summer temperature above 7.6 °C which is thought

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[16] Not presented here due to low quality of the available illustration.

[17] The authors used the term „minumum developmental threshold“ which is frequently used to describe the minimum temperature below which no growth occurs.

[18] Not presented here due to low quality of the available illustration.

to have been the pre-settlement limit of birch woodland, suggesting that the woodland extent could have been up to c. 40 % of Iceland‘s territory.

Even though arguing for a similar temperature as the study of Ólafsdóttir and colleagues, this estimate proposes considerably greater extent of woodland cover. It also suggests much greater woodland extent than was proposed by the Icelandic Institute of Natural History. Hence, with respect to micro-locations, this map suggests that, for instance, in the region of Vestur-Eyjafjallahreppur, not just that the entire area between the northern side of the glacier and the northern part of Markarfljót river was covered with birch, but it allows for the possibility that woodlands could have stretched further towards the highland areas and onto even higher ground.

4.1.2.4 The estimate of Christoph Wöll: 24 % of forest, 40 % of total woodland

The most recent estimate of the potential extent of birch cover in Iceland, which can be used to describe the state of forests at the time of the Settlement, was proposed by Christoph Wöll in 2008. In his study, Wöll developes a detailed picture of potential elevational extent of birch of various stature (species limit, 1 m and 2 m tall) and suggests that about 41,500 km^2 or 40 % of the country can be seen as a potential area for birch woodland (species line threshold) and 25,000 km^2 or 24 % for birch forest. Wöll proposes this estimate based upon a series of temperature tree-line relationships for mountain birch, information about the treeline positions in different parts of the country and also by taking oceanity into consideration. Wöll also suggests that in the absence of livestock grazing (which would limit regeneration), natural disturbance areas such as glacial outwash plains and lava fields but also wetlands would be colonised by birch (Wöll 2008, p. 103) which is an argument that further supports the idea of extensive forest cover prior to the arrival of the first settlers.

4.1.2.5 A note on the most recent estimates

The most recent, 21st century estimates, undoubtedly improved the state of the art first and foremost by providing the first detailed visualisations of the woodland cover. Also, the resolution of the overall work has obviously increased and the scientific data have started to be appreciated more than ever before. However, considerable differences between the estimates suggest that there is still a lack of consensus about the methodological approach and the types of data that can be seen as crucial in an attempt to reconstruct the structure and extent of the original woodland cover.

4.2 The map of forest cover used in this project. Sample study areas

In spite of the significance and quality of the previously mentioned maps, their careful analysis suggests that they can be further improved, i.e. corrected, by using the data from the modern forestry research about the modern birch growth limits with particular regards to altitude, slopes, coastal areas and vicinity of the glaciers. Precisely by doing so – i.e. correcting one of the maps discussed above – it was possible to acquire a more relevant depiction of the forest cover for the period under discussion. The map that was the subject of further corrections was the map made by the Icelandic Institute of Natural History. That map was corrected mainly by using data from modern forestry research. The corrected map, representing a more sophisticated picture of the aboriginal forest cover, involving the average number of tree units per hectare, was used when making the series of agent-based models. The first step was to create a map for the entire territory of Iceland and subsequently, to cut out the areas of Vestur-Eyjafjallahreppur, Borgarfjörður and Mývatn and convert them into ASCII files[19], making them ready for integration into NetLogo.

This map is not just a correction of the existing (Icelandic Institute of Natural History) map, but also a simplification of the current view of pre-*landnám* forests – primarily due to lack of data. For instance, there were in reality no sharp boundaries between different vegetation cover types, as are represented on the map, nor is their exact location known (e.g. it is impossible to recreate an accurate and sharp distinction/border between woodland and grassland areas for this period, even though the map suggests that there was one). Also, many of the species with a minor or even major presence at that time were neglected (e.g. rowan and tree-size willows are not represented on the map, even though scholars agree upon their presence during this period). Also, regional differences in birch growth were not taken into account (e.g. density, stature, altitude limits, etc.). It can therefore be said that it is far from being a detailed picture of the pre-*landnám* woodlands with respect to micro-location and woodland characteristics. However, the pressing need for a map of this kind, for the purpose of modelling, leaves no alternative but to work with what we have.

4.2.1 Data from modern Icelandic forestry research

4.2.1.1 One type of forest cover – first simplification

Modern and pre-*landnám* birch woodlands are not entirely comparable, since deforestation and utilisation (e.g. coppicing) have affected woodland development in the course of eleven centuries, for example in terms of distribution potential, stature, form and density. Nevertheless, knowledge of modern Icelandic forests, gained through empirical research represents a constituent part of this study. The need for a comparison with modern forestry data is obvious and such a comparison is unavoidable, since total reliance on palaeobotanical work is impossible, primarily due to its scarcity.

One of the discrepancies frequently encountered in various studies lies in the type of forest cover. Thus, while some authors included birch shrub as woodland, without giving a clear definition of the types of vegetation involved and/or arguing for generally higher estimates of the total woodland cover for the period under discussion (e.g. Bjarnasson 1971), others defined woodlands as consisting only of trees of two metres in height or more, thereby arriving at lower area estimates (e.g. Ólafsdóttir *et al.* 2001). Indeed, the separation of *Betula pubescens* („real“ trees, tall or short) and *Betula nana* (shrubs) is a problematic issue, recently discussed by Erlendsson (Erlendsson 2007, p. 66). Nevertheless, in cases like this some simplification is

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[19] File format necessary for integration into raster-based ABM (in this case, NetLogo platform).

necessary and the assumed woodland cover chosen for the modelling consists here of a single species, *Betula pubescens*. That this is a realistic picture of woodland cover for the period under discussion has been confirmed by some of the leading experts in the field who have identified tree-birch as the only type of trees that could have formed forests in Iceland during the Holocene (e.g. Hallsdóttir, 1987, p. 7). Shrub (e.g. *Betula nana*) undoubtedly existed, but the indications are that its spread was much more limited, especially in relative terms, than it is today.

That *Betula nana* was not predominant over large areas before and during the *landnám* period, as it is today, is an idea that other scholars agree upon too (Eysteinsson – pers. comm.), based on modern forestry research. Since *Betula pubescens* woodland was in all likelihood the tallest vegetation type in Iceland and was distributed throughout the lowlands, it is reasonable to assume that it was the dominant vegetation type everywhere where it could grow. *Betula nana*, on the other hand, is lower-growing than the two shrubby willow species *Salix phylicifolia* and *Salix lanata* and does not grow at higher elevations than they do. *Betula nana* also tolerates grazing much better than both *Betula pubescens* and willows. Today, *Betula nana* is found all over Iceland up to about 700 m, although it is less common in the south, and is often dominant on rather wet land as well as dry land because it does not have to compete with taller shrubs and trees for light (all of these species are light-demanding and quickly die off if something taller shades them out). *Betula nana* is therefore a „winner“ resulting from post-*landnám* land use, whereas *Betula pubescens* and willows are „losers“. It can therefore be assumed that before the *landnám*, both wet areas and higher elevation areas were dominated by willows and that *Betula nana* was a relatively uncommon (compared to the modern state of vegetation) and marginal species.

Simplification of the forest cover undoubtedly affected the relevance of the map postulated with this project as well as the series of agent-based models, but only to a lesser degree. As discussed in the lines above, it was not just a necessary but also a logical step.

4.2.1.2 Density

Another simplification has been made regarding the density of forest cover. In the real world density is affected in complex ways by different factors (e.g. disturbance, successional stage, soil type, altitude, slope, etc.). Data from modern forestry provide some supporting information, but unfortunately, there are no complete and exact published data on tree density, stem volume and tree biomass of the modern natural birch woodlands for the entire territory of Iceland. Existing studies, such as the one by Ása L. Aradóttir (Aradóttir *et al.* 2001), offer useful data which are unfortunately limited to the northern part of the country. A five-year survey was recently completed for the entire country by the Iceland Forest Service; the results have not been published yet (Arnór Snorrason – pers. comm.) but hopefully they will be available soon. However, through the kindness of Þorbergur Hjalti Jónsson (also of Icelandic Forestry Research), unpublished data from his work on tree density and standing volume were available to this project and were used here to model the density of birch forests. As this is unpublished research, those data will not be presented here, although they were used in the subsequent modelling.

4.2.1.3 Altitude limit of birch growth – 600 m

Several scholars have proposed estimates of the extent of woodlands, stressing in particular the maximum altitude limit of a birch growth during the period under discussion. Thus, Hákon Bjarnason suggested the existence of birch on land up to 300 m a.s.l. in some parts of the country and 500 m a.s.l. in others (Bjarnasson 1971). Sigurðsson (1990) pointed on a maximum altitude of 550 m a.s.l., based on its actual presence in Skagafjörður at this altitude (Sigurðsson 1990, p. 111). Sturla Friðriksson, who proposed one of the „lower“ woodland cover estimates (18,000 km²), suggested a maximum altitude limit of only 200 m a.s.l., thus restricting the possibility of birch growth to the lowland areas only (Friðriksson 1987, p. 175).

Birch woodlands could have extended to even higher altitudes, up to 600 m or more in certain places, resulting in far greater figures for the entire woodland cover. Remnants of forests can be found today up to an altitude of about 600 m a.s.l. (Guðbergsson and Einarsson 1996). But what is even more important for the recreation of the map of woodlands is that the highest occurrence of pollen of *Betula* has been found at the site Tjarnarver south of the glacier Hofsjökull, at an altitude of about 600 m a.s.l., which indicates the existence of pre-settlement birch forests in the vicinity (Hallsdóttir 1995). An upper altitude limit of 600 m was therefore assumed.

4.2.1.4 40° degree slopes

Steeply sloping ground is not a factor that prevents birch growth, and we can assume that this was also the case in the past. However, most steep slopes in Iceland are „scree“ slopes (*talus*), where rocks falling from the cliffs above cause so much disturbance that continuous vegetation cannot become established. Following yet unofficial inclinometer-based assumptions (Eysteinsson – pers. comm.), it appears that 40° slopes should be set as the limit of birch growth.

4.2.1.5 North-facing slopes

Even though many studies throughout the world suggest that treelines are primarily determined by heat deficiency (Holtmeier 2003) and that growth is often retarded on north-facing slopes, this is not the case in Iceland. Although no general survey has been carried out comparing woodland growth with respect to slope aspect, there are many examples of birchwoods on north-facing slopes that are growing at least as well as those on nearby and similar slopes facing other directions (Eysteinsson – pers. comm.).

4.2.1.6 Coast, rivers and glaciers

The immediate vicinity of coastal areas, glaciers and rivers was also taken into consideration when producing the map.

Coast and rivers

Nowadays, birch is found in many places on exposed, low peninsulas such as Reykjanes, Snæfellsnes and Tjörnes, but it is always low growing. It is found growing quite close to the South coast in Herdísarvík and survives elsewhere when planted, such as in Vík and Höfn, but it never grows tall in these areas either. In sheltered fjords it grows down to the beach. The strip along the coast where birch could not grow at all was probably quite narrow, perhaps 100 m wide. The treeless strip along lakes and rivers was smaller, from 0 m along steady rivers and small lakes to 10 m along rivers with variable flow and large lakes. Therefore, when producing the map, 100 m wide strip along the coast and up to 10 m wide strips along the rivers and lakes were marked as treeless.

Glaciers

The absence of birch in the immediate vicinity of the glaciers is more difficult to model, mostly because they were smaller at the time of *landnám* than they are now. Birch can occupy land very close to glaciers, as is the case in Skaftafell at present. It will seed itself into areas where glaciers recede within a few years or decades. The birch-free area around glaciers was therefore not necessarily huge – up to a maximum of 100 m – this figure was considered when producing the map. The glacial outwash plains are more problematic. They are very extensive and can make a big difference in the estimates of birch cover. They are natural disturbance areas, due to frequent subglacial volcanic eruptions accompanied by floods, and would have been occupied by birch to varying extents depending on the length of time since the last disturbance. Even though some scholars suggest that these areas can easily be colonised by birch (e.g. Marteinsdóttir *et al.* 2007), they are today generally not wooded. Also, because they are disturbance-driven land forms, their size and shape differ with time, making it impossible to know exactly how they were during a specific period. For the purpose of this map and the accompanying series of models, the outwash plains are shown in their present distribution.

4.2.2 Map production

Map production involved the application of certain procedures to the existing (Icelandic Institute of Natural History) map.

Firstly, woodland areas that were coincident with the areas above 600 m a.s.l. and gradients over 40° were erased. Furthermore, the woodland cover was also excluded from a 100 m wide coastal belt which was previously created through inner buffering. The next step was to apply a regular buffer procedure for glaciers (100 m around their perimeters) and lakes and rivers present in the map (10 m along the banks, as suggested above), and those areas were subsequently also designated as being free of woodland cover.

Also, by following the existing palaeobotanical evidence from the island of Heimaey (Hallsdóttir 1984), woodland cover there was replaced by „other dryland vegetation“.

As the final step, areas corresponding to the modern extent of birch woodlands as established by recent research by Iceland Forest Service (2009: unpublished; Traustason – pers. comm.) were added to this map. According to this research, 279 km² are now covered by birch forest with trees of 2 m or higher. Here, the idea was to follow the general assumption that the present extent of woodland probably formed part of the woodland cover during the period under discussion.

Remark on the extent of other vegetation categories

It is obvious that other environmental categories/vegetation cover types should not be disregarded and that some fine-tuning of estimates for the extent of such cover must be made. Exploitation of woodland would have been determined to a considerable degree by the presence of and reliance on other environmental resources. For example, the need to clear woodland to obtain pastures would have depended largely on the availability of wetlands and/or grasslands in the vicinity. Still, due to a lack of empirical evidence and appropriate survey data for other environmental categories shown on the map, such as grasslands, wetlands, „other dryland vegetation“ and „sparsely vegetated areas“ (as shown on the map made by the Icelandic Institute of Natural History) on a country-wide scale, even further simplification is inevitable.

Areas deducted from the woodland category as shown on the original map were assigned to other adjacent environmental categories reflecting their micro-location. Thus, for some areas that were designated as woodlands on ground with a gradient of more than 40°, designations of „other dryland vegetation“ and/or „sparsely vegetated“ were assigned, depending on the micro-location. Around the coastal areas and glaciers where woodland cover was cut off (by buffer or inner buffer), the category „sparsely vegetated“ was assigned. Around the rivers, where woodlands were cut off by buffer, no other category was assigned – instead, only the zone/width of river streams was increased by the buffer zone. In locations where woodlands abutted onto wetlands, after the cut-off, those areas were assigned to wetlands. Though this is another simplification, for the same reason(s) – lack of sufficient (empirical) evidence, appropriate country-wide scale survey data and research in general – it is unavoidable at present. The same grid code as that on the map made by the Icelandic Institute of Natural History (colours of land-covers) was used for the new map.

Caveat: modern water bodies and further reduction of the extent of forests

At this stage, the map produced based on the abovementioned premises indicates the presence of woodland (birch - *Betula pubescens*) coverage of 23,844 km² (23 % of modern Iceland’s territory) which is not significantly different from that shown on the existing woodland map (made by the Icelandic Institute of Natural History) of 24,761 km² (24 %). However, the possible extent of the pre-*landnám* forests on a country-wide scale was most likely lower than that (see section 4.2.2.1. below) – at several micro-locations there was a necessity to further exclude woodland cover around some of the water bodies which were unfortunately incomplete or simply absent in the original map provided by the Icelandic Institute of Natural History. Those water bodies were complete and present in the separate map of the modern water bodies provided by the same institution. A further and final reduction of woodland cover was made based upon that map and only for each of the sample study areas.

Caveat: absence of empirical testing

One of the limitations that needs to be recognised is that the newly produced map has not been the subject of empirical testing, i.e. direct comparison with the palynological datasets at relevant locations. Unfortunately, such comparison would be in this case, simply irrelevant since the newly produced map represents only the estimated extent of forest cover involving the average number of tree units per hectare; it does not therefore represent different degrees of presence of birch cover at specific locations and areas throughout the country which is suggested by the existing pollen diagrams.

4.2.2.1 The woodland cover of Vestur-Eyjafjallahreppur, Mývatn and Borgarfjörður

The putative pre-*landnám* woodland cover for the regions of Vestur-Eyjafjallahreppur, Mývatn and Borgarfjörður was created by clipping the newly produced map with the previously created and superimposed rectangular shapefiles (covering the areas of c. 857, 2096 and 2022 km², respectively). Also, as said above, due to the incompleteness of the water bodies in the shapefile format of the original map provided by the Icelandic Institute of Natural History (e.g. incompleteness of some of the major rivers, such as Markarfljót in the south, or absence of lakes, such as Helluvaðstjörn in the north), the modern water bodies[20], involving present locations of rivers and lakes were added to the map of each of the sample study areas – this additional correction further reduced the extent of woodland cover. At places where modern rivers and lakes do not correspond to rivers and lakes as suggested by the original map, options of extend/trim edit task in ArcGIS were applied. Trimming and extension of river streams obviously affected the accuracy of the map, but it was an unavoidable step in the map production. The extent of the forest cover that was actually the subject of the subsequent process of modelling was at some locations defined by the natural boundaries and at others by the property boundaries extracted from the RALA property boundary map (RALA 2005).

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[20] The map of the modern water bodies provided by the Icelandic Institute of Natural History.

Vestur-Eyjafjallahreppur

The total woodland cover for Vestur-Eyjafjallahreppur was c. 306 km². However, in the subsequent modelling only the dark-green areas (to the east and south of the Markarfljót river) were considered – therefore, the extent of woodland cover in focus is c. 160 km^2 (Figure 2).

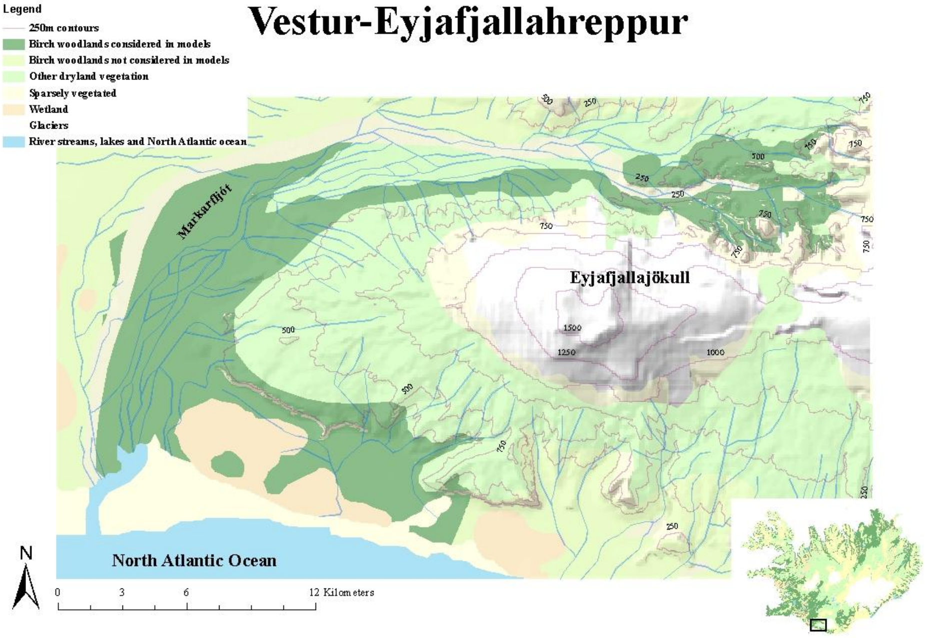

Figure 2. The estimated extent of woodland cover in Vestur-Eyjafjallahreppur. Only dark-green areas were considered in the process of modelling. They also represent the limits of the study area.

Mývatn

The total woodland cover for Mývatn was c. 1257 km². However, only the dark-green areas were considered in the process of modelling – therefore, the extent of the woodland cover in focus is c. 732 km^2 (Figure 3).

Figure 3. The estimated extent of woodland cover in Mývatn. Note that only dark-green areas were considered in the process of modelling. They also represent the limits of the study area.

Borgarfjörður

The extent of birch cover in the region of Borgarfjörður was c. 1006 km². As for the region of Mývatn, in the subsequent modelling only the dark-green areas were considered – therefore, the extent of the woodland cover in focus is c. 608 km² (Figure 4).

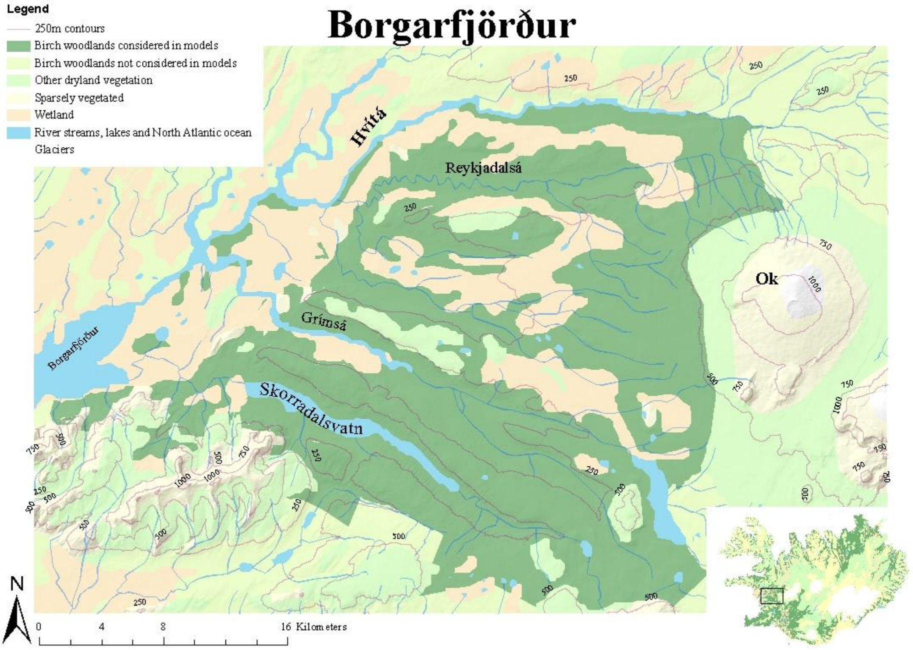

Figure 4. **The estimated extent of woodland cover in the region of Borgarfjörður. Only dark-green areas were considered in the process of modelling. They also represent the limits of the study area.**

5 Estimating the degree of impact on woodlands

5.1 Household requirements

In the following section the impact on woodlands due to subsistence requirements of early Icelandic farmsteads is estimated: the needs for living space and hayfields, building material and fuel are each considered in turn.

5.1.1 Spatial requirements

When it comes to examining the total extent of woodlands that were cleared in the settlement period, the first step is to examine the amount of woodland clearance necessary to establish a farm.

5.1.1.1 Positioning of settlements. Necessity or non-necessity of woodland clearance

The generally accepted hypothesis suggests that woodlands were not among the optimal choices for settlement sites by the *landnám* population and that the initial phase of settlement was most likely concentrated in coastal and estuarine environments, this being due mainly to easy access to fodder resources as a vital component of an animal husbandry economy (Vésteinsson 1998; 2000b). Those kind of environments also provided sufficient extent of treeless space appropriate for housing and primary hay production. Even though Ari fróði in his *Íslendingabók* mentions woodlands which once stretched „between the mountains and the shore" (Benediktsson (ed.) 1968, p. 5), it is unlikely that all the lowlands were entirely covered in woodlands with no space suitable for the establishment of farms. At many locations, woodland clearance related to the establishment of the initial farms was most probably not necessary. It is also clear that in some cases, woodland clearance was not applied at all due to indications for the absence of woodlands in close vicinity of farms (e.g. Grelutóttir or Aðalstræti/Suðurgata in downtown Reykjavík, which were all situated close to the shore) or otherwise entire regions (e.g. in the Westman Islands; at Ketilsstaðir in Mýrdalur)[21]. Still, we need to consider the assumption that at some locations settlers had to carry out some clearance in order to gain sufficient space; palynological indicators of any possible woodland clearance of that kind in this very short phase would most probably be very limited. However, if any woodland clearance was required, it seems reasonable that the degree of such activity is reflected in the size of home-fields of these settlements.

If, following Vésteinsson (Vésteinsson 2000b, p. 167), we assume that the best land had been claimed by AD 880, it would then be logical to allow for the second wave of settlers being forced to turn their attention to the less attractive wooded areas. The clearance of

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[21] As is suggested by palynological research of Hallsdóttir (Hallsdóttir 1984) and Erlendsson (Erlendsson 2007), respectively.

woodlands in order to gain sufficient woodless space to establish farms therefore might have become a matter of necessity, where the size of a home-field could be seen as a minimum of woodland clearance needed to establish a farm. Still, the distribution of the second wave of settlers and clearance for their home-fields should not be seen in such strict and simplistic terms. We may also assume that at least some of those late-coming farms were established on remote and high-altitude non-wooded locations, (until then) uninhabited parts of coastal areas or simply in woodless areas with low quality of land which had only poor access to valuable natural resources vital for their subsistence. In those cases, we can assume that the clearance was not applied at all.

5.1.1.2 Tún. Relation to farm value and status. Size

Home-fields (in Icelandic „*tún*“), were usually semi-circular or subrectangular areas centred around the farms; they were sometimes bounded by walls, but in many cases surrounding natural features defined their boundaries. From the 9th century to the present day, they constituted a relatively small part of total grazing land. They were cultivated and primarily used for hay/fodder production, crucial for the overwintering of livestock.

A survey of all home-field areas was carried out in the early 20th century (*Túnakort* 1918), but the analyses and estimates of earlier boundaries are a difficult and complex research issue, i.a. due to the fact that home-field boundaries went out of maintenance before early modern times, most probably in the 13th century (Vésteinsson 2008, p. 66). The nature and size of home-fields has been examined in a limited number of recent studies (e.g. Ólafsson 2012).

Sometimes, the plans of the *landnám* farms indicate the size of the home-fields, but in general, their size has to be estimated from the farm value, related to the number of cows and sheep the farm can support, based on zooarchaeological data and/or other estimates and related to the amount of hay/fodder that can be produced from the home-field. This way of estimating the home-field area can not apply equally well to different types of environments (e.g. coastal areas or shielings) where the use of other resources (e.g. sea-weed or extensive grasslands) would have increased the total capacity of the farms. In these, home-fields could have been even smaller, not corresponding to the value criteria for other farms; this factor, of the fodder potential of locally accessible environmental resources, thus is very important, if not crucial, when defining the size of home-fields.

However, some general ideas about the size of home-fields can be developed by comparison of analyses with the research of later periods. Thus, the vegetation reconstruction for the Hofstaðir estate in 1712, supported by the data of the farm’s value gained from *Jarðabók,* indicates that the home-field area was 4.5 ha, and even if this figure is reduced to 3.5 ha, the field could have produced enough fodder for the period October to May for the reported number of cattle (Thomson 2003, p. 216, 221; Thomson and Simpson 2007, p. 162).

The number of livestock however cannot be taken by itself as an indication of the size of the home-field of a certain farm. Thus, according to the available plans of the low-ranking farm of Gjáskógar (Eldjárn 1961, p. 9), the home-field area, surrounded by walls and natural features, could have had a size of up to c. 3 ha, while the estimated number of cattle (12) and sheep and goats (72) was based on the farm's architectural potential (for cattle) and estimated proportion (for sheep and goats), in this case 1:6 (McGovern *et al.* 1988, p. 240, Table 1).

When comparing these values with those of Hofstaðir according to the 1712 reconstruction – 4.5 (3.5) ha of home-field, 4 cows, 55 milk-ewes, 25 lambs, 34 wethers (Thomson and Simpson 2007, p. 158, Table V), it becomes quite clear that the ratio of size of home-fields does not correspond to the ratio of the estimated numbers of livestock between these two farms. If we accept a basic relationship between the size of the home-field and the number of livestock, we would expect at least a higher number of cattle at Hofstaðir (which may have been the case during the Viking Age). This discrepancy could be explained in various ways, including the different potential of environmental resources of these sites and particularly different degree of application (or non-application) of grazing management. On the one hand, we could assume that in the wooded areas of Þjórsárdalur, the founders of the farm Gjáskógar (300 m a.s.l.) may have needed to clear c. 3 ha of woodlands in one spot, in order to acquire a home-field, which would, followed by a period of overgrazing, inevitably lead to soil erosion. This was characteristic for other sites at high altitudes (Dugmore *et al.* 2000; Sveinbjarnardóttir 1992). To put it simply, it is quite possible that at the site of Gjáskógar, the numbers of livestock were not sustainable in terms of the hay resources. The reason why Gjáskógar did not have a larger home-field was that at first it was a small smithy, dependent on some of the prosperous valley farms, probably obtaining fuel through selective cutting of trees and thus not requiring any significant scale of woodland clearance; it was only later that it was converted into a small farm (McGovern et al. 1988, p. 243). Gjáskógar therefore probably did not have „its own" woodlands, which in the end was the crucial reason for the relatively limited extent of woodland clearance. On the other hand, the significant potential of different kinds of other resources available for hay/fodder production (e.g. grassy heaths), as proposed by the vegetation reconstruction for Hofstaðir of 1712 (Thomson 2003, p. 217, Table 6-1), could have meant that a home-field area of 4.5 ha (or even only 3.5 ha) was sufficient. The Mývatn area is far from ideal as a cattle environment, but it has good sheep grazing all year round (Vésteinsson 1998, p. 10); grazing may have been kept within the limits of the potential by appropriate management. In the end, Gjáskógar, with the above-mentioned size of home-field and estimated livestock numbers, was probably abandoned due to overgrazing, and possibly soil erosion (Eldjárn 1961, p. 46), while the values of Hofstaðir appear as sustainable and sufficient to avoid overgrazing.

The size of home-fields was also not necessarily related to the status of a particular farm. Thus, some of the farms with the same status could have had home-fields significantly different in size. For instance, a serious discrepancy appears between the status and home-field size of, e.g., low-middle ranking farms such as Granastaðir and Höfðagerði. According to the available plans (Einarsson 1995, p. 74), it can be roughly estimated that the home-field of the low-middle ranking farm at Granastaðir, bounded by an embankment and natural features, was c. 4 ha, while that of the home-field of Höfðagerði, which was probably also low-middle ranking (as described by Oscar Aldred – pers. comm.), and was also partially bounded by natural features, at least according to the available plan could have been almost c. 7 ha, which appears to be larger even than the home-fields at some of the high-ranking sites (e.g. Hrísheimar, mentioned below in the text).

The status of farms, therefore, was not necessarily reflected in the size of their home-fields. The extent of initial woodland clearance in order to acquire a home-field was most likely not determined by the the social standing of the settlers, but by their simple needs and/or capacity to exploit the surrounding environmental resources which were of different potential. The farm at Granastaðir thus might not have needed a huge home-field due to the fact that the area of Eyjafjörður otherwise offered productive meadows (Vésteinsson 1998, p. 6), while we can imagine that this might not have been the case with Höfðagerði due to limits on the cattle-raising potential in the area; again, the environmental factor therefore might have played a decisive role.

Different degrees of access to other resources could also mean that differences in size between the home-fields of high-ranking farms on the one hand and/or low-ranking farms on the other sometimes appear less significant than one would expect. It is possible that sometimes high-status farms did not require very large home-field areas because they had access to other available resources suitable for an animal husbandry economy. Opposite to this, it is possible that some of the low and middle-ranking farms were, due to relatively restricted access to other resources, forced to have larger home-field areas than one would expect. For instance, the farm at Hrísheimar, which could be seen as being of high status (McGovern and Woollett 2003, p. 15), had a home-field of c. 5 ha (Vésteinsson 2002, p. 62), which is not that different from those of Gjáskógar (c. 3 ha).

In general, it is hard to express the size of all the home-fields in specific figures. In many cases, the boundaries have not been identified, while in many others we can only produce rough estimates. However, although there is an obvious lack of data for the *landnám* period, existing research does indicate some figures. In Mývatnssveit, home-fields ranged between 1 and 9 ha, which so far appears as the largest size, and was identified at the site of Þorleifsstaðir, where occupation began between 871± 2 and ~ 940 (Vésteinsson 2008, pp. 20, 66 – 67). In the later periods, home-fields rarely appear smaller than 1 ha (e.g. c. 0.5 ha for the pre-1104 Hringanes in Skagafjörður; Aldred 2008, p. 308, Table 2, calculated from Sveinbjarnardóttir 1992), this could also have been the case with many shieling sites (e.g. Öxl, Svartibakki; Sveinbjarnardóttir 1992) or „intermediate“ sites - which were „too small to be farms and too large to be plain animal stalls“ (Vésteinsson 2008, pp. 64, 67). This range (1 – 9 ha) corresponds to that of Mývatnssveit in 1919 which goes from 1 to 7.7 ha (Vésteinsson, *ibid*, p. 67, referring to *Skútustaðahreppur. Túnakort. Jarðadeild. Þjóðskjalasafn Íslands*), indicating the possiblity that not much changed in the Mývatn area, but also to the range found in Skilmannahreppur (west Iceland) for the period 1707-1918 (Aldred 2008, p. 308, Table 1) which goes from c. 2.3 to 7.8 ha. Estimated areas of hayfields (Thomson 2003, author uses this term and „hay-meadow“ interchangeably when refering to „*tún*“) of farms in Vestur-Eyjafjallahreppur (southern Iceland) for the early 18th century range from 1 to 21.6 ha. While the lower end of the size range corresponds to that found in other areas and periods, the upper limit, being so high, is unlikely to reflect general conditions in the *landnám*. According to Thomson, only 1 out of 50 farms there had a home-field larger than 20 ha (2 % in total), at only 7 farms home-fields ranged between 9 – 20 ha (14 %) while at most of the farms (42 farms, i.e. 84 %) home-fields were not larger than 9 ha. It is of course possible that some of the farms in this area had home-fields larger than 9 ha during the *landnám*, but it is also reasonable to assume that most of the largest home-fields were not larger than 9 ha and were presumably of the size which would more or less correspond to those of the Mývatn area (as mentioned above, the largest there was c. 9 ha).

5.1.1.3 Social aspects

It is possible that woodland clearance in connection with the establishment of farms was not carried out entirely for economic reasons. Particularly in the case of high-status farms, we can easily imagine that one of the intentions of the early settlers was to establish their farms as the dominant sites in their districts. Clearance of the woodland in their immediate surroundings would increase the visibility of their farms and apart from improving communications, it would also make them noticeable from a distance, contributing to an overall intention of being recognised as local/regional centres. In other words, having a large home-field and/or large woodless areas around the farm would create an impression of a powerful and notable site to neighbours and to any newcomer or passer-by.

5.1.1.4 Significance or insignificance of impact

The examples described above do not cover the issue of home-fields in its totality; they mostly come from the northern part of the country, but they do suggest some general ideas about the size of home-fields and thus the degree of initial woodland clearance necessary to establish them. As has been mentioned, the size of home-fields was often not an exact reflection of the estimated numbers of livestock and sometimes not of the status of the farms either. The location of farms and the potential of the surrounding environmental resources might be the most influential factors when it comes to defining the size of home-fields and the first clearance of woodlands, although the social aspect of visibility did have its role; only a careful reading of the landscape of each particular farmstead can indicate the likely degree of clearance.

By using the aforementioned size-range for home-fields (1 – 9 ha or, expressed in square kilometres, 0.01 – 0.09 km²) and assuming the possibility of the existence of about 4,000 farms at the time[22] (see also: Vésteinsson and McGovern 2012), the total amount of woodland clearance needed to establish farms can be roughly estimated; even using the maximum variant of the size range (allowing for a scenario in which all the farms would be obliged to carry out woodland clearance), this estimate would produce from c. 40 to no more than 360 km², where the actual clearance would have been spread around the country, thus having no significant environmental impact in one location. In general, even if we allow for examples with no woodland clearance in originally woodless areas, and settlements with perhaps the minimum degree of woodland clearance during the establishment of the farms, on the one hand, and exceptions such as the relocation of the farms, and settlements with a

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[22] 4,560 was the number of tax-paying farmers given by Ari fróði in the 12th century (Benediktsson (ed.) 1968, p. 23).

relatively significant degree of woodland clearance during the foundation process on the other, we can assume that in total, the impact on the woodlands in order to gain sufficient building space to set up farms was insignificant in relation to estimates of the pre-*landnám* woodlands. As a ratio, this represents between 0.016 – 1.51 %, if we take into account the previously mentioned rough estimate of the forest cover of 23,844 km^2.

5.1.2 House-building requirements

In the process of foundation of the farms, the actual construction of farm buildings would have been another activity with a bearing on overall woodland clearance. Though the quantities involved were minor compared to turf, wood was an indispensable element in Viking Age architecture and birch forests were also cleared in order to obtain building material.

5.1.2.1 Birch as building material

The birch species that could have been used for building purposes was *Betula pubescens*, the only tree known to have formed forests in Iceland in the Holocene (Hallsdóttir 1987, p.7; Karlsdóttir *et al.* 2009, p. 1). It was an element in the *landnám* woodland areas, as has been confirmed through palynological research (e.g. Svínavatn: Hallsdóttir 1987; Viðey: Hallsdóttir 1993). However, there is an evident discrepancy between modern scholars' opinions when it comes to arguing which subspecies of *Betula pubescens* is typical for Iceland. Some authors focus on *Betula pubescens* Ehrh.[23] (Levanič and Eggertsson 2008), which grows up to a height of 25 m (Wöll 2008, p. 7). Some also mention *Betula pubescens tortuosa*, sometimes known as „mountain birch" (Karlsdóttir, *ibid*) due to its relatively low stature and shrub-like growth form. Still, others opt for *Betula pubescens* var. pumila, which grows up to 12 m, using the same name, „mountain birch", to describe it and suggesting that about 28,000 km² of Iceland is within its climatic species limit (Jónsson 2004, p. 753).

It is easy to imagine that *Betula pubescens* could have been used for building construction. Indeed, the mentioned height values for all of the argued subspecies support this possibility to some extent, but birch is not an appropriate material for all building purposes. Icelandic birch trunks are often contorted making them unsuitable for hewing into boards and planks. However, its relative unsuitability for architectural needs appears particularly in its resistance to decay – it appears only as relatively resistant (Highley 1995, p. 416, Table 2) while some scholars describe it as only slightly resistant or even non-resistant (Trechsel 2001, p. 69, Table 2). According to outdoor experiments, „birch posts lose 5 cm of their diameter from fungal decay in less than 5 years and are therefore classified as perishable" (Milek 2006, p. 295, referring to Agate 1986; Desch 1973; Findlay 1962). Undoubtedly, their durability could be much greater if they are positioned inside buildings. Milek suggests (Milek 2006, pp. 295, 296) that „a 10 cm diameter birch post set in a post hole would lose half of its diameter and would have to be replaced in 5-10 years". Furthermore, Milek suggests that if set on a post pad it could last twice as long. By following

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[23] The abbreviation *Ehrh.* is used to indicate Jacob Friedrich Ehrhart as the author of this botanical name.

that estimate, it seems reasonable to propose that posts with diameters of 15 – 20 cm, set in post holes, could last c. 20 years and even more if they are placed on post pads.

5.1.2.2 Driftwood as preferred building material

Driftwood, on the other hand, saturated with salt, is a hard and enduring construction material. Apart from imported wood, it was the main building timber in Iceland (Byock 2001). Unfortunately, there are no experimental data available on driftwood decay resistance in Iceland. However, Milek stresses that „since resistance to fungal infection is determined by the level of toxins in the wood, it may be assumed that the sea salts that have impregnated driftwood will impart on it a natural durability equivalent to that of European oak, yew, and chestnut – durable woods that take 15 – 25 years to lose 5 cm of their diameter in outdoor British conditions“ (Milek 2006, p.296). Milek further suggests (Milek, *ibid*) that positioned inside they can last 20 – 30 years. Considering that it was „only available to higher-status farms“ (Sveinbjarnardóttir *et al.* 2007, p. 204), it is reasonable to assume that driftwood had its own value, most likely higher than birch timber, and that it was the preferred construction material. Building on this assumption, we could expect that high-status farms made no significant impact on woodlands in order to obtain sufficient building material and that their construction needs could have been fulfilled with driftwood, as a „better“ option, or at least that this would have been the owners‘ policy. *Betula pubescens* was more likely an option for the middle or low-status sites, especially for those in remote areas, far from the coast, and/or less able to gain driftwood through exchange, due to economic dependence and lower position in the social hierarchy. It therefore seems likely that the lower and middle-ranking farms would have been responsible for the major part of woodland clearance to meet the constructional needs.

5.1.2.3 The Eiríksstaðir replica. Actual needs

What then were the architectural requirements for wood? The best answer to this question can be obtained through studying full-scale replicas. Unfortunately, the paucity of experimental work of this kind precludes a definitive understanding of the needs for wood for construction purposes. Still, some clues can be found. While the full-scale replica at Stöng does not reflect the exact building technique, as it contains modern-age materials, the reconstructed house at Eiríksstaðir could indicate the amount of wood necessary to build a house in the *landnám* period. By calculating the amount of wood used for building the full-scale replica at Eiríksstaðir and comparing it to the size of other Viking Age houses (Figure 5), we can estimate the total extent of construction-related woodland clearance.

The reconstructed Viking Age house at Eiríksstaðir, with the approximate dimensions of 4 x 12 m (48 m²), was built in 2000. It was built in correspondence with the original layout of the house, as revealed by archaeological excavations in 1997 – 1999. Apart from the usual construction timber-frame, the house contains interior panelling and a ceiling with rafters and a brushwood lining, while a triple layer of turf was used to form the roof. Unfortunately the exact building specifications are not available today and the building data are not included in any of the existing published work. However, the designers of this replica, the architects

Stefán Örn Stefánsson and Grétar Markússon kindly provided the plans of the project (shown below, Figure 6) and it was possible to calculate that the total amount of wood used for building this house was 15.27 m³.

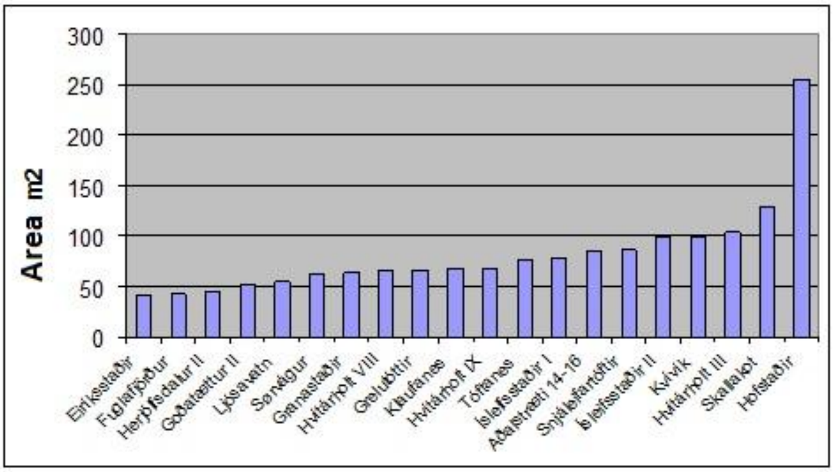

Figure 5. Sizes of Viking Age houses from Iceland and other countries (Roberts *et al.* 2002).

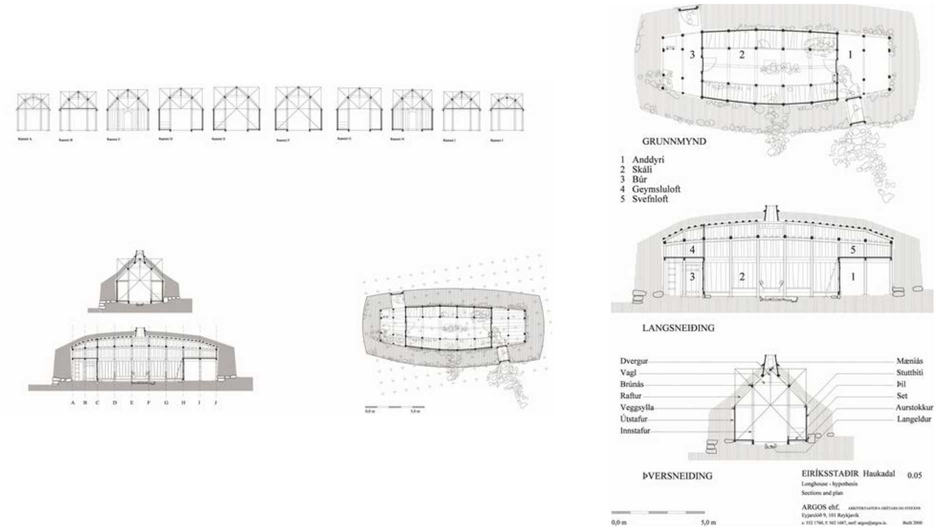

Figure 6. Plans of the full-scale replica house in Eiríksstaðir (Argos ehf.).

Although the replica at Eiríksstaðir was built entirely out of driftwood, the total amount of wood used there can be used in comparisons to indicate how much wood was required for building houses at farms which had to rely on birch forests for their construction materials. However, basing estimates simply on the proportion between house-sizes can be misleading, since some houses of different construction types might have required more wood (e.g. for different roof requirements), while others could have used less wood for building per m² (e.g. if they did not have interior panelling). In addition to this, comparisons based on similar experimental work done abroad do not offer useful data, due to significant differences in building customs. For instance, the data gained through building of a replica of an Iron Age house at Gene Fornby (Edblom 2004) in Sweden cannot be used for the present study since the house there had inner wooden walls and a heavy wooden roof, and thus required far more wood. For this house measuring 7 x 40 m, as much as 1,000 m³ of wood and 5 tons of birch bark was used (Edblom 2004, p. 205). Nevertheless, the Eiríksstaðir requirements can be used to propose at least rough estimates for other sites.

Thus, we can expect that for most Viking Age houses of similar construction, and floor areas of up to 100 m², excluding annexes (see Table 1, below), the amount of wood required would have been less than 30 m³, while for the extremely large houses such as that at Hofstaðir (276 m²), this amount could have been about 90 m³.

At most of the Viking Age sites, additional buildings and annexes were a significant part of farmsteads. However, the absence of experimental work related to the building of pit-houses, smithies, storage rooms, latrines, byres, barns and stables prevents us from estimating the exact amount of wood required for their building. Nevertheless, some estimates can be given. The total size of all the additional buildings and annexes at a Viking Age farm was generally smaller than the size of the main house; e.g. at Hofstaðir the pit-houses A4, A5 and G had a total size of 70.1 m²; the annexes A2, C2, D1 had a total size of 74.7 m²; E2, which was most probably a latrine, had a size of 22 m², bringing the total „additional“ space to 166.8 m²; as a ratio, this represents 60 % of the size of the *skáli*. Furthermore, based on the plans of the Eiríksstaðir *skáli*, it is possible to calculate, that in order to build a feature of that size (48 m^2) but with lower interior comfort criteria, i.e. without interior panelling and furniture (which was most probably the case at auxiliary features), it would take 11.9 m^3 of wood. Following the size-ratio pattern, it turns out that the amount of wood required for building all the annexes, pit-houses and latrine at Hofstaðir could have been about 41.35 m^3, which is 46 % of the amount of material required for building the *skáli*. It is therefore obvious that sometimes the amount of wood used for building auxiliary features was not insignificant compared to the amount used for building the main house.

Outhouses like byres also need to be taken into consideration when making estimates of this kind. Although they required less building material per m^2 than longhouses (same as the abovementioned features), the total amount of wood used for their construction was far from insignificant. According to Berson (Berson 2002), byres at medieval Icelandic farms ranged between 29.6 m^2 (at the farm of Gröf) and 59.64 m^2 (at the farm of Bergþórshvoll) and it is reasonable to assume that those two figures could indicate the size range of byres in early Iceland. Following the size-ratio pattern as above, it is possible to calculate that the amount of wood required for their building could have been between 7.33 m^3 (Gröf) and 14.78 m^3 (Bergþórshvoll).

5.1.2.4 Degree of impact

The question that must be asked is what extent of birch forest had to be cleared in order to obtain the amount of wood required for the building of a farmhouse of the size of the

Eiríksstaðir replica and for other Viking Age houses. The unpublished data from the previously mentioned work on tree density and standing volume (see above: pers. comm: Þorbergur Hjalti Jónson, Iceland Forest Service) can help to determine the amount of wood that had to be cleared in order to obtain sufficient timber. According to this work, 1 ha of forest with trees of 4 – 12 m in height, contains 57.38 m³ of stemwood with a top diameter of 5 cm. Based on these data, it can be calculated that if the maximum size potential of every tree cut were used, and if every tree was of a shape appropriate for processing for construction purposes, at least 0.26 ha (0.0026 km²) of woodland would be needed to fulfil the requirements of the house at Eiríksstaðir. This would thus be the minimum required for a small Viking Age house of the type found on a low-status farm. With an assumed durability of birch timber of up to 20 years (see above), we could estimate that with completely rational and effective exploitation and use of the timber it would have been necessary to fell at least 1.69 ha (0.0169 km², see Table 1, below) of forest by the end of the 10th century to meet the constructional needs of a small farm such as Eiriksstaðir (the main farmhouse). Following the size-ratio pattern, we could estimate that in order to fulfill the construction requirements of the skáli at Hofstaðir, which is the biggest so far identified in Iceland, 1.53 ha (0.0153 km²) of forests would have needed to be cut, while by the end of the 10th century the requirement would have been at least 9.94 ha (0.0994 km², Table 1).

Table 1. The estimates of the extent of forests required to be cut in order to meet the house-building requirements at Eiríksstaðir and Hofstaðir

Site	**Building (20 years) requirement**	**Until the end of the 10th century**
Eiríksstaðir	0.0026 km²	0.0169 km²
Hofstaðir	0.0153 km²	0.0994 km²

As with the home-field size issue, if we assume the existence of about 4,000 farms at the time, it is possible to give a rough estimate of woodland clearance needed to fulfil the building requirements of main farmhouses of between 67.6 to no more than 397.8 km² by the end of the 10th century. Taking into account additional buildings and annexes, the estimate would go up to between 98.69 and not more than 580.78 km². Finally, including outhouses (byres), this estimate would go from 129.89 [24] to no more than 645.58 km² [25]. This represents 0.5 – 2.7 % of the total woodland cover.

This range should be understood in a very flexible way, since not all the timber cut for building purposes would have been of appropriate shape or height, nor would the process of building the houses always have been highly efficient. A factor that could reduce the estimate significantly is the possibility that high-ranking farms might have made little impact or even none at all, due to their preferred use of driftwood or imported timber. However, the most significant factor that could reduce the estimated total rate of deforestation is that the

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[24] Given that all farms had a byre similar to the one at Gröf.

[25] Given that all farms had a byre similar to the one at Bergþórshvoll.

cutting was selective (since only some trees were of a suitable size and form), and not applied thoroughly over a continuous area, thus involving no permanent loss of entire woodland areas. If selective cutting was practiced, that would mean that the deforestation rate was slower due to continued forest growth. Data on volume production of birch woodlands in Iceland indicate that 1 ha of forest with trees of 4 – 12 m in height gains, on average, 2.29 m³ of volume per year (Jónsson – pers. comm.). This would imply that for every selective cutting made once in 20 years a forest would re-gain 45.8 m³ of volume per/ha which would result in a significantly lower total rate of deforestation (i.e. in the case of Hofstaðir, assuming the maximum total cutting of 90 m³ from for instance two one-hectare plots of woodland every 20 years, the forest at those plots would, in theory, re-gain the entire volume of wood required to replace the house). On the other hand, it is as likely that trees unsuitable for building material were cut for fuel, charcoal or fodder and that browsing by livestock prevented regeneration, thereby removing the forest growth potential that would otherwise have been maintained.

Whatever the truth of this, it is obvious that the impact on woodlands caused by architectural requirements during the late 9th and the entire 10th century was not extremely significant.

5.1.3 Household fuel requirements

The fuel requirements of early Icelandic households were also among the causes of the clearance of birch woodlands. In addition to the contemporary use of other fuel categories such as peat, turf, dung, willow, driftwood, seaweed and even fishbones (Simpson *et al.* 2003), the birch woodlands were seen as a fuel source, particularly in cases where they were easy to access and exploit, but exactly how important birch was as a fuel source is a difficult question.

5.1.3.1 Utilisation policy

Despite the general modern view of woodlands as the principal source of fuel in the period under discussion, the fuel strategy of the *landnám* period did not recognise the birch woodlands as the primary target when it came to obtaining sufficient fuel resources. The first settlers who arrived in Iceland would have become aware of the fuel resource potential of Icelandic landscapes, and their fragility, in a very short time, and would generally have relied on the practice of utilisation mix rather than using a particular resource exclusively. Studies of fuel ash residues from Hofstaðir and Sveigakot (Simpson *et al.* 2003) indicate that birch was far from being the most popular fuel, despite its presence in the vicinity of both sites. That the birch woodlands were only of secondary significance concerning the fuel requirements of early Icelandic farmsteads is seen also at other sites in Iceland (e.g. Reykholt: Sveinbjarnardóttir *et al.* 2007). At the high-status site of Hofstaðir, despite some use of birch, peat was the main fuel category for high-temperature combustion (probably for industrial purposes) and mineral-based turf was used in low temperature combustion activities while wood appears as prevalent in the later phases of midden formation (Simpson *et al.* 2003, pp. 1413, 1415). Nor was birch the focus of consumption as a fuel type at the more marginal, secondary sites. Thus, the aforementioned study at Sveigakot, where wood-ash residues were generally less frequent than at Hofstaðir, indicated a utilisation mix where wood with mineral-based turf was used both for low and high-temperature combustion. In general, the impression is that it was peat rather than other fuels (including birch), that was seen as the preferred fuel resource. This might reflect the high status and power of a particular site, in this case Hofstaðir, while the absence of peat and the reliance on more marginal fuel resources are indicators of the lower status of Sveigakot. The use of wood as a secondary rather than primary source of fuel ultimately meant that the impact on woodlands due to fuel needs was not drastic in terms of the total woodland cover. The increase in the use of wood in the later periods, possibly followed by woodland management (Simpson *et al. ibid*, p. 1415) also indicates that even in the periods when the use of birch was perhaps inevitable, its exploitation for fuel purposes was controlled rather than causing deliberate clearance and drastic loss of woodlands.

5.1.3.2 Possibility or impossibility of comparison with available experimental results

Unfortunately, the absence of appropriate experimental research in Iceland prevents us from determining the rate of woodland clearance resulting from the fuel requirements of early Icelandic households. However, work done in Sweden and Denmark, although not fully comparable, does allow us to propose very generalised and rough estimates.

The experimental work related to the reconstruction of the already mentioned Iron Age (6th century) house at Gene Fornby in northern Ångermanland, in Sweden (see previous chapter), implied that wood was used for maintaining the interior temperature. Despite the absence of specific data on cooking activities, clear information is given for the fuel requirements for interior temperature maintenance, in a case where wood was the only fuel used. The experiment, which aimed at maintenance of the interior temperature at an average of 12.4º C (which seems surprisingly low) with an average outdoor temperature of - 10.5º C, indicated that about 0.6 m³, or 180 kg of birch (specific weight of c. 300 kg/m³) would need to be burnt every day (Edblom 2004, p. 240). However, although the experiment was carried out in January, and thus based on a low ambient temperature, the proposed total consumption on an annual basis with an average interior temperature of between 15 – 18º C was considerably lower, 40 – 50 m³, or c. 15 tons of wood. However, the fact that this replica is not comparable to Icelandic architectural features prevents any direct application of the research data to examples from Iceland, though some comparison could be allowed. On the one hand, because the house in Gene Fornby (approximate dimensions: 7 x 40 m) had wooden walls as an extra inner insulation, it can be assumed that in general it would require less fuel for interior heating than a comparable Icelandic example would require (Hofstaðir, being of similar size, 276 m², as the most comparable one). Furthermore, higher summer temperatures in Sweden than in Iceland argue for less fuel being required (e.g. Tomasson 1980, p. 59, Table 3-2).[26] On the other hand, average temperatures in January and February are significantly lower in Central Sweden than in Iceland, which would imply that the

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[26] Average temperature values are given for the period of 1931 – 1960, which is also suggested as being similar in climatic conditions to that at the beginning of the Settlement period of Iceland (Sigurðsson 1990, p. 110).

Icelandic examples would require less wood to burn as fuel in the most critical months of the year. All in all, it is difficult to discuss the comparability of fuel requirements for these two cases, but if we apply the values from Gene Fornby in conjunction with the modern Icelandic forestry research results on density of woodlands (values related to the defoliated biomass and density of tree units per ha), it would appear that in theory a house of this size (c. 280 m²) would require clearance of an area of about 0.33 ha (0.0033 km², for a forest with trees of 4 – 12 m in height) on an annual basis, or 42.9 ha (0.429 km²) until the end of the 10th century. If shrubs (up to 2 m in height) were the exploited category, this impact would be almost 0.92 ha (0.0092 km²) per year, or 119.6 ha (1.196 km²) until the end of the 10th century. However, the aforementioned utilisation mix, and the fact that birch was not the only, or even the principal fuel at Hofstaðir, which is similar in size to the reconstruction in Gene Fornby, allows us to consider the possibility of an even lower impact on woodlands in Iceland resulting from the need for fuel for heating the interiors of the main houses.

A practical study made at the experimental centre in Lejre, Denmark, in February 1999 in a reconstructed house from the Danish Iron Age (500 BC – 700 AD) with a size of 73 m² and a volume of 194 m³, indicated that 74 kg (± 4 kg) of firewood (predominantly elm) was required every day to maintain comfortable temperature but also for cooking (Skov *et al.* 2000, p. 3802) which could be the reason for the higher rate of consumption than was the case at Gene Fornby. Although the simple size proportion pattern could be seen as inappropriate for comparative analyses, one can argue for a rough and very generalised estimate. As with the house in Gene Fornby, the main constructional difference in comparison to Icelandic Viking Age houses are the wooden walls, which could, as an extra inner insulating element, mean that the house in Lejre required less fuel in order to heat the interior than the Icelandic examples of this size would require.[27] Considering the relatively higher average outdoor temperature in Denmark (Tomasson 1980, p. 59, Table 3-2), this appears as even more obvious. The fact that elm was used in Lejre instead of birch does not rule out the possibility of this kind of comparison since these two species have similar calorific values (Poole 2009, p. 123). However, using the same comparative basis as at Gene Fornby, the outcome indicates an even greater rate of woodland clearance for fuel for house heating. Thus, Icelandic Viking Age houses of a similar size (e.g. Grelutóttir) could have required even more than 74 kg per day, if wood was used as the sole type of fuel, which partially corresponds to the ethno-archaeological work of Trbojević and others (Trbojević *et al.* 2011). By using the same proportional estimates to calculate the total annual consumption, and allowing for a significant decrease in fuel needs in the summer months, as was the case in Gene Fornby, it could be estimated that at least about 6.16 tons of wood could have been consumed in an Icelandic house of similar size (e.g. Grelutóttir) per year, which would require clearance ranging between 0.12 ha (0.0012 km², for woodland consisting of trees of 4 – 12 m in height) annualy, or 15.6 ha (0.156 km²) for the entire period under discussion, and up to 0.37 ha (0.0037 km², per year on land covered in shrubs up to 2

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[27] Although it is possible that having turf walls could occasionaly provide much better insulation.

m in height), or 48.1 ha (0.481 km²) until the end of the 10th century, if wood was the sole source of fuel used for heating the interior but also the cooking activities in main farmhouses of this size. However, the utilisation mix, the fact that birch was not the only and often not the principal fuel, as well as selective cutting, indicate that the overall impact on woodlands caused by the need for fuel for heating was considerably lower than these figures suggest.

5.1.3.3 Charcoal production requirements

One of the frequently mentioned causes for deforestation in the *landnám* period was the huge quantity of wood required for the production of charcoal, which was the main fuel and source of carbon used in iron production. However, the work of Þórarinn Þórarinsson (Þórarinsson 1974) showed that although it was significant in comparison with the figure for daily fuel requirements discussed above, clearance of woodlands for charcoal production was not of vast proportions when seen in the context of total deforestation. Relying on comparative and experimental data, Þórarinsson concluded that over the first 500 years of human habitation, about 65,000 barrels of charcoal were needed annually. Converted into roundwood and birch cover, this would represent clearance of about 10 km² of woodlands per year (Þórarinsson 1974, p. 29). In terms of long-term deforestation this would imply the loss of 1,300 km² by the end of the 10th century.

5.1.3.4 Degree of impact

In general, the impact on woodlands caused by the fuel requirements of early Icelandic households was significant but probably not of an astonishing degree. If we accept the possibility that daily household heating requirements were met entirely by exploitation of the birch woodlands, the total extent of woodland clearance needed to meet the needs of c. 4,000 farms for daily heating would have been between 260 – 832 km² [28] and 1,716 – 4,784 km² [29], and each farm's requirements ranging from between 0.065 – 0.208 km² (for the smallest feature, e.g. Eiríksstaðir, calculated by size proportion, Table 2) and between 0.429 – 1.196 km² (for the biggest feature, the *skáli* at Hofstaðir, described above, Table 2).

Table 2. The estimates of the extent of shrub areas and forests required to be cut in order to meet the household fuel requirements at Eiríksstaðir and Hofstaðir

Site	Forest/per year	Shrub/per year	Forest/per 130 years	Shrub/per 130 years
Eiríksstaðir	0.0005 km²	0.0016 km²	0.065 km²	0.208 km²
Hofstaðir	0.0033 km²	0.0092 km²	0.429 km²	1.196 km²

Including the abovementioned figures for charcoal production, we arrive at an estimate of between 1,560 – 3,016 km² for the total forest clearance (*Betula Pubescens* cover) resulting

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[28] In cases where all the main houses would require the amount of firewood proposed for the smallest examples; values given for *Betula Pubescens* and *Betula nana* woodland cover, respectively.

[29] In cases where all the main houses would require the amount of firewood proposed for the largest examples; values given for *Betula Pubescens* and *Betula nana* woodland cover, respectively.

from the daily needs for heating and industrial activities over the course of 130 years, subject to the margins of assumption and theoretical limitations outlined above. This represents between 6.5 – 12.6 % of the postulated pre-*landnám* forest cover (23,844 km^2). In the case of shrubland, the estimate would go up to between 2,132 and not more than 6,084 km². However, the fact that utilisation mix was the dominant practice both in low and high-intensity combustion activities and that birch was not the predominant fuel type, indicates that the total extent of woodland clearance for these purposes was considerably lower.

As with clearance for housing requirements, selective cutting of trees could have prevented permanent loss of woodlands in particular areas and could, together with the birch regeneration/regrowth potential, play a significant role in estimates of the degree of deforestation, resulting in an even lower estimate. The previously mentioned data on volume production of birch woodlands in Iceland indicate that woodland can re-gain significant percentage of its volume on an annual level. Those figures further suggest that during the *landnám*, not only that the total rate of deforestation was significantly lower due to the annual increase in volume of remaining birch woodlands, but also that in a case of halted exploitation and prevented livestock browsing, (the volume of) woodland cover could have been recovered at many locations in a matter of decades.

Conclusion

It has been demonstrated here that none of the three timber requirements that can be seen as fundamental for the subsistence of the population in the late 9th and entire 10th centuries could have played a significant role in the overall woodland clearance process that resulted in the drastically deforested landscape. Although clearances made to meet the needs of c. 4,000 farmsteads for living space, building materials and fuel are generally accepted as having played a role equal to that played by clearance for pastures in the devastation of woodlands during the *landnám* period, in fact, even clearance at the maximum, worst-case scenario rates, deliberately presented above, resulting in the loss of between 1729.89 – 4021.58 km² of forest over the course of 130 years (AD 871±2 – 1000), would not have had any major impact; as a ratio this represents only between 7.25 and 16.86 % of the postulated forest cover. For the reasons elaborated in the sections above, however, it may be assumed that the actual figures were even lower.

From an ecological point of view, only the first requirement, where the need for living space resulted in total woodland clearance in a given area, necessarily led to permanent woodland loss on the farmsteads. But even in that case, the clearance of an area of between c. 1 and 9 ha per farm, spread around the country, had no significant total environmental impact in terms of a permanent loss of large areas of woodlands; such loss was local, and limited. Regarding the other two requirements, i.e. building material and fuel, selective exploitation and the regrowth potential of birch probably played an ecologically „positive“ role, by slowing down the net rate of deforestation.

5.2 Meeting the needs of animal husbandry

Since deforestation activities motivated by the needs for living space, hayfields, building material and fuel were mostly limited and selective, and deforestation was to some extent offset by woodland regrowth, clearance for the needs of early Icelandic farmsteads listed above would have left a localised and relatively small environmental signature. Other factors must then explain the rapid and drastic loss of woodlands that occurred throughout Iceland.

The remaining basic requirement, i.e. requirement for pastures, and eventually uncontrolled livestock browsing, are the most likely candidates to explain the overall degradation of the aboriginal birch woodlands. Unlike the exploitation related to household needs, which may have been intensive, but was most likely concentrated in small areas around the settlements, woodland clearance related to the creation of pasturelands would have been extensive, resulting in permanent loss of large stretches of woodlands over time. Although possibly beneficial for the economy of early Icelandic society in terms of obtaining sufficient amounts of livestock fodder, this type of impact on the woodlands was, in the ecological context, extremely destructive leading to severe and permanent damage to the natural environment.

However, as is the case with the basic household needs, more than a century of academic research on the subject of *landnám* forests and their destruction has failed to give an adequate explanation of the deforestation alleged to have been caused by humans due to the needs of animal husbandry. Furthermore, although unrestricted animal browsing has been cited by many authors as the crucial factor in the drastic loss of woodlands, its destructive effects have not been examined in detail. Therefore, in the following pages I will examine in detail how the needs for new pasture land, exacerbated by animal browsing, could have affected the fate of the original Icelandic forests in the late 9th and 10th centuries. Additionaly, methods of woodland clearance are briefly discussed.

5.2.1 Acquiring new pastures. Additional fodder value of the forests

The large number of pollen diagrams that indicate a rapid decline in birch pollen percentages with a corresponding rise in grass pollen percentages at the beginning of the settlement period (e.g. Einarsson 1962; Hallsdóttir 1987) constitute the basis of the interpretation that the woodlands were replaced by open grasslands. Indeed, it is easy to imagine that in order to gain sufficient extent of grassland, clearance of woodlands was practised at many locations. From the perspective of a settler who did not have sufficient pastures at his disposal, understory vegetation – i.e. grasses and forbs on the floor of the birch forests – were attractive bio-categories that could have provided the answer to the fodder-demands of his livestock; clearance was thus the most attractive option. Still, the clearance for pastures should not necessarily be depicted in absolute terms – it also seems conceivable that at least at some locations, minor pockets of woodlands, i.e. scattered groups of tree units may have been intentionally left uncut, serving as reservoirs of firewood and/or building material. Areas cleared in that way may therefore be seen as open parklands. But was it actually necessary to clear the large extent of forests in order to obtain pastures or could the settlers rely on other sources of fodder in order to sustain their livestock herds?

If we take into account the probable extent of wetland and dryland vegetation areas (supposedly including grasslands) in each of the regions prior to the arrival of the settlers (the map of vegetation cover postulated with this project; also, see Table 11 for the extent of different types of vegetation cover in each of the regions), assumptions about livestock numbers (*Jarðabók*) and fodder requirements (Thomson 2003), and if we rely on modern knowledge of the utilisable biomass of grasslands and wetlands (as suggested by Thomson 2003), it turns out that there was no need for clearance for pastures at all, beyond a small extent needed for space, i.e. for home-fields. So, why did the settlers choose to clear woodlands and provide themselves with new pastures?

An obvious explanation is that land ownership was established by the very first settlers in each region, with the result that subsequent settlers did not necessarily have access to good pastures even though they existed.

Another explanation could be that grasslands and wetland areas were not in the condition that we assume, possibly due to frequent and heavy snowfalls, preceding volcanic eruptions or floods that may have considerably affected their grazing potential or simply because supposed grasslands and wetlands were more wooded than comparable areas are today.

With regards to volcanic eruptions, one needs to be aware that occasionally, deposition of tephra can have a positive impact on biomass production (Dugmore and Vésteinsson 2012, p. 74). Still, if it is very thick, tephra can have damaging effects on vegetation and the productivity of farmstead areas. Thus, for instance, the *landnám* tephra was considerably thick around Stóra-Mörk, in the region of Vestur-Eyjafjallahreppur, where it „might have prevented the flowering of lower-built plants for some time“ (Erlendsson 2007, p. 154). Damaging effects of tephra deposition were recorded elsewhere in the country during the later periods. For instance, five farms were abandoned for a year or more due to thick tephra layers originating from Hekla 1693 eruption, while one of them, covered by a 25 cm thick layer of tephra, was never resettled (Thorarinsson 1979, pp. 134, 136).

One also needs to take into consideration a series of major floods prior to the age of settlement, for instance in the Markarfljót valley (Smith and Dugmore 2006), which may also have affected not only the quality but also the overall extent of the treeless grasslands and wetlands.

It may also be said that local grasslands could have been extremely fragile. Smith and Dugmore (2006) suggest that it would have taken only a small fracture in the soil cover of this region to trigger erosion which was a one-way process since there was no way for the soils to be restored. McGuire suggests (McGuire 2006, p. 20) that „such breaks could have been caused by both animal grazing and human traffic through the regions“. In general, we may assume that after the first signs of erosion (of which we have empirical evidence: Dugmore and Buckland 1991[30]) the settlers became aware of the fragility of the local grasslands, and at that moment there was nothing else for them to do but to start clearing forests for pastures that seemed to be a more reliable grazing resource.

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[30] With respect to the area of Seljalandsheiði in Vestur-Eyjafjallahreppur.

Whatever the truth of this matter is, one also needs to be aware of the possibility of sustaining livestock even without clearance of woodlands. Cattle and ovines can graze and browse in woodlands and survive by doing so and in that case, settlers would, through time, probably just need a greater area of woodlands that could support their growing livestock herds. Nevertheless, it also seems conceivable that settlers were aware that they could make the most efficient use of their land through extensive clearance of woodlands and their transformation into pastures – that way they could provide their livestock with high-quality grassy fodder that would improve their growth but also their reproduction rates. Clearance for pastures can therefore also be regarded as an optimal use of resources and not the absolute necessity.

Scholars involved in research on the *landnám* forests and their loss have, both directly and indirectly, noted that woodland areas were probably rich in understorey vegetation, which would make them a potential source of fodder. However, their work also indicates that the composition and quantity of understory vegetation were not uniform in all locations, and thus were not of equal significance for the settler population in terms of meeting the requirements of their livestock. Thus, while some have suggested that, apart from the grasses, sedges were the category that dominated the wetter areas within the woodlands (Arnalds 1987, p. 509), others have stressed that, again apart from the grasses, a luxuriant undergrowth of forbs could have been the dominant category (Thorsteinsson *et al.* 1971, p. 88, Figure 7, below). Some authors are decisive in their claim that woodland density is a major limiting factor when it comes to the composition and quantity of understory biomass, stressing that the growth of vegetation in forests with dense canopies is limited due to competition with the tree roots for a share of the available moisture and nutrients and lack of sunlight (e.g. Sigurðsson *et al.* 2005; Elmarsdóttir *et al.* 2008).

Figure 7. Example of a relatively tall Icelandic birch with a luxuriant undergrowth of forbs and grasses (taken from Thorsteinsson *et al*. 1971).

A full understanding of the understory vegetation of the *landnám* birch forests and the potential of its exploitation as grassland would require reconstructions of the bio-diversity of the *landnám* birch forests for all parts of Iceland. Unfortunately, the absence of this type of research forces us to rely on the comparative analyses based on studies of the understory vegetation of modern Icelandic woodlands. Thus, recent research in Hallormsstaðarskógur, a native birch forest in eastern Iceland, indicating that light obstruction is a major factor in decreasing the total biomass of mosses, grasses and sedges, shows that the ground vegetation biomass in a 97-year-old birch forest is only half that of the nearby treeless pasture area (Sigurðsson *et al.* 2005, p. 884, Fig. 2). The measurements of utilisable biomass of grasslands and ungrazed woodlands made by Thomson (Thomson 2003), suggest almost the same ratio in the north of the country (Mývatn: ungrazed woodlands contain 51 % of the utilisable biomass of treeless grasslands) whereas in the south (Eyjafjallahreppur) the utilisable grazing biomass of ungrazed woodlands appears to be much higher (87 % of the biomass available at treeless grasslands: Thomson 2003, p. 145, Figure 4 – 9). „Utilisable biomass“ is the term that Thomson used to describe herbaceous vegetation that is available to grazing livestock. It therefore may involve a different spectrum of plants that livestock can graze than would be the case in treeless pastures. Although these results may not be fully applicable for the entire country during the *landnám* period and for birch woodlands of different density, they clearly indicate that the grazing potential of grasslands gained through woodland clearance probably varied greatly.

In cases where the new grasslands gained through clearance were not exposed to grazing immediately after removal of the trees, but instead were rested, both their biomass and their quality would have increased due to undisturbed growth and exposure to sunlight. In theory, that way, through time, they could have become just as productive as a source of animal fodder as natural treeless pastures. Several studies from abroad suggest that resting of grasslands can considerably increase their grazing potential (Hidalgo and Cauhépé 1991), but those studies originate from regions that are hardly comparable to Iceland. There are no research studies in Iceland with regards to this issue. Whether the early settlers practiced some kind of subsequent management of these grasslands that would have made them similar in grazing value to natural pastures is unknown. Although that kind of management may have been applied, it would be inconvenient to argue for it based only upon the existing empirical (e.g. palynological) datasets, primarily because of their scarcity and low resolution.

Taking into account the fodder value of leaves, as well as twigs and bark which were part of the livestock diet (mostly sheep and goats), the overall „fodder-potential“ of the forests was higher than the understory vegetation indicates. Apart from being a target of livestock browsing (as is explained in further detail below), birch leaves could have been collected through so-called „lopping“, a very old form of fodder-harvesting involving chopping off the twigs, removing the leaves and their subsequent drying and storing as fodder for later consumption by livestock. This practice is documented in Norway since the Iron Age. Where this method was used, leaves in particular were considered an important supplement to hay (Austad and Hauge 2006). Regarding the *landnám* deforestation, if we take into account the average values of foliated biomass of modern Icelandic woodlands (Unpublished data: Þ.H. Jónsson, Iceland Forest Service – pers. comm.), it becomes clear that settlers who applied „lopping“ along with or immediately after tree-felling would have derived a double benefit (in addition to the primary benefit of obtaining the wood for fuel and/or building). They would gain the extra grassland area, and also a fairly significant amount of leaf-fodder. In addition to this, with the amount of other types of edible material (e.g. collected twigs but not the bark)[31] which are readily eaten by livestock, the fodder-value of forests would rise even more. Unfortunately, there are no research studies that indicate the amount of twigs that could be harvested from one hectare of woodlands.

5.2.1.1 Controlling grazing

An issue that is not much noted in archaeological or forest related research but is a practical concern of modern sheep farmers in Iceland is the fact that sheep easily disappear from view in the mostly low-growing Icelandic woodlands and are then difficult to find. Rounding up sheep in woodlands is an arduous task requiring many people and therefore one that was likely avoided as much as possible. In low woodlands, wool also gets snagged on branches, which translates into loss of wool to the sheep owner. Having in mind those problems it is easy to assume that during the *landnám*, maintaining control over livestock herds was an extra, practical incentive for clearing pastureland and possibly for removing adjacent woodlands (Eysteinsson – pers. comm.). Although some of the authors (Simpson *et al.* 2001) argue for the absence of adequate shepherding in early Iceland, some sort of livestock control must have been applied and it is possible that this could have been done through clearance of woodlands and creation of treeless areas where livestock could have been kept in sight. Moreover, that sort of shepherding of livestock, to keep it in one location, where it could be seen (on the pastures rather than in the woods) could also explain early overgrazing and soil erosion (Eysteinsson – pers. comm.).

5.2.2 Methods of woodland clearance

Putting aside the possible impact of herbivores on woodlands (described in section 5.2.3), reduction of woodlands in the *landnám* period was accomplished most probably through axe-felling and/or burning (described in section 5.2.2.1 below, and 5.2.2.2.).

5.2.2.1 Methods of woodland clearance: felling

Without any intention of proposing it as a strict rule, it seems probable that felling was the preferred method of clearance when it came to gaining new pastures; this way the settlers would have gained immediate access to the new grasslands/pastures and, as mentioned before, a significant amount of leaf-twig-bark fodder. Although the clearance of large areas of woodland through tree-felling required the involvement of a relatively high number of people, and was time-demanding, it immediately provided benefits for the local animal husbandry economy.

Pollen diagrams such as those from Borgarmýri and Skálholt (Einarsson 1962), or those from Svínavatn, Þrándarholt, Mosfell or Vatnsmýri (Hallsdóttir 1987) provide a direct

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[31] Livestock in Iceland today has no interest in birch bark. It is also difficult to peel bark off a birch stem in a way that the cambium (the nutritious part for livestock) is removed (Eysteinsson – pers. comm.). Therefore, it is highly unlikely that the birch bark was harvested as fodder, except in times of extreme famine. Also, some authors suggest that consumption of birch bark can lead to poor growth and survival of animals (Harju 1996, p. 720).

empirical confirmation of the deforestation process in which the woodlands were transformed into grasslands. In these, while birch-pollen percentages show a decline, grass-pollen percentages show a corresponding increase. I propose that clearance at these locations was accomplished through felling, due to the absence of sufficiently thick charcoal layers which would indicate the use of fire either through simple forest clearance or application of slash-and-burn techniques. Even at sites where charcoal has been identified and where its value in the pollen diagrams increased during periods that are contemporary with the loss of woodlands, we still cannot argue for woodland clearance by fire, since the charcoal values do not reach sufficiently high levels. This could have been the case e.g. in Stóra-Mörk, where the charcoal values are not high, yet the woodland taxa dwindle, indicating that the woodlands were not cleared by fire (Erlendsson 2007, p. 155).

Appropriate experimental work has not been carried out in Iceland that might indicate how efficient different kinds of woodland clearance were during the *landnám* period. Results of experiments done in other countries, although not fully comparable and obviously limited since they originate from only simulated past environmental conditions and labour techniques, are still of some use.

Thus, concerning tree-felling, although an experimental study from Ireland (Figure 8, below) is not fully comparable[32], it does allow us to propose very generalised and rough estimates.

Figure 8. Tree-felling experiment from Ireland. Taken from: web-link 1 Last consulted on 09.10.2013. (Credits: Aidan O'Sullivan / Graeme M. Warren – UCD School of Archaeology)

This study showed that felling a birch tree with a trunk up to 15 cm in diameter took 16 minutes. Taking into account the average values for tree density in Icelandic birch forests (Jónsson – pers. comm.) and following the estimate that stone axes could have required up to

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[32] Primarily due to the use of a stone axe, which has lower efficiency than iron axes, as confimed through various analyses and experimental work (e.g. Mathieu and Meyer 1997).

six times more time than metal axes[33], this implies that in order to clear 1 ha of forest consisting of trees of 4 m in height or more, 185 man-hours of work would be required using metal axes. Clearing 1 ha of forest with 2-4 m tall trees, also with metal axes, would take 174 man-hours. What also needs to be taken into consideration is that differences in the diameter of the trees represent the factor that most seriously affects this estimate.

In real terms, how much time would actually be required? Apart from the actual felling, a worker would need several rest-breaks and time for the consumption of food as a basic requirement for such hard physical work. Felling could also have been followed by lopping and removal of the material from the sites, both of which are time-consuming activities. Taking this into account, clearing 1 ha of forest would take much more than simply 174-185 hours of work (100 % of efficiency). It seems more realistic to assume that maximum actual efficiency in practice would be no more than 50 %.

Very generalised comparative estimates are presented in Table 3, which shows the time required to clear 1 ha of forest, expressed in man-hours/12-hour working days[34], and allowing for different types of forest cover:

Table 3. Time required for felling of 1 ha of forest, expressed in man-hours/12-hour working day, allowing for different types of forest cover: a) 1 ha of forest with trees of height of 2 - 4 m b) 1 ha of forest with trees of height of over 4 m

1 ha	50 % efficiency	25 % efficiency
a)	348 h / 29 days	696 h / 58 days
b)	370 h / 31 days	740 h / 62 days

Unfortunately, it is hard to offer a precise number of people available on *landnám* farms for such labour, which limits the accuracy of any assumption regarding the possible rate of the tree-felling activities. Scholars' opinions differ widely when it comes to estimating the number of people that could have inhabited certain farms. Bearing in mind that the composition of these individual communities varied widely (e.g. in terms of age, sex, physical condition etc.), it is obviously very difficult to state definite figures of this type.

However, some generalised estimates indicating potential rates and limits of tree-felling can be given and they are presented in the pages below. Still, it is important to stress that those estimates are in their large part given on the basis of a common-sense approach and can only be regarded as logical assumptions; these are not reality-based formulations.[35]

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[33] Feldman, L. H. 1974, p. 135, referring to Saraydar and Shimada 1971.

[34] Where a 12-hour working day does not necessarily refer to summer (relative to high number of hours of daylight). It is rather a generalized depiction that should not be associated with any particular season.

[35] As it stands at present, there are no relevant empirically-based research studies which can suggest a likely degree of workforce employment and/or degree of its efficiency at any of the farms.

Sample cases: clearance for home-fields

As can be seen from the estimates in the table above, it would take between c. 4 (50 % efficiency) and 9 (25 % efficiency) man-weeks to clear an area of 1 ha, which is proposed as the smallest extent of the *landnám* home-fields (see section 5.1.1.2). With the involvement of 5 people, this would take 6 – 12 days, working 12 hours per day; with 10 workers, it could have been done in 3 – 6 days (Table 4). Clearing an area of 9 ha, which is proposed as the home-field area at Þorleifsstaðir (Vésteinsson 2008, p. 20), the largest known so far, would take between 261 man-days (50 % efficiency) and 555 man-days (25 % efficiency), working 12 hours per day. Shared by 5 people, the task would take 52 – 111 days; with 10 workers, it could have been done in 26 – 55 days (Table 4).

Table 4. Time required for home-field (1 – 9 ha) clearance

Area	5 people	10 people
1 ha	6 – 12 days	3 – 6 days
9 ha	52 – 111 days	26 – 55 days

These proposed estimates generally suggest that tree-felling should not be seen as an insurmountable problem but it was definitely a costly activity. In general, the process of establishment of a farmstead area was a long-term process and an expensive investment.

On the other hand, the size range of 1 – 9 ha of home-fields to meet the needs of animal husbandry was most probably related to the time of the peak of the home-field requirements, when the number of livestock was at its maximum. At the initial stage of inhabitation the settlers probably possessed smaller numbers of livestock which could have been sustained with smaller home-fields, requiring smaller areas to be cleared initially, with less labour involved. Unfortunately, the pollen diagrams are not of sufficient resolution to give accurate time estimates of the tree-felling on an annual scale, and it is not easy to estimate livestock numbers at the time of the initial establishment of the farms. As a result, we cannot propose the actual rate of woodland clearance necessary in the initial stage of inhabitation of a certain area. Woodland clearance could have increased in scale gradually, over the years, keeping pace with the increase in the number of livestock. In this case, it was most probably a feasible and not extremely time-consuming operation, and one that was accepted as necessary in order to gain home-field areas. Furthermore, it also seems conceivable that settlers could have killed the trees by girdling, which is a process of removing a strip of a bark, causing the tree’s death due to removal of the phloem and inability of leaves to transport sugars to the roots, vital for its subsistence. Through the use of girdling, they would have left the trees to die slowly over several years, rather than felling them down. This way the total rate of actual felling would have been further diminished. Finally, it is also reasonable to assume that in many cases settlers selected glades to locate their farms and as a consequence, the clearance for home-fields was applied only to an insignificant degree, or it was not applied at all.

5.2.2.2 Methods of woodland clearance: burning

When it comes to burning, a simple, „wipe-the-area“ burning of woodlands was the easiest method available to clear land for homesteads, improve the visibility of the estate from a distance or to improve communications. Although there was a possibility that the fires might go out of control, resulting in large-scale deforestation, this was still the easiest and, in terms of time required, the most efficient method of forest clearance. Charcoal layers identified at the following sites might indicate the use of fire for clearance:

- in Þjórsárdalur: Snjáleifartóttir (Þórarinsson 1943), Skeljastaðir (Þórarinsson *ibid*), Skallakot (Þórarinsson *ibid*), Þórarinsstaðir (Þórarinsson 1949),
- in Borgarfjörður: Ísleifsstaðir (Stenberger 1943), Reykholt (Sveinbjarnardóttir *et al.* 2007; Gathorne-Hardy *et al.* 2009),
- in Berufjörður: Broddaskáli (Sveinbjarnardóttir 1992), and
- on the island of Papey: Goðatættur (Buckland *et al.* 1995; Buckland 2000).

However, charcoal horizons are not ubiquitous and in regions like Mývatn, where many trenches have been made, charcoal has only been observed in a tiny minority of cases (only at Geldingatættur: Vésteinsson 2008, p. 15, and possibly Oddastaðir: Vésteinsson 2004, p. 63). Also, in Vestur-Eyjafjallahreppur, charcoal values are not sufficiently high to fully support such an interpretation (Erlendsson 2007). Therefore, the archaeological evidence of charcoal layers which can actually be used to support the idea of deliberate burning of woodlands has only been revealed at a small number of sites and for that reason this type of activity can be regarded as uncommon. Nevertheless, it needs to be discussed.

Major pros and cons of burning woodlands

Burning becomes a more likely option if we consider that settlers who used fire clearance prior to the establishment of the farms most probably aimed for more benefits than merely free space; a large cleared area could be used for both building (in one part) and the development of pastureland but also arable land based on the ash-enriched soil (on the remainder). Burning releases nutrients that fertilise the soil, while ash increases the pH value of the soil, makes the nutrients more available and increases the intensity of subsequent growth of grasses and/or crops in a burned area.

However, burning of woodlands in order to gain pastures also has drawbacks that make this way of clearance generally unattractive. By resorting to simple and quick burning, settlers would have deprived themselves of access to leaf-twigs-bark fodder and also to supplies of wood as a building and fuel material; it is hard to imagine that they would so easily abandon easy access to these resources. Also, the threat to the resources posed by a risk of uncontrolled fires would be another disadvantage. For these reasons, we may assume that burning of woodlands for this purpose was most probably not a highly-favoured method and would have been applied on a limited scale, and only as an occasional alternative to tree-felling and/or when it was required by the livestock management strategy. It might have formed part of the overall management strategy; on a small scale, fire would have been easy to control and the leaf-fodder potential of a certain estate under woodland would not have been significantly diminished.

Burning and the farm status

What we can state with certainty is that site status was not a decisive criterion when it comes to possible woodland clearance by burning. Woodlands could have been burned both at the lower and higher-ranking sites. Thus, some sort of burning may have taken place in the initial stage at sites such as Geldingatættur in Mývatn region (Vésteinsson 2008, p. 15), which belonged to a very small group of so-called „intermediate“ sites that were too small to be farms and too large to be plain animal stalls. This was also the case at low-middle ranking farms like Goðatættur on the island of Papey (Buckland *et al.* 1995; Buckland 2000) in the east and Snjáleifartóttir (Þórarinsson 1943), and/or Þórarinsstaðir (Þórarinsson 1949), in the south of the country. Some sort of burning also took place at farms with higher hierarchical position/power; this was the case, for instance, at the mid/mid-high Broddaskáli in Berufjörður (Sveinbjarnardóttir 1992), in the east, the mid-high Skeljastaðir and also at Skallakot (Þórarinsson 1943) in Þjórsárdalur. Burning also appears to have been used at the mid-high Ísleifsstaðir (Stenberger 1943), and can be taken into consideration as a possibility e.g. at the high-ranking Reykholt (Sveinbjarnardóttir *et al.* 2007, p. 202; Gathorne-Hardy *et al.* 2009, p. 420).

Burning in relation to forest stature and location

In spite of the abovementioned lack of evidence, it could also be argued that there were differences in the use of fire to clear woodlands for pastures related to forest stature and location. It is easy to imagine that in most of the cases, relatively tall forests and those located close to farmsteads were cleared by felling and at the same time used as building material, fuel and fodder as described above. On the other hand, low-growing, shrubby woodlands, especially at high altitudes and greater distances from households are more likely to have been burned due to their lower resource value and/or lack of manpower to fell and transport material. The existing scarcity of archaeological evidence for burning at and around the farmstead areas does not preclude the possibility that birch shrubland in sparsely inhabited (or uninhabited) areas (where little or no archaeological research has been done) was burned.

Slash-and-burn technique

Burning of woodlands could have been applied through the so-called „slash-and-burn“ technique, aimed primarily at obtaining arable land or improving meadows. Compared with clearance in order to acquire pastures, clearance of forest in order to gain arable land could have taken place on a small scale. Owing mostly to environmental, but also cultural factors, the settler population established animal husbandry as the basis of the *landnám* economy, leaving crop cultivation in a minor role in the society of early Iceland. Most of the existing research indicates that, despite the substantial demands for cereals suggested by the sagas, cereal production, mostly of barley, was on a very limited, subsistence level (Simpson *et al.* 2002). Cereals were grown in only a few places (most likely on high-status farms: Sveinbjarnardóttir *et al.* 2007, p. 203), mostly in the southern and western/north-western parts of the country (e.g. Guðmundsson 1996; Icelandic Agriculture 1997[36]) and most probably until the 14th century (e.g. Smith 1995, p. 329). It is

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[36] Text written by the Icelandic Agricultural Information Service. Neither the name of the author(s) nor the editor(s) are stated. Available at the Library of the University of Iceland.

tempting to assume that especially in the first years of the Settlement, when livestock herds were still small, cereal cultivation would have been more important than later and that most of it actually took place in coastal, i.e. treeless areas.

Apart from the very rare locations where the fertility of the natural soil was high enough to allow cultivation, and others where the soil was most probably fertilized by domestic waste, fuel residue and/or animal manures, as was the case, e.g., at Akurey and Ketilsstaðir (although with low manure application rates: Simpson *et al.* 2002), it is reasonable to allow for the possibility that the land in some areas could have been adapted to sustain agricultural activity through the use of slash-and-burn techniques.

Slash-and-burn clearance was a particular shortcut to arable land, suitable for small-scale agriculture such as that current at the time of the *landnám*. Also known as swidden, it was used since the Late Mesolithic (e.g. Innes and Blackford 2003) and widely applied throughout the Viking world (e.g. it was encouraged by the authorities in Sweden until the 17th century: Hamilton 1997, p. 21). Woodland clearance by means of fire is even nowadays used extensively for agricultural purposes, and is also the subject of numerous palaeoecological experimental studies (e.g. Rösch *et al.* 2004; Eckmeier *et al.* 2007).

Figure 9. Slash-and-burn experiment (Rösch *et al.* 2004). Up: Woodland clearance and burning. Down, left: A field in spring, burned and sown in autumn. Down, right: A field shortly before harvest.

When slash-and-burn clearance was carried out, timber useful for building and fuel, and also leaves, twigs and bark could have been felled, removed and preserved prior to burning, and the rest of the vegetation left to dry out. This way, leaf-twigs-bark fodder and building and fuel material could have been saved, which makes it a multi-benefit process. After burning, the soil could have been cultivated / used for agricultural production for only a short cycle of continuous use, with yields falling over time (usually 3 – 4 years: Hamilton 1997, p. 23). While this could easily have been seen as a drawback, it could have been offset by the fact that these areas could subsequently be used as pastures.

Even though it involved a certain delay, and the land could only be used for a limited period for cultivation (usually 3 – 4 years), the slash-and-burn technique could have been preferred as a shortcut activity, not only to gain land for agricultural purposes, but also to establish home-field areas for long-term hay production.

In Sweden (at least from the 9th century onwards) slash-and-burn clearance was particularly common among the poor crofters in the hilly forested areas, and the size of the burn ranged from 0.25 up to about 3 ha (Hamilton 1997, pp. 21, 23). This suggests that it would have been practiced mainly at the low-ranking sites in Iceland during the Settlement period. Since many of these were probably positioned in the more wooded areas, and probably lacked access to arable land and the labour resources to undertake massive felling activities, it is reasonable to assume that particularly in these locations, slash-and-burn clearance was applied as a shortcut to gain fertile land, suitable for home-fields or for agriculture and/or pastures with quality grass; especially if leaves-twigs-bark fodder, as well as building/fuel material was removed prior to burning. Assuming that it took several decades to create a fully operational and useful home-field area (Adderley *et al.* 2008), then the use of „slash-and-burn“ is a logical shortcut step. However, it is hard to establish that this was the case: to stress again, there is, in general, no substantial evidence indicating that extensive intentional woodland burning took place.

Taking into account the low intensity of agricultural work / cultivation and the general lack of archaeological evidence for burning, it seems likely that slash-and-burn was used on a considerably smaller scale than other types of woodland clearance.

More on the lack/type of evidence

It is also important to note that the existing scarce archaeological evidence for burning of the woodlands cannot clarify whether it was slash-and-burn or simple clearance-burning that was applied at certain sites. It is also hard to state whether burning was accomplished particularly due to the need for free space / ease of travel / ease of spotting and rounding up livestock, or whether the settlers were also aiming for the subsequent extensive grass growth. As previously mentioned, in some instances, the concentration of charcoal is not sufficiently high to be interpreted as demonstrating the intended burning of an area (e.g. Stóra-Mörk: Erlendsson 2007, p. 155) and it may even be questioned if the charcoal layers mentioned in earlier studies were substantial enough to suggest intentional burning of woodlands. Furthermore, charcoal layers identified over large areas in Iceland but also in other countries are not always interpreted as a result of intentional woodland burning. For example, Smith

(1995) states that the identified charcoal layer at the site of Háls should instead be related to the „heavy traffic between the iron-production complex and outlying charcoal pits“ (Smith 1995, p. 335). Also, the most recent study from Greenland (Bishop *et al.* 2013, p. 3890) suggests that the charcoal-rich layer identified at the Ø69 site in the Eastern Settlement was actually formed by the addition of midden material to the infields (as a part of a soil amendment strategy) and not through deliberate *in situ* burning of vegetation.

Finally, one also needs to be aware of the possibility that charcoal layers identified throughout Iceland can actually originate from wildfires. Today we know that forest wildfires can occur in the country. For example, 9.1 ha of the forested area were affected by a wildfire in 2008 (FRA 2010). Unfortunately, there is no systematic registration of wildfires in Iceland for the time before 2006 (FRA 2010) and it is impossible to estimate their frequency in the past and the extent of areas affected by fire. In general, they are rare, and it is reasonable to assume that during the *landnám* they were also uncommon, primarily due to wet Icelandic climate which precludes much fire activity.

5.2.3 Significance of livestock browsing of woodlands

In addition to the causes and methods of woodland clearance discussed above, livestock browsing is another frequently mentioned reason for the enormous deforestation of the *landnám* period. Many scholars involved in research on this environmental change suggest that both willows (*Salix sp.*) and birch trees (*Betula pubescens*) suffered from extensive browsing by domestic animals. Compared to those species, the impact on *Betula nana* was most probably insignificant since, as previously mentioned, it was not a common component of woodlands. Browsing of mountain birch, which is described as being of medium palatability (e.g. Thorsteinsson 1980), by sheep and goats and root digging by pigs, undoubtedly contributed to the loss of the original woodlands, and also to soil exposure and subsequent erosion. However, it remains unanswered up to what degree. The question which arises is: can we actually associate browsing with rapid and drastic reduction of the woodland cover?

5.2.3.1 Utilisation and actual degree of degradation

In contrast to grass, with its seasonal variation in palatability, woody shrubs remain digestible by animals all year round (Thomson 2003, p. 126). They therefore represent a constant fodder resource. However, some scholars argue that livestock browsing would have been seasonal, with an uneven impact on woodlands over the year. Thus, while willows and birch were palatable in summer, the availability of grass and forbs at that time of the year reduced the need for browsing. Woody plants (including both *Salix sp.* and *Betula pubescens*) were, in general, more important in winter, representing up to 80 % of the livestock diet in the period December-March (Thomson 2003, p. 127). Due to the decrease/end of the grass growth in autumn, and its lower palatability and reduced accessibility (due to snow cover) later in the winter, browsing of the woodland vegetation would have become more important for livestock maintenance.

However, the utilisation rate would not have been uniform throughout the period September to March. Cumulative utilisation of woodlands per hectare could have been significantly lower, e.g. in September, than in March (Thomson, *ibid*, pp. 187, 188, Fig. 5-2b, 5-2e).[37] Until September, after the period of intensified growth during spring and summer, and while the livestock could still have fed mainly on other, preferred resources, the fodder potential of woodlands (i.e. the entire woodland biomass) would have increased to a maximum level. The moderately intensified browsing in September thus would not have damaged it to a very significant degree. However, gradually, as the utilisable biomass of the grassland diminished, browsing pressure on the woodlands would have risen, reaching its peak in March to May, depending on snow cover and the arrival of spring. Thomson suggests that utilisation of these two categories (shrub and forests) would have risen significantly from mid-December, reaching its peak in mid-March and falling to its lowest level in April/May, as vegetation growth started again. Therefore, the period of late winter/early spring (March – April) appears as critical regarding the browsing of woodland vegetation and its eventual over-exploitation; this especially if we take into the account the possibility of failure to remove domestic livestock before the end of the growing season and an absence of shepherding (Simpson *et al.* 2001).

Unfortunately, there are no empirical studies that can help us clarify the degree of impact of browsing on willows and birch-trees and expressing it in actual numbers. Still, the modelling study of Thomson (2003) can be of some use. This study suggests how to define over-utilisation and how the over-utilisation affects the vegetation. Finally, it may give a hint of the overall pace of degradation. By using the results from RALA grazing research projects undertaken in the 1970s and 1980s as well as Þorsteinsson's study (Thorsteinsson 1980), Thomson developed threshold-values for different types of vegetation cover: 40 % of utilisable biomass for the grassy heath and birch woodland, and 15 % of utilisable biomass for the dwarf shrub heath. According to Thomson, if utilisation exceeds those threshold values, the mean utilisable biomass will be reduced by 20 % in the following period (Thomson 2003, p. 166, 167). This reduction implies that, eventually, the overall utilisable biomass can be considerably reduced, if not lost, but it is clear that this can happen only if the livestock continuously browse at the same location. It is however notoriously hard to estimate for how long livestock would browse one particular patch since there are no relevant existing studies on uncontrolled movement of livestock herds – it is therefore hard to estimate the actual rate of degradation due to browsing. Nevertheless, we may assume that due to lack of pastures, heavy browsing was the case at some locations during the *landnám*. There, areas of willow and low-growing birch might have been lost through browsing.

With regards to the impact on *Betula pubsecens*, which is the focus of this dissertation, it is important to stress that there is a lack of studies which can indicate the actual degree of degradation due to browsing. However, some of the existing studies suggest that browsing could hardly be the reason for rapid and drastic loss of forest cover.

If livestock browse birch leaves and twigs at a relatively low height (supposedly up to 1.5 m for sheep; for further explanation: see the major reference in the following paragraph), birch plants respond by compensatory growth – their leaf toughness and leaf mass-area increase in the following season, and the shape and the structure of the plant alters (Lehtilä *et al.* 2000; Riipi *et*

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[37] Thomson proposed these values on the assumption that all the livestock-edible plants were available.

al. 2005). Only in the case of the total loss of leaves and twigs it is likely that bark would be browsed which would be the final and fatal damage to the plant. Here, the effect of bark-eating was the same as of girdling. However, having in mind the previously mentioned considerable amount of utilisable biomass in woodlands, most probably bark-eating was not frequent. All in all, it arises as logical that only minor parts of the birch forests could have been lost that way.

The key argument for dismissing the idea of browsing as the main cause of rapid and drastic deforestation is the height of trees. A recent experimental study from Norway (Speed *et al.* 2011) on the growth limitation of mountain birch (*Betula pubescens tortuosa*) caused by sheep browsing, suggests that „browsing likelihood was greatest at intermediate birch heights of between 50 and 150 cm" (Speed *et al.* 2011, p. 1350).[38] The authors of this experimental study also stress that the results support the idea of higher tolerance of established and taller trees to browsing (Speed *et al. ibid*, p. 1351). Indeed, when investigating the possibility of degradation of the *landnám* forests through browsing, one needs to take the height factor into consideration as probably the most significant one. *Betula pubescens* with at least two metres in height was already in its *size refuge*[39] when livestock was introduced to Iceland by the end of the 9th century. Therefore, at first glance, destruction of forests was not the consequence of browsing.

On the other hand, it is well known that browsing animals (including livestock) often preferentially browse regenerating vegetation, including seedlings and root collar sprouts, simply because this material is within easy reach. There is evidence of this in Icelandic birchwoods where regeneration was nearly absent in grazed woodland but plentiful in adjacent protected woodland (Ása L. Aradóttir and Þröstur Eysteinsson unpublished data). Repeated browsing of regeneration and thus continual regeneration failure in woodland results in the old trees gradually dying off, leaving first treeless patches and eventually a treeless landscape. In Icelandic birchwoods, where birch is not very long-lived, with most stems living less than 100 years, this process takes decades or perhaps centuries depending on the intensity of browsing and whether or not there were intermittent periods of regeneration success due to less browsing. Unfortunately, this mode of deforestation is very poorly researched and is therefore not readily quantifiable. Still, it may be stated with certainty that it is a long-term process and does not explain the apparent rapidity of deforestation in the initial stages of the *landnám*. So, how to explain rapid and drastic loss of Icelandic woodlands?

5.2.4 Clearance for pastures

Taking into account the small significance of clearance for home-fields, building material and firewood as well as the previously discussed livestock browsing, it appears that the major part of the process of deforestation should be associated with clearance for pastures.

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[38] Authors stress that these figures go in line with the earlier studies on sheep browse-heights (e.g. Wilson *et al.* 1975; Zamora *et al.* 2001; McEvoy and McAdam, 2008)

[39] A term used to describe the height at which individual tree units escape or increase resistance to browsing.

5.2.4.1 Possible degree of impact

A closer examination of the possible degree of clearance caused by the needs of animal husbandry is presented below through the examples of four farms: Gjáskógar, Sveigakot, Stöng and Hofstaðir. These, along with other examples, should bring us closer to the nature of deforestation caused by farms of different hierarchical position/power. Explaining the extent of deforestation caused by these farmsteads, however, should not be understood as a precise assessment of the impact caused by farms of one status or another. Not all farms of the same status had the same livestock and environmental potential, i.e. access to vital natural resources, nor can we claim that there was the same deforestation pattern/policy at each farm of the same status. Nevertheless, the research results from the aforementioned sites offer us sufficient data to indicate the degree of clearance of woodlands made in order to meet the needs of animal husbandry economy in the most effective way – through provision of sufficient amounts of grassy biomass which was most probably the best source of fodder for the *landnám* livestock herds. The areas of Mývatn and Þjórsárdalur are taken as examples not just because of their characteristics and differences in methods of woodland exploitation, but also because the most complete research data come from sites in these regions – primarily data on the possible numbers and composition of livestock holdings which are a crucial parameter when it comes to estimating the degree of impact on woodlands resulting from meeting pasture requirements.

5.2.4.2 Low-ranking farms: Gjáskógar

The farm at Gjáskógar can serve as an example of the deforestation impact caused by animal husbandry at low-ranking farms, particularly those positioned in wooded, inland regions such as Þjórsárdalur.

McGovern and others (McGovern *et al.* 1988) proposed that an area of c. 450 ha could have been the pasture territory for Gjáskógar. This figure was selected from the range of 103 – 516 ha, suggested as necessary to meet the fodder needs of its livestock (cattle: 12, ovines: 72 - depending on different productivity levels of pasture areas; 200 kg/ha – 1000 kg/ha: McGovern *et al.*1988, p. 240, 241, Table 1, 2). On the other hand, following Þorsteinsson's estimate of the livestock grassland requirement as being 0.3 ha/ewe/month (Thorsteinsson *et al.* 1971, p. 90), and following the same estimate of livestock ratio (i.e. 1:6), we would come to a significantly higher figure – 518.4 ha of quality grassland would have been required to meet total grazing needs

However, rather than adopting one of these estimates, I instead offer an estimate of the clearance for the worst-case scenario in which the area around Gjáskógar was fully forested. I base the estimate on the estimated number of livestock for the site of Gjáskógar and their fodder requirements (average values also used for other sites; requirements for the period of 12 months, thus allowing for winter-grazing). These estimates do not allow for the possibility of applying different kinds of management (e.g. reducing the number of livestock by culling in September, or preservation of the grassland areas from overgrazing), which would have reduced the pasture requirements and thus the degree of woodland clearance necessary. This estimate could be seen as a maximum possible degree of clearance at farms similar to that of Gjáskógar.

According to Thomson (Thomson 2003, p. 221), a dairy cow requires 180.15 kg of hay per month. On an annual level, this would imply the consumption of 2,162 kg of hay, which is less than half the estimate given by McGovern and others, of as much as 4,400 kg/cow (McGovern *et al.* 1988, p. 238); 12 cows would thus require 25,942 kg of hay per year. If we apply the fodder-requirement ratio of 1:6 (cattle to ovines), we arrive at an estimate that sheep population of 72 would require the same amount of fodder per year. This implies that 51,883 kg of fodder was necessary every year for the subsistence of the livestock holdings at farms the size/rank of Gjáskógar. So, what extent of woodland needed to be cleared in order to meet this requirement – assuming that the pasture area was initially fully wooded?

Assuming that the utilisable biomass (UB) of the forest floor was c. 50 % of the treeless natural pastures (see figures above: Sigurðsson *et al.* 2005, Thomson 2003) and that the amount of available UB of grasslands in August was c. 3132 kg per hectare (calculated as the mean value of available UB recorded at grasslands in the North and South by Thomson 2003, p. 145, Table 4-10), then birch forest floor had c. 1566 kg/ha of UB at the peak of a season. Furthermore, by using the seasonal rate of variation in the available biomass (calculated from Thomson 2003, p. 180, Figure 4-21)[40], it is possible to calculate the seasonal variations of the available UB at the newly created pastures (Figure 10).

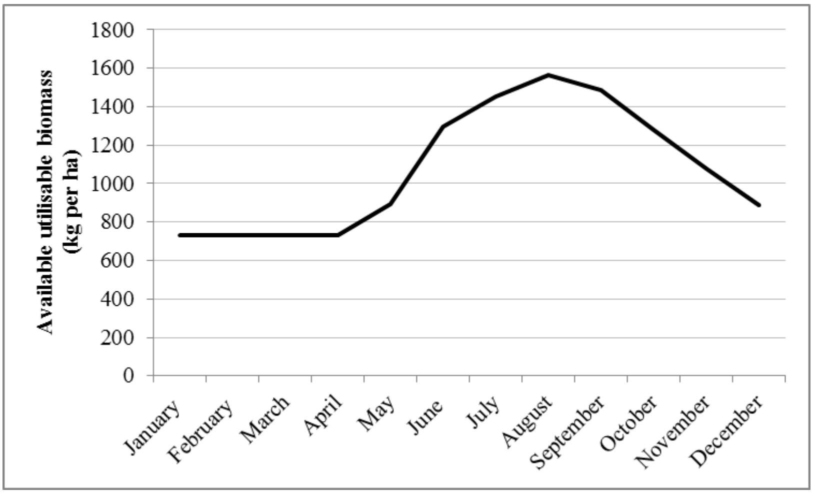

Figure 10. Available utilisable biomass of pastures created through clearance of birch forests

Assuming at least some sort of awareness by early settlers of the actual grazing-potential, i.e. fragility of the newly created pastures, and assuming the utilisation-related threshold value of 40% (of the total UB), the actual pasture (grazing)-potential would have been considerably lower (Figure 11).

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[40] Ratio between available utilisable biomass for each of the months.

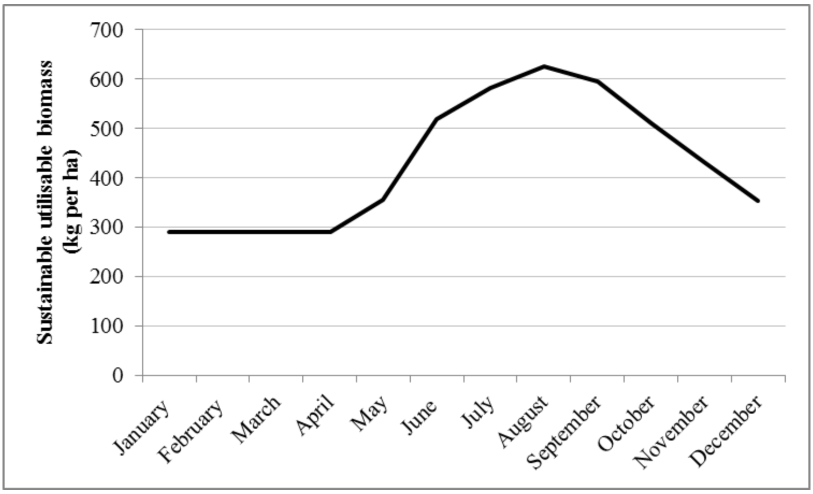

Figure 11. Sustainable utilisable biomass of pastures created through clearance of birch forests

In other words, if the utilisation of pastures exceeded the values shown in Figure 11 (626 kg/ha as the highest one), overgrazing would have occurred and production of biomass in the subsequent period would have been diminished. Also, in the case of significant overgrazing, it is possible that patches of land would have been denuded and hence opened to soil erosion.

The mean seasonal value of UB that could have been grazed from newly created pastures without overgrazing was c. 429 kg/ha, implying that the livestock holding of Gjáskógar would have required c. 121 ha of pasture areas. This figure can be used to suggest the possible degree of clearance of woodlands at and around low-ranking farms of the size of Gjáskógar. It is important to stress that this clearance would have provided sufficient livestock fodder for 12 months in an „average“ year. We may assume that during harsh winters, with heavy snow cover, particularly at high altitudes, as was the case at Gjáskógar, livestock could have been fed with hay made previously in areas already cleared for that purpose. The amount of fodder necessary for winter feeding could have been obtained from pastures already established through woodland clearance as described above. If they were used only for 8 months for grazing, they would still have offered sufficient biomass to be harvested in order to supply winter fodder. This way, not only could the livestock have been fed during the winter, but the possibility of increased pressure (and over-grazing/over-browsing) on the snow-free pastures and/or birch woodlands could have been avoided. However, taking into account the possibility of winter indoor feeding of dairy cattle with hay previously harvested from the home-field or wetland areas, and that the lambs, wethers, yearlings and barren ewes were usually driven to the highland pastures to graze during the summer, it appears that the need for pastures could have been even lower.

However, one needs to be aware that owing to the seasonal variation in UB, the effects of regrowth of birch as well as possible replacement of grasses by grazing-tolerant species (described in the sections 5.2.5.3 and 5.2.5.4.), the extent of clearance could have varied greatly, necessitating a modelling approach.

Applying the estimates of the rate of tree-felling, it would take between c. 10 (50 % efficiency) and 20 years (25 % efficiency) of continuous/permanent felling by 1 person, and between 3 (50 %) and almost 7 years (25 %) if 3 persons were involved in felling (Table 5); these figures indicate that the clearance for pastures was a long-term project.

Table 5. Time required for pasture clearance for the site of Gjáskógar (121 ha), with the involvement of 1 or 3 persons

Gjáskógar	**1 person**	**3 persons**
50 % eff.	c. 10 years	c. 3 years
25 % eff.	c. 20 years	c. 7 years

A problematic factor in estimates of this kind is that we do not know the number of people inhabiting the farms and thus the number of people available for such an activity. Nevertheless, some estimates exist and/or can be made.

A rough estimate can be made based upon the study of Friðriksson (1972). He proposed that 6 ewes and half a cow could have produced sufficient food for one man per year. Then, based on the estimated number of cattle (12) and sheep and goats (72), based on the farm’s architectural potential (byre, for cattle) and estimated proportion (for sheep and goats), in this case 1:6 (McGovern *et al.* 1988, p. 240, Table 1), at least 12 people lived at the farm, at the time of the maximum livestock potential. In that case, accepting the aforementioned estimates, it seems reasonable to assume that 2 (or 3) persons could have been involved in the tree-felling for the purpose of establishing the home-field areas, and that this involvement would not have disturbed other daily activities at the farm significantly.

This estimate is not that far from the one of McGovern (2003) who suggests that the household size of the low/mid-low ranking farm of Sveigakot, in the eleventh-early twelfth century AD, as estimated from the hall size, was between 7 and 10 people. Again, having 2 or 3 persons out of 10 largely occupied with felling activities does not seem an unreasonable deployment of labour.

However, some scholars suggest considerably lower figures (Thomson and Simpson 2007, p. 157), proposing that 3 – 5 people per low-ranking farm may be a more realistic estimate. Also, Vésteinsson and McGovern suggest that possibly no more than 2 or 3 people lived in Sveigakot during the earliest phase (Vésteinsson and McGovern 2012, p. 215). In the light of those figures, involvement of 2 or 3 persons in long-term clearance activities at low-ranking farms was an extremely expensive, if not unacceptable investment.

Indeed, it is hard to imagine permanent employment of adult work-force for clearance activities during the age of Settlement. We have to assume that the rate and efficiency of clearance at each farm varied frequently and greatly over the course of time (it is logical to assume that frequently there were no clearance activities at all). It is unfortunately very difficult to estimate how and when those variations occurred – and this is another reason for the modelling approach in which stochasticity played a significant role.

It is not suggested that this was the case at all low-ranking farms. For instance, at those positioned close to the coast (e.g. Grelutóttir), the possibility of using seaweed as a part of the livestock diet could have reduced pasture requirements and thus the degree of woodland clearance. At others (e.g. Háls), the type of economy (iron industry) was one that did not require significant extent of pasture areas or clearance for this purpose; there, the woodlands were maintained longer than in the area close to the nearby high-ranking farm of Reykholt (Sveinbjarnardóttir *et al*. 2007, p. 203).

5.2.4.3 Low-ranking farms: Sveigakot

Sveigakot serves as an example to illustrate the impact caused by sites of comparable or lower status to that of Gjáskógar, and possibly also a different policy of woodland exploitation in different environmental conditions (those of the Mývatn district, as opposed to Þjórsárdalur). In the case of Sveigakot, it is easier to arrive at estimates of this kind than was the case with Gjáskógar since Thomson and Simpson (2007) proposed possible vegetation reconstructions and grazing requirements on the Sveigakot estate, relying on more precise, realistic and, not least, newer estimates of the feed value of the grassland/woodland areas than McGovern and others (McGovern *et al.*1988) did in their study of Gjáskógar. Thomson and Simpson‘s study is a useful model for making this kind of estimate.

Thomson and Simpson proposed two vegetation reconstructions for the *landnám* period for the estate of Sveigakot. In the first, „birch“ reconstruction variant (Thomson and Simpson, *ibid*., p. 157), birch woodland and grassy heath would have covered 116 ha, while dwarf shrub heath would have covered 35 ha. The „heath“ reconstruction, on the other hand, implied the presence of 232 ha of grassy heath, 35 ha of dwarf shrub and no birch woodlands. Thomson and Simpson‘s study of grazing management suggested that both vegetation reconstructions could have supported sufficient livestock for the postulated household size (12 dairy cattle, 10 calves, 13 ewes, 9 lambs, 10 immature sheep, 4 wethers, 1 horse) with the appropriate management, while in the extreme cold scenario, the dwarf shrub heath would have suffered damage. As is the case with Gjáskógar, winter indoor feeding of livestock would have helped to avoid over-grazing/browsing in all the climate scenarios. Still, in the extreme cold scenario, it would have required both the culling of all the lambs and immature sheep in the autumn and haymaking on 16 ha each year in order to avoid over-grazing of shrub areas. The most serious danger for the estate of Sveigakot, even though it had sufficient resources, according to Thomson and Simpson, was the relatively small area of the estate, with little room to manoeuvre. If one of the Kráká river channels changed its course, it would have destroyed the wet meadow pastures, which were a necessity for winter fodder production. This might have been one of the reasons for shifting from a cattle- to sheep-intensive strategy by the end of the 10th century as is suggested both by the increasing ratio of sheep to cattle and the dereliction and non-replacement of the byre.

…if the area was fully forested

But what could have been the impact if the area was fully forested? Accepting that 116 ha was a minimum pasture area for the estimated number of livestock, it would follow that exactly this area would have had to be cleared to obtain sufficient pasture. Winter indoor feeding would require the clearance of 16 ha; in total this would imply that the livestock of Sveigakot could have been maintained, through appropriate management, involving the clearance of 132 ha if the area was originally fully forested.

The clearance of 132 ha of woodlands would take 11 – 22 years, if 1 person was involved in tree-felling year-round and 4 – 8 years if 3 persons were involved (Table 6). As is the case with Gjáskógar, these values suggest that pasture-clearance was a „long-term“, i.e. a multi-year, if not a multi-decade project.

Table 6. Time required for clearance for the site of Sveigakot (132 ha), with the involvement of 1 or 3 persons

Sveigakot	**1 person**	**3 persons**
50 % eff.	c. 11 years	c. 4years
25 % eff.	c. 22 years	c. 8 years

However, these deforestation figures calculated for Sveigakot are not proposed as an accurate reflection of the impact on woodlands by sites of this or similar status. Thus, it could be argued that not all sites of lower status would have applied the same livestock management measures. The archaeofaunal remains from the low-mid-ranking Granastaðir (Einarsson 1995), with a cattle: ovine ratio very similar to that of the high-ranking Hofstaðir, indicate that even farms of lower status applied a grazing/browsing policy similar to that applied at farms of the higher status, suggesting that they would have been responsible for woodland reductions in the same ratio due to the need for new pastures (primarily related to the needs of dairy cattle) and unrestricted animal browsing (mainly reflecting the needs of sheep).

5.2.4.4 Mid-high ranking farms: Stöng

The mid-high ranking farm at Stöng could give an indication of the possible impact caused by mid-high ranking farms, particularly those in wooded areas such as Þjórsárdalur.

According to McGovern and others (1988) the mid-high ranking farm at Stöng owned 20 cattle, while the population of both cattle and ovines, taking into account a cattle: ovines ratio of 1:5.13, was 103. As with the case of Gjáskógar, the authors of this study gave an estimate of the extent of pasture required to meet the needs of the local animal husbandry. Depending on the productivity of the pasture areas (200 – 1,000 kg/ha), the authors propose that 160 – 799 ha would have had to be mown in order to provide sufficient fodder. If the area was fully forested, the clearance would thus have been in the range of between 160 and 799 ha. The authors suggested 314 ha as the estimated site territory pasture, which seems surprising, at least in comparison with the larger territory pasture at Gjáskógar (450 ha). Nevertheless, as with the previous examples, an estimate of a maximum possible impact on the woodlands will be used here, based on a scenario in which the area was originally fully wooded, based mostly on the results produced by Thomson (2003) and Thomson and Simpson (2007). The estimates given will not allow for the application of management techniques that would lower the degree of woodland clearance required.

Taking into account the previously discussed values for fodder requirements and the productivity of grasslands, meeting the pasture requirements of the cattle at Stöng would have required the clearance of c. 101 ha of woodland. The sheep population at Stöng would require c. 87 ha of grazing throughout the year (12 months). In total this would imply that it would have been necessary to clear 188 ha. Clearance of this area through tree-felling would have taken c. 16 – 32 years if 1 person was involved and c. 5 – 10 years if 3 people were involved, and between c. 3 and 6 years if 5 persons were involved in the work (Table 7).

Table 7. Time required for pasture clearance for the site of Stöng (188 ha), with the involvement of 1, 3 and 5 persons

Stöng	**1 persons**	**3 persons**	**5 persons**
50 % eff.	c. 16 years	c. 5 years	c. 3 years
25 % eff.	c. 32 years	c. 10 years	c. 6 years

Even taking into account that Stöng, as a mid-high ranking site had more inhabitants, and thus a larger workforce than low, and low-mid ranking sites, and/or that it may have been able to involve people even from other sites in such activity, due to its power/hierarchical position, these values can be seen as costly and time-demanding. These values would be appropriate for a scenario in which the livestock grazed all year round. If winter indoor-feeding was practised for 4 months it could be assumed that the amount of fodder (hay) necessary would have been equal to the amount of grass that the livestock would have grazed on during four months, and indoor winter-feeding would also avoid the impact of browsing on the woodlands during that time, although some of the winter fodder may have been lopped stems of trees.

5.2.4.5 High-ranking farms: Hofstaðir

Research results and scholars’ estimates of livestock numbers for the site of Hofstaðir serve to indicate the possible impact on the woodland cover caused by high-ranking farms, particularly those in the region of Mývatn. As was the case with Sveigakot, the estimates given by Thomson and Simpson (2007) were used as a basis for this assessment.

Thomson suggested that the livestock population at the site of Hofstaðir could have consisted of 7 dairy cattle, 7 calves, 2 immature cattle, 29 ewes, 19 lambs, 15 immature sheep, 21 wethers/rams and 4 horses. She suggested two possible environmental reconstructions for the Hofstaðir estate:

1. A „birch“ reconstruction, with 739 ha of birch woodlands and 122 ha of dwarf shrub heath, on the one hand and 422 ha of grassy heath, 62 ha of bog and 133 ha of riverine vegetation on the other.

2. A „heath“ reconstruction, with 523 ha of birch woodlands and 245 ha of dwarf shrub heath on the one hand, and 422 ha of grassy heath, 123 ha of bog and 164 ha of riverine vegetation on the other.

Thomson and Simpson also suggested that the estate of Hofstaðir, under both of these environmental reconstructions, could have avoided overgrazing by applying appropriate management and that farming could have been sustainable even with a higher number of people and livestock in the long term. Even in the extreme cold-climate scenarios, overgrazing and/or shrub damage could have been prevented by management involving indoor-feeding of cattle, with ewes fed over the winter up to three months, and culling of immature sheep and lambs in September; haymaking on an extra 26 – 31 ha (depending on which of the two environmental reconstructions is chosen) would have yielded sufficient extra fodder for the over-winter requirements of the livestock. Thus, if management of this type were practised, no exploitation of the birch forests, dwarf shrub browsing or clearance in order to gain pastures would have been necessary at all. Apart from the extant pollen diagram (Lawson *et al.* 2007) that indicate almost no reduction of the woodlands at the beginning of the period, the fact that soil instability appeared later, in the medieval period (Simpson *et al.* 2004) could be confirmation both of Thomson and Simpson’s environmental reconstructions for the *landnám* period and also of the management applied, resulting in no, or minimal impact on woodlands.

…if the area was fully forested

As with the previous cases, an estimate of the possible impact on the woodland cover where the area was fully forested can be made, based on the estimated livestock numbers for the site of Hofstaðir. These estimates do not make allowance for the application of management of various types which could lower the pasture requirements and thus the degree of woodland clearance. These estimates suggest what could have been the maximum possible impact caused by farms similar to Hofstaðir that were positioned in heavily wooded areas.

In order to meet the needs of dairy cattle mentioned above, c. 81 ha of grassland would have been needed for grazing, taking c. 429 kg of hay into the account as an average fodder value of a hectare of grassland. This area (c. 81 ha) could have been sufficient for grazing demands through the summer periods, and could also have provided sufficient hay for the winter. In order to meet the needs of the sheep in both summer (grazing) and winter (hay), c. 71 ha would have been needed. Thus, meeting the basic fodder-requirements of the livestock at Hofstaðir would have necessitated the clearance of c. 152 ha if the locality was fully forested to begin with.

With 3 persons involved, tree-felling of this area would have taken between about 4 (50 % efficiency) and 9 years (25 % efficiency) and between 3 and 6 years if 5 persons were involved on the work (Table 8).

Table 8. Time required for pasture clearance for the site of Hofstaðir (c. 152 ha), with the involvement of 1, 3 and 5 persons

Hofstaðir	1 person	3 persons	5 persons
50 % eff.	c. 13 years	c. 4 years	c. 3 years
25 % eff.	c. 26 years	c. 9 years	c. 6 years

These values should not be understood as an ultimate reflection of possible clearance of woodlands at high-ranking farms. Thus, the information on the size of livestock population extracted from *Jarðabók* suggest for instance that the sheep population at Stóra-Mörk was more than 300, indicating that the degree of clearance for pastures may have been much higher. On the other side of the spectrum, the impact could have been lower due to different degrees of access to natural pasturelands and wetlands and/or possibly applied grazing management.

5.2.5 In essence

The requirements for pastures resulted in a significant degree of deforestation. Possible clearance in order to gain sufficient extent of pasture areas, reckoning with c. 4,000 farms at the time, could have been between c. 4,840 km²[41] and 7,520 km²[42]. As a ratio, this represents c. 20 – 32 % of the pre-*landnám* woodland area of almost 23,844 km². These figures suggest that the reduction of birch forest cover on a country-wide scale, although significant, still was not approaching near-total deforestation, which, in turn, is an idea that can easily be inferred from many of the existing pollen diagrams.

Clearance for pastures was a time-demanding and costly activity. Tree-felling was most probably the preferred method of clearance owing to the multiple benefits it involved, as outlined above. The use of fire, on the other hand, cannot have been frequently practiced, as there is simply very limited evidence for such activity; also, consideration of the pros and cons of burning supports this conclusion.

5.2.5.1 So, what was it all about?

Clearance for home-fields (0.016 – 1.51 %) and clearance for pastures (20 – 32 %) overlapped with needs of the settlement population for firewood and building material. In other words there was no need to clear woodlands for other requirements due to clearance for home-fields and pastures. Also, unlike the clearances for building material and firewood, which were most probably at low rates and were carried out only periodically and through selective cutting (with regards to the latter one, see Church *et al.* 2007), clearances for home-fields and pastures were carried out over vast areas and were the ones that left by far the most significant environmental signature. Thus, they can be seen as the main cause, the essence of the process of deforestation and for that reason they are the only types of clearances considered when creating the scenarios and series of agent-based models.

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[41] Given that all farms cleared an area similar to that cleared at Gjáskógar.

[42] Given that all farms cleared an area similar to that cleared at Stöng.

Caveat

Taking into account the limitations outlined before – the fact that not all of the farms were obliged to carry out clearance in order to meet the spatial, building and fuel needs and different degree of access to natural pasturelands and wetlands, but also occasional periods of light grazing (especially during the summer months when lambs, wethers, yearlings and barren ewes were driven to highland pastures to graze) which would allow for an increase in the production of grassy biomass and possibly applied management – for instance short-term prevention of grazing of pastures, the overall clearance could have been considerably lower than suggested above.

On the other hand, if we take into account factors such as woodland regrowth and replacement of grasses with species tolerant to grazing and possible damage due to overgrazing, clearance for pastures may have been even larger than suggested by the figures above.

The subsequent series of models, among other things, investigates in which way those factors affected the overall dynamics of woodland clearance.

5.2.5.2 Prevention of grazing at newly created pastures and occasional periods of light grazing

It is tempting to assume that the *landnám* was a period of increasing grazing pressure, as compared to initial availability of pastures, and that there was no place for prevention of grazing that would result in considerable increase of utilisable biomass. Still, we need to take into account the possibility that there were periods, conceivably soon after the removal of woodland cover, during which grazing was prevented in order to enhance production of existing grassy biomass.

Even though the abovementioned amount of utilisable biomass at newly created pasturelands (c. 50 % of the natural treeless pastures) would have been considered by the settler population as substantial, it is clear that it was still insufficient to cover the needs of projected livestock holdings. Needless to say, that amount of utilisable biomass could have been increased through temporary prevention of grazing and exposure to sunlight and it seems reasonable to assume that settlers were aware of that possibility, primarily due to the obvious and rapid increase in grass production during the summer months. Logically, this sort of management could have been applied in the early stage of settlement when the initial and still small livestock herds could have been fed with hay mowed in wetlands and/or even seaweed in coastal areas.

In addition to management, it is reasonable to assume that there were occasional periods during which grazing was light enough to enable even further (although only minor) increase in the grass production, this being primarily due to occasional changes in relationship between fluctuating livestock numbers and seasonal variations in utilisable biomass.

Unfortunately, there is a lack of research on possible rates of increase of biomass in pastures during periods of light grazing and/or total absence of grazing. Most of the available research originates from abroad, in locations that can hardly be regarded as comparable to Iceland. However, some values can be applied.

One of the assumptions behind this project is that the effect of prevention of grazing is inversely proportional to the loss of biomass due to regrowth of birch described below (section 5.2.5.3.). Therefore, the hypothesis is that in the case of total absence (prevention) of grazing, biomass would increase by c. 28 % in 22 years, which in turn implies growth of 1.2 % per year. In the case of light grazing, i.e. if utilisation would not exceed 40 % of utilisable grassy biomass, the assumption is that the rate of increase would have been two times less than in the case of total absence of grazing – c. 14 % in 22 years, and 0.6 % per year. Both of these possibilities were assessed in the subsequent process of modelling.

It is important to underline that the values suggested here indicate a linear rate of increase of biomass which can be regarded as a simplification of this environmental change. In reality it is more likely to expect that the rate of increase would follow a sigmoid curve which is, unfortunately, hard to reconstruct, primarily due to a lack of appropriate data.

5.2.5.3 Potential of regrowth

The regrowth potential of birch is nowadays known from forestry work, and this knowledge can contribute to the interpretation of the *landnám* woodland growth and regeneration, especially in the absence of browsing. Regrowth of birch should also be considered in the context of decrease of grazing biomass of the ground vegetation – with reappearance of birch, UB of the pasturelands would have diminished which would frequently imply additional clearance for pastures.

Firstly, knowledge of birch growth potential can contribute a key understanding to interpretations of dynamics of woodland cover changes, i.e. its regeneration and decline in the cases of absence and presence of livestock browsing. Thus, the existing studies show that birch regeneration after cutting is rapid and certain in the absence of browsing (Eysteinsson 2012) but rare and limited in the presence of browsing (Jónsson 2004). In general, regrowth of birch can be described as variably rapid, occasionally very slow, taking decades to reach 50 cm in height and occasionally very fast, taking only 1 year (Jónsson 2004).

Secondly, regrowth of birch also needs to be seen in the context of loss of UB of local grasslands. According to Sigurðsson and others (Sigurðsson *et al.* 2005: site B1, Figure 2, p. 884) after 22 years without grazing, the total biomass of birch forest floor was only c. 72 % of the nearby natural, treeless pasture.

These figures suggest that the regrowth of birch could have been a significant factor in the process of deforestation. Logically, it was given considerable attention in the subsequent process of modelling.

It is important to point out that the interpretation presented here is only a simplification of the process of regrowth. In reality, regrowth of birch was a more complex issue which did not depend solely upon the prevention of browsing and/or removal of livestock away from the landscape – it also depended on various other factors (e.g. state of local ecosystems, climate etc.), and it differed from one part of the country to another. Unfortunately, it is still poorly researched and its effects are therefore difficult to quantify in an appropriate way. As a result, it is extremely difficult to reconstruct it in its totality.

5.2.5.4 Replacement of grasses with grazing-tolerant vegetation

Over a long period of time (decades), with more or less continuous grazing, there is a possibility that grasses and forbs at newly created pastures would have been replaced by more grazing-tolerant vegetation – mostly ericacious dwarf shrubs, *Betula nana* or sometimes sedges, depending on location, site characteristics and the level of grazing.

It is likely to assume that during the *landnám*, the pasture potential increased in the years just after the forest clearance. In the following decades however it would have gradually declined since dwarf shrubs would replace grasses and forbs, eventually resulting in the dwarf-shrub heaths that cover much of Iceland today. Needless to say, a decrease in pasture-potential could trigger further clearance for pastures and as a result, the overall extent of deforested land could increase. Moreover, this means that the process of deforestation was a long-term activity since the pasture-potential of deforested areas was in permanent decline. Unfortunately, there are no existing studies in Iceland that can clarify the timing and rates of replacement. Still, some guesses can be made.

Today we know that vegetational succession depends on several factors such as distance to seed sources and dispersal mode of grazing-tolerant species, intensity of grazing, soil moisture, but also disturbances such as regular burning of grassland, a once common practice that has been declining only in recent decades. But above all, it is necessary to emphasise that the arrival of new vegetation to the site simply takes time. Studies around the world suggest different timing of replacement. Thus, at some locations, in the north-west of Spain, shrub cover increased greatly already after three years of sheep grazing (Benavides Calvo 2008, p. 130), while at others, in North America, this transition was more than obvious four years after the introduction of native herbivores (Briggs *et al.* 2005, p. 245). Unfortunately, these studies originate from the regions that are hardly comparable to Iceland and thus cannot be considered as relevant. Still they do provide hints about the possible range of values that can be taken into general consideration when building commonsensical assumptions about this process.

In general, we may assume that in Iceland, the replacement took a longer time after the *landnám* than it would today: the populations of grazing-tolerant species would have been smaller and more dispersed at the time of *landnám* than now. Today, the succession would most likely start within 5 years while during the *landnám*, the replacement would probably start within 10 years in areas close to the farms but perhaps not until after a century or even more in less grazed areas (Eysteinsson – pers.comm.).

The studies from abroad suggest annual rates of replacement that are considerably different from one another. Thus, in North America (Barger *et al.* 2011), the rate of replacement ranges from 0.5 – 2 %, while in southern Africa (Roques *et al.* 2001) shrub cover increased from 2 – 31 % in 43 years, implying (if we would take linear growth into consideration) the average annual increase of only 0.67 %. With regards to Iceland, unfortunately, as for the timing of replacement, estimates about the rate of replacement can only be given in the form of best-guess based information.

It is tempting to assume that in Iceland, the rate of replacement would probably be 5 – 10 % per year if the grazing was sufficient to prevent regeneration of the forest. During the *landnám* it is likely that the replacement rate would be slow, probably no more than 5 % per year with respect to heavy grazing and probably less than 1 % per year under lighter grazing (Eysteinsson – pers.comm.).

In general, a high degree of grazing pressure would increase the rate of succession by providing more opportunities for seeding due to removal of competing vegetation and livestock trampling creating openings. Contrary to that, the absence of grazing pressure would most likely result in regrowth of birch forest or birch/willow shrub depending on the site. Repeated burning would retard the rate of succession by killing woody plants thus maintaining a high proportion of grasses. Soil moisture is another important issue here: it affects succession by species, with species such as *Empetrum*, *Arctostaphylos* and *Calluna* becoming dominant on dry sites, *Vaccinium* and *Betula nana* on moister areas and mostly *Carex* on wet areas (Eysteinsson – pers. comm.)

In brief, we may easily envision a scenario in which, with time, as the area of forest declined, the area of grazing-adapted vegetation increased. As time passed, the rate of change after tree-felling would have been faster, simply because of greater seed influx of grazing adapted species from surrounding areas. As a result, the pasture-potential would have decreased and the re-initiation of clearance would have been inevitable.

The interpretation presented here is based on vegetation in Iceland today, which is largely the legacy of past land use. That it is a land use legacy is supported by the fact that succession can be reversed simply by excluding grazing, with the result that the dwarf-shrub heath is replaced by woodlands with a grass/forbs understory (Sigurðsson *et al*. 2005).

Still, this interpretation needs to be recognised as a simplification which does not provide accurate depiction of the overall process of replacement of grasses by grazing-tolerant vegetation on a country-wide scale. For instance, today in Iceland it is easy to notice considerable differences in grazing-tolerant vegetation between soil types and various parts of the country. Thus, some areas of Iceland, in particular those with intermediate soil moisture tend to still be grassy even after centuries of grazing. On the other hand, wetter and dryer areas contain ericacious, *Betula nana* or moss heath while the dryest ones are usually eroded. In some areas in the north-west of Iceland (Dalasýsla, Húnavatnssýslur and Skagafjörður and to some extent Eyjafjörður), the grazing land is, to a great extent, still grassland. In the Northeast and parts of East, South and West of Iceland there are ericaceous heaths whereas moss heaths predominate in large parts of the East, South and West Iceland. It is therefore obvious that there is a significant degree of variation in the outcomes of grazing throughout the country and it is reasonable to assume that there was also an enormous variation in the timing of this environmental change (Eysteinsson – pers. comm.).

Unfortunately, as previously stressed, there are no references that can clarify uncertainties regarding the issue of vegetation replacement, e.g. the time factor and its degree. Also, it would be difficult to extrapolate that kind of information from the existing pollen diagrams since the grazing-tolerant vegetation is largely insect-pollinated and therefore not well represented in the sediments (Eysteinsson – pers.comm). Consequently, research studies like this need to rely on best-guess based information in an attempt to deal with a variable that obviously exists in the environment but which in terms of numerical expression still remains a conundrum.

6 Scenarios of deforestation

6.1 Introduction

An analysis of the state of the art suggests that there is no simple and single interpretation of the deforestation process. Instead, the studies already made indicate that the trajectory of this environmental change, i.e. its essence – clearance for home-fields and pastures – has to be explained in different ways, through different descriptive narratives, i.e. scenarios. Furthermore, it is obvious that the whole process can be analysed from various palaeoecological, archaeological and/or sociohistorical perspectives. As a result, an innumerable number of scenarios can be developed to explain its course. I propose here that the modern knowledge on the course of deforestation can be reduced to four distinct scenarios. Each scenario depicts a plausible projection of the course of deforestation, in relation to the general extent, pace and allocation of clearance, the possibility of clearance for common benefits, patron-client relationships and the general engagement of the labour force as some of the keys to understanding the dynamics of impact on woodlands.

The four proposed scenarios are:

Scenario 1

This scenario allows for permanent, uncontrolled and unlimited woodland clearance. In this scenario, each farm, regardless of its status and/or patron-client relationship, cleared the forests independently.

Scenario 2

This scenario suggests limited clearance, made in accordance with the projections of future needs of the planned livestock herds at each of the farms. Those projections, in turn, would have been carried out in accordance with the contemporary alterations in the utilisable biomass available at the newly created pastures. According to this scenario, each farm, regardless of its status and/or patron-client relationship, cleared the forests independently.

Scenario 3

With regards to patron and client farms, this scenario allows for continuous and collaborative, but limited clearance of forests, made in accordance with the projections of future needs of the planned livestock herds in a particular community, i.e. cluster of farms. It envisages that clearance was initiated by the patron, drew on labour from each newly established, incoming client farm, and was applied until the pasture requirements of patron and of both existing and planned dependent client units were met. In most cases, as client farms would not have been established at the same time, not all would have participated in clearance. In some cases clearance would have been done solely by the patrons, in others they would have been assisted by the occupants of the first client farms, and this effort could have been sufficient for the pasture clearance planned for later clients as well. In the case of independent farms, this scenario allows for an autonomous, self-governing clearance limited by the projections of future needs of their livestock, as is also allowed for in Scenario 2.

Scenario 4

In the case of the clusters of farms, this scenario allows for a phased and collaborative, limited forest clearance dictated by the projections of future needs of the planned livestock herds of all the farms from a cluster present at any given time. Clearance would have been initiated by the patron, drawing on labour from the newly-established client units until the projected pasture requirements of all the farms from a cluster present at the time were met. The process would have been repeated with the establishment of each new farm, i.e. arrival of new settler unit. Thus, more manpower would have been available for each new clearance effort. This communal approach to clearance resulted in later-established farmsteads needing less effort, proportionate to available man-power, to clear the woodlands than those established earlier. In general, the phased nature of this scenario is shaped by the rhythm of the influx of new settlers; the more spread out the influx was, the more phased the clearance was. With respect to independent farms, this scenario allows for autonomous, self-governing clearance limited by the projections of future needs of their livestock, as is also suggested by Scenarios 2 and 3.

Caveat

This chapter establishes only the theoretical basis for the quantitative exercise discussed in Chapter 7.

6.1.1 Differences between scenarios

Before proceeding to an examination of the scenarios, it is important to stress the principal differences between them (see Table 9).

The major difference lies in the extent of clearance they allow for. Scenario 1 allows for permanent, uncontrolled and unlimited clearance that can be expected to have resulted in a drastic reduction of woodland cover. Under scenarios 2, 3 and 4 the process of deforestation was for the most part limited and dictated by the projections of future needs of the planned livestock herds for pastures. The expectation is that these scenarios lead to significant, but not drastic loss of woodland.

With regards to the clusters of farms, the most important difference is that the first two scenarios, i.e. Scenarios 1 and 2, allow for an independent, self-governing clearance, made at the discretion of the inhabitants of each farm, regardless of their hierarchical position, whereas the last two, i.e. Scenarios 3 and 4, allow for a conjoined, collaborative clearance for common benefits, thus taking account of different types of social and tenurial relationships.

The major distinction between scenarios 3 and 4 lies in the pace of clearance – whereas scenario 3 allows for continuous clearance, scenario 4 suggests phased, periodical clearance of woodlands.

Finally, only the first two scenarios allow for two different variants concerning the location of clearance for clients’ pastures. According to variant „a“, clearance for clients’ pastures was concentrated in the vicinity of their own households, whereas variant „b“ suggests that clearance for the same purpose was located around patrons’ farmsteads and their pastures.

Table 9. Overview of scenarios

Farms \ Scenarios		**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
		Unlimited clearance	Limited clearance	Limited clearance	Limited clearance
Independent		Self-governing	Self-governing	Self-governing	Self-governing
		Initiated around its own home-field	Initiated around its own home-field. Limited by projections of future needs of its own planned livestock herds	Initiated around its own home-field. Limited by projections of future needs of its own planned livestock herds	Initiated around its own home-field. Limited by projections of future needs of its own planned livestock herds
Cluster	**Patron**	Self-governing	Self-governing	Collaborative (continuous)	Collaborative (periodical)
		variant a: Initiated around its own home-field	***variant a:*** Initiated around its own home-field. Limited by projections of future needs of its own planned livestock herds	Initiated around its own home-field. Limited by projections of future needs of its own planned livestock herds and planned livestock herds of both existing and planned client units	Initiated around its own home-field. Limited by projections of future needs of its own planned livestock herds and planned livestock herds of existing client units
		variant b: Initiated around its own home-field	***variant b:*** Initiated around its own home-field. Limited by projections of future needs of its own planned livestock herds		
	Client	Self-governing	Self-governing	Collaborative (continuous)	Collaborative (periodical)
		variant a: Initiated around its own home-field	***variant a:*** Initiated around its own home-field. Limited by projections of future needs of its own planned livestock herds	Initiated around patron‘s home-field and/or pastures. Limited by projections of future needs of its own planned livestock herds and planned livestock herds of patron and both existing and planned client units	Initiated around patron‘s home-field and/or pastures. Limited by projections of future needs of its own planned livestock herds and planned livestock herds of patron and other existing client units
		variant b: Initiated around patron‘s home-field	***variant b:*** Initiated around patron‘s home-field and/or pastures. Limited by projections of future needs of its own planned livestock herds		

6.2 Preambles to scenarios 1 and 2

6.2.1 Reasons for self-governing clearance

The key argument for supporting the idea of self-governing clearance is the general shortage (and hence high cost) of labour.

Clearance of woodlands was a labour- and time-consuming activity (see Chapter 5) and, depending on a farm's status, to a greater or lesser degree, an expensive investment, not least in light of the general shortage of labour which can be assumed for the period under discussion. Shortage of labour was however not just a *landnám*-related problem. As many authors suggest, it was a considerable obstacle in the overall agricultural and farming economy even later in the medieval period (Durrenberger 1990; Kristinsson 2000, pp. 276 – 278).

As Thomson and Simpson suggested (Thomson and Simpson 2007, p. 159), household sizes at high-ranking sites could have ranged from 10 to 15 people[43]. Taking into account the use of slave labour, this was more or less sufficient to fulfill all the requirements for home-field- and pasture-clearance within a period of three decades (see estimates for Stöng, section 5.2.4.4, and Hofstaðir, section 5.2.4.5.). Thus, it may be assumed that high-ranking farms were self-sustainable and capable of establishing efficient pastoral economies relatively soon. However, any deployment of labour at other locations, especially remote or poorly accessible ones, would have been expensive. Thus, it can easily be imagined how costly it would have been for the large patrons at, for instance, Holt in Vestur-Eyjafjallahrepur to clear home-fields and/or pastures for each of its dependent farms, especially if at the same time they were working on the development of their own property. Even if an early clearance would have been applied for the benefit of prospective clients, it could take several years, if not decades, to establish pastures for the newcomers, and this would have, of course, delayed the patrons' goal of establishing fully operational client-pastures as early as possible.

In theory, the entire process of early woodland clearance could have been accomplished rapidly through burning. However, as mentioned previously in Chapter 5, there is a lack of evidence which could be used to support this idea (e.g. Erlendsson 2007, p. 155).

To complicate the issue further, we must also allow for a post-clearance process that would also require a large number of man-hours. After a given area had been deforested through cutting, a huge amount of both foliated and non-foliated biomass would have remained that would have needed to be further processed. Leaving it on site would not have served the patrons' purposes and above all, pastures would not have been easily passable for people or livestock. Thus, processing of the trees cut down for leaf-fodder and/or building material/firewood would have been necessary, and this would have raised the overall cost of clearance which, in the end, might have been a reason why patrons avoided clearance solely for clients' home-fields and pastures.

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[43] Vésteinsson and McGovern (2012), aiming to establish a minimum estimate, argue for considerably lower historical average which was taken into account in the modelling stage of this project.

In cases where livestock numbers were insufficient to do the job through browsing, an appropriate subsequent maintenance of pastures, i.e. prevention of birch regrowth through repeated cutting, would have required long-term labour deployment, even though it would only have been on an occasional basis. The knowledge of growth (regrowth) potential of birch can illustrate how hard it must have been to maintain newly gained pastures in good condition. The figures shown in Chapter 5 indicate that forests could have regained much of their biomass relatively quickly, i.e. in a matter of decades, which would have seriously diminished the effectiveness of an early clearance and in general would have increased the overall cost of clearance for pastures. Unless regrowth was prevented by livestock browsing or through swidden, for which there is insufficient evidence, prevention of birch regrowth would have been a highly demanding and expensive activity.

Therefore, extensive clearance for the benefit of future clients would have required an enormous labour investment and the logical conclusion is that patrons would have decided to leave it to the newcomers (clients).

In addition to this, one also needs to be aware how unsustainable a converse situation could have been in which the same clients could have been called upon when the patron’s farm needed extra manpower. Clients could, in later times, be obliged to provide various kinds of labour-support to their patrons such as *dagslátta* (cutting of hay) and *mannslán* or *skipsáróðrarkvöð* („serving on the landlord’s fishing boat for part of the year“, Thomson 2003, p. 44). However, labour-force borrowing could not have been on a very large scale, since a substantial deployment of labour away from client farms would have diminished their labour potential and thus the efficiency of their own farming, and hence productivity and ability to pay rent. A lack of labour at those farms would also have resulted in a smaller amount of collected hay for example, which could have had serious implications for overwintering of the livestock.

Therefore, it may be assumed that borrowing labour and/or deploying it at other locations was avoided. Hence, self-governing, independent clearance was the only option for settlers, regardless of their hierarchical position and/or patron-client relationship.

6.2.2 Allocation of clearance for pastures

Variant „a“ and variant „b“

As noted above, scenarios 1 and 2 allow for two variants concerning the allocation of clearance for clients’ pastures:

a) variant „a“ suggests that clearance for clients’ pastures was allocated in the vicinity of the clients’ home-fields, while

b) variant „b“ allows for the idea that clearance for the same purpose was concentrated around patrons’ farmsteads and their pastures.

Variant „a“ covers the motives for establishing new pastures at remote locations for at least two obvious reasons. Firstly, this was the most logical way of marking the extent of a patron’s property – through clearance of woodlands at remote locations they would have been able to claim the ownership of distant areas and express the „greatness“ of their estate. Secondly, in the event of failure on the part of a client to manage pastures properly (e.g. if the rate of clearance was lower than the rate of livestock growth, which would lead to overgrazing and possibly subsequent soil erosion), the central pasture areas around the patrons' households would still be in the desired condition, dependent only on the efficiency of the patrons' management. Also, any environmental degradation of the remote clients' pasture areas would not have had considerable negative effect on the patrons' home-fields and/or pastures situated in the immediate vicinity of their households.

Variant „b“ reflects the aim of patrons to concentrate the largest possible extent of pastures in one location, close to the central household, for the following reasons. Apart from easier monitoring and control of land use or simply easier pasture maintenance, this would have enabled improved pastoral management through interchangeable use of grazing areas within one large pasture, which would have allowed settlers to maintain the overall quality of the newly gained grasslands. Therefore, this variant would undoubtedly have been beneficial for the patrons.

6.3 Scenario 1: Self-governing and unlimited clearance. Overoptimistic expectation of the Settlement population

The main assumption behind this scenario is that the Settlement population had overoptimistic expectations regarding the growth of livestock population.

In general, clearance of woodlands would have been practised at many locations where areas chosen for settlement were fully forested or where existing nearby pastures were insufficient to meet the needs of a growing animal husbandry economy. Clearing the areas of trees would have exposed forest floors to sunlight, and if they were periodically rested they could, at a suitable interval following clearance, gain sufficient biomass to be used as quality pastures.

Reconstructions of livestock numbers (e.g. McGovern *et al.* 1988) and grazing needs (calculated from Thomson 2003) have been used as a basis for quantifications of clearance for pastures (see Chapter 5). But going beyond numbers, I propose here, under this scenario, that it was unrealistic supposition regarding the development of animal husbandry economy that was the actual cause of the high impact on woodlands. Put simply, the drastic decimation of woodlands resulted from over-optimistic expectations of the early settlement population regarding the growth of their livestock herds. How are these over-optimistic expectations to be explained?

If we examine simple calculations based on a heifer's reproductive rate, we reach the conclusion that the settlers could easily have established a „high-hopes“ economy. For instance, with a starting population of two, a dairy-cattle herd can in theory be easily expected to increase up to a dozen in the first 10 years (calculated from Alvard and Kuznar 2001; Kennett and Winterhalder 2006). A high number of dairy cattle is therefore, in theory, easy to reach. Exponential growth of livestock numbers would have entailed increasing needs for pastures, which, in turn, would have been the reason for unlimited deforestation. In addition, even though the increase in livestock numbers may not have developed as planned, clearance of woodlands can have continued for the simple reason that owning large pastures implied having the potential to sustain large livestock herds in the future, which implies profit and in the end, power. Therefore, it may be concluded that pasture-clearance became the foremost among the patrons' priorities regarding development of their properties. As some authors stress, „pasture was the ultimate source of wealth and power“ (McGovern *et al.* 2007, p. 29).

In addition to this, if we take into account the lack of any authority or established set of regulations that could have operated in favour of environmentally-friendly policies on the part of the settlers, it becomes obvious that a situation similar to a „tragedy of the commons“ (Hardin 1968), i.e. an uncontrolled exploitation of resources motivated only by individual interests of the farmers, could have easily happened. In simple terms, the absence of a ceiling on the first settlers' ambitions would have meant that the initial impact would have been immense. In the absence of a rationally governed economy, huge clearance for pastures could have taken place, following an exponential growth of the number of cattle.

6.4 Scenario 2: Self-governing and limited clearance. Reasons for limited clearance

The principal assumption behind this scenario is that at some stage, after years of clearance for pastures, settlers would have reached projected numbers of livestock and fulfilled their initial expectations regarding the size of their animal husbandry economies. Consequently, further clearance for pastures would not have been necessary and it would have been halted.

An idea supporting this scenario is that at some stage, settlers may have become aware of the degree of destruction of natural environment and the possibility that eventual further expansion of their economies (which would imply further environmental degradation, i.e. further clearance for pastures and possibly overgrazing) would inevitably lead to unaffordable decimation of natural resources. We may assume that settlers were aware that reaching those points would endanger not just development but also the survival of their economies. Also, settlers may have realised that they could not exploit natural resources in a way they did in their homeland regions whose environments were simply more stable and resilient (Ogilvie and McGovern 2000, p. 392). Needless to say, clearance of woodlands for pastures would have been terminated.

6.5 Additional remark on scenarios 1 and 2: A rudimentary type of land tenure

According to scenarios 1 and 2, each farm was responsible for clearance of its own home-fields and pastures, regardless of its status. High-ranking and independent settlers who settled the country in the first phase of the settlement process, would have claimed large areas of land and cleared the forests solely for their own benefit – establishing sizeable pastures carrying considerable numbers of livestock, some of which would have been offered for domestic and international trade, already well developed during this period (Short 2010, p. 124). In any case, it seems conceivable that those settlers who decided to rent out the land to newcomers would generally have rented out only uncultivated areas and less productive land. No intentional investment of labour would have been made in those areas and frequently unavoidable clearance of forests for home-fields and pastures was thus left to be done by newcomers (clients), upon their arrival.

However, due to differences in the dates of the establishment of farms, these two scenarios allow for the possibility that some of the farms that were established early cleared very large areas of woodland and thus deforested not only their immediate neighbourhood but also remote areas where other farms were established later on.

Hence, while sometimes the land tenure system involved renting uncultivated, wooded areas only, on other occasions it involved the renting of cleared areas – and therefore cannot be considered as being of one constant pattern during the period under discussion.

The bottom line of these two scenarios is that there would have been no labour-borrowing and/or deployment of labour at other locations, or engagement of the labour force for someone else's benefit. Primarily due to this absence of pre-arrangement of areas that were to be rented out, but also due to the lack of subsequent, cooperative activities and labour-network, these two scenarios may be regarded as ones that allow for a rudimentary, elementary land tenure system.

The efficiency or inefficiency of strategies applied within scenarios 1 and 2 depended mainly on the time of the establishment of each of the farms as well as the rates of clearance, growth of livestock population and environmental response. These variables were addressed in the series of agent-based models, as in the other scenarios.

6.6 Preambles to scenarios 3 and 4

6.6.1 Collaborative clearance for common benefit

The idea of collaborative clearance for common benefit is based on the assumption that occasionally, intense communal effort could have been employed in farming activities in spite of the general lack/high cost of labour. This assumption is corroborated, albeit indirectly, by written sources and has been stressed by many authors as a particularly important factor in the overall management of the use of natural resources (e.g. Thomson 2003). Hence, on the one hand, patrons, in addition to clearance for their own pastures, would have initiated and participated in clearance of woodlands for clients' pastures at an early stage. On the other hand, newcomers/clients, apart from clearing woodlands for their own pastures, participated in clearance for the patrons and also for other clients' pastures. As a consequence, the land tenure system occasionally (depending on the time of the establishment of farms and extent of early clearance) involved the renting of cleared areas.

6.6.2 Collaborative clearance – where and why?

The frequently quoted sentence from the *Landnámabók,* of the wealthy man Blund-Ketill in Borgarfjörður, who „had cleared the forests and established the settlements there"

(Benediktsson (ed.), 1968, p. 84), can be used to support the idea of early clearance, done for the benefit of the client population. Obviously, this description does not necessarily imply that patrons would have cleared all of the forests in the corresponding areas. More importantly, and what these two scenarios suggest, they would not have accomplished clearance solely by their own workforce, but with the help of clients‘ workforce. What this sentence suggests is that patrons might have been willing to take the risk of investing labour in woodland clearance for the benefit of the incoming population, soon to become clients. This labour would pay off quickly since clients would pay rent in livestock and dairy products relatively shortly after settling. Also, patrons would be able to monitor and manage the growth of grass and thus grazing potential of the cleared areas by themselves. Therefore, the productivity of newly created grasslands would depend on their own decision-making and not the labour potential and/or efficiency of the client communities.

I propose here, under Scenarios 3 and 4, that this early clearance should be seen as consisting solely of clearance for pastures at locations in the immediate vicinity of patrons’ farmsteads. Even though scenarios 3 and 4 suggest that a long-term investment of man-power for creating clients’ pastures was an „acceptable“ option and not an extremely heavy burden for high-status farms, we may still assume that it was an expensive activity at remote locations. Also, the possibility of the abovementioned close monitoring and direct management of the newly established pastures, together with the control of overall livestock numbers, could have been an equally solid reason for this.

With respect to clearance done by the client population, it is necessary to stress that these two scenarios do not allow for the „a“ variant. The client labour population would only have cleared woodlands for home-fields in the immediate vicinity of their households, whereas clearance for pastures would have taken place only in the immediate vicinity of the patrons’ pastures, this being primarily due to the aforementioned patrons’ aim of having pastures in a single location. This pattern of clearance would therefore have entailed centralized labour and thus relatively easier livestock and pasture management than the patterns suggested in Scenarios 1 and 2.

6.7 Scenario 3: Continuous collaborative clearance. Principal reasons behind continuous clearance

The principal advantage of continuous clearance, suggested by scenario 3, was to obtain pasture areas as soon as possible – patrons were aware that renting out areas cleared of woodlands would increase the agricultural potential of rented land and thus the rent itself. Cleared areas would, after a period of resting, have a greater fodder potential, hence raising the value of their rent.

Another premise for this kind of clearance was a demarcation of the pastoral profile of the patrons’s property – the location, size and potential of the future pastures and of each of the planned, dependent settlements. Hence, this scenario also suggests that the *landnám* period was at least up to some degree a stable one, since predictive plans of that kind were possible.

6.8 Scenario 4: Phased collaborative clearance. Principal reasons behind phased clearance

The first argument supporting a scenario with a phased clearance of woodlands is the limited labour available. The labour force would have grown with the arrival of every new group of settlers (the majority destined, after the initial phase of the *landnám*, to become clients). This pattern of phased clearance, even though limited by only occasional presence of sufficient labour force, was a way of containing the overall cost of clearance.

This pattern also suggests the absence of predictive, long-term plans about development of the land-tenure system and thus the pastoral economy. The absence of plans reflects instability in the settlement dynamics; settlers probably knew neither the number or timing of the establishment of the incoming farms, nor their size and potential and thus power, and therefore relationships. This scenario, which suggests that the rate and extent of clearance depended on the number of settlements at any given time, reflects only short-term plans of rich people regarding the growth of their property, and may also reflect a variety of socially unpleasant circumstances (e.g. political conflicts, strife and violence) both in Iceland and their homelands. In other words, unlike Scenario 3, this one therefore assumes that the *landnám* was a politically unstable period. On the other hand, the short-term plans can also imply that some sort of a time-wise buffering strategy has been applied in order to slow down the overall rate of clearance and break down the continuity of environmental degradation, which became apparent after a certain period of time.

6.9 Additional remark on scenarios 3 and 4: A more networked society.

Scenarios 3 and 4 allow for a more networked society than proposed in Scenarios 1 and 2. Here, the land tenure system is more complex and occasionally allows for the renting of woodless areas. Labour would have been employed in all directions and for the benefit of all the members of the community. A more networked society would naturally involve more regulations and rules, which could possibly involve higher efficiency, although it is well known that throughout history, introduction of more rules and regulations has not neccesarily led to progress and higher economic efficiency (e.g. Sée 2004, p. 87). In any case, the efficiency or inefficiency of these two scenarios, as with the first two, depends mostly on the variables examined in the accompanying series of agent-based models: the time of establishment of farms, rates of clearance, livestock growth and environmental response. In other words, these two scenarios could, like the others, have resulted in serious environmental degradation, due to erroneous or simply inappropriate management, reflected in a mismatch between rates of clearance and growth of livestock numbers. Whether this was the case or not was clarified by examining those variables in the series of agent-based models.

6.10 Prior to modelling: caveat

It is important to stress that this project does not propose a chronological order of the abovementioned scenarios. However, it should not be neglected that for instance, the first or the second scenario could have been applied only as the initial one and only for a short period of time, i.e. only a few years or a decade, after which the *landnám* population switched to a more networked economy with, for instance, conjoined clearance for common benefit, shaping overall land use in a different way, i.e. an economy such as the one proposed in the last two scenarios. In general, social-organization changes, which might have entailed changes in the land tenure system and which were common in non-state societies, frequently brought with them improvements in productivity. This is something that many scholars agree upon (e.g. Durrenberger 1988, p. 244) and this could also have been the case with early Icelandic society at some stage. Nevertheless, for the purpose of this project, these scenarios were modelled each as a separate whole that lasted until the end of the 10th century.

7 The *ICELANDEF* models

7.1 Introduction

This chapter gives a description of the series of *ICELANDEF* models. The models were constructed using the ODD protocol (basic and updated version: Grimm *et al.* 2006 and Grimm *et al.* 2010) which consists of three blocks:

I Overview

1) Purpose
2) Entities, state variables and scales
3) Process overview and scheduling

II Design concepts

1) Basic principles
2) Emergence
3) Adaptation
4) Objectives
5) Prediction
6) Sensing
7) Interaction
8) Stochasticity
9) Observation

III Details

1) Initialization
2) Input
3) Sub-models

7.2 Purpose of the models

The purpose of the *ICELANDEF* models is to investigate the process of clearance for home-fields and pastures as the most significant parts of the process of the loss of Iceland‘s original woodland cover. The models simulate the process of deforestation through four scenarios in the regions of Vestur-Eyjafjallahreppur, Mývatn and Borgarfjörður, with the aim of clarifying its timing, dynamics and consequences.

7.3 Entities, state variables and scales

7.3.1 Entities and state variables

Individual agents, collectives, spatial units and the environment are entities in each of the models. Each *agent* in a model represents a farm and a *collective* represents a cluster of patron and client farm(s). Each *spatial unit*, i.e. grid cell, represents a fraction of a certain type of land cover whereas *environment*, which consists of spatial units, refers to the recreated and spatially explicit environment of each of the sample study areas. The state of each of these entities is characterised by its „state variables“ or attributes.

7.3.1.1 Individual agents and patches

Each of the individual agents and patches are characterised by their constant and changeable state variables. Whereas constant state variables are defined and put in order during the setup procedure prior to every simulation run, changeable state variables alter in the course of time, during the simulation run. A list of agents, some of their constant state variables and some of the major parameters of the models is shown in Table 10 below.[44]

Table 10. List of agents and their constant state variables

Vestur-Eyjafjallahreppur:

Farms/Agents	**Rank**	**Status**	**Establishment (AD)**	**Home-field (ha)**	**Livestock heads (cattle/ovines)**
Cluster 1					
Holt	High	Patron	871 – 891	4 – 9	47 – 126
Ormskot	Low	Client	* – 1000	1 – 5	23 – 46
Vallatún	Low	Client	* – 1000	1 – 5	57 – 150
Gerðakot	Low	Client	* – 1000	1 – 5	26 – 81
Hellnahöll	Low	Client	* – 1000	1 – 5	21 – 54
Efstakot	Low	Client	* – 1000	1 – 5	19 – 35
Efri-Grund	Low	Client	* – 1000	1 – 5	14 – 30
Cluster 2					
Ásólfsskáli	High	Patron	871 – 891	4 – 9	37 – 112
Skálakot	Low	Client	* – 1000	1 – 5	19 – 86
Moldnúpur	Low	Client	* – 1000	1 – 5	19 – 102
Cluster 3					
Ysti-Skáli	High	Patron	871 – 891	4 – 9	44 – 184
Aurgata	Low	Client	* – 1000	1 – 5	10 – 26
Cluster 4					
Efri-Holt	Low	Patron	871 – 891	1 – 5	33 – 103
Efri-Hóll	Low	Client	* – 1000	1 – 5	16 – 42
Syðri-Hóll	Low	Client	* – 1000	1 – 5	21 – 74
Cluster 5					
Fit	High	Patron	871 – 891	4 – 9	12 – 49
Fitjarmýri	Low	Client	* – 1000	1 – 5	35 – 89

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[44] Due to the large volume of data, other, less important state variables are shown in other tables in this chapter.

Farms/Agents	**Rank**	**Status**	**Establishment (AD)**	**Home-field (ha)**	**Livestock heads (cattle/ovines)**
Cluster 6					
Sandar	Low	Patron	871 – 891	1 – 5	no data; (8 – 57) / (12 – 150)
Hjáleigusandar	Low	Client	* – 1000	1 – 5	20 – 13
Rotin	Low	Client	* – 1000	1 – 5	11 – 12
Cluster 7					
Stóri-Dalur	High	Patron	871 – 891	4 – 9	14 – 48
Neðri Dalur	Low	Client	* – 1000	1 – 5	28 – 106
Króktún	Low	Client	* – 1000	1 – 5	9 – 26
Dalskot	Low	Client	* – 1000	1 – 5	8 – 23
Eyvindarholt	Low	Client	* – 1000	1 – 5	31 – 125
Cluster 8					
Stóra-Mörk	High	Patron	871 – 891	4 – 9	69 – 342
Sýðsta-Mörk	Low	Client	* – 1000	1 – 5	19 – 116
Miðmörk	Low	Client	* – 1000	1 – 5	14 – 103
Independent farms					
Varmahlíð	Low	Independent	871 – 891	1 – 5	39 – 54
Björnskot	Low	Independent	871 – 891	1 – 5	13 – 44
Rimahús	Low	Independent	871 – 891	1 – 5	18 – 55
Miðskáli	Mid	Independent	871 – 891	4 – 9	31 – 90
Núpur	High	Independent	871 – 891	4 – 9	64 – 263
Hvammur	Low	Independent	871 – 891	1 – 5	23 – 74
Vesturholt	Low	Independent	871 – 891	1 – 5	31 – 39
Nýibær	Low	Independent	871 – 891	1 – 5	24 – 58
Sauðhúsvöllur	Low	Independent	871 – 891	1 – 5	16 – 30
Seljaland	High	Independent	871 – 891	4 – 9	36 – 181
Tjarnir	Low	Independent	871 – 891	1 – 5	31 – 57
Hamragarðar	Low	Independent	871 – 891	1 – 5	11 – 48
Brúnir	Low	Independent	871 – 891	1 – 5	no data; (8 – 57) / (12 – 150)
Borgareyjar	Low	Independent	871 – 891	1 – 5	18 – 68
Dalssel	Low	Independent	871 – 891	1 – 5	20 – 92
Steinmóðarbær	Low	Independent	871 – 891	1 – 5	21 – 89

Mývatn:

Farms /Agents	Rank	Status	Establishment (AD)	Home-field (ha)	Livestock (cattle/ovines)
Cluster 1					
Skútustaðir	High	Patron	871 – 891	4 – 9	12 – 162
Álftagerði	Low	Client	* – 1000	1 – 5	4 – 64
Cluster 2					
Reykjahlíð	Mid	Patron	871 – 891	4 – 9	9 – 90
Gröf	Low	Client	* – 1000	1 – 5	3 – 50
Stöng	Low	Client	* – 1000	1 – 5	no data; (2 – 12) / (25 – 204)
Independent farms					
Brettingsstaðir	Low	Independent	871 – 891	1 – 5	no data; (2 – 12) / (25 – 204)
Beinistaðir	Low	Independent	871 – 891	1 – 5	no data; (2 – 12) / (25 – 204)
Steinbogi	Low	Independent	871 – 891	1 – 5	no data; (2 – 12) / (25 – 204)
Helluvað	Low	Independent	871 – 891	1 – 5	no data; (2 – 12) / (25 – 204)
Litlu-Gautlönd	Low	Independent	871 – 891	1 – 5	no data; (2 – 12) / (25 – 204)
Arnarvatnssel	Low	Independent	871 – 891	1 – 5	no data; (2 – 12) / (25 – 204)
Gautlönd	Low	Independent	871 – 891	1 – 5	12 – 139
Girðingar	Low	Independent	871 – 891	1 – 5	no data; (2 – 12) / (25 – 204)
Hörgsdalur	Mid	Independent	871 – 891	4 – 9	no data; (2 – 14) / (12 – 192)
Hrísheimar	High	Independent	871 – 891	4 – 9	no data; (9 – 12) / (119 – 162)
Þorleifsstaðir	Mid	Independent	871 – 891	4 – 9	no data; (2 – 14) / (12 – 192)
Baldursheimur	Low	Independent	871 – 891	1 – 5	6 – 133
Sveinsströnd	Low	Independent	871 – 891	1 – 5	6 – 110
Arnarvatn	Low	Independent	871 – 891	1 – 5	12 – 204
Mýnesás	Low	Independent	871 – 891	1 – 5	no data; (2 – 12) / (25 – 204)
Haganes	Low	Independent	871 – 891	1 – 5	7 – 146
Selhagi	Low	Independent	871 – 891	1 – 5	no data; (2 – 12) / (25 – 204)
Grænavatn	Mid	Independent	871 – 891	4 – 9	no data; (2 – 14) / (12 – 192)
Sveigakot	Low	Independent	871 – 891	1 – 5	no data; (2 – 12) / (25 – 204)
Oddastaðir	Low	Independent	871 – 891	1 – 5	no data; (2 – 12) / (25 – 204)
Garður	Low	Independent	871 – 891	1 – 5	6 – 81
Brjánsnes	Low	Independent	871 – 891	1 – 5	3 – 25
Kálfaströnd	Low	Independent	871 – 891	1 – 5	12 – 110
Geiteyjarströnd	Low	Independent	871 – 891	1 – 5	8 – 111
Vogar	Mid	Independent	871 – 891	4 – 9	7 – 93
Fagranes	Low	Independent	871 – 891	1 – 5	4 – 81
Grímsstaðir	Low	Independent	871 – 891	1 – 5	8 – 117
Selholt	Low	Independent	871 – 891	1 – 5	no data; (2 – 12) / (25 – 204)
Sýðri-Neslönd	Low	Independent	871 – 891	1 – 5	no data; (2 – 12) / (25 – 204)
Ytri-Neslönd	Low	Independent	871 – 891	1 – 5	5 – 54

Farms /Agents	**Rank**	**Status**	**Establishment (AD)**	**Home-field (ha)**	**Livestock (cattle/ovines)**
Raufarhóll	Low	Independent	871 – 891	1 – 5	no data; (2 – 12) / (25 – 204)
Vindbelgur	Low	Independent	871 – 891	1 – 5	3 – 42
Brenna	Low	Independent	871 – 891	1 – 5	no data; (2 – 12) / (25 – 204)
Geirastaðir	Low	Independent	871 – 891	1 – 5	5 – 73
við Kleifarhólma	Low	Independent	871 – 891	1 – 5	no data; (2 – 12) / (25 – 204)
Hofstaðir	High	Independent	871 – 891	4 – 9	9 – 119
Laugasel	Low	Independent	871 – 891	1 – 5	no data; (2 – 12) / (25 – 204)
Svartárkot	Mid	Independent	871 – 891	4 – 9	2 – 12
Víðiker	Low	Independent	871 – 891	1 – 5	3 – 39
Stóra-Tunga	Mid	Independent	871 – 891	4 – 9	2 – 38
Bjarnastaðir	Low	Independent	871 – 891	1 – 5	3 – 82
Lundarbrekka	Mid	Independent	871 – 891	4 – 9	14 – 192
Engidalur	Mid	Independent	871 – 891	4 – 9	5 – 60
Sandvík	Low	Independent	871 – 891	1 – 5	no data; (2 – 12) / (25 – 204)
Sigurðarstaðir	Low	Independent	871 – 891	1 – 5	7 – 124
Hrappstaðir	Low	Independent	871 – 891	1 – 5	no data; (2 – 12) / (25 – 204)
Jarlstaðir	Low	Independent	871 – 891	1 – 5	5 – 60
Arnarstaðir	Low	Independent	871 – 891	1 – 5	no data; (2 – 12) / (25 – 204)
Brenniás	Low	Independent	871 – 891	1 – 5	no data; (2 – 12) / (25 – 204)
Kálfaborgará	Low	Independent	871 – 891	1 – 5	3 – 35
Heiðarsel	Low	Independent	871 – 891	1 – 5	no data; (2 – 12) / (25 – 204)
Arndísarstaðir	Mid	Independent	871 – 891	4 – 9	7 – 76
Einarsstaðasel	Low	Independent	871 – 891	1 – 5	no data; (2 – 12) / (25 – 204)
Úlfsbær (Bær)	Low	Independent	871 – 891	1 – 5	4 – 52
Rauðá	Low	Independent	871 – 891	1 – 5	6 – 92
Narfastaðir	Mid	Independent	871 – 891	4 – 9	7 – 95
Narfastaðsel	Low	Independent	871 – 891	1 – 5	no data; (2 – 12) / (25 – 204)
Hólkot	Low	Independent	871 – 891	1 – 5	no data; (2 – 12) / (25 – 204)
Stafn	Low	Independent	871 – 891	1 – 5	4 – 123
Hallbjarnarstaðir	Mid	Independent	871 – 891	4 – 9	10 – 113
Máskot	Low	Independent	871 – 891	1 – 5	2 – 33
Víðar	Low	Independent	871 – 891	1 – 5	3 – 49
Hallskot	Low	Independent	871 – 891	1 – 5	no data; (2 – 12) / (25 – 204)
Víðatóft	Low	Independent	871 – 891	1 – 5	no data; (2 – 12) / (25 – 204)

Borgarfjörður:

Farms/Agents	Rank	Status	Establishment (AD)	Home-field (ha)	Livestock (cattle/ovines)
Cluster 1					
Mófellstaðir	Mid	patron	871 – 891	4 – 9	29 – 104
Kolbeinsstaðir	Low	client	* – 1000	1 – 5	8 – 15
Cluster 2					
Fitjar	High	patron	871 – 891	4 – 9	34 – 163
Bakkakot	Low	client	* – 1000	1 – 5	8 – 67
Cluster 3					
Hvanneyri	High	patron	871 – 891	4 – 9	31 – 81
Ausa	Low	client	* – 1000	1 – 5	20 – 77
Ásgarður	Low	client	* – 1000	1 – 5	no data; (4 – 41) / (12 – 155)
Tungutún	Low	client	* – 1000	1 – 5	15 – 28
Hamrakot	Low	client	* – 1000	1 – 5	8 – 12
Bárustaðir	Low	client	* – 1000	1 – 5	8 – 31
Cluster 4					
Geirshlíð	Mid	patron	871 – 891	4 – 9	20 – 102
Geirshlíðarkot	Low	client	* – 1000	1 – 5	10 – 66
Cluster 5					
Skáney	High	patron	871 – 891	4 – 9	14 – 51
Skáneyjarkot	Low	client	* – 1000	1 – 5	no data; (4 – 41) / (12 – 155)
Cluster 6					
Deildartunga	High	patron	871 – 891	4 – 9	14 – 69
Brekkukot	Low	client	* – 1000	1 – 5	11 – 62
Independent farms					
Neðri-Hreppur	Low	Independent	871 – 891	1 – 5	20 – 83
Efri-Hreppur	Low	Independent	871 – 891	1 – 5	20 – 62
Horn	Low	Independent	871 – 891	1 – 5	10 – 16
Indriðastaðir	Mid	Independent	871 – 891	4 – 9	38 – 113
Litla-Drageyri	Low	Independent	871 – 891	1 – 5	12 – 47
Stóra-Drageyri	Low	Independent	871 – 891	1 – 5	9 – 31
Vatnshorn	Low	Independent	871 – 891	1 – 5	20 – 38
Efsti-Bær	Low	Independent	871 – 891	1 – 5	9 – 51
Sarpur	Low	Independent	871 – 891	1 – 5	14 – 58
Háafell	Low	Independent	871 – 891	1 – 5	no data; (4 – 41) / (12 – 155)
Stálpastaðir	Low	Independent	871 – 891	1 – 5	10 – 90
Dagverðarnes	Low	Independent	871 – 891	1 – 5	10 – 36
Hvammur	Low	Independent	871 – 891	1 – 5	16 – 67
Vatnsendi	High	Independent	871 – 891	4 – 9	24 – 103
Hálsar	Low	Independent	871 – 891	1 – 5	11 – 32

Farms/Agents	**Rank**	**Status**	**Establishment (AD)**	**Home-field (ha)**	**Livestock (cattle/ovines)**
Grjóteyri	Low	Independent	871 – 891	1 – 5	12 – 37
Tunga	Low	Independent	871 – 891	1 – 5	10 – 31
Árdalur	Low	Independent	871 – 891	1 – 5	19 – 45
Ytri-Skeljabrekka	Low	Independent	871 – 891	1 – 5	21 – 43
Innri-Skeljabrekka	Low	Independent	871 – 891	1 – 5	15 – 20
Grímarsstaðir	Low	Independent	871 – 891	1 – 5	15 – 49
Hvítárvellir	High	Independent	871 – 891	4 – 9	52 – 135
Þingnes	High	Independent	871 – 891	4 – 9	56 – 189
Bakkakot	Low	Independent	871 – 891	1 – 5	16 – 59
Langholt	Low	Independent	871 – 891	1 – 5	22 – 81
Bær	Mid	Independent	871 – 891	4 – 9	46 – 179
Varmalækur	High	Independent	871 – 891	4 – 9	36 – 172
Eyri	Low	Independent	871 – 891	1 – 5	22 – 114
Múlastaðir	Low	Independent	871 – 891	1 – 5	4 – 33
Hestur	Low	Independent	871 – 891	1 – 5	36 – 134
Kvígsstaðir	Low	Independent	871 – 891	1 – 5	20 – 96
Heggstaðir	Low	Independent	871 – 891	1 – 5	10 – 29
Vatnshamrar	Low	Independent	871 – 891	1 – 5	16 – 35
Miðfossar	Mid	Independent	871 – 891	4 – 9	9 – 24
Syðrifossar	Low	Independent	871 – 891	1 – 5	21 – 82
Mávahlíð	Low	Independent	871 – 891	1 – 5	21 – 107
Gröf	Low	Independent	871 – 891	1 – 5	12 – 49
Kross	Low	Independent	871 – 891	1 – 5	17 – 49
Kistufell	Low	Independent	871 – 891	1 – 5	10 – 22
Skarð	Low	Independent	871 – 891	1 – 5	24 – 56
Snartarstaðir	Low	Independent	871 – 891	1 – 5	17 – 88
Hóll	Low	Independent	871 – 891	1 – 5	26 – 107
Iðunnarstaðir	Low	Independent	871 – 891	1 – 5	11 – 70
England	Low	Independent	871 – 891	1 – 5	13 – 97
Gilstreymi	Low	Independent	871 – 891	1 – 5	no data; (4 – 41) / (12 – 155)
Þverfell	Low	Independent	871 – 891	1 – 5	13 – 67
Reykir	Low	Independent	871 – 891	1 – 5	16 – 81
Brenna	Low	Independent	871 – 891	1 – 5	14 – 92
Tungufell	Low	Independent	871 – 891	1 – 5	19 – 125
Brautartunga	Low	Independent	871 – 891	1 – 5	9 – 41
Oddstaðir	High	Independent	871 – 891	4 – 9	23 – 176
Gullberastaðir	Low	Independent	871 – 891	1 – 5	15 – 59
Lundur	Low	Independent	871 – 891	1 – 5	41 – 137
Arnþórsholt	Low	Independent	871 – 891	1 – 5	19 – 82

Farms/Agents	**Rank**	**Status**	**Establishment (AD)**	**Home-field (ha)**	**Livestock (cattle/ovines)**
Skálpastaðir	Mid	Independent	871 – 891	4 – 9	12 – 60
Múlakot	Low	Independent	871 – 891	1 – 5	17 – 85
Brúsholt	Low	Independent	871 – 891	1 – 5	15 – 68
Skógar	Low	Independent	871 – 891	1 – 5	12 – 50
Hrísar	Low	Independent	871 – 891	1 – 5	7 – 28
Hæll	Low	Independent	871 – 891	1 – 5	9 – 62
Brennistaðir	Low	Independent	871 – 891	1 – 5	15 – 102
Litli Kroppur	Low	Independent	871 – 891	1 – 5	9 – 50
Steðji	Low	Independent	871 – 891	1 – 5	10 – 49
Kálfanes	Low	Independent	871 – 891	1 – 5	8 – 42
Stóri Kroppur	High	Independent	871 – 891	4 – 9	25 – 90
Hamrar	Low	Independent	871 – 891	1 – 5	15 – 70
Kleppjárnesreykir	Low	Independent	871 – 891	1 – 5	12 – 41
Snældubeinsstaðir	Mid	Independent	871 – 891	4 – 9	12 – 48
Kjalvararstaðir	Low	Independent	871 – 891	1 – 5	17 – 98
Kópareykir	Low	Independent	871 – 891	1 – 5	14 – 79
Vilmundarstaðir	Low	Independent	871 – 891	1 – 5	18 – 78
Steindórsstaðir	Low	Independent	871 – 891	1 – 5	23 – 146
Breiðabólsstaður	Low	Independent	871 – 891	1 – 5	22 – 143
Reykholt	High	Independent	871 – 891	4 – 9	57 – 227
Grímsstaðir	Low	Independent	871 – 891	1 – 5	16 – 87
Sturlureykir	Mid	Independent	871 – 891	4 – 9	18 – 75
Grafarkot	Low	Independent	871 – 891	1 – 5	12 – 44
Hurðarbak	Low	Independent	871 – 891	1 – 5	28 – 116
Norður-Reykir	Low	Independent	871 – 891	1 – 5	6 – 33
Signýjarstaðir	High	Independent	871 – 891	4 – 9	incomplete; (23 – 69) / (51 – 270)
Bolastaðir	Low	Independent	871 – 891	1 – 5	4 – 37
Refsstaðir	Low	Independent	871 – 891	1 – 5	no data; (4 – 41) / (12 – 155)
Sigmundarstaðir	Low	Independent	871 – 891	1 – 5	11 – 48
Kollslækur	Low	Independent	871 – 891	1 – 5	8 – 43
Uppsalir	Low	Independent	871 – 891	1 – 5	10 – 68
Hofstaðir	Low	Independent	871 – 891	1 – 5	25 – 155
Úlfsstaðir	Low	Independent	871 – 891	1 – 5	9 – 39
Rauðsgil	Low	Independent	871 – 891	1 – 5	16 – 50
Búrfell	Low	Independent	871 – 891	1 – 5	7 – 25
Auðsstaðir	Low	Independent	871 – 891	1 – 5	9 – 59
Giljar	Low	Independent	871 – 891	1 – 5	9 – 48
Augastaðir	Low	Independent	871 – 891	1 – 5	13 – 82
Stóri-Ás	High	Independent	871 – 891	4 – 9	37 – 270
Hraunsás	Low	Independent	871 – 891	1 – 5	17 – 107

Caveat

1) Independent and patron farms are established in the first 20 years of settlement, whereas client-farms are established by random choice of a year between the year subsequent to the year of establishment of their patron's properties and AD 1000. For further description, see section 7.5.9.1.
2) The number of livestock individuals in cattle (including horses) and ovine (including goats) herds represent the number of animals as recorded in *Jarðabók*. Note that for many of the sites there are no data on the size of livestock herds – for those sites, the projected, maximum size of livestock holdings has been randomly chosen, during the setup procedure, from the range of livestock numbers available for other sites of comparable rank and status in each of the regions.

Constant state variables of individual agents, i.e. farms, are:

- power-rank: high-, mid- or low,
- status: related (patron and client farms) or unrelated (independent farms),
- time of establishment,
- initial location,
- projected extent of home-field,
- initial (starting) size of the cattle holdings (including horses),
- initial (starting) size of the ovine holdings (including goats),
- final (maximum) size of cattle holdings (including horses) ,
- final (maximum) size of ovine holdings (including goats).

Constant state variable of patches:

The only constant state variable of patches is location. Also, patches where individual agents were sprouted, i.e. where farms were established, contain information about the date of establishment of farms and maximum size of their livestock herds. Patches where client farms were established contain information about the location of their patron farm.

Changeable state variables of individual agents are:

- location,
- rate of clearance,
- proportion of woodlands cleared for home-fields,
- proportion of woodlands cleared for pastures,
- proportion of newly created pastureland areas with sufficient amount of utilisable grassy biomass, i.e. areas still used for grazing,
- proportion of areas with total loss of utilisable grassy biomass,

- total amount of utilisable grassy biomass at agent’s pastureland,or at cluster‘s pastureland, where applicable,
- memorised month with lowest rate of grass growth,
- total amount of utilisable grassy biomass at agent’s pastureland, or at cluster‘s pastureland, where applicable, during the month with the lowest rate of grass growth,
- size of cattle-herd (including horses),
- size of ovine-herd (including goats),
- grazing pressure of both livestock herds per ha,
- number of recorded cases of overgrazing at the newly created pastureland,
- extent of the home-field established at a previously cleared area – where applicable, for instance if a home-field was established at an area previously cleared by another agent,
- information on timing of initiation of clearance for pastures,
- period of resting applied immediately after initiation of clearance for pastures.

Changeable state variables of patches are:

- timing of deforestation – where applicable, depending on the type of land cover and/or if the deforestation was applied or not,
- ownership, i.e. information about the farm that deforested the patch,
- amount of utilisable grassy biomass, expressed in kg,
- grazing pressure, i.e. the amount of grassy biomass (expressed in kg) utilised by the livestock every time-step, i.e. month,
- decrease of utilisable biomass due to regrowth of birch,
- decrease of utilisable biomass due to replacement of grasses by grazing-tolerant species,
- increase of utilisable biomass due to resting effect,
- amount of utilisable biomass regained through post-grazing regrowth (recovery) of grasses,
- information on whether grazing has started or not,
- information on whether the patch has ever suffered from overgrazing or not,
- information on whether the patch is suffering from overgrazing or not.

Global variables:

In addition to those agents’ and patches’ variables, it is important to stress the following global variables, which are associated with all the agents and affect the outcomes of simulation runs:

- intrinsic rate of growth of agent's cattle-herds,
- intrinsic rate of growth of agent's ovine-herds,
- degree of culling of agent's cattle-herds,
- degree of culling of agent's ovine-herds,
- period after which replacement of grasses by grazing-tolerant species at agents' pasturelands begins,
- degree of replacement of grasses by grazing-tolerant species in the case of heavy grazing,
- degree of replacement of grasses by grazing-tolerant species in the case of sustainable grazing,
- seasonal variation in utilisable grassy biomass,
- seasonal variation in post-grazing recovery of grasses,
- seasonal variation in resting effect of pastureland areas,
- change of seasons (winter/summer).

7.3.1.2 Collectives

Each of the models comprises clusters of patron and client farms which may be regarded as collectives and/or distinguished as entities. The district of Vestur-Eyjafjallahreppur comprises 8 collectives whereas the regions of Borgarfjorður and Mývatn comprise 6 and 2 collectives respectively. State variables of these collectives are deduced from their individual agents. The list of all the collectives is presented in Table 10.

7.3.1.3 Spatial units

The basic spatial units are cells, or as they are named in a NetLogo context, „patches". Each of these patches represents one of the following types of land cover:

- woodlands that were subject to clearance – areas in the primary focus of models
- other woodlands
- wetlands
- other dryland vegetation – as named in the legend of the map made by the Icelandic Institute of Natural History, which was the origin of the advanced map, later imported and used in the NetLogo environment.
- sparsely vegetated areas
- glaciers
- water bodies: rivers, lakes and sea.

Patches that represent woodlands that were subject to clearance can change their state (colour on the resulting maps) due to a variety of occurrences, such as clearance for pastures and/or home-fields as well as overgrazing and finally total loss of utilisable grassy biomass. Patches that represent wetlands and dryland vegetation are characterised by their colour: orange and light-green, respectively, which can change due to the establishment of home-fields. State variables of other types of land cover are outside the qualitative focus of the models – they are solely used to represent natural boundaries that limit the movement of agents.

7.3.1.4 Environment

Environment refers to spatially explicit recreated environments of each of the sample study areas. The extent of each of the land cover types at each of these areas is given below in Table 11.

Table 11. Extent of land cover types at each of the areas

Land cover	Vestur-Eyjafjallahreppur	Mývatn	Borgarfjörður
Woodlands in focus	13478 ha/patches	70926 ha/patches	57111 ha/patches
Other woodlands	12855 ha/patches	50813 ha/patches	36922 ha/patches
Wetlands	3424 ha/patches	21354 ha/patches	39508 ha/patches
Other dryland vegetation	21985 ha/patches	20992 ha/patches	32977 ha/patches
Sparsely vegetated	11740 ha/patches	29862 ha/patches	15246 ha/patches
Glaciers	9518 ha/patches	/	981 ha/patches
Water bodies (total)	12725 ha/ patches	15610 ha/patches	19472 ha/patches
Total	857.25 km^2/85725 p.	2095.57 km^2/209557 p.	2022.17 km^2/202217 p.

7.3.2 Scales

Each of the simulation models proceeds in discrete time steps, defined as „ticks“ in NetLogo, and each of the ticks in the series of models represents one month in a calendar year. Models run for 1560 ticks, which therefore simulate the period of 130 years, i.e. the period AD 871 (i.e. January 871) – 1000 (i.e. January 1001).

Since building of the series of simulation-models requires explicit absolute dates, it was necessary to suggest the absolute starting and closing point. Therefore:

1) The starting point is the year AD 871, which we may assume as the initiation of the settlement of Iceland, based upon the archaeological records, which suggest that most of the settlements were established just above the *landnám* tephra layer, which has been successfully dated with a margin of error of less than four years on the basis of the study of ice-cores from the Greenland ice cap (e.g. Grönvold *et al*. 1995). Since the establishment of first settlements would obviously have marked the start of human impact on the environment, this date is taken as the starting point for the time-scale of this research project.

2) The closing point on the time-scale of this research is the year AD 1000, as the end of the 10th century and a year that can be used to roughly denote the end of the settlement process in Iceland.

The landscape of each of the models is represented as a toroid, two-dimensional grid with the resolution, i.e. cell-size, of 1 ha. The vegetation cover for each of the models is set according to the available grid code and is represented according to the legend of the extant map

7.4 Process overview and scheduling

7.4.1 Prior to each simulation run – setting up the model

The constant state variables of agents, abovementioned global variables and spatial units, and therefore the environment, are set in a NetLogo world with the setup procedure. The starting values of state variables of agents and associated global variables are set randomly by a programme (NetLogo) from previously mentioned ranges of values shown in Table 10. The environment is set through the import of GIS-based files into NetLogo. Subsequently, and prior to the simulation run, the modeller can set up the following switches and choice buttons. It is important to stress that it is not possible to change these settings during the simulation run.

7.4.1.1 Choice buttons

Variants

This choice button allows the modeller to choose between two variants, which define the location where the clearance for client pastures will be initiated. Variant „a“ suggests that client agents initiate clearance at one of the woodland patches at a minimal distance from their own home-fields. Variant „b“ suggests that they initiate clearance at one of the woodland patches in the immediate vicinity of the patron’s farm.

Scenarios

This choice button allows the modeller to set the scenario according to which the simulation will be run. A concise description of each of the scenarios with respect to its agents’ behaviour follows below. The flow charts of each of the scenarios are presented in Figures 12, 13, 14, and 15.

Scenario 1: Once settled (in NetLogo: *sprouted*), agents clear woodlands permanently, until the end of the simulation or until the total loss of woodland cover. This scenario allows the choice between two variants in the way described above (see the paragraph above about the „Variants“ choice button).

Scenario 2: Each of the agents clears woodlands according to projected pasture-needs of their planned livestock herds. This scenario allows the choice between two variants in the same way as for Scenario 1.

Scenario 3: Scenario 3 does not allow the choice between two variants. Independent agents clear as in Scenario 2 – according to projected needs of their planned livestock herds. In the case of a cluster of farms, patrons initiate the clearance in the immediate vicinity of their home-fields and clear until pasture requirements, i.e. projected needs of planned livestock herds of all the farms from that cluster, whether present or not, are met. During this clearance, and depending on the time of establishment, each of the new client farms joins this clearance until the needs of all the farms from that cluster are met. Each of the incoming client farms that joins the clearance chooses one of the woodland patches with the minimum distance from the patron‘s household, expanding the pasture-area away from it. Agents that settle after the clearance for farms in that cluster is finished do not clear any woodland.

Scenario 4: Scenario 4 does not allow the choice between two variants. Independent agents clear as in Scenario 2 – according to projected needs of their planned livestock herds. In the case of clusters of farms – the patron, once having accomplished clearance for his own pastures in the immediate vicinity of his own home-fields, continues clearance for clients only if some client agents are present at that time – otherwise, he will pause in his clearance. If, however, some client agents are present, clearance is continued, in the immediate vicinity of patron’s home-fields, until the needs of both patron and present client(s) are met. Subsequently, they pause their clearing. With the arrival of every newcomer client, each of the farms from a cluster present at that time will re-initiate the clearance, which lasts, again, until the pasture requirements of each of the farms from that cluster, present at that time are met. This phased clearance is terminated if the needs of all the farms belonging to that cluster are met.

7.4.2 Simulation run

This section gives concise information about the major processes that are built into the „run“ procedure of the models. Following the suggestion of the authors of ODD, these processes, which are regarded as sub-models, are only briefly listed here – they are further described in the pages below. Although this dispersion of information in separate sections may be criticised as redundant, it is in fact „needed to make sure that readers know and understand the context of each sub-model“ (Grimm *et al*. 2010, p. 2766). The following processes are built into the simulation run procedure:

With regards to agents/farms:

- Establishment of farms
- Clearance for home-fields
- Clearance for pastures
- Changes in size of the livestock holdings (growth and culling).

With regards to patches/environment:

- Seasonal changes in available utilisable biomass

- Reduction of utilisable biomass at agent’s pastureland due to grazing, overgrazing, regrowth effect and replacement of grasses by grazing-tolerant species
- Increase of utilisable biomass due to resting effect, i.e. prevention of grazing.

7.4.2.1 Execution of activities and updating of the state variables

During the simulation run, upon the request of the higher-level controller, defined as the „observer“ in NetLogo, patches (where applicable) execute settling (sprouting) of agents and update the information on their own changeable state variables mentioned above at every tick, i.e. month. Agents execute clearance activities, i.e. they change the colour (state) of patches and they also update the information on their own changeable state variables at every tick. Since agents are sprouted at different moments in time, activities of agents can intermix / run concurrently. Hence, while one agent clears woodlands for home-fields, another one could be clearing for pastures and a third could be not clearing. Consequently, values associated with the changeable state variables of patches (e.g. grazing pressure) and agents (e.g. proportion of woodlands cleared for pastures) can vary greatly from one patch/agent to another.

7.4.2.2 Termination/pausing of woodland clearance

With respect to Scenario 1, the simulation terminates in the case of total loss of woodland cover or if the simulation length reaches it maximum, i.e. 1560 ticks.

With respect to scenario 2, agents pause their clearance if the amount of utilisable biomass at their pasturelands is sufficient to meet the projected needs of their planned livestock herds.

When it comes to scenarios 3 and 4, „independent“ agents clear as in Scenario 2 – according to projected needs of their planned livestock herds, whereas „cluster“ agents clear until the amount of utilisable biomass is sufficient to meet the projected needs of all the planned and/or present livestock herds in the cluster.

7.5 Design concepts

7.5.1 Basic principles

The theory underlying the design of models is that the effort of the settler population to establish a pastoral economy in a short period of time resulted in an enormous clearance of the woodlands for home-fields and pastures throughout the country. The imbalance between the time of the establishment of farms, resting, grazing-potential, amount of available grassy biomass at the newly created pastures, rates of clearance, woodland regrowth, replacement of grasses with grazing-tolerant species, growth of livestock herds and cliency-strategies resulted firstly in a degree of clearance that often surpassed initially assumed subsistence requirements of the *landnám* communities and secondly in frequent environmental degradation. Understanding these factors and the way they were interlaced is the key to understanding the dynamics of this environmental change. This is precisely what this series of models tackles through the investigation of each of the sub-models and their combination.

7.5.2 Emergence

Clearance of woodlands is imposed phenomenon in this series of models. The major system-level phenomena that emerge from individual traits and adaptive, variable behaviour of the agents are the timing, dynamics, rate, degree and spatial distribution of the overall process of deforestation and the proportion and distribution of areas exposed to overgrazing, regrowth of birch and spread of grazing-tolerant vegetation. Those phenomena were tightly linked and interdependent, making this environmental change complex.

7.5.3 Adaptation

In the establishment of home-fields, the agents adapt their movement in relation to vegetation types and natural boundaries, i.e. rivers and streams. When it comes to clearance for pastures, they adapt their movement in relation to the current location of woodland patches, i.e. their movement depends on the changes in the environment (removal of forest cover).

Agents also adapt the duration of their clearance for pastures to demands of their livestock for fodder and in relation to the variations in available utilisable biomass. That variation is in turn caused by seasonal variations in growth of grasses and post-grazing recovery of grasses, overgrazing, effects of regrowth and replacement of grasses by grazing-tolerant species.

Changes in duration of clearance for pastures also become obvious in the case of clusters of farms, in Scenarios 3 and 4, where duration is reduced with the arrival of each new settler. The overall rate of clearance in a cluster increases, but the time necessary to clear pastures decreases.

Agents also modify their choice of rates of clearance in the case of overgrazing. If overgrazing occurs at the agents' pastureland patches, the agents apply solely non-zero rates from the range of rates of clearance – that way the agents increase their average rates of clearance in an attempt to provide a sufficient extent of pastures (and hence a sufficient amount of UB) for their growing livestock holdings, and in order to prevent further overgrazing.

7.5.4 Objectives

The primary objective of each of the agents is to reach the amount of grazing biomass that is sufficient to cover the needs of livestock herds for the entire calendar year. Since the agents are aware of the seasonal variations in utilisable biomass they especially aim to provide livestock with the extent of pastures (and hence amount of utilisable biomass) sufficient to cover its grazing needs during the winter, i.e. the period of the year with the lowest amount of utilisable biomass.

With respect to micro-allocation, the main criteria when clearing for home-fields is to clear the patches at a minimal distance from the centre of origin, i.e. the location of the household. In clearance for pastures, the criterion is twofold – the aim of an agent is to clear:

a) patches as close as possible to the home-field area, or

b) patches as close as possible to the present patch in any given case.

Scenario 1

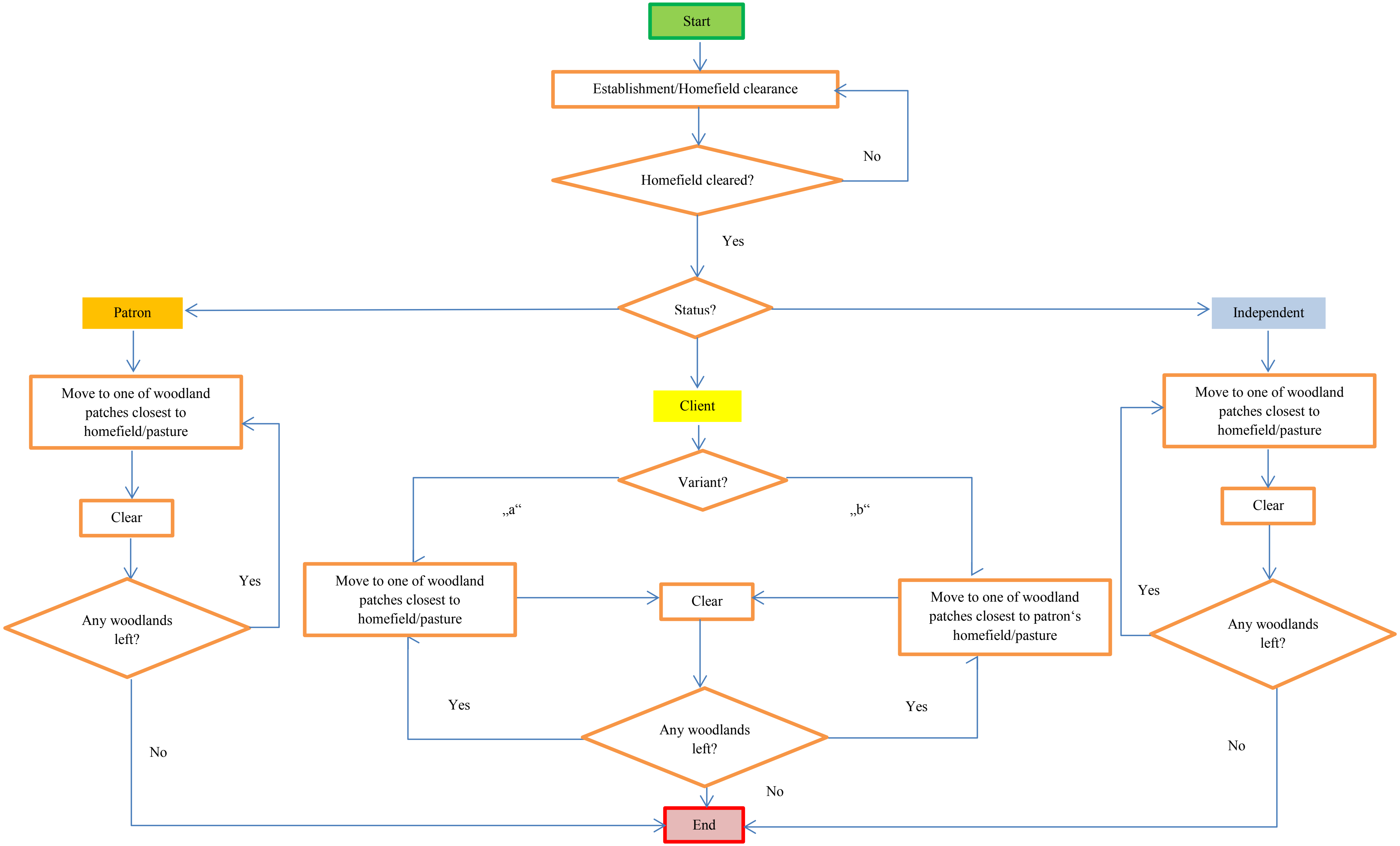

Figure 12. Scenario 1, flowchart

Scenario 2

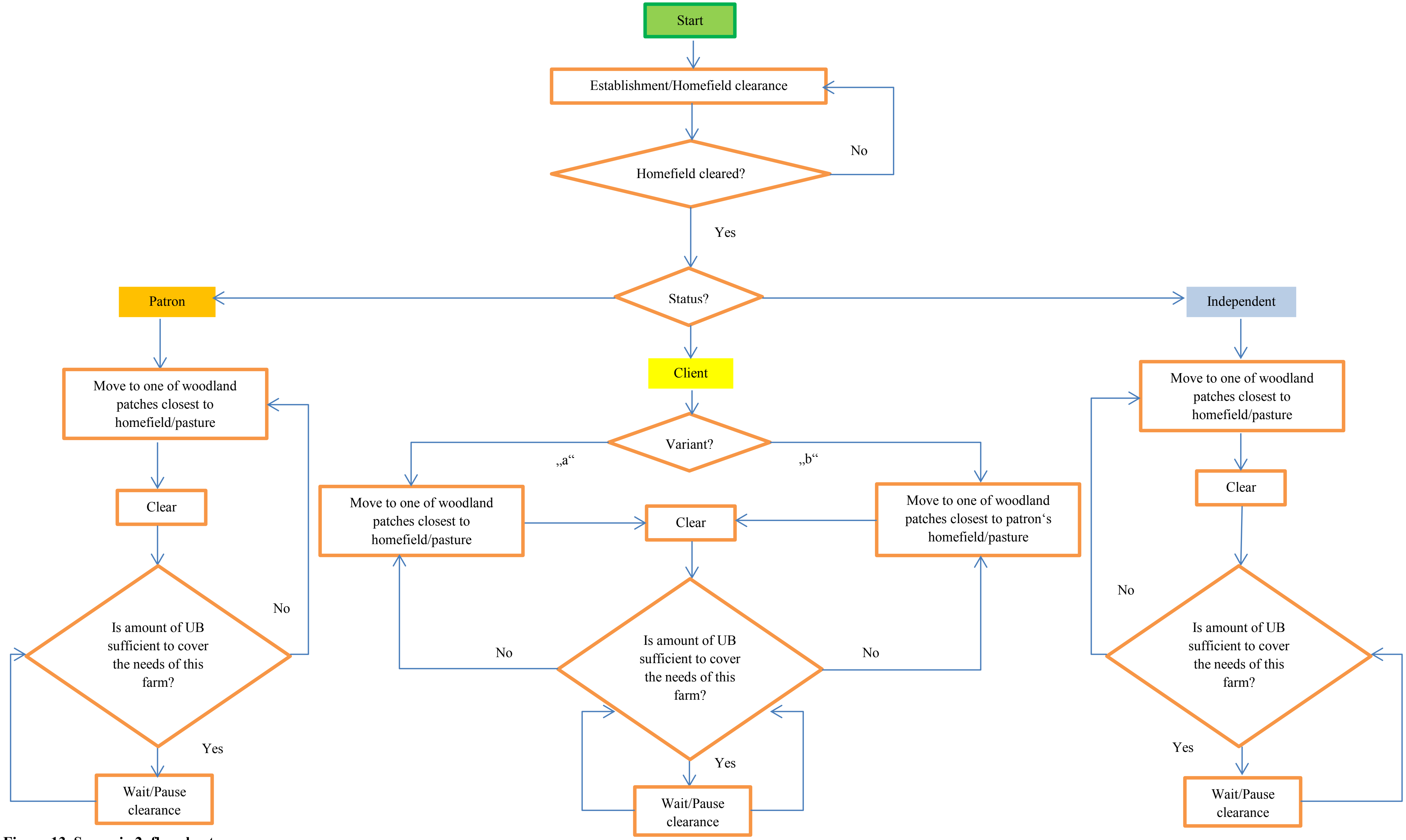

Figure 13. Scenario 2, flowchart

Scenario 3

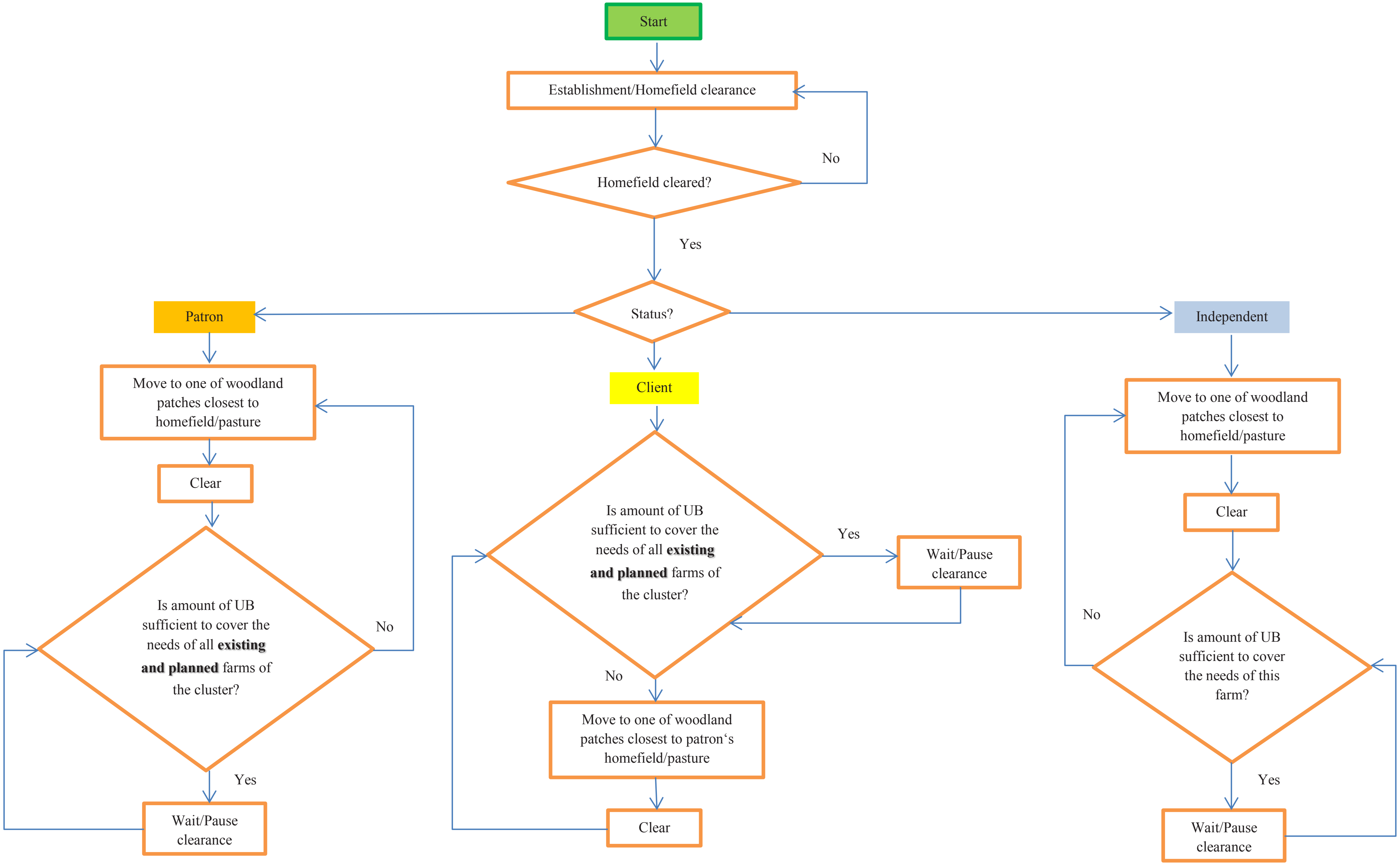

Figure 14. Scenario 3, flowchart

Scenario 4

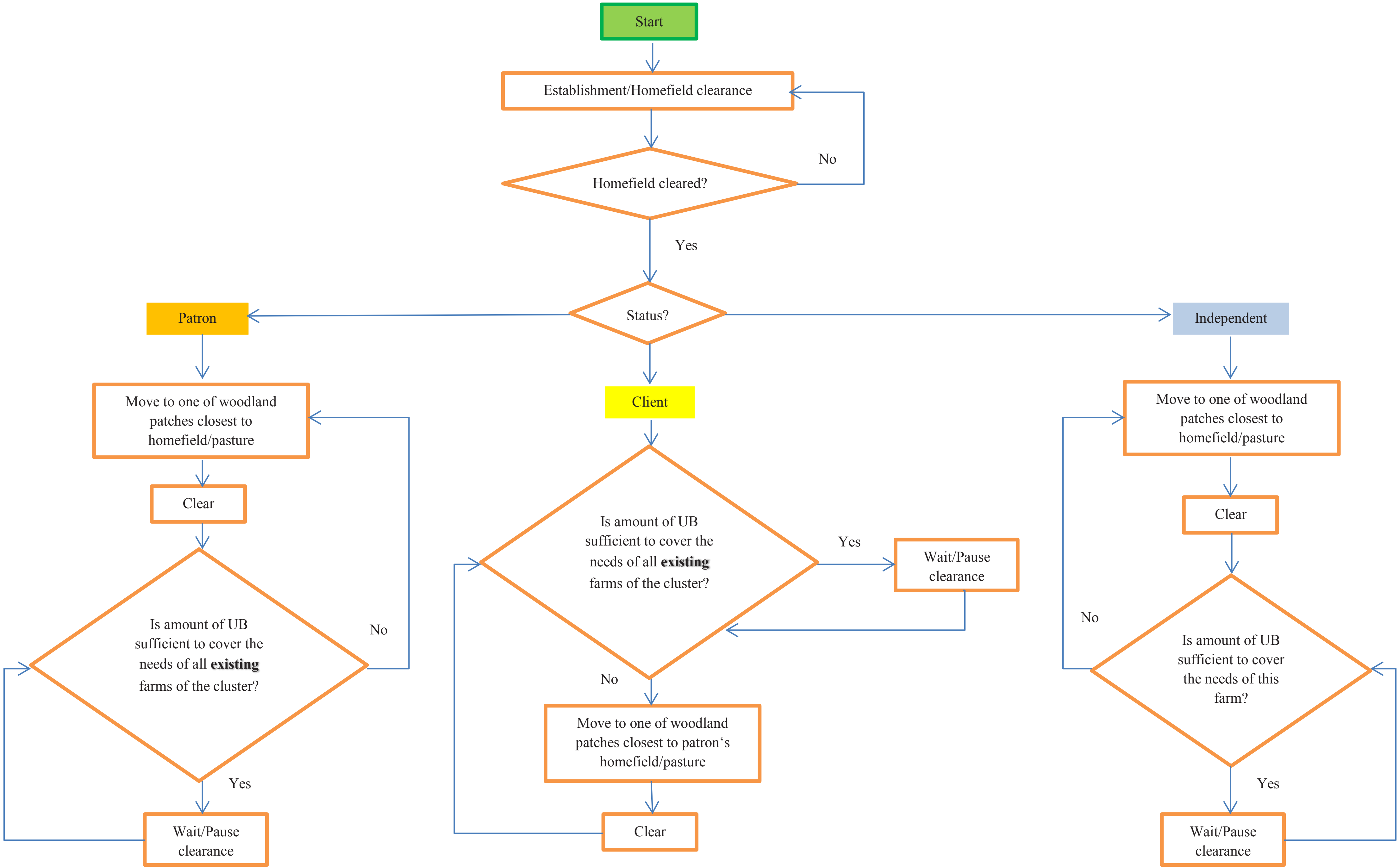

Figure 15. Scenario 4, flowchart

7.5.5 Learning

Agents learn about the seasonal variations in utilisable biomass and make their own estimates about the month with the lowest amount of UB. Agents therefore learn to recognise the month with the lowest rate of grass growth as the most critical period of the calendar year. With regards to the clusters of farms, the client farms adopt the patron’s estimate about the month with the lowest amount of UB.

7.5.6 Prediction

Each of the agents projects the size of their livestock holdings. This simulates the logical assumption that settlers had an idea of the maximum size of their economies, in terms of livestock numbers – as explained above, those numbers were taken from *Jarðabók*. Also, Scenario 3 allows patron agents to predict the extent of clearance for pastures sufficient to cover the needs of each of their client farms.

7.5.7 Sensing

Agents can sense some of the state variables of other agents from the same cluster. Thus, the patron and client(s) in a certain cluster are aware of the size of each other’s livestock holdings, the extent of overgrazed areas and records of the „worst month“, i.e. the month with the lowest rate of grass growth and the lowest amount of available UB at their pastures. In particular in Scenarios 3 and 4 they act in accordance to those state variables in a way that reflects the patron-client relationships, as described in Chapter 6.

7.5.8 Interaction

Agents interact among themselves, although only indirectly, via competition for woodland resources, i.e. patches that represent woodlands. Two agents cannot occupy the same patch and therefore cannot clear the woodlands on the same patch. If they are located close together they will occupy neighbouring patches of woodlands.

Agents interact with the environment through the clearance of forests, i.e. transformation of the landscape. The response of the environment to this impact is shown through the seasonal variation in utilisable biomass of newly created pastures, the increase of utilisable biomass due to the resting effect, the decrease of utilisable biomass due to overgrazing, the birch regrowth effect and the replacement of grasses by grazing-tolerant species. All those environmental responses affect the duration of clearance performed by the agents.

7.5.9 Stochasticity

During the process of modelling, stochasticity arises as an unavoidable factor since for many of the aspects of this environmental change we cannot suggest precise and particular values. For example, for the timing of the establishment of farms or the projected size of home-fields we possess only the range of values, and it is impossible to suggest the right one. The random choice of one of these values is the simplest solution. Also, in the process of clearance it would be absurd to suggest its true rate and to explain the actual cause of its variabilities. Here, we can also use stochasticity to recreate those variabilities.

The random choices applied in this series of models refer to a uniform discrete distribution where each of the proposed values is equally likely to be chosen. This can be expressed through the equation nr. 1:

$$\mathbf{P = 1/N}$$

where **P** is the probability outcome and **N** is the number of possible values equally spaced and equally probable.

The reason for the use of this simple type of randomness and not some other, like for instance *Gaussian* (normal) where outcome data tend to be located around the mean, central value, is that each value in the range of values that we operate with needs to be taken equally into consideration – for none of those values can it be claimed that one or another is more or less likely to have been the case.

7.5.9.1 Date of establishment of farms and possible temporal distribution of population pressure

Values for this state variable are defined prior to every simulation run within their setup procedure. Whereas patron and independent farms are established in a year randomly chosen sometime in the first 20 years of the settlement period (i.e. between AD 871 – 891), as suggested by some of the existing research studies (e.g. Vésteinsson 1998; Vésteinsson and McGovern 2012), the rest of the farms (i.e. dependent, client farms – always new settlers and not offspring units of the patron farms) are established by random choice of a year between the year subsequent to the year of establishment of their patron's properties and AD 1000 as the year that marks the end of the period under discussion. Thus, for instance, if the farm at Holt, which was one of the major centres in the area of Vestur-Eyjafjallahreppur, was established in AD 875, each of its client farms (e.g. Gerðakot) could have been established in any of the years during the period AD 876 – 1000. Here the assumption is that setting up a patron-property could have been accomplished already within one year.

The assumption behind the model is that, in the region of Vestur-Eyjafjallahreppur, at least 24 out of 44 farms (in total) are established during the first 20 years of the Settlement (Table 10). This further implies (taking into account their rank and different number of inhabitants; see section 7.5.9.4.) that at least 70 % of the overall Vestur-Eyjafjallahreppur population settled the region during the first two decades.

In the region of Mývatn, there are at least 66 out of 69 farms established in the same period, implying that at least 95 % of the total Mývatn population settled the region during this period.

Finally, in the region of Borgarfjörður, at least 100 out of 110 farms are established in the first 20 years of settlement. Following the same estimates of the number of people inhabiting the farms, this would imply that at least 93 % of the Borgarfjörður settlers came into the region before AD 891.

What is however obvious is that the application of the uniform discrete distribution over such long time-spans (i.e. AD 871 – 891 and especially → AD 1000) can lead to erroneous outcomes which do not correspond to the existing empirical evidence. For that reason, where applicable, i.e. at the locations from which we have empirical evidence, further reductions of those time-spans were considered (see section 8.2.1.3.).

7.5.9.2 Projected extent of home-field area

The value of the projected extent of home-field area was chosen upon the establishment of a farm, from the range of values between 1 and 9 ha (Chapter 5). The assumption behind the series of models is that the extent of home-fields of low-ranking farms could have been between 1 – 5 ha and that the extent of home-fields of mid- and high-ranking farms could have been between 4 – 9 ha.

7.5.9.3 Number of starting livestock and projected size of livestock population

The number of starting livestock population was chosen during the setup procedure by the program from the following range of values (Table 12):

Table 12. Starting numbers of livestock herds

Livestock category	**Cattle**	**Ovines**
Size of starting herd	2 – 5	2 – 10

This range of values was defined based upon results of the experimental runs, conducted in order to calibrate the models in a way that would make them yield reasonable outcomes. Those runs suggested that having higher starting livestock numbers in the models (i.e. cattle > 5 and ovines > 10) would lead to erroneous outcomes.

The projected maximum size of livestock holdings was defined, depending on the scenario, prior to each simulation run, or straight upon the establishment of a farm, upon the size of livestock holdings recorded in *Jarðabók*. However, for many of the farms there was no information on the size of livestock holdings (see Table 10). In those cases the projected maximum size of livestock holdings was chosen in a random way, by the programme from the following range of values (Table 13):

Table 13. Ranges of projected maximum size of livestock holdings

Region	**Cattle[45] (high/mid/low ranking)**	**Ovines[46] (high/mid/low-ranking)**
Vestur-Eyjafjallahreppur	12 – 69; 31; 8 – 57	48 – 342; 90; 12 – 150
Mývatn	9 – 12; 2 – 14; 2 – 12	119 – 162; 12 – 192; 25 – 204
Borgarfjörður	23 – 69; 9 – 46; 4 – 41	51 – 270; 24 – 179; 12 – 155

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[45] Including horses

[46] Including goats

That range of values was created based upon the minimum and maximum number of livestock recorded in *Jarðabók* for each of the sample study areas.

7.5.9.4 Rate of woodland clearance

The rates of clearance were repeatedly chosen by agents from the range of values at every time-step, i.e. every month, thus reflecting variations in monthly rates of clearance. The range of values was calculated based upon the experimentally-based estimates of cutting-efficiency of an adult individual, density of tree units per ha and estimates of the numbers of people living on the farms in each class of the farms. This range of values, described in Chapter 5 is also presented here.

In general, the rate suggests that up to 30 % of the workforce of the farms could have been employed in clearance activities, taking into account 50 % work efficiency per individual. Here, 30 % of the work-force connotes 1 person (at low-ranking farms) and 3 persons (at mid- and high-ranking farms). Those values were developed from the previously discussed extant estimates of the number of people inhabiting Viking Age farms (Chapter 5). This implies that low-ranking farms can clear up to 1 ha per month (either 0 or 1 ha per month) whereas mid- and high-ranking farms can clear between 0 – 3 ha per month (Table 14). It is important to stress that manul, trial-and-error calibration of the models confirmed the previously mentioned assumption that the 100 % work efficiency (implying two times higher rates of clearance) can be regarded as unrealistic (see section 5.2.2.1). Separate experimental runs performed in order to test that possibility provided outcomes that cannot be described as entirely reasonable and that do not correspond properly to the existing set of empirical evidence.

Table 14. Rates of clearance, expressed through the range of patches per tick (ha per month)

Rank	Low-ranking	Mid- and High-ranking
Rate	0 – 1	0 – 3

Notice:

An agent in NetLogo cannot change the colour of only a part, for instance 35 % of a patch, only an entire patch at a time. Consequently, an agent can thus clear only 0, 1, 2 or more patches (hectares) of woodlands with each tick. For this reason, the rates of clearance are expressed in whole numbers. As a consequence, due to the resolution of 1 ha, the number of options with respect to the rate of clearance at every tick is very limited:

0 – 1 (patches, and hence hectares per month) for the clearance made by low-ranking farms,

0 – 3 (patches, and hence hectares per month) for the clearance made by mid- and high-ranking farms.

As mentioned above (section 7.5.3), in the case of overgrazing, the agent applies solely non-zero rates from these range of rates of clearance.

7.5.9.5 Stochasticity and decision-making

The existing studies give no indications of preference of distribution of clearance in terms of elevations (high or low ground) and/or directions of clearance. The factors that were mostly taken into consideration when modelling clearance activities of agents were the choice of scenario, status, rank, vicinity of the household and previously cleared patches and also natural boundaries, as well as the presence and/or absence of woodlands. However, in the cases when agents were about to choose between two or more equally-attractive patches to be cleared next, the choice was based on the „one-of“ NetLogo primitive, which reflects the uniform discrete distribution.

7.5.10 Observation

Each of the major aspects of the simulated process of deforestation was observed and recorded. Subsequently, data were exported to Excel files for further interpretation, whereas some of the visual outcomes (demonstrative/exhibitory and some of the experimental runs) of the NetLogo world were exported as .png files. Particular attention was paid to changes in the woodland cover at and around areas/locations from which the data used for validating outcomes of the models originated. For instance, during the simulation run, the spatial distribution and timing of clearance, and also the increase in livestock numbers as well as regrowth effect in particular areas (e.g. the relevant pollen source area of the lake of Helluvaðstjörn in Mývatn) were observed. In general, along with the starting parameters (with respect to the degree of culling of the cattle and ovine population, their intrinsic rate of growth, timing/initiation of replacement of grasses by grazing-tolerant species and rates of replacement during the light/heavy grazing regimes), the following outcomes were recorded in relation to time-steps:

- sum of individual rates of clearance,
- rates of clearance at and around the farms of Varmahlíð, Þorleifstaðir and Oddstaðir (randomly selected from the list of independent farms in order to monitor and record the dynamics of clearance made by single independent households in the regions of Vestur-Eyjafjallahreppur, Mývatn and Borgarfjörður, respectively),
- state of forest cover (including patches with undisturbed forest cover and once deforested patches with more than 50 % of regrown forest cover)[47],
- extent of overgrazed areas,
- extent of areas with more than 50 % of grazing-tolerant vegetation,
- extent of areas with more than 50 % of regrown birch cover,
- extent of clearance for home-fields,
- numbers of livestock,
- data required for validation of vegetation changes at particular areas/sites.

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[47] If it was not disturbed, i.e. cleared, forest cover is considered to be static.

The aim of the observation was to reveal the particular circumstances under which the process of deforestation led to results compatible with empirical research data.

7.6 Initialisation

The initial state of recreated environments, i.e. the extent of each type of vegetation cover at time t-0 at each of the regions, is shown in Table 11. The initial state of the models does not involve the existence of any agent since it represents a recreation of environments as they were prior to arrival of the first settlers.

The environments are set with the same initial values with each simulation setup whereas the constant state variables of the agents that will be sprouted at certain periods in time vary between each simulation.

7.7 Sub-models

7.7.1 Establishment of farms

The establishment of farms, or *sprouting* of the agents, is the initial process in each of the simulations. Each of the agents is sprouted at a random moment in time by a patch that corresponds to the previously identified GIS-based coordinates of the location of that farm.[48]

Sprouting of an agent is independent from the chosen scenario and/or status and rank. The idea behind this sub-model was to investigate the frequency of settlement in relation to the entire process of woodland depletion.

7.7.2 Clearance for home-fields

Upon the establishment of farms, each of the agents arranges their own home-field area, either by clearance of woodlands up to the extent that is projected as a home-field or through establishment of home-field areas over other types of vegetation cover – if the location where the agent was sprouted is already cleared of woodlands or if it is covered with another type of vegetation.

In each case, the agent moves away from the location of the household, equally in all directions, taking account of natural boundaries, i.e. rivers/streams, and with the rate of speed randomly chosen at each tick. While it moves, the agent changes the colour of the patch underneath it to red, thereby marking the extent of the home-field.

The establishment of home-fields is considered to be a process independent of the chosen scenario. The main goal of this sub-model was to estimate the possible degree and timing of

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[48] Unfortunately, owing to partial lack of correspondence between those coordinates and the vegetation map made by the Icelandic Institute of Natural History and consequently the newly produced map, some of the farms at Mývatn, which were supposed to be located at the very edge of some of the water bodies (Lake Mývatn), ended up being located in those water bodies. Subsequently, their location was set onto adjacent non-water patches inside the NetLogo modelling platform. This correction obviously affected the accuracy of the models; however, it was an unavoidable step.

impact on woodlands due to the needs of settlers of all classes for space, through establishment of their home-fields.

7.7.3 Clearance for pastures

Upon the establishment of home-fields, each of the agents terminates their existence and the newly sprouted agent of the same breed[49], i.e. representing the same farm, initiates the clearance for pastures. Agents clear the woodlands for pastures alone or together with other related agents, in a way that is defined by the chosen scenario and which is limited by the natural boundaries. The clearance is initiated at the location defined by the chosen variant of the scenario. During the clearance, the agent moves only across the patches representing woodlands that are in the focus of the model and changes the colour of patches underneath them to yellow, representing pasture areas. The duration of clearance for pastures is heavily dependent on the chosen scenario, rates of clearance, numbers of livestock and effects of overgrazing, regrowth, replacement of grasses by grazing-tolerant species and potential increase of biomass of pastures through prevention of grazing. The objective of this sub-model was to clarify the most significant part of the overall process of deforestation.

7.7.4 Prevention of grazing

The initial stage of clearance for pastures is also marked by a period during which grazing of newly created pastures is prevented. One of the assumptions behind the series of models is that the settlers were aware that prevention of grazing would promote intensified grass growth and would lead to rapid increase of utilisable biomass.

Therefore, along with the process of clearance for pasture, each of the agents randomly choose a period during which grazing is prevented – it is reasonable to assume that this period, which starts with the initiation of clearance for pastures, could not have been shorter than one calendar season (12 months, i.e. ticks) nor longer than two seasons (24 months/ticks).

The objective of this sub-model was to clarify the importance of preparation of newly created pastures for the following period of grazing.

7.7.5 Livestock: growth, fodder requirements, grazing pressure per ha, overgrazing

Immediately after the sprouting of agents and contemporary with the establishment of home-fields, each of the agents introduces their own livestock holding, expressed only as a number in the model. During the simulation run, this number grows to the maximum suggested by the choice during the simulation setup. After the period of prevention of grazing, whenever the needs of livestock outstrip 40 % of the amount of UB, processes of overgrazing occur.

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[49] Technical term used in NetLogo programming language to denote agents of the same kind.

Consequently, this affects the duration of clearance for pastures since the process of overgrazing diminishes production of biomass in the subsequent period by 20 %. [50]

7.7.5.1 Calculating livestock numbers

Numbers of each species of livestock at any given time are calculated by using the equation nr. 2:

$$\mathbf{P = (P_{ex} + P_{inc}) - P_{cull}}$$

where P is the current population, P_{ex} is the existing livestock population (initial livestock population or population recorded at previous tick/month), P_{inc} is the increase in the number of livestock (added in May every year), and P_{cull} is the number of animal culled from the herd (deducted from the total livestock number every September).

Increase in the number of livestock (P_{inc}) is in turn calculated by using the equation nr. 3:

$$\mathbf{P_{inc} = P_{ex}} \text{ x } \mathbf{I_r}$$

where I_r is the intrinsic rate of growth, randomly chosen by the programme in the setup procedure from a range of values (calculated from: Alvard and Kuznar 2001; Kennett and Winterhalder 2006; Table 15):

Table 15. Intrinsic rates of growth of livestock population

Livestock category	**Cattle**	**Ovines**
Intrinsic rate of growth	0.2 – 0.255 (20 – 25 %)	0.3 – 0.6 (30 – 60 %)

The number of animals culled from the herd every September (P_{cull}) is calculated by using the equation nr. 4:

$$\mathbf{P_{cull} = P_{ex}} \text{ x } \mathbf{C_{deg}}$$

where C_{deg} is the degree of culling, randomly chosen by the programme in the setup procedure from a range of values shown in the Table 16 below. That range of values was in turn defined based upon results of the separate experimental runs performed in order to calibrate the models. Logically, those results suggested that the culling rate had to be set as lower than the intrinsic rate of growth, thus enabling the growth of livestock herds.

Table 16. Degrees of culling of livestock herds

Livestock category	**Cattle**	**Ovines**
Degree of culling	0.01 – 0.1 (1 – 10 %)	0.01 – 0.15 (1 – 15 %)

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[50] Based upon the work of Thomson (2003, pp. 166 – 167).

Degrees of culling and intrinsic rates of growth were given as constant values, different for every simulation run. The idea behind the models‘ design was that they represent average values given for the period under discussion. They therefore do not change during the simulation run. The main reason for this simplification was to avoid unnecessary over-complication of the models which would then produce outcomes that can hardly be validated with the existing empirical datasets. It is logical to assume that the *landnám* households were changing their needs and plans with regards to growth of their livestock herds over the course of 130 years, but at present there are no studies which suggest the possible course of alterations in their decision making.

7.7.5.2 Fodder requirements

In theory, the total fodder requirement of a sheep is 30.025 kg of hay and 180.15 kg of hay for a head of cattle, per month, all year round (Chapter 5). However, the assumption behind the models is that woody plants will always, up to a greater or lesser degree, be a part of the livestock diet and that the demand for hay/grassy biomass is actually lower than the abovementioned figures suggest. The precondition of the models is that during the summer period (May – September) the basic fodder requirement was c. 27 kg per months for a sheep and c. 162 kg per month for a head of cattle, which implies that grassy biomass form 90 % of the livestock diet whereas woody plants form 10 % of the livestock diet. During the winter period (October – April) however, the fodder requirements would be even smaller – only 6 kg per head of sheep and 36 kg per head of cattle, which implies that grassy biomass form only 20 % while woody plants form 80 % of the livestock diet (Table 17; Based upon the work of Thomson (2003)).

Table 17. Fodder requirements during each of the seasons

Period	**Ovines / Cattle**
Summer	27 / 162 kg
Winter	6 / 36 kg

Calculating total fodder requirements

One of the assumptions behind the series of models is that the dairy cattle herds were kept indoors during the winter period and fed with hay previously harvested from the home-field and/or wetland areas. Therefore, during the winter season (October – April), only the ovine population utilise the newly created pastures with the previously mentioned „winter“ fodder requirement of 6 kg per ovine head per month (Table 17 above).

Table 18. Utiliation of newly created pastures during the calendar year

Month	Types of livestock
January	Ovine population (6 kg per head)
February	Ovine population (6 kg per head)
March	Ovine population (6 kg per head)
April	Ovine population (6 kg per head)
May	Ovine and cattle population (27 kg and 162 kg per head)
June	Cattle population (162 kg per head)
July	Cattle population (162 kg per head)
August	Cattle population (162 kg per head)
September	Ovine and cattle population (27 kg / 162 kg per head)
October	Ovine population (6 kg per head)
November	Ovine population (6 kg per head)
December	Ovine population (6 kg per head)

During the summer season (May – September) livestock herds utilise pastures in a more complex way. In May, pastures were utilised by both types of livestock population with a „summer“ fodder requirement of 27 kg per ovine head per month and 162 kg per cattle head per month. During the period June – August ovine population graze the highland pastures and the only impact made upon the newly created pastures is the one made by the cattle population (fodder requirement of 162 kg per cattle head per month). In September, the ovine population is brought back to the lowlands and the grazing impact is made by both livestock categories with the rate of grazing (per head) the same as in May (Table 18).

7.7.5.3 Calculating grazing pressure per ha and overgrazing

When designing the models it was decided to consider the grazing pressure as evenly distributed across the pastureland – this was a logical step due to the previously mentioned absence of shepherding but also because of the difficulties in modelling uncontrolled movement of livestock, both of which would suggest positioning of livestock in the landscape and hence distribution of grazing pressure.

Each of the patches of an agent's[51] pastureland therefore witnesses the same degree of grazing pressure. The grazing pressure per patch/ha (Gr_{ha}, expressed in kg: see equation below) is calculated at every tick, in the following way: the number of grazing livestock heads of an agent/cluster of agents is multiplied by their fodder-requirements and divided by the number of pasture-patches of that agent/cluster of agents, as shown in the equation nr. 5:

$$Gr_{ha} = (P_{gr} \times F_{req}) / P_{patch}$$

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[51] Or cluster of agents, where applicable and depending on a chosen scenario.

where $\boldsymbol{P_{gr}}$ is the number of grazing livestock heads, $\boldsymbol{F_{req}}$ are their fodder-requirements and $\boldsymbol{P_{patch}}$ is the number of pasture-patches of an agent/cluster of agents.

A patch is considered as overgrazed if the grazing pressure (per ha) outstrips 40 % of the amount of its biomass. The process of overgrazing is simulated in the following way: patches suffering from overgrazing become grey. As a consequence, their pasture-potential, i.e. UB, decreases by 20 % in the subsequent period (based upon the work of Thomson; 2003, pp. 166 – 167). Actual decrease of the UB due to overgrazing is expressed through multiplication of the available UB by the overgrazing factor (0.8). In the case of the total loss of utilisable grassy biomass, patches become black and devoid of grazing pressure.

The sub-model described in this section clarifies the significance of the changes in the numbers of grazing livestock and related grazing pressure.

7.7.6 Changes in utilisable biomass

The seasonal variation in the amount of utilisable biomass available for grazing at a single hectare of the newly created pastures immediately after tree felling is shown in Figure 15. The total amount of utilisable biomass at an agent's pastures equals the sum of the amounts of UB present at any point in time at the patches that an agent has deforested. The total amount of UB therefore also varies over the course of 12 months. Apart from such seasonal variation and the abovementioned loss of biomass production due to overgrazing, the factors described in the sections below also affect changes in the amount of utilisable biomass during the simulation runs.

It is necessary to emphasise that the inter-annual variability of growth at newly created pastures has not been taken into consideration due to lack of appropriate data that can be used for its assessment and application within the series of models.

7.7.6.1 Decrease of utilisable biomass

The effects of birch regrowth

The effects of regrowth of birch are considered both in terms of the effects of reappearance of birch biomass on UB of the ground floor vegetation, i.e. grass, and the recovery of standing trees.

The reappearance of birch diminishes the biomass of a patch by c. 1.27 % per year and hence 0.1 % per month (calculated from Sigurðsson *et al.* 2005, site B1). The actual amount of UB (expressed in kg) lost due to regrowth is expressed through the multiplication of the available UB by this rate.

The birch cover/standing trees recover at twice the rate of the ground floor biomass reduction, i.e. c. 2.5 % per year and 0.2 % per month. When building the model, the assumption was that due to regrowth, ground vegetation would be eventually reduced down to 50 % of its value which is the value of the ground vegetation biomass of the old birch forest (Sigurðsson *et al.* 2005, site B2 at which grazing was prevented over the course of 97 years). Therefore, in theory, the reduction of UB by 50 % (due to regrowth) would imply the existence of mature, developed forest cover (i.e. 100 % forest cover). Correspondingly, the reduction of UB by 1.27 % per year due to regrowth would imply recovery of the birch cover by 2.5 %.

It is important to stress that regrowth is taken into consideration only in the case of total absence of grazing – either during the period of prevention of grazing (see section 7.7.4) or in the case of total loss of utilisable grassy biomass at a certain patch. It needs to be recognised that this is a simplification of the impact of grazing on woodlands and that the regeneration of woodlands did not depend solely upon the absence/presence of livestock in a given landscape. Today we know that it also depended on various other factors (e.g. state of local ecosystems, climate etc.) and that occasionally, though very rarely, it occured even in the presence of browsing (Jónsson 2004).

Replacement of grasses by grazing-tolerant species

As discussed in Chapter 5, we may assume that the replacement rate was probably no more than 5 % per year in the case of heavy grazing and probably less than 1 % per year under lighter grazing. Hence, the loss of biomass due to this factor was a maximum of 0.42 % per month in the case of heavy grazing (represented as overgrazing in the series of models) and maximum 0.083 % in the case of light grazing. Therefore, during the setup procedure the program makes a random choice of degree of replacement of grasses by grazing-tolerant species from the following range of values (Table 19):

Table 19. Monthly degree of replacement of grasses by grazing-tolerant species during each of the grazing regimes

Grazing regime	**Light grazing**	**Heavy grazing (overgrazing)**
Degree of replacement	0.0083 – 0.083 %	0.083 – 0.42 %

The amount of UB (expressed in kg) lost due to replacement is expressed through the multiplication of the available UB by the appropriate degree of replacement.

Also, the actual moment of initiation of replacement, which is suggested to have started sometime between 5 and 10 years after the initiation of grazing is randomly chosen by the program in the setup procedure – between 60 and 120 ticks (months) after the beginning of clearance for pastures and initiation of grazing.

7.7.6.2 Increase of utilisable biomass

Post-grazing recovery

The assumption behind the model is that the growth of grassy biomass during the post-grazing recovery is possible throughout the period May – September. The rate of growth (shown in Figure 16, below) is calibrated in accordance with the seasonal rate of variation in the utilisable biomass discussed in Chapter 5, which is in turn calculated from the work of Thomson (Thomson 2003). Every portion of the grassy biomass utilised in the process of grazing recovers at this rate.[52] The actual amount of UB (expressed in kg) regained through the process of post-grazing recovery is calculated by multiplying the monthly grazing pressure (Gr_{ha}) by the corresponding degree of recovery.

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[52] Except in the case of total loss of UB when there is no recovery of grasses.

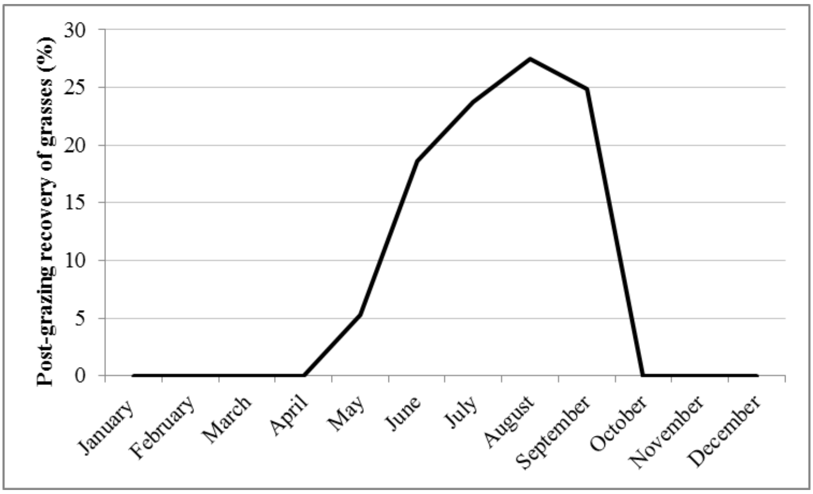

Figure 16. Seasonal variation in the post-grazing recovery of grasses. Increase of utilisable biomass due to prevention of grazing and/or light grazing.

Prevention of grazing/Light grazing

As previously discussed (see section 5.2.5.2.), during the period of prevention of grazing, UB increases by 1.27 % per year and in average, 0.1 % per tick/month. In the case of light grazing, UB increases by 0.6 % per year and in average, 0.05 % per tick/month. The actual amount of UB acquired due to prevention of grazing and/or light grazing (expressed in kg) is calculated by multiplying the available UB by the appropriate rate of increase, which corresponds to the values shown in the Figure 20.

Conclusive equation

The following equation (nr. 6) summarises the factors discussed in the abovementioned paragraphs and explains the way of calculating UB at every tick and at each of the pastureland patches:

$$UB_{present} = (UB_{previous} \; x \; Og_{fact}) - Gr_{ha} - D_{rgrw} - D_{repl} + Pg_{recov} + Inc_{pg/lg}$$

where $UB_{present}$ is the amount of UB at the present month/tick, $UB_{previous}$ is the amount of UB at the previous tick, Og_{fact} is the overgrazing factor[53], Gr_{ha} is the grazing pressure per ha, i.e. the amount of grassy biomass utilised per ha, D_{rgrw} is the decrease of UB due to regrowth of birch, D_{repl} is the decrease of UB due to replacement by grazing-tolerant vegetation, Pg_{recov} is the amount of UB re-gained through post-grazing recovery and $Inc_{pg/lg}$ is the amount of UB acquired through prevention of grazing or light grazing.

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[53] Which is 1 in the case of sustainable grazing and 0.8 in the case of overgrazing.

8 Validation of simulation models and discussion of their outcomes

8.1 Introduction

The first part of this chapter presents a comparison between the model outcomes and the real-world empirical data. Such comparisons indicate the degree to which the series of *ICELANDEF* models can be regarded as valid, i.e. reasonably true representations of what actually happened to the Icelandic birch forests in the late 9th and 10th centuries. The second part of this chapter further discusses the outcomes of the series of models.

8.1.1 Prior to definite simulation runs

8.1.1.1 Experimental runs

Calibration

Prior to making conclusive simulations, a series of experimental, trial-and-error runs was performed in order to calibrate the models. The results of those experimental runs suggested that several reservations, which are described in the previous chapter, had to be made. In spite of that, it may be said that the simulation models are still imperfectly calibrated. For many of the parameters it was only possible to suggest broad range of values and not the actual single values. The principal reason for this is the scarcity and low spatial and temporal precision of the existing available datasets that can be used for their calibration. Unfortunately, this is one of the inherent weaknesses of archaeology-related agent-based models. Future empirical studies will hopefully provide sufficient amount of high-resolution data that can be used for further, detailed calibration of the models and/or refinement of their structure.

Disregarding of Scenario 1

The series of experimental runs also suggested that Scenario 1 cannot be regarded as entirely realistic. The empirical research of Church and others from Vestur-Eyjafjallahreppur (Church *et al.* 2007), Lawson and others from Mývatn (Lawson *et al.* 2007) and Erlendsson from Borgarfjörður (Erlendsson 2007) indicates the existence of considerable areas of woodlands in those regions after the period under discussion. The experimental modelling outcomes of Scenario 1, on the other hand, indicated a total loss of continuous woodland cover in those areas before the end of the 10th century. For this reason Scenario 1 was excluded from further consideration. This exclusion implies that the deforestation activities were limited by projections of future needs of the planned livestock herds, in a way that is suggested by the remaining scenarios 2a, 2b, 3 and 4.

8.1.1.2 Total number of simulation runs

Apart from the series of experimental runs, only the simulation runs of Scenarios 2, 3 and 4 are therefore considered in the subsequent discussion. Table 20 shows the number of courses run in each of those scenarios. The total number of simulation runs, from which results have been used for validation and subsequent discussion, was therefore 240.

Table 20. Number of simulation runs

Study area	**Vestur-Eyjafjallahreppur**	**Borgarfjörður**	**Mývatn**
Scenario 2	20 + 20 (both variants)	20 + 20 (both variants)	20 + 20 (both variants)
Scenario 3	20	20	20
Scenario 4	20	20	20

Remarks on the number of simulation runs

Choosing the number of simulation runs that need to be applied in a simulation study is recognised as a very delicate issue. Since the early 1980s (e.g. Adam 1983), the challenge of determining the required number of runs in simulation-experiments has been addressed in different ways. Unfortunately, even though many scholars have since then proposed a variety of approaches to this problem (e.g. Díaz-Emperanca 1996; Burton *et al.* 2006), very few simulation studies today actually provide a thorough explanation of the chosen number of simulation runs.

With respect to the *ICELANDEF* models, in an ideal situation, simulation runs would involve testing each of the possible values from the range of parameters for each of the variables for each of the agents. Moreover, the large number of patches of woodland in these spatially-explicit models (e.g. the Mývatn model: 70,926 woodland patches) further increases the number of possible variations in a given course of deforestation. It is obvious that this kind of simulation procedure would therefore require hundreds of thousands of simulation runs, which would be extremely time-consuming. For this reason, it was decided to perform a relatively small but hopefully a sufficient number of simulations. This relied on a limited random choice of some of the parameters and corresponded to standards applied by other scholars (Thomson 2003: 20 times each model run; 509 in total including runs for sensitivity analysis; Griffith *et al.* 2010: 30 times each model run, for a total of 90 simulations).

The simulations (240 in total) produced a large amount of data, and analysing each of the variations in the parameters separately would be highly time-consuming. In the absence of appropriate automated tools, which would allow for a rapid and detailed analyses of the outcomes, most of the interpretations were carried out upon the average values of outcomes for each of the possible courses; in addition to this, standard deviations were calculated.[54]

A complete set of the simulation outcomes can be found in the Appendix 1 of this dissertation. The most important outcomes are presented and discussed in the section 8.3. below. Before proceeding to the analysis of the outcomes, it was necessary to illuminate the degree of validity of the *ICELANDEF* models.

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[54] Abbreviated as AVG and SD.

8.2 Validation of the model outcomes

> *„…validation is not simply a state that either holds or does not for a model“*
>
> (Bryson *et al.* 2007, p. 1686)

> *„Essentially, all models are wrong, but some are useful“*
>
> (Box 1979, p. 202)

In order to test the validity of the models, the outcomes of the simulations were compared with a variety of the existing empirical data. The following sections describe this comparison.

8.2.1 Validation of the model of Vestur-Eyjafjallahreppur

The outcomes of the simulation model of Vestur-Eyjafjallahreppur were compared with the following research studies:

a) archaeobotanical study (Church *et al.* 2007),
b) palaeoentomological research study from Holt (Buckland *et al.* 1991a),
c) stratigraphic study of sediment-accumulation rates and macrofossil remains from Mörk and Dalur (Mairs *et al.* 2006),
d) palynological study from Stóra-Mörk (Erlendsson 2007).

8.2.1.1 Archaeobotanical study: Church et al. 2007

The archaeobotanical study of charcoal remains by Church and others (Church *et al.* 2007) can be used for general validation of the ABM of the region of Vestur-Eyjafjallahreppur.

The study by Church and others indirectly suggests the existence of large areas of woodlands in north and northeast Vestur-Eyjafjallahreppur, towards Þórsmörk, after the period under discussion. The model presented here also suggests the existence of woodlands in those areas after this period. Almost none of the scenarios (apart from the excluded Scenario 1) ends up with a significant degree of deforestation by which most of the areas in the north of Vestur-Eyjafjallahreppur would have been completely deforested (Figure 17 below). This is the first point where the outcomes of the model fit to the empirical data of the „real world“.

8.2.1.2 Palaeoentomological study from Holt: Buckland et al. 1991a

The results of the palaeoentomological study by Buckland and others correspond, although only partially, to the agent-based model for the region of Vestur-Eyjafjallahreppur. Firstly, with respect to the type of woodland cover at the location of Holt at the beginning of this period, the authors suggest that although stools of tree birch were found *in situ* beneath the *landnám* tephra layer, nutlets found were identified as *Betula nana* (Buckland *et al.* 1991a, p. 259). Uncertainties regarding the type of woodland thus remain. The particular argument that can be used to validate the model discussed here is the presence of *Bryaxis puncticollis* (Buckland *et al.* 1991a, p. 265, Table 4), a short-winged mould beetle, that is associated with the existence of woodlands (e.g. Vickers *et al.* 2011, p. 989) in the layers belonging to the period before the fall of the *landnám* tephra layer. Its absence from the later phases of human inhabitation at this location can be interpreted as meaning that the woodland cover had been lost. The authors also suggest that the expansion of the long-winged forms should be seen as indicating the disappearance of woodlands „at the hand of settlers“ (Buckland *et al.* 1991a, p. 268). The outcomes of each of the scenarios generally correspond to the results of this study. They suggest the early disappearance of woodland cover at this location which was presumably the home-field of the farm of Holt.

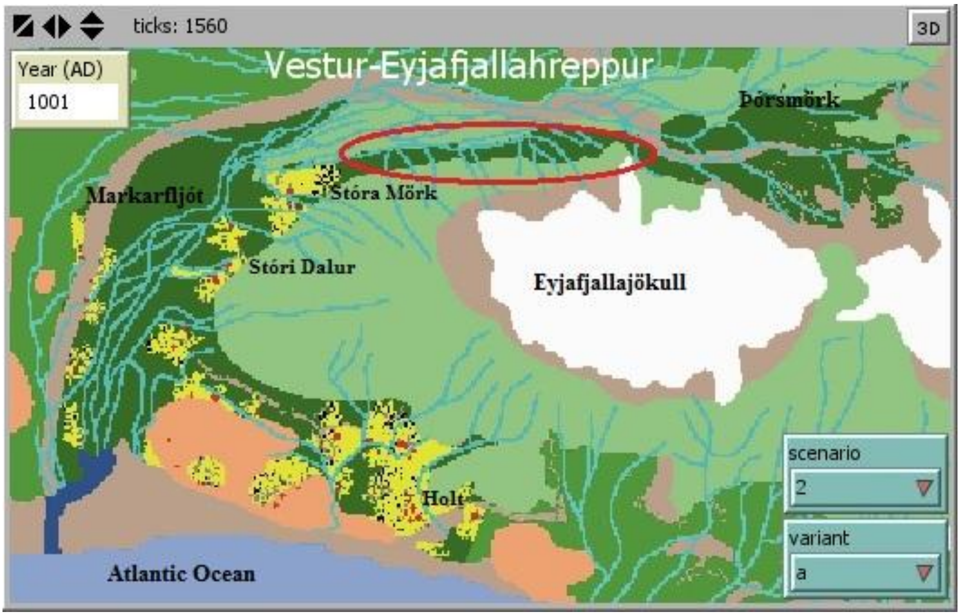

Figure 17. Vestur-Eyjafjallahreppur: Visual output from single simulation run (Scenario 2a - at AD 1001) Note that the areas further north and north-east (circled in red colour) towards Þórsmörk are still covered with woodland.

However, this correspondence can hardly be regarded as appreciably valuable – it is clearly expected since the structure of the model implies the clearance of woodlands in this area in the first two decades of the settlement period. What however comes out of the simulation runs and can actually be considered as important to the present study, are the outcomes of Scenario 3 with regards to timing and nature of the pasture clearance around Holt – those outcomes correspond, up to a certain degree, to the empirical study of Buckland and others.

In their study, Buckland and others also noted that „high inorganic input to the peat at Holt appears to be of later date, which may reflect an increase in grazing pressure on middle-altitude rangelands as a result of the shorter growing season during the Little Ice Age“ (Buckland *et al.* 1991a, p. 256). Therefore, the conclusion could be that after the initial deforestation, there was no considerable degradation of the nearby environment in the late 9th and entire 10th centuries, i.e. during the period in which client farmers may have inhabited this area and when degradation may have happened. Further, this may indicate that pasture areas set in the immediate vicinity were „prepared“ for the arrival of the client farmers, i.e. that the forests were cleared by the patrons’ work-force prior to the establishment of client farms and that consequently client farms left no considerable environmental signature, in terms of deforestation and overgrazing. This interpretation corresponds to Scenario 3 which by definition suggests early clearance of forests and preparation of area for the subsequent arrival of the client population.

8.2.1.3 Stratigraphic study of macrofossil remains and sediment-accumulation rates: Mairs et al. 2006

The results of the stratigraphic and archaeobotanical analysis of 50 soil and peat profiles from the areas of the farm groupings of Mörk and Dalur (Mairs *et al.* 2006) can be used to suggest the degree of validity of the agent-based model of this region.

According to the study of Mairs and others, there was a complete disappearance of birch macro-fossils from the trench-sections in the Mörk area before the deposition of the Katla tephra in AD 920 (Mairs *et al.* 2006, p. 368). This observation does not fully correspond to the outcomes of the majority of the simulation runs, since at most of the cases, NetLogo program-based random choice of timing of the establishment of client settlements in this area, suggests the arrival of the dependent settlers in the later stages of the period under discussion and hence much later depletion of the forest cover. At first glance therefore, it may be argued that the models do not correspond appropriately to the real-world data. However, the outcomes of the additionally calibrated simulation run in which dependent farms (i.e. Syðsta Mörk and Miðmörk) were established soon (only few years) after the establishment of the central, patron farm (i.e. Stóra-Mörk), correspond to the research results presented in the work of Mairs and others since it does suggest disappearance of the birch cover before AD 920 (see Figure 18). Precisely this point can be used to:

a) further calibrate the model[55] and suggest earlier establishment of dependent farms in those particular areas (i.e. within the first 20 years of the *landnám* period), and to

b) stress that this type of random choice of timing of establishment of farms can sometimes lead to inappropriate simulation outcomes.

In any case, it is important to stress that most of the corresponding outcomes originate from scenario 2, variant „a“ which can be regarded as logical since this scenario suggests pasture clearance around each of the farmsteads (regardless of its hierarchical position) and hence throughout the area from which the mentioned research results originate. Opposite to this, most of the outcomes of variant „b“ of scenario 2, but also scenarios 3 and 4 suggest that the clearance was distributed mainly around the farm of Stóra-Mörk and further north and northeast, towards Þórsmörk. According to the outcomes of those scenarios, large areas around dependent farms (i.e. Syðsta Mörk and Miðmörk), positioned south of Stóra-Mörk

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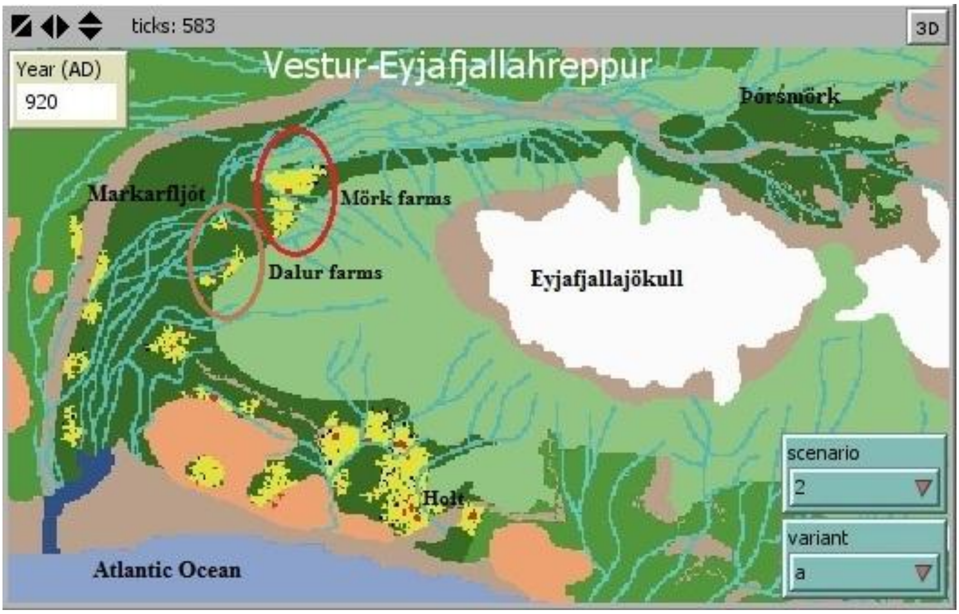
[55] See discussion on the correspondence of the model‘s outcomes with the results of the Erlendsson‘s palynological study (section 8.2.1.4.)

would have been left wooded, which does not correspond to the empirical evidence presented in the work of Mairs and others.



ticks: 583

Year (AD) 920

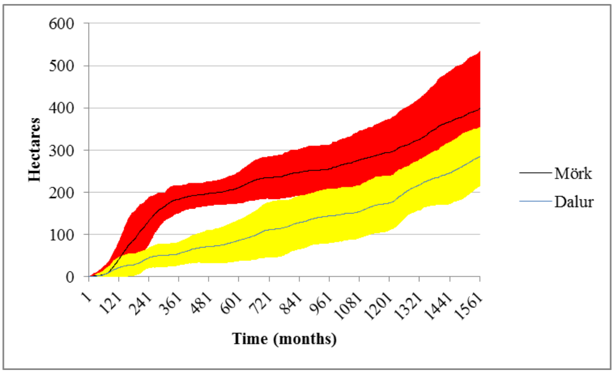
scenario 2

variant a

Figure 18. Vestur-Eyjafjallahreppur: Visual output from single separate simulation run (Scenario 2a - at AD 920). Note that the Mörk area (circled in red colour) is deforested.

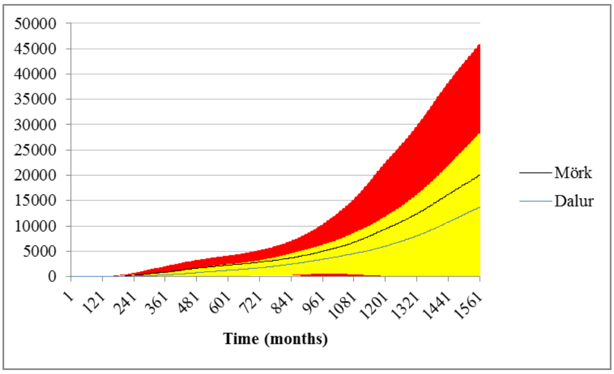
Secondly, the first increase in sediment accumulation rate is identified in the period AD 871 – 920 in both the Dalur and the Mörk areas (Mairs *et al.* 2006, p. 367, 368). This fact indirectly corresponds to the results of the simulation runs which suggest a considerable degree of deforestation but also the occurrence of overgrazing (although only up to a lesser degree) during this period in the vicinity of the farms discussed in the study (Figures 19 – 20 below). For the reasons outlined above, it may be said that it was scenario 2, variant „a“ that most likely took place in the Dalur and the Mörk areas.

Mairs and others also suggest that the degree of environmental change in the Dalur area was lower than that in the Mörk area. The model outcomes, one of which is shown above (Figure 18), correspond to this research result. Mairs and colleagues propose a simple explanation for this: woodland cover at and around the Dalur farms was not as significant as it was in the Mörk grouping; the lighter the woodland cover was, the less significant would have been the consequences of deforestation and possible subsequent soil erosion due to overgrazing. However, I propose here that the reason for the different degrees in land degradation between these farm groupings simply lies in the different numbers of livestock and that the greater numbers of livestock in the Mörk grouping resulted in a greater environmental impact.



Note:—— average —— standard deviation; —— average —— standard deviation

Figure 19. Exent of deforestation at the estates of Mörk and Dalur farms



Note:—— average —— standard deviation; —— average —— standard deviation

Figure 20. Total number of occurrences of overgrazing at the estates of Mörk and Dalur

Exception

Mairs and others also suggest that less than 50 years after the initial degradation, a second stage of changes in sediment-accumulation rates occurred in the Mörk area, increasing to nearly four times that of the period AD 871 – 920. At the same time, the authors stress that sediment-accumulation rates in the Dalur area decreased after AD 920 (Mairs *et al*. 2006, p. 368). The outcomes of the simulation runs correspond only partially to those research results – they suggest repeated and increased degradation both in the Mörk and Dalur areas (Figures 19 and 20, above) which would eventually lead to a remarkable degree of deterioration; still, it is highly unlikely that it could have led to abandonment of the areas since there would still have been sufficient extent of pastures to sustain livestock herds.

At first glance, the absence of repeated degradation in the Dalur area (which could perhaps be dated to the second part of the 10th century) is hard to explain. However, it is possible that the farms in the Dalur grouping were simply exceptions in terms of duration of the assumed grazing strategies. This series of models, unfortunately, does not focus on possible micro-changes in grazing strategies and hence changes in vegetation cover at micro-locations (or for instance changes in degrees of culling and intrinsic rate of growth), that could account for the absence of this late, local degradation. In other words, the absence of later disturbance in the landscape could have been the result of one or more factors that are outside the scope of this series of models.

8.2.1.4 Palynological study: Erlendsson 2007

Erlendsson's palynological study (Erlendsson 2007) suggests that at a site located c. 500 m south of the farm Stóra-Mörk, „there is evidence of land use activities and reduction of tree cover with increased appearance of agricultural indicators sometime around the middle point between AD 871 and 920" (Erlendsson 2007, p. 154).[56] The outcomes of the scenarios considered which indicate a disappearance of woodland cover at this location (Table 21) therefore only partially correspond with this argument.

Table 21. Outcomes of 20 simulation runs – clearance of forest cover recorded at the location of Stóra-Mörk

Clearance at Stóra-Mörk	**Scenario 2a**	**Scenario 2b**	**Scenario 3**	**Scenario 4**
AVG (rounded)	After 832 months	After 692 months	After 585 months	After 485 months
SD (rounded)	531	342	553	438

Further calibration of the model, in a way that is suggested above for the farms of the Mörk grouping could provide the outcomes that would entirely correspond to Erlendsson's research results. It is logical to assume that the most appropriate among those outcomes would originate from scenario 2a, for the reasons suggested in section 8.2.1.3. However, taking note of Erlendsson's further suggestions, this step may not be necessary.

Erlendsson stresses that massive destruction of birch forests and subsequent soil erosion actually appeared later, „at the onset of the post- AD 920 period" (Erlendsson 2007, p. 155). Since the aforementioned applied timing of the establishment of the farm of Miðmörk frequently implies total clearance at this location (for pastureland at Miðmörk) after AD 920, further calibration of the model is therefore unnecessary. As an addition to this, one also needs to bear in mind the possibility that the area around the site at which the sample was taken could have been part of the „pockets" of woodland that may have been intentionally left wooded for a certain period of time since they could represent a reliable source of firewood but also building and browsing material located close to the farmstead. Those areas

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[56] It is important to stress that in the model presented here, this site is located in an area that is more likely to have belonged to the pasture area of Miðmörk rather than to that of Stóra-Mörk; it is closer to Miðmörk and natural boundaries (rivers) also clearly indicate that they most probably belonged to the property of Miðmörk.

may have been cleared later and hence after the deposition of Katla ash in AD 920. Although this possibility occurs in a small number of runs, it is still worth consideration.

In any case, Erlendsson's interpretation of the post- AD 920 massive deforestation is considerably different from the one suggested by Mairs and others (section 8.2.1.3.) which implies complete disappearance of the birch cover before AD 920. This is one of the critical points where palynological evidence does not correspond to archaeobotanical macrofossil evidence. In general, pollen studies are considered as a less reliable research tool than macrofossil analyses[57], which suggests that we should rather rely on the research results of Mairs and others. Nevertheless, Erlendsson's palynological study is undoubtedly relevant to the validation process and also needs to be taken into consideration when creating the interpretations of the process of deforestation during the period under discussion.

What is also stressed in Erlendsson's study is that the charcoal values at the site did not reach high proportions and therefore one can hardly talk of clearance with the use of fire. This argument supports one of the claims made earlier in this thesis: burning can be ruled out as a significant method used to clear woodland in the vicinity of farms, even though it may have been employed to some degree elsewhere. Unfortunately, since there is little empirical evidence from areas away from habitations, it is hard to state to what degree burning may have been used.

To sum up: Vestur-Eyjafjallahreppur

It may be argued that at many of the locations each of the considered scenarios (i.e. sc. 2a and 2b, 3 and 4) could be, at least partially, used for interpretation of the deforestation process. However, I propose here that particular attention should be given to scenarios 2a and 3, due to the highest probability of scenario 2a in the area around the Mörk grouping of farms and since at and around Holt it is scenario 3 that most probably took place.

8.2.2 Validation of the model of Mývatn

The outcomes of the simulation model of Mývatn were tested against the following research studies:

a) palynological study of Helluvaðstjörn (Lawson *et al.* 2007),
b) series of interdisciplinary studies of various locations in the Mývatn area (McGovern *et al.* 2007; Lawson *et al.* 2009; Simpson *et al.* 2004).

8.2.2.1 Pollen study of Helluvaðstjörn: Lawson et al. 2007

Probably the most important study for validation of the agent-based model of Mývatn is the analysis of pollen samples from the lake Helluvaðstjörn by Lawson and others (Lawson *et al.* 2007). Lawson and others suggest that, unlike other locations throughout Iceland (e.g.

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[57] Scholars frequently stress that macrofossil analysis is a more reliable research tool than palynology (e.g. Hallsdóttir 1987, p. 2; Tinner 2007, p. 2376). This being mainly due the higher spatial resolution than is possible in pollen studies; macrofossil records also have higher taxonomic resolution.

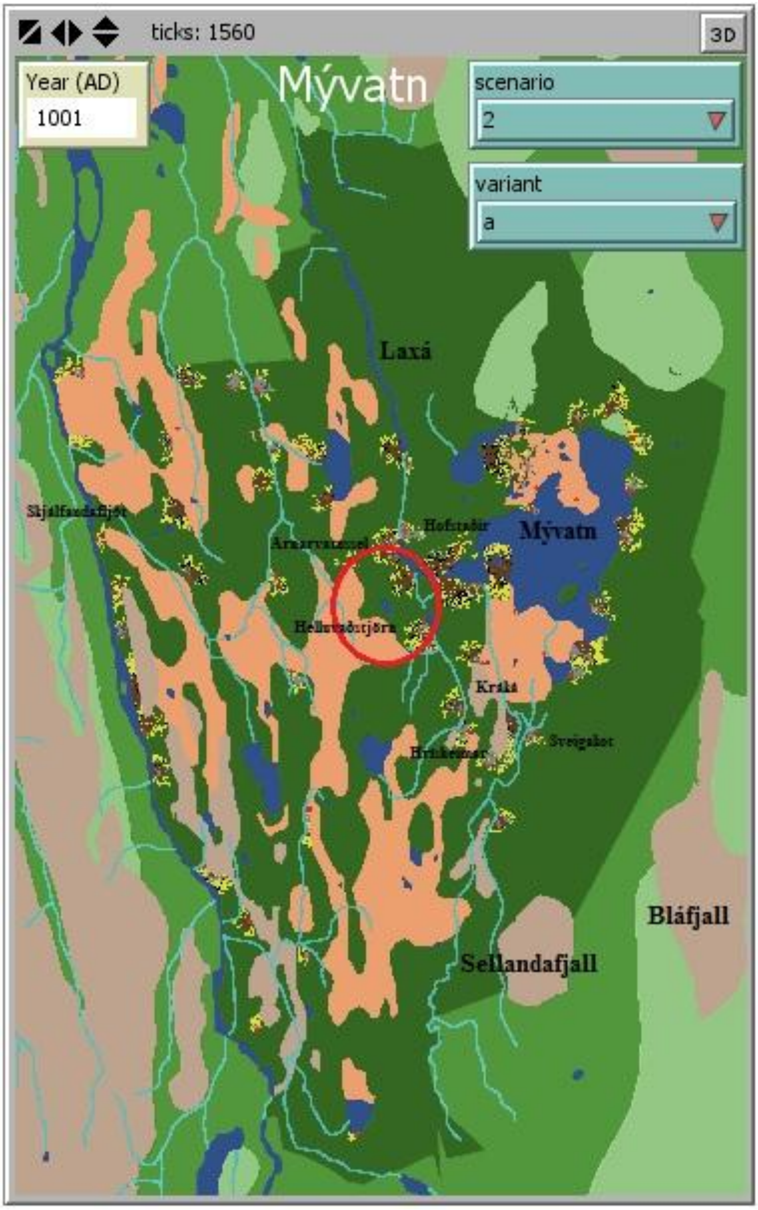
Hallsdóttir 1987, Einarsson 1957), birch underwent a less intense and prolonged downturn in the area around the lake during the *landnám*. This study is one of the first to indicate that the *landnám* deforestation may not in fact have been a drastic one. An equally important aspect of this study is that it indicates that the process of birch cover reduction may have been intermittent, with obvious periods of birch pollen reappearance which may suggest periods of regrowth. So, do the model outcomes fit this study, and if so, then how? Before answering that question, the pollen catchment area of this lake needs to be discussed.

One of the critical questions with respect to the pollen diagram from Helluvaðstjörn is the exact size of the area from which vegetation changes are reflected in the lake's pollen core, i.e. how large is the pollen catchment area? The answer to this question lies in estimating the extent of the Relevant Pollen Source Area (RPSA), i.e. the area from which vegetation changes are reflected in a certain pollen diagram. Producing an estimate of the RPSA for a lake is not an easy task and is the subject of extensive debates; i.e. scholars are not in agreement on the methodological approach to this problem.

The transportation mode of pollen is one of the most important aspects of this issue. For instance, in many cases it is hard to estimate how much of the pollen enters the lake from the catchment by overland flow and/or how much of it is transported by wind. A number of palynologists argue that the amount of pollen transported by overland flow is usually insignificant and that in most cases, pollen is transported by wind (Lawson – pers.comm). Adopting this assumption, it becomes possible to estimate the RPSA of a certain lake. Scholars such as Sugita (e.g. Sugita 1993) even suggest a model that can be used to calculate the RPSA. Briefly, estimating the RPSA involves calculations based on a variety of data (Lawson – pers.comm), such as diameter of the lake basin, sedimentation rate of the pollen and speed of the wind in the area; it is also important to stress that there are many more factors that need to be taken into consideration: for instance quantifications of soil and peat erosion, pollen grain sizes and relative weight and intensity of pollen „rain" (with respect to the density of woodland cover). Sadly, with respect to Iceland, for many of those and other factors we do not have any appropriate data that could be useful.

Nevertheless, estimates of the RPSA from other lakes in Iceland can be useful here. Erlendsson (Erlendsson 2007), made an estimate of the RPSA of Breiðavatn (Borgarfjörður, western Iceland), basing it on a comparison with small Danish lakes (Nielsen and Sugita 1995). He suggests an RPSA of 2.5 km^2, based on a radius of 2,000 m from the centre of Breiðavatn (Erlendsson 2007, p. 171). Erlendsson also supports the general assumption that the larger the lake and basin size, the wider the relevant pollen source area. With respect to the case of Helluvaðstjörn this would imply a considerably larger RPSA, since Helluvaðstjörn is a larger lake (c. 800 by 400 m, as opposed to Breiðavatn which is c. 100 by 300 m) and the surrounding landscape is more open.

However, Lawson (pers. comm.) suggests that if one allows a high estimate for Helluvaðstjörn (i.e. a RPSA of more than 2.5 km in radius), then lake pollen records from a given region would be indistinguishable from each other. This opinion partially corresponds with the standpoint of Sugita (Sugita 1994) suggesting that a relevant source distance from the lake edge is between 600 – 800 m for medium-size lakes with diameter of 250 m.



ticks: 1560

Year (AD)
1001

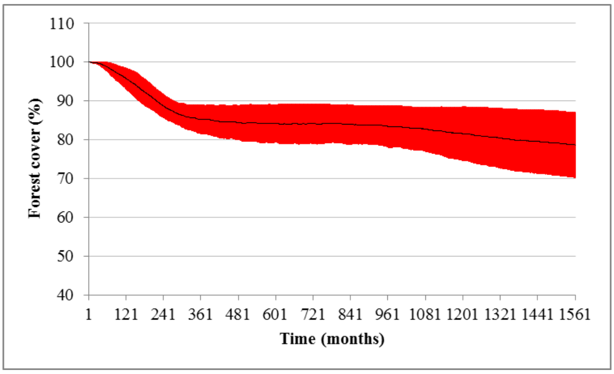
scenario
2

variant
a

Figure 21. Mývatn: Visual output from single separate simulation run (Scenario 2a – at AD 1001). Note the approximate extent of RPSA of Helluvaðstjörn (circled in red colour).

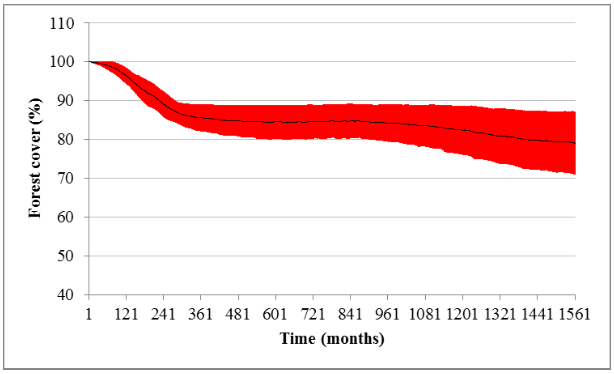
Taking all the foregoing into account, and also the natural surroundings of Helluvaðstjörn, it is proposed here that the RPSA would extend 2,500 m from the edge of the lake; this would reflect changes in the woodland cover over an area of 1423 ha, roughly set between the river Laxá and Arnarey on the one side and the Gautlandamýri wetland area on the other side. During the simulation runs, the changes in the birch cover over these 1423 ha were recorded (Figure 21 above); the values are expressed in percentage units (%) of land area. The effect of birch regrowth was added to this, also expressed in percentage units. The design of the model limited the maximum birch cover presence at 100 %.

In brief: the simulation runs of each of the considered scenarios (i.e. sc. 2a, 2b, 3 and 4) correspond, albeit imperfectly to the results from the palynological study of Lawson and others (Figures 22 – 25).



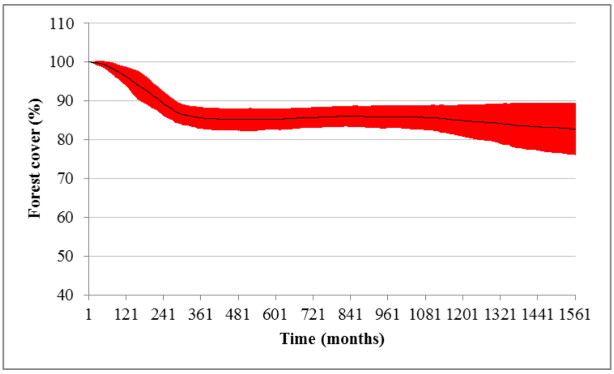
Note:—— average —— standard deviation

Figure 22. Scenario 2a: Forest cover around the lake of Helluvaðstjörn



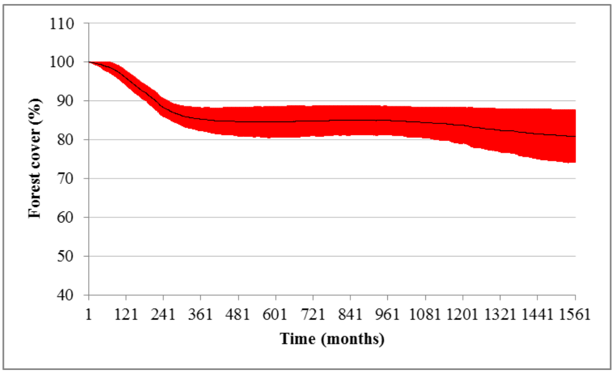
Note:—— average —— standard deviation

Figure 23. Scenario 2b: Forest cover around the lake of Helluvaðstjörn



Note:—— average —— standard deviation

Figure 24. Scenario 3: Forest cover around the lake of Helluvaðstjörn



Note:—— average —— standard deviation

Figure 25. Scenario 4: Forest cover around the lake of Helluvaðstjörn

It is easy to notice that curves representing forest cover in the RPSA (Figures 22 – 25) do not follow completely the curve shown in the pollen diagram made by Lawson and others (Figure 26).

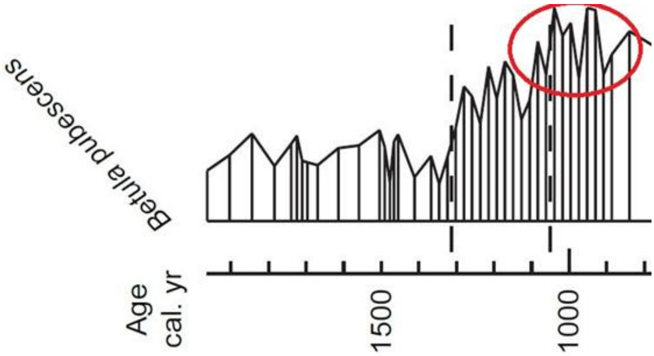


Figure 26. Sequence of the pollen diagram (taken from Lawson *et al.* 2007, p. 7, Figure 6.). Note the fluctuations of the birch cover (circled in red colour). Also note the inverse direction of the time scale.

However, one needs to be aware that the variability in the pollen record does not necessarily reflect actual changes in the forest cover. Those variations could also be the result of differences in pollen production (for instance, good flowering years on birch come only every 10 – 20 years in North Iceland) or reflect specific pollen deposition events (i.e. a strong wind from a certain direction when pollen was being shed) (Eysteinsson – pers. comm.). Lawson and others, refering to Tauber (Tauber 1965), also allow for the possibility that „as the woodland began to be opened up, the increased effectiveness of pollen transport by wind in a partly deforested environment led to higher pollen loadings in the lake“ (Lawson *et al.* 2007, p. 10).

In any case, it is important to stress that the figures shown above present the average values of 20 simulation runs. Some of the single simulation runs however suggest greater variations in the forest cover and can therefore be regarded as more realistic representations of this environmental change (Figure 27).

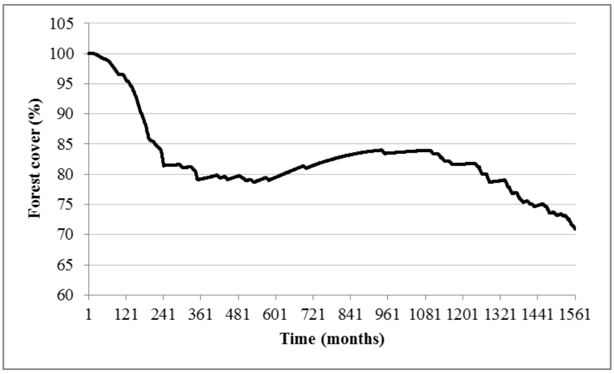


Figure 27. Scenario 2b: Forest cover around the lake of Helluvaðstjörn. The outcome of the single simulation run (nr. 2).

If we accept the figure shown above as (in broad terms) a reasonably realistic representation of the deforestation process, then the basic parameter values (Table 22 below), randomly chosen by the program in the setup procedure and used to produce this output, can be seen as relevant.

Table 22. („a“ above and „b“ below). Starting parameters of the single simulation run (Mývatn, Scenario 2b, simulation run nr. 2).

Cattle cull	Ovines cull	Cattle growth	Ovines growth
7 %	11 %	24.5 %	58 %

Starting cattle	Starting ovines	Initiation of replacement	Replacement (heavy grazing)	Replacement (light grazing)
5	9	After 74 months	0.32 % (per month)	0.05 % (per month)

Still, the approval of parameter values presented here should be approached with caution. The outcomes of another simulation run which suggest very similar changes in the forest cover (and supposedly acceptable in terms of validation; Figure 28 below) are produced with obviously different starting parameter values (Table 23), which implies a certain level of equifinality.

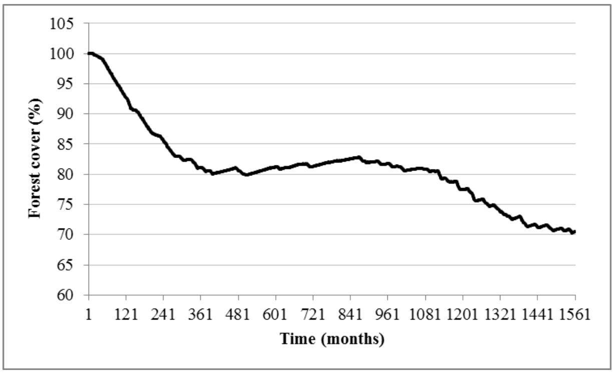


Figure 28. Scenario 3: Forest cover around the lake of Helluvaðstjörn. The outcome of the single simulation run (nr. 6).

Table 23. („a“ above and „b“ below). Starting parameters of the single simulation run (Mývatn, Scenario 3, simulation run nr. 6).

Cattle cull	Ovines cull	Cattle growth	Ovines growth
7 %	4 %	25.2 %	43.7 %

Starting cattle	Starting ovines	Initiation of replacement	Replacement (heavy grazing)	Replacement (light grazing)
5	5	After 97 months	0.1 % (per month)	0.06 % (per month)

The reason for the state of equifinality, i.e. fortuity of yielding „appropriate“ outcomes with different parameters, can be explained primarily by the combined effect of various factors introduced during the simulation runs and independent of the initial conditions: decision making with regards to spatial distribution of clearance (described in section 7.5.4.), clearance-rate fluctuations (section 7.5.9.4.) and different periods of prevention of grazing (section 7.7.4.). Unfortunately, our knowledge about those factors is undoubtedly limited and as a result, further clarification of the entire deforestation process and final identification of the best-fitting parameters arises as an extremely difficult, if not an impossible task. Further research with regards to those factors is therefore obviously needed.

Another conclusion that may be drawn from this situation of having two different sets of basic parameters producing very similar (and supposedly „right“) outcomes, is that the parameter values presented here can be seen (in broad terms) as only contingent conditions – which happened to produce „true“ outcomes but could produce „false“ outcomes as well, depending on the effect of the mentioned factors introduced during the simulation runs.

In general, the charts representing model outcomes do indicate that woodland was present throughout the period and that it did not decline significantly, which generally corresponds to the results of Lawson and others. This correspondence can be explained in a simple way – the clearance for pastures in the area around the lake could not have been very significant owing to a relatively small number of farms that could have been involved in clearance around the lake: the farms of Helluvað, Litlu-Gautlönd, Arnarvatnssel, Steinbogi, and perhaps, although only occasionally, the farms of Gautlönd, Hofstaðir, Arnarvatn and Beinistaðir.

Finally, the reason for the lack of clear distinction between the outcomes of different scenarios lies in the fact that all the farms involved in the clearance around the lake were independent. As previously mentioned (Chapter 6), the course of their clearance for pastures was same for each scenario.

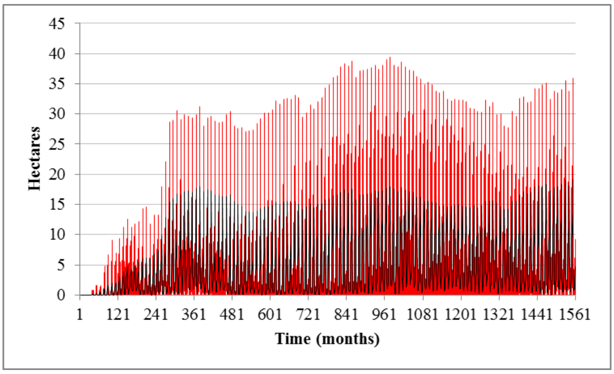
8.2.2.2 The series of interdisciplinary studies

An entire series of interdisciplinary studies already completed provides empirical research data that can be used to validate the outcomes of the model at particular localities in the regi on of Mývatn. The following lines briefly explain the correspondence between the model outcomes and the real-world data.

Changes in sediment-accumulation rates / overgrazing

One of the most convincing arguments used to confirm the idea of remarkable impact of humans and their economy on natural environment during the *landnám* is the considerable increase in sediment-accumulation rates, which many scholars (e.g. Þórarinsson 1961) have explained to be a consequence of soil erosion. For decades scholars have strengthened the idea that erosion originated, among other reasons, from breaks in the vegetation cover, which were in turn a result of overgrazing by livestock (e.g. Dugmore *et al.* 2009). Today we know that timing and degree of erosion processes in Iceland (which resulted in changes in sediment-accumulation rates) differed from one location to another. Erosion first occurred in the marginal upland areas, as opposed to lowlands, which were more resistant to vegetation breaches and where erosion became significant later on (Dugmore *et al.* 2009). Some of the research results suggest that it also differed from one part of the country to another (e.g. McGovern *et al.* 2007). Thus, as opposed to the southern part of the country, geomorphological and tephrochronological studies made close to the sites of Sveigakot and Hrísheimar indicate smaller sediment-accumulation rates during the *landnám* period (McGovern *et al.* 2007, p. 39).

The outcomes of each of the considered scenarios indirectly correspond to this observation. The number of possibly overgrazed patches of land which may indicate soil erosion at the pastures of those farms is smaller than in the south of the country (see Figures 29 – 36, below. For further comparison see figures in Appendix 1, showing the total extent of areas possibly affected by overgrazing in Vestur-Eyjafjallahreppur[58]). Also, the model suggests a patchy occurrence of overgrazing throughout the Mývatn area and in particular at the estates for which we have empirical evidence of changes in sediment-accumulation rates: Arnarvatnssel and Hofstaðir (Lawson *et al.* 2009, pp. 40 – 44; Also, see Figures 37 – 44 below).



Note:—— average —— standard deviation

Figure 29. Scenario 2a: Extent of areas affected by overgrazing at the estate of Sveigakot

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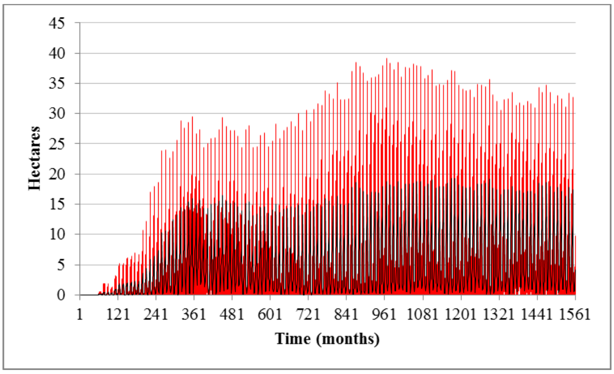
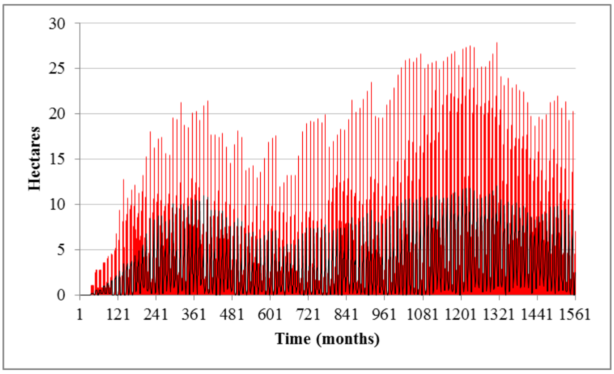
[58] Note that there were 44 farms in the region of Vestur-Eyjafjallahreppur. In average, the extent of possibly overgrazed areas in that region (per farm) is higher than the extent of possibily overgrazed areas at the estates of Sveigakot and Hrísheimar.



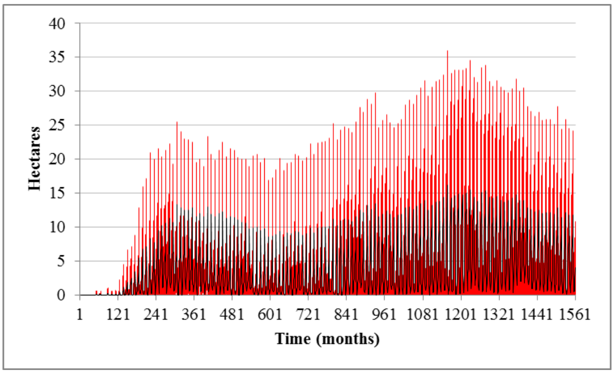
Note:—— average —— standard deviation

Figure 30. Scenario 2b: Extent of areas affected by overgrazing at the estate of Sveigakot



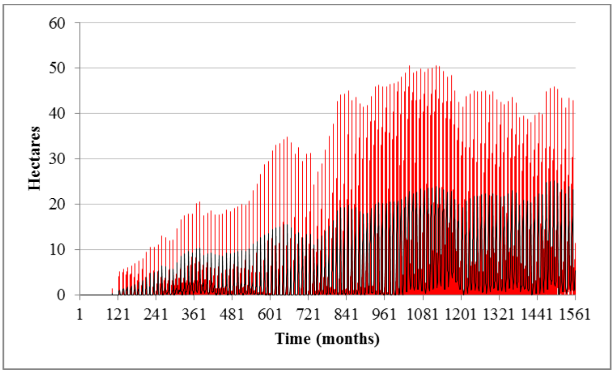
Note:—— average —— standard deviation

Figure 31. Scenario 3: Extent of areas affected by overgrazing at the estate of Sveigakot



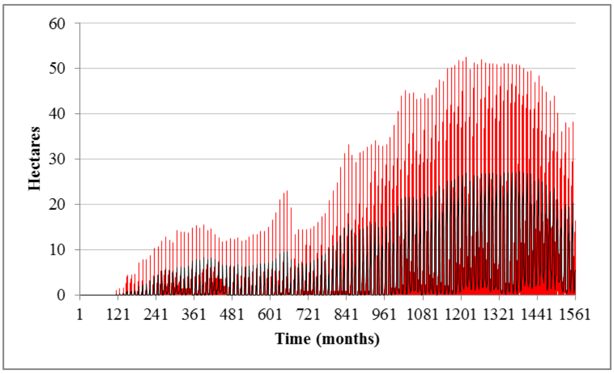
Note:—— average —— standard deviation

Figure 32. Scenario 4: Extent of areas affected by overgrazing at the estate of Sveigakot



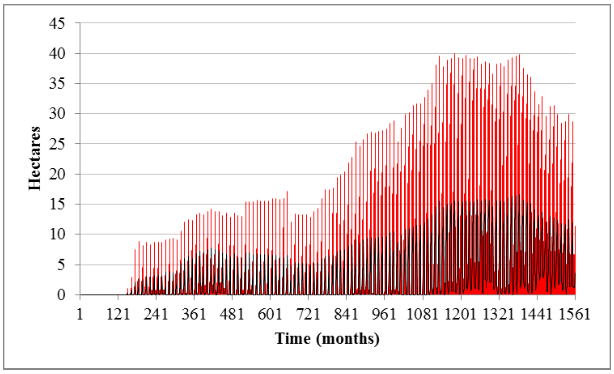
Note:—— average —— standard deviation

Figure 33. Scenario 2a: Extent of areas affected by overgrazing at the estate of Hrísheimar



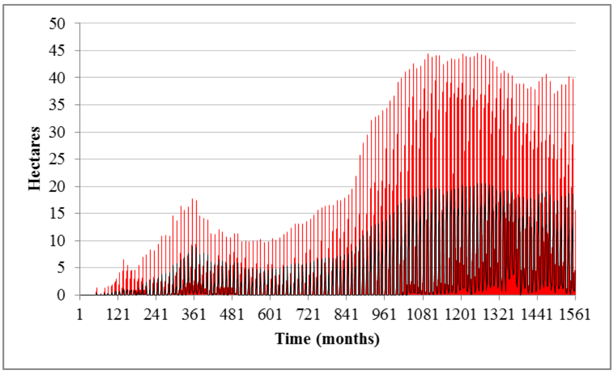
Note:—— average —— standard deviation

Figure 34. Scenario 2b: Extent of areas affected by overgrazing at the estate of Hrísheimar



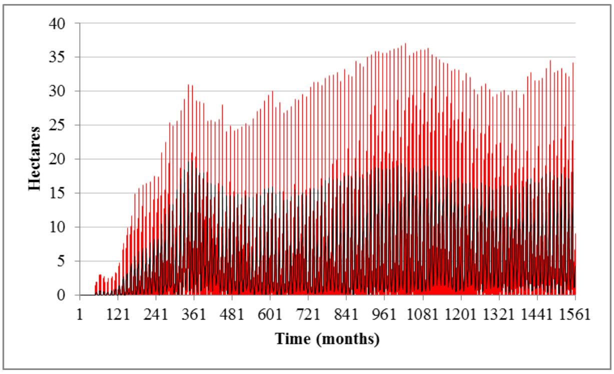
Note:—— average —— standard deviation

Figure 35. Scenario 3: Extent of areas affected by overgrazing at the estate of Hrísheimar



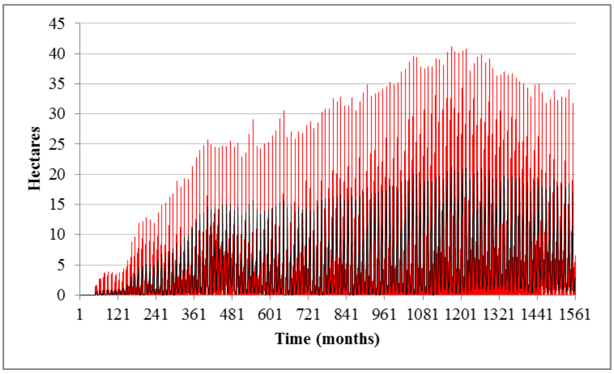
Note:—— average —— standard deviation

Figure 36. Scenario 4: Extent of areas affected by overgrazing at the estate of Hrísheimar



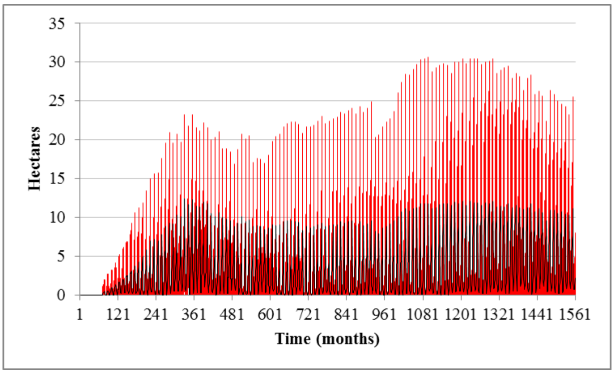
Note:—— average —— standard deviation

Figure 37. Scenario 3: Extent of areas affected by overgrazing at the estate of Arnarvatnssel



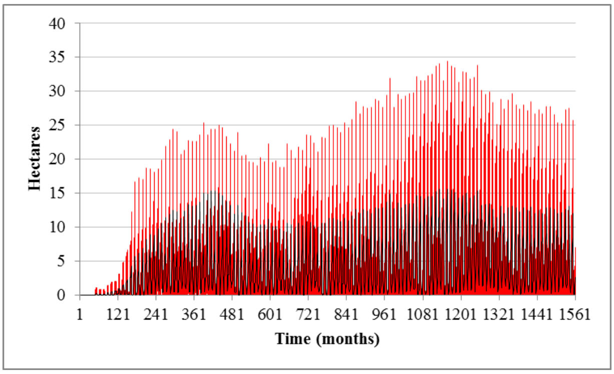
Note:—— average —— standard deviation

Figure 38. Scenario 2b: Extent of areas affected by overgrazing at the estate of Arnarvatnssel



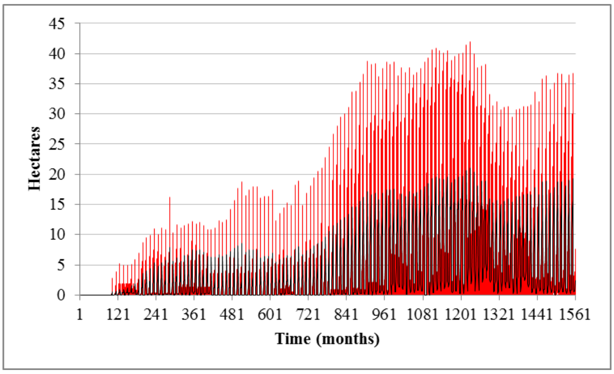
Note:—— average —— standard deviation

Figure 39. Scenario 3: Extent of areas affected by overgrazing at the estate of Arnarvatnssel



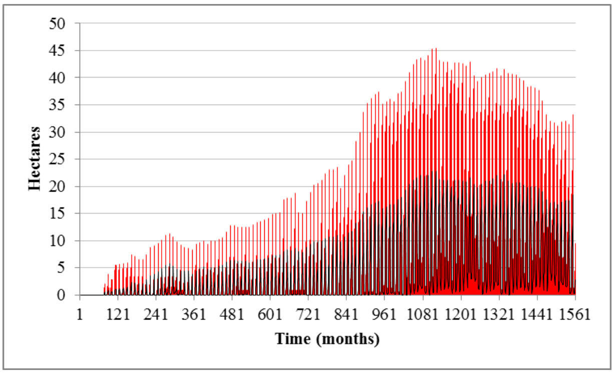
Note:—— average —— standard deviation

Figure 40. Scenario 4: Extent of areas affected by overgrazing at the estate of Arnarvatnssel



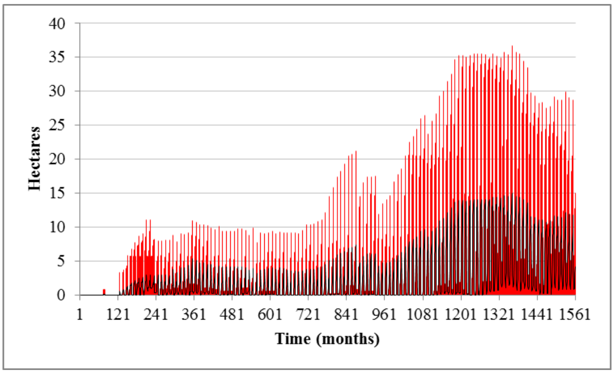
Note:—— average —— standard deviation

Figure 41. Scenario 2a: Extent of areas affected by overgrazing at the estate of Hofstaðir



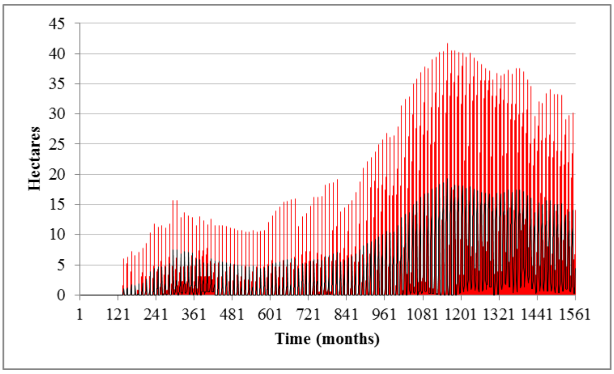
Note:— average — standard deviation

Figure 42. Scenario 2b: Extent of areas affected by overgrazing at the estate of Hofstaðir



Note:— average — standard deviation

Figure 43. Scenario 3: Extent of areas affected by overgrazing at the estate of Hofstaðir



Note:— average — standard deviation

Figure 44. Scenario 4: Extent of areas affected by overgrazing at the estate of Hofstaðir

In general, less land degradation (i.e. overgrazing) than in Vestur-Eyjafjallahreppur (in terms of the extent of overgrazed areas) can be explained in a simple way – smaller livestock numbers mean less deforestation, less grazing and hence less degradation.

Variations in the extent of overgrazed areas around some of the farms in Mývatn, shown in the figures above, suggest which periods over the course of 130 years can be considered to have had the highest degree of grazing-related deterioration that eventually may have resulted in soil erosion. The results of the simulation runs suggest that the pasturelands owned by the low-ranking farms (Sveigakot and Arnarvatnssel) suffered from significant overgrazing very early on, i.e. already after c. 25 years of utilisation. On the other hand, the high-ranking farms (Hofstaðir and Hrísheimar) managed to keep less significant overgrazing at their pasturelands for more than c. 70 years. This dissimilarity can be explained, up to certain extent, by the difference in their work-force population numbers (considerably higher at the high ranking farms) and hence their possible rates of clearance applied in order to counter the occurrence of overgrazing. Still, the figures presented here also suggest that even the high-ranking farms, in spite of their high-labour recruitment potential could not prevent significant increase in overgrazing during the second part of the period under discussion. Put simply, not even their rates of clearance could entirely follow demands for pastures of their livestock herds.

Finally, same as the regional-scale figures, the figures presented here suggest considerable oscillations in the extent of overgrazed areas over the course of a single season. Those oscillations suggest the occurrence of overgrazing (and hence possibly soil erosion) during the late winter/early summer periods.

To sum up: Mývatn

Although there is a lack of empirical evidence to validate fully the model of environmental changes in Mývatn during the *landnám* period, the studies mentioned above suggest that the model can be regarded as a resonable representation of the actual processes in the past.

The empirical evidence used to illuminate the degree of validity of the model of Mývatn originate from locations and areas which were inhabited by independent farmers. As already mentioned, the course of their clearance for pastures was same for each considered scenario (i.e. sc. 2a, 2b, 3 and 4) and as a result, it is not possible to make clear distinctions between the outcomes of those scenarios and to suggest which particular scenario should be regarded as the most probable at those locations and areas and finally, for the entire region of Mývatn.

8.2.3 Validation of the model of Borgarfjörður

Compared to the regions of Vestur-Eyjafjallahreppur and Mývatn, the region of Borgarfjörður is less well covered by empirical research data that can be used for validation of the agent-based model. Still, the existing data, and first and foremost the work of Erlendsson (Erlendsson 2007), may be regarded as sufficient to suggest that the structure and outcomes of the model are generally realistic.

8.2.3.1 Palynological study: Erlendsson 2007

The modelling outcomes were compared with two major aspects of environmental change during the *landnám*: changes in sediment-accumulation rates, which indicate possible soil erosion, which in turn may have been the consequence of overgrazing and changes in the percentage of the birch pollen, indicating clearance of the woodland.

The RHD1 site

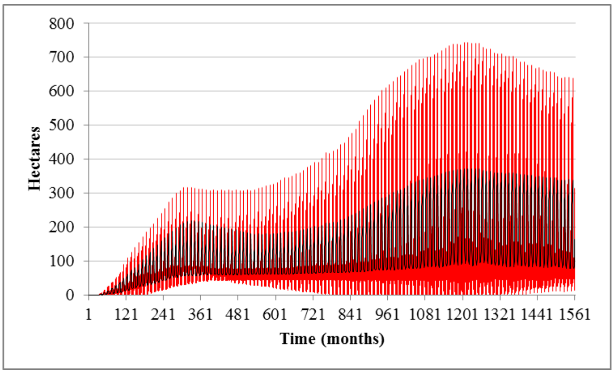
Erlendsson's study of the RHD1 site, which is located on meadow-pastureland close to the farm of Reykholt, indicated an almost instant reduction of the woodland cover during the age of settlement (Erlendsson 2007, p. 250[59]). This result partially corresponds to the outcomes of each of the considered scenarios of the model of Borgarfjörður which suggest that removal of woodland cover in this area happened in the first part of the *landnám* (Table 24).

Table 24. Borgarfjörður: Forests clearance at the RHD1 site. The outcomes of simulation runs

Clearance at RHD 1 site	**Scenario 2a**	**Scenario 2b**	**Scenario 3**	**Scenario 4**
AVG (rounded)	After 210 months	After 156 months	After 175 months	After 257 months
SD (rounded)	247	85	94	305

Erosion in the Reykholtsdalur valley

Erlendsson (Erlendsson 2007, p. 209) also identifies a significant rise and subsequent fall of *Pteropsida (monolete) indet.*, which may indicate soil erosion in the valley. The outcomes of the model of Borgarfjörður indirectly correspond to this indication. During each of the simulation runs, the extent of areas possibly affected by overgrazing was recorded. As shown in the Figures 45 – 48 below, there was a considerable number of overgrazed patches in the valley, which may indicate soil erosion.



Note:—— average —— standard deviation

Figure 45. Scenario 2a: Extent of areas affected by overgrazing in Reykholtsdalur valley

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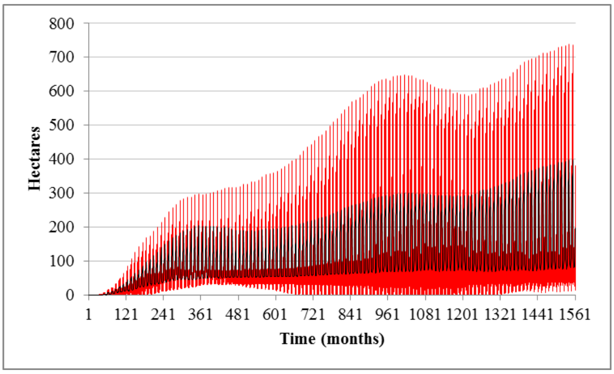
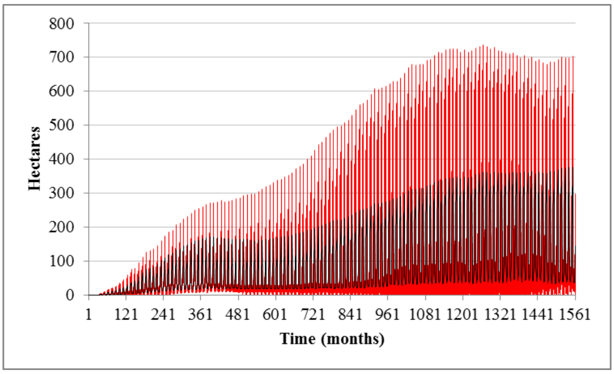
[59] Although Erlendsson suggests that „the apparent change in vegetation is perhaps exaggerated as a consequence of palynomorph taphonomy" (Erlendsson 2007, p. 250).



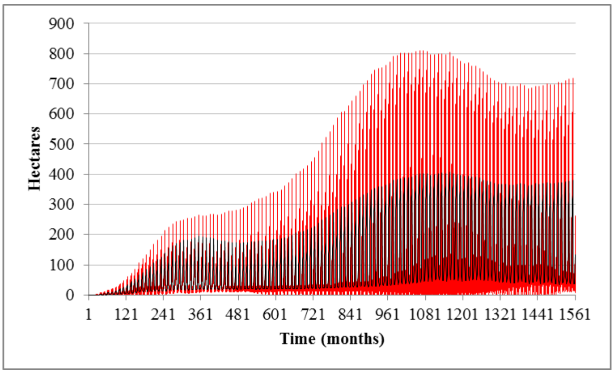
Note:—— average —— standard deviation

Figure 46. Scenario 2b: Extent of areas affected by overgrazing in Reykholtsdalur valley



Note:—— average —— standard deviation

Figure 47. Scenario 3: Extent of areas affected by overgrazing in Reykholtsdalur valley



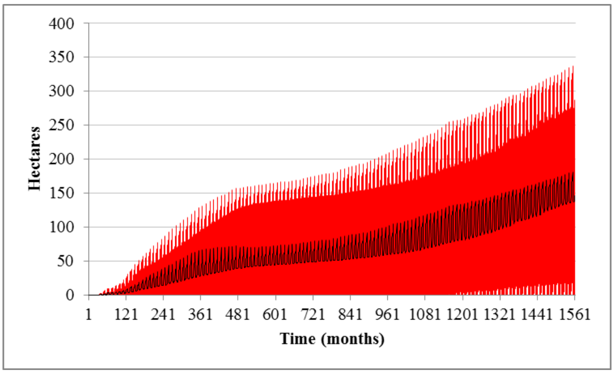
Note:—— average —— standard deviation

Figure 48. Scenario 4: Extent of areas affected by overgrazing in Reykholtsdalur valley

Variations in the extent of overgrazed areas shown in the figures above suggest broad similarity to those presented in the figures which indicate the extent of the overgrazed areas around the high-ranking farms of Hrísheimar and Hofstaðir in Mývatn (section 8.2.2.2.). Probably the main reason for this similarity is the involvement of 6 mid- and high-ranking farms in clearance activities and utilisation of the newly created pastures in the valley. Because of their work-force population numbers and potential rates of clearance, those farms were probably responsible for the similar, if not the same type of temporal and spatial distribution of overgrazing visible around the high-ranking farms in Mývatn. In other words, mid- and high-ranking farms obviously left their mark in the form of notable increase in overgrazing during the second part of the *landnám*. The reason why the variations presented here do not completely follow the variations presented in the high-ranking Mývatn figures is because there were also 13 low-ranking farms in the valley around which overgrazing may have developed in different and more steady way, probably similar to that around the low-ranking farms of Sveigakot and Arnarvatnssel. Finally, as can be seen from the figures above, the intra-annual oscillations in the extent of the overgrazed areas in Reykholtsdalur valley suggest the increase in overgrazing during the late winter/early summer periods.

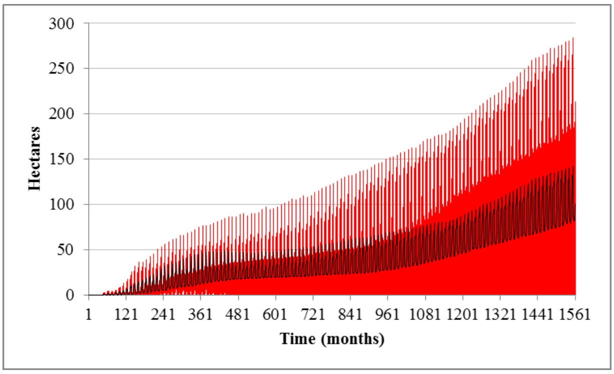
The lake Breiðavatn

Research results from Lake Breiðavatn offer data that suggest dynamics of land cover changes over a larger area than is the case with the RHD 1 site. Erlendsson’s results indicate that although there is no increase in sedimentation rates, „there are signs of an increasing degree of soil reworking and input into the lake“ (Erlendsson 2007, p. 229). Gathorne-Hardy and others (Gathorne-Hardy *et al.* 2009, p. 421), discussing the Breiðavatn lake sediment evidence, suggest that „considerable changes to the environment, particularly increased erosion, followed the arrival of humans at the end of the 9th century AD“. The model outcomes indirectly correspond to this empirical evidence, since at and around the sites that were most likely involved in the clearance of woodlands around Breiðavatn, there are indications of overgrazing and thus possible changes in the soil (Figures 49 – 52).



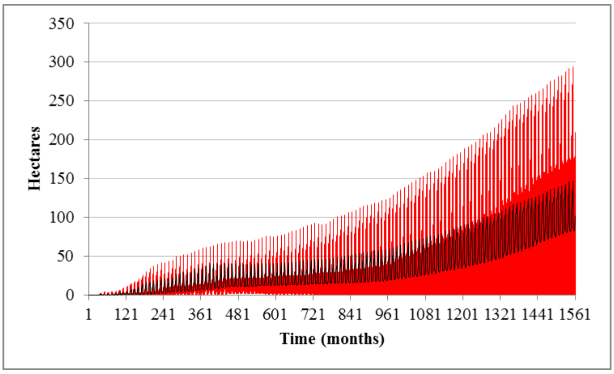
Note:—— average —— standard deviation

Figure 49. Scenario 2a: Extent of areas affected by overgrazing around the lake of Breiðavatn



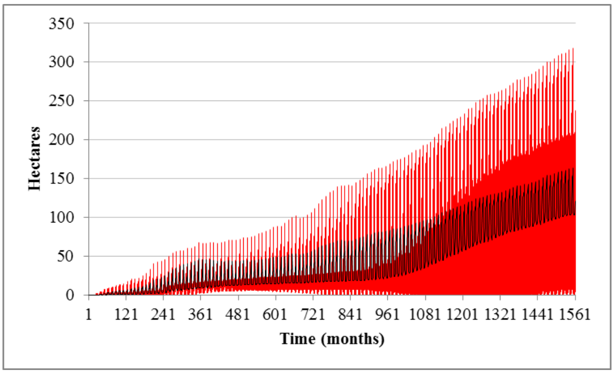
Note:—— average —— standard deviation

Figure 50. Scenario 2b: Extent of areas affected by overgrazing around the lake of Breiðavatn



Note:—— average —— standard deviation

Figure 51. Scenario 3: Extent of areas affected by overgrazing around the lake of Breiðavatn



Note:—— average —— standard deviation

Figure 52. Scenario 4: Extent of areas affected by overgrazing around the lake of Breiðavatn

Variations in the extent of overgrazed areas around the lake of Breiðavatn appear to be less significant than in the Reykholtsdalur valley. The graphs shown above suggest more or less steady increase in the rate of degradation. A major reason for the absence of great oscillations, as it was the case in the Reykholtsdalur valley, lies in the fact that most of the farms present here during the *landnám* were actually low-ranking farms (7 of those; as opposed to only 2 high-ranking farms), around which there were no sudden and significant increases in overgrazing during the second part of the *landnám*. Finally, the intra-annual oscillations, as for the Reykholtsdalur valley, suggest increase in overgrazing during the late winter/early summer periods.

Erlendsson's study in general indicates that unlike most sites in Iceland, the woodland cover around Breiðavatn did not suffer a drastic reduction during the period under discussion (Erlendsson 2007, pp. 228 – 230; p. 251, Figure 152).

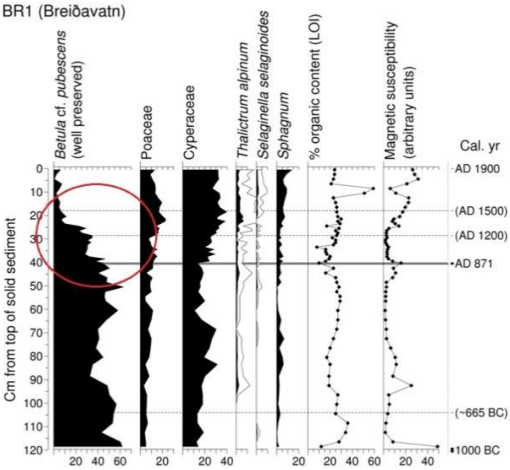
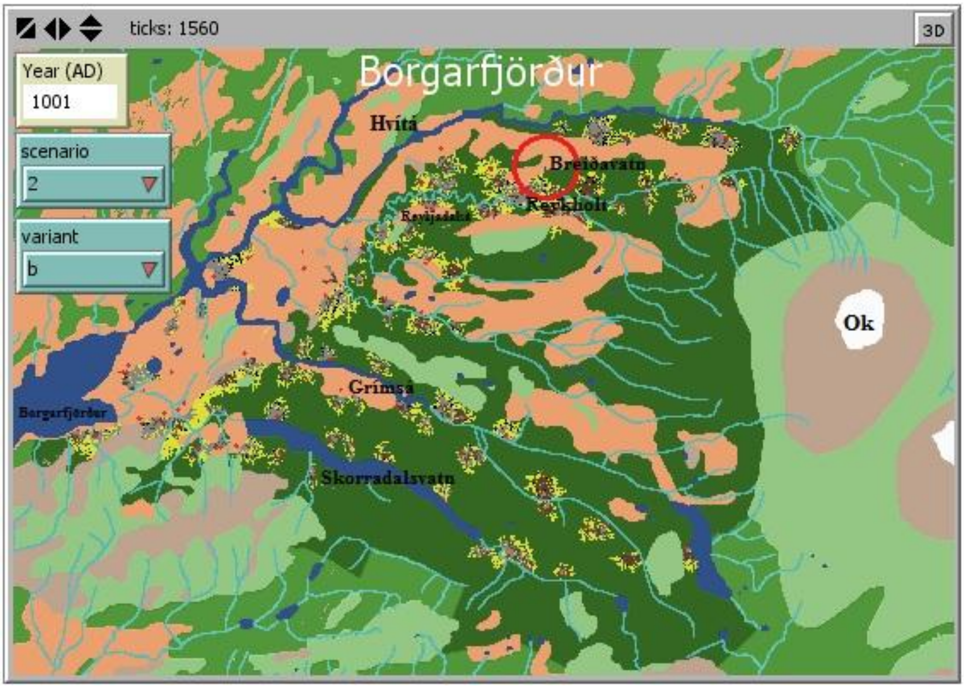


Figure 53. Pollen percentage of selected taxa from Breiðavatn (Analyst: Egill Erlendsson; taken from Gísladóttir *et al.* 2011, p. 30, Figure 2.). Note the sequence of the figure circled in red which suggests the fluctuations of the birch cover during the period of *landnám*.

This result, although only indirectly and imperfectly, corresponds to the model outcomes (Figures 55 – 58 below). Like in the model of the Mývatn area, during the simulation run, the state of the woodland cover was monitored with respect to a catchment area (Figure 54 below), which in the case of Breiðavatn had a diameter of 2,000 m (Erlendsson 2007, p. 172, Figure 6.1). As with Helluvaðstjörn, the explanation for the relatively moderate and slow decline of the woodland cover here is to be found in the somewhat small number of farms involved in the clearance of woodlands around the lake.



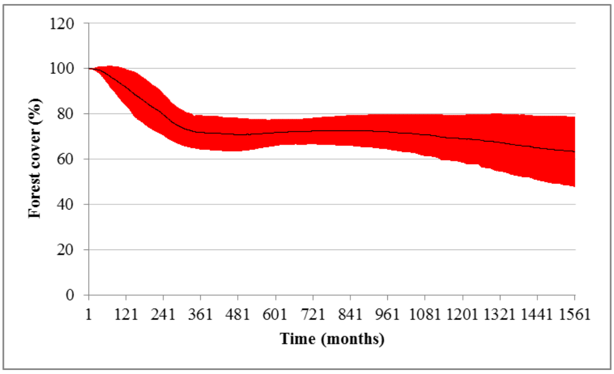
ticks: 1560

Year (AD)
1001

scenario
2

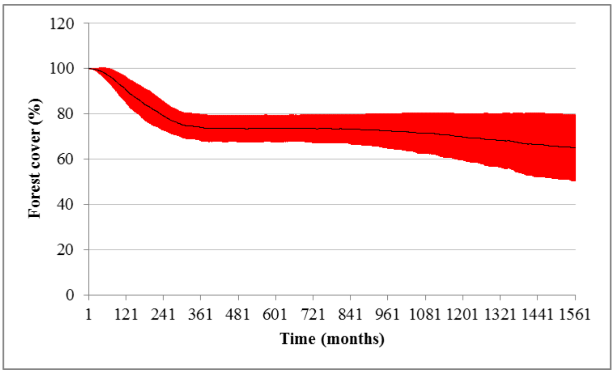
variant
b

Figure 54. Borgarfjörður: Visual output from single separate simulation run (Scenario 2a – at AD 1001) Note the approximate extent of RPSA of Breiðavatn (circled in red colour).



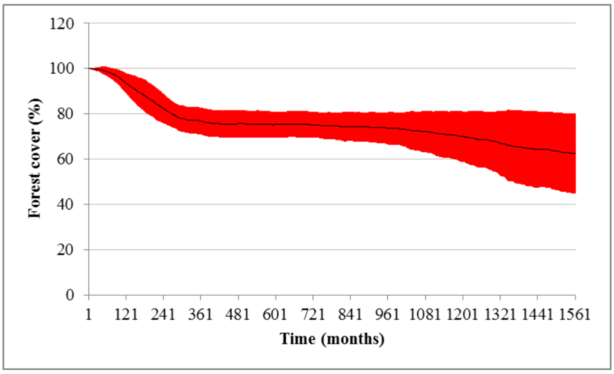
Note:—— average —— standard deviation

Figure 55. Scenario 2a: Forest cover around the lake of Breiðavatn



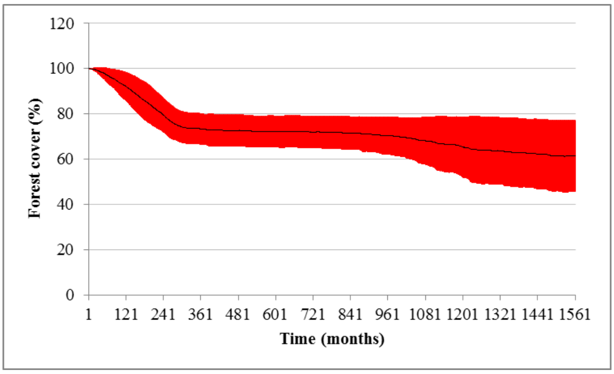
Note:—— average —— standard deviation

Figure 56. Scenario 2b: Forest cover around the lake of Breiðavatn



Note:—— average —— standard deviation

Figure 57. Scenario 3: Forest cover around the lake of Breiðavatn



Note:—— average —— standard deviation

Figure 58. Scenario 4: Forest cover around the lake of Breiðavatn

As for the lake of Helluvaðstjörn, it is important to stress that the figures shown above present the average values of 20 simulation runs. Some of the single simulation runs show fluctuations in the forest cover that may be regarded as more realistic (Figure 59).

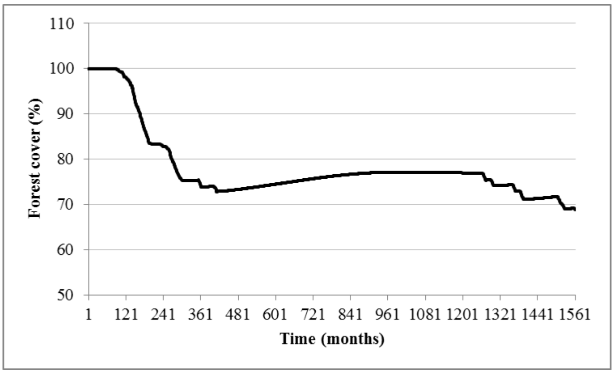


Figure 59. Scenario 3: Forest cover around the lake of Breiðavatn. The outcome of the single simulation run (nr. 20)

Accepting the outcome shown above as the one that corresponds (in broad terms) to the empirical evidence, implies that the starting parameter values (Table 25 below) used to produce it can be seen as relevant.

Table 25. („a“ above and „b“ below). Starting parameters of the single simulation run (Borgarfjörður, Scenario 3, simulation run nr. 20).

Cattle cull	**Ovines cull**	**Cattle growth**	**Ovines growth**
7 %	7 %	24.9 %	34.4 %

Starting cattle	**Starting ovines**	**Initiation of replacement**	**Replacement (heavy grazing)**	**Replacement (light grazing)**
5	2	After 101 months	0.4 % (per month)	0.05 % (per month)

However, another simulation run (Figure 60 below) suggests that similar and still „appropriate“ outcomes can also be reached with a considerably different set of starting parameters (Table 26 below) which implies that a certain level of equifinality needs to be recognised in the model.

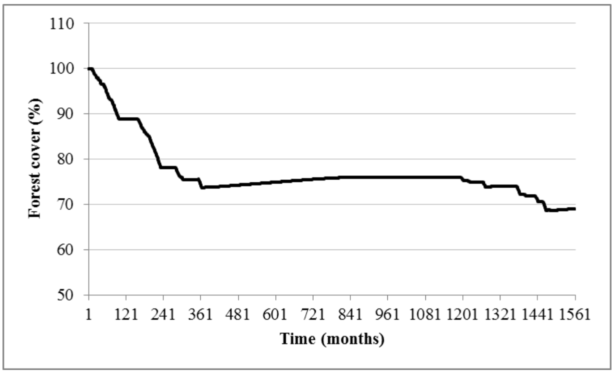


Figure 60. Scenario 2b: Forest cover around the lake of Breiðavatn. The outcome of the single simulation run (nr. 3)

Table 26. („a“ above and „b“ below). Starting parameters of the single simulation run (Borgarfjörður, Scenario 2b, simulation run nr. 3).

Cattle cull	Ovines cull	Cattle growth	Ovines growth
2 %	7 %	22.8 %	35.1 %

Starting cattle	Starting ovines	Initiation of replacement	Replacement (heavy grazing)	Replacement (light grazing)
2	8	After 81 months	0.32 % (per month)	0.05 % (per month)

Therefore, as for the case of the lake of Helluvaðstjörn, parameter values used to produce a „successful“ outcome here can only be seen as contingent conditions (see section 8.2.2.1.). As previously said, careful analysis of the models suggests that the possible explanation for the equifinality lies in the combined effect of factors introduced during the simulation run. Unfortunately, those factors still remain poorly understood and as a result, it is difficult to improve our understanding of the deforestation process and to identify the set of the most appropriate starting parameters. Further investigation of those factors is therefore unequivocally needed.

To sum up: Borgarfjörður

Whereas Erlendsson‘s study at least to some degree indicates the validity of the model in this area (Reykholtsdalur and area around the lake of Breiðavatn), the absence of empirical studies from other parts of Borgarfjörður weakens the validity of the model. Also, as in the case of Mývatn, it is hard to make clear distinctions between the outcomes of different scenarios (i.e. sc. 2a, 2b, 3 and 4) and suggest which one actually took place in specific locations/areas and/or in the entire region of Borgarfjörður.

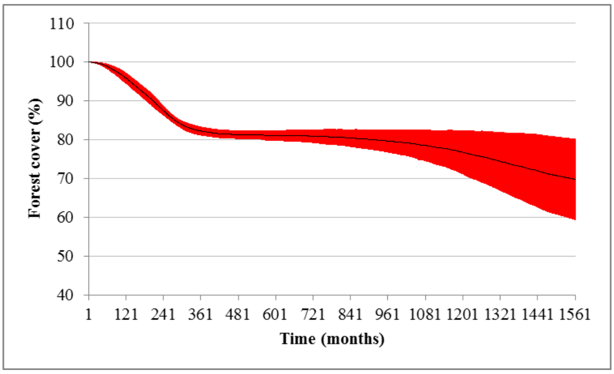
8.3 Modelling outcomes and their discussion

8.3.1 Degree of deforestation

The outcomes of 240 runs of the *ICELANDEF* series of models, presented in the Appendix 1 of this dissertation, suggest that the deforestation for definable practical reasons, i.e. deforestation for home-fields and pastures during the late 9th and 10th centuries was undoubtedly significant, but scarcely catastrophic. As shown in the Table 27 and Figures 61 – 63 below, in Vestur-Eyjafjallahreppur reduction of the woodland cover most likely did not exceed 30.23 % (Scenario 3), at Mývatn 6.25 % (Scenario 2b) and in Borgarfjörður 15.22 % (Scenario 4)[60,61]; because of the noteworthy degree of uncertainty about the conclusive degrees of deforestation[62], these values however need to be approached with caution. In general, it may be said that the process of deforestation did not result in a greatly altered landscape and that large areas of woodland were left undisturbed throughout the country. The outcomes of the models therefore correspond to some of the recent studies which suggest a prolonged and moderate reduction of the woodland cover during the age of Settlement (e.g. Lawson *et al.* 2007, Erlendsson 2007).

Table 27. Degree of deforestation at each of the sample study areas

Study area	Original woodland cover	Reduction of woodland cover
Vestur-Eyjafjallahreppur	13,478 ha	30.23 %
Mývatn	70,926 ha	6.25 %
Borgarfjörður	57,111 ha	15.22 %



Note:—— average —— standard deviation

Figure 61. Scenario 3: Extent of forest cover in Vestur-Eyjafjallahreppur

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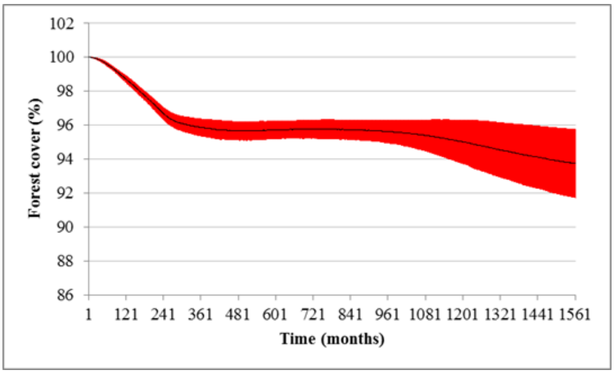
[60] Average values of the outcomes of 20 simulation runs.

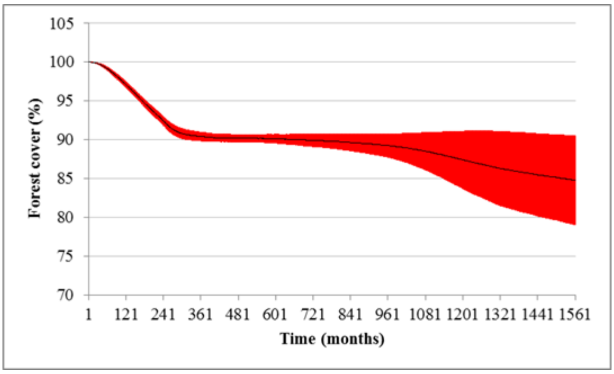
[61] Taking into account the effects of regrowth, i.e. deforested patches with more than 50 % of regrown birch cover.

[62] Further discussed in section 8.3.4.



Note:—— average —— standard deviation

Figure 62. Scenario 2b: Extent of forest cover in Mývatn



Note:—— average —— standard deviation

Figure 63. Scenario 4: Extent of forest cover in Borgarfjörður

8.3.2 Phases of deforestation

The outcomes of the series of simulations suggest that the 9th and 10th century deforestation can actually be seen as a two phase process. The first phase involved clearance for home-fields and essential clearance for pastures while the second involved periodic clearance which was aimed at maintaining sufficient pasturelands with high grazing potential, i.e. providing a sufficient amount of utilisable grassy biomass.

The first phase may be viewed as compulsory and expected since the structure of the models suggests the intentional clearance of forests for home-fields and pastures at many locations at the beginning of the settlement period. What however comes out of the simulation runs and can actually be described as a novelty useful to the existing state of the art, is the information about timing, duration, rate and dynamics of this part of the deforestation process.

The second phase may be regarded as one of the system-level phenomena that emerge from changes in the natural environment (i.e. regrowth of birch, replacement of grasses by grazing-tolerant vegetation, decrease of UB due to overgrazing but also its increase due to resting effect) but also variations in behaviour of the agents. Although it may be conjectured that this stage of clearance was only a continuation of the initial one, the charts shown below suggest that it was a distinctive phase of the deforestation process.

8.3.2.1 A note on intra-annual timing and rates of clearance

The outcomes of the simulation runs suggest that in both phases clearance activites were accomplished without regard to any specific period of the year (i.e. season). The clearances were made both during the summer and winter seasons and their timing and duration were obviously shaped by the agents‘ contemporary estimates about the need for pastures.

The results of the simulations also suggest that in most of the cases, and irrespective of the phase of clearance, settlers have switched their rates of clearance to non-zero values due to occurence of ovegrazing (see section 7.5.3.). That way, the average rates of clearance have been increased in order to quickly acquire sufficient extent of pastures (and thus adequate amount of UB) which would prevent further overgrazing. However, at many locations, even the change (i.e. increase) in the rate of clearance did not prevent further overgrazing and degradation of the pastures.[63]

8.3.2.2 The first phase – clearance for home-fields and essential clearance for pastures

Clearance for home-fields

The first part of the initial phase of deforestation occurred along with the process of establishment of the farms – this was clearance to establish home-fields. In many locations it was an unavoidable and relatively short-term activity. Speaking generally, most of this part of deforestation happened before the end of the 9th century and in most of the cases, it had come to an end before c. AD 890[64].

However, the structure of the simulations also allows for the possibility that a part of this phase could have been accomplished later, throughout the 10th century, due to later establishment of client farms and their subsequent need for spatial clearance.

In the region of Vestur-Eyjafjallahreppur, in theory, 20 client farms could make such a clearance. However, validation of the model suggests that it was, at least partially, Scenario 3 that most probably happened there, a scenario suggesting that clients’ home-fields (if located close enough to the patron’s home-fields) may have been arranged by the patron, prior to their arrival and hence in the first stage of settlement. For this reason, it seems conceivable that part of the clearance for clients’ home-fields took place during the initial stage of settlement, i.e. before AD 890.

In the region of Borgarfjörður, 11 client farms could eventually make late clearances for home-fields. Unfortunately, since it is almost impossible to suggest which particular scenario actually took place there, it is hard to estimate what part of that kind of clearance happened as late as in the 10th century.

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[63] Further discussed in section 8.3.3.2.

[64] See figures in the appendix of this dissertation which show extent of areas cleared for home-fields.

Only a minor part of clearance for home-fields at Mývatn could have occurred throughout the 10th century; this being primarily due to the low number of client farms (3) that could have been established in the second phase of settlement.

Initial clearance for pastures

This part of the first phase of deforestation may be termed „major". It represents clearance for pastures from its initiation until the time when clearance had become only an occasional activity, shaped by the combined effects of seasonal variations in utilisable biomass, regrowth of birch and replacement of grasses by grazing-tolerant species. During this stage, the essential part of the clearance for pastures occurred. The baseline extent of pastures that was supposed to cover the needs of the planned livestock herds was reached and in most of the cases, livestock holdings were fully developed (section 8.3.3.1.). It may therefore be said that after this stage, the *landnám* animal husbandry economy was almost fully established. This stage, which involved permanent clearance activities, logically, started after the end of the first phase of deforestation – the clearance for home-fields. It ended in most cases before AD 900 (Figures 64 – 66 below[65]), therefore after c. 30 years of Settlement, which is compatible with modern research (e.g. Dugmore *et al.* 2000, 2005).

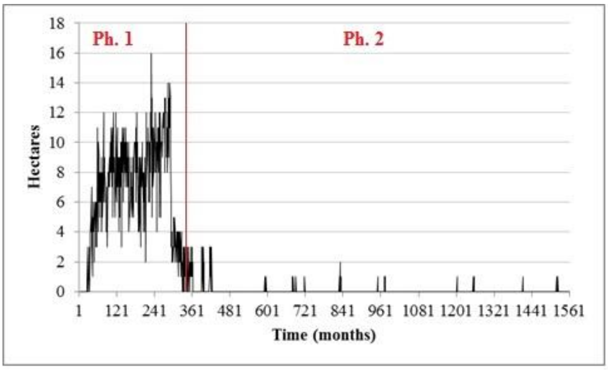

Figure 64. Total forest clearance in Vestur-Eyjafjallahreppur. Scenario 3. The outcomes of the single simulation run showing distinct phases of clearance. Note that the first phase includes both clearance for home-fields and pastures

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[65] The outcomes of single simulation runs, representing the overall rate of forest clearance in each of the regions.

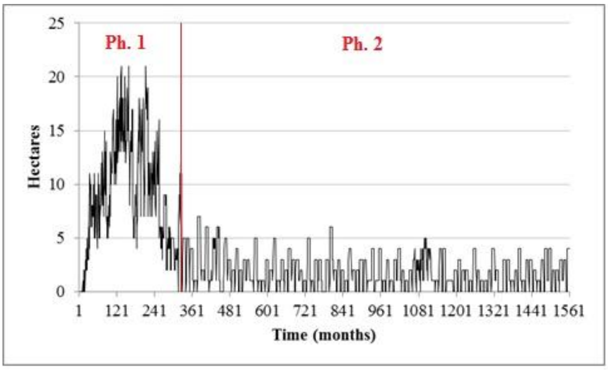


Figure 65. Total forest clearance in Mývatn. Scenario 2a. The outcomes of the single simulation run showing distinct phases of clearance. Note that the first phase includes both clearance for home-fields and pastures

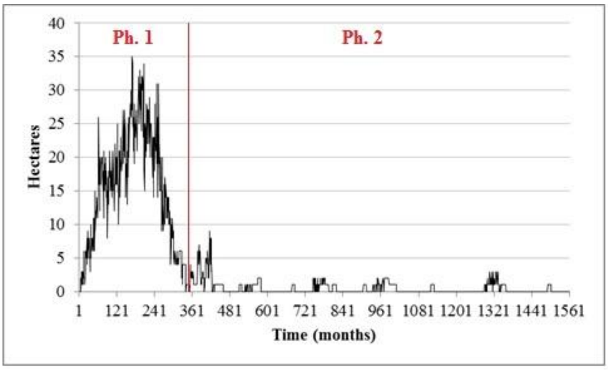


Figure 66. Total forest clearance in Borgarfjörður. Scenario 2b. The outcomes of the single simulation run showing distinct phases of clearance. Note that the first phase includes both clearance for home-fields and pastures

In total, the outcomes of 66 out of 80 runs (82.5 %) of the model of Vestur-Eyjafjallahreppur suggest that this phase ended before AD 900. The outcomes of 73 out of 80 (91.25 %) runs of the Borgarfjörður model correspond to this result, while the vast majority (79/80, i.e. 98.75 %) of the runs of the model of Mývatn suggest the same. In general, differences in the outcomes can be explained by the differences in the number of client farms which in most of the cases initiated their basic-clearance activities later than patron and independent farms. These results therefore correspond (up to a certain extent) to degrees of initial populaton pressure in each of the region. As previously stressed (section 7.5.9.1.), initial population pressure was enormous in the first 20 years in the regions of Borgarfjörður and Mývatn (at least 93 % and 95 % of the total population, respectively), and less extreme, but still also significant in the region of Vestur-Eyjafjallahreppur (at least 70 % of the total population).

The simulation outcomes also suggest that the clearance for pastures and home-fields during this first phase of the deforestation process fully overlapped with needs of the

Settlement population for firewood and building material. Hence, as it was suggested before (Chapter 5), it may even be said that due to clearance for home-fields and pastures, there was no need to clear woodlands for other requirements. It is tempting to assume that separate selective chopping (for firewood and building material), if applied at all, most likely took place during the later stages of the *landnám*, and evidently, only in the periods during which there was no clearance for pastures.

8.3.2.3 The second phase: periodical clearance

The second phase of deforestation was marked by occasional clearance activities shaped by the combination of the effects of regrowth of birch and replacement of grasses and sedges with grazing-tolerant species. This is a much longer phase of clearance which began after the end of the major, initial stage of clearance. According to the outcomes of simulation runs, it lasted throughout the entire 10th century.

In each of the sample study areas, this phase is marked only by intermittent clearance activities. However, occasionally, this phase overlapped with the previous phases, since some of the client farms were establishing their home-fields and pasturelands, i.e. accomplishing the major part of clearance.

Unlike the average values of 20 simulation runs (see Appendix 1), the outcomes of single simulation runs which show the overall rates of clearance on regional scales suggest that this phase can be described in different ways. On the one hand, it may be said that this phase was sporadic, with more or less negligible rates of clearance (Figures 67 – 69 below). In total, 28 out of 80 runs (i.e. 35 %) of the model of Vestur-Eyjafjallahreppur suggest the outcome of this kind. The outcomes of 30 out of 80 (37.5 %) runs of the Mývatn model suggest that the second phase of deforestation was only sporadic and/or with the limited rates of clearance, while even 38 out of 80 (47.5 %) runs of the model of Borgarfjörður suggest the same.

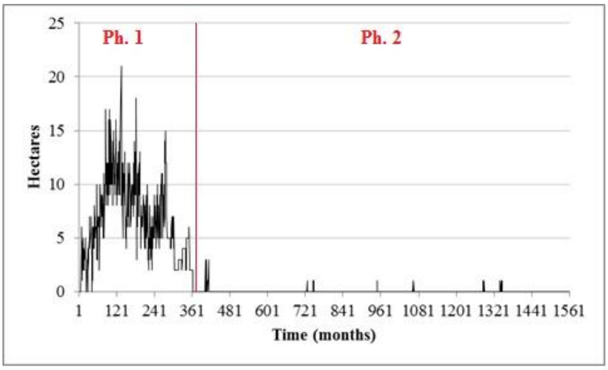


Figure 67. Total forest clearance in Vestur-Eyjafjallahreppur. Scenario 3. The outcomes of the single simulation run showing sporadic second phase of clearance. Note that the first phase includes both clearance for home-fields and pastures

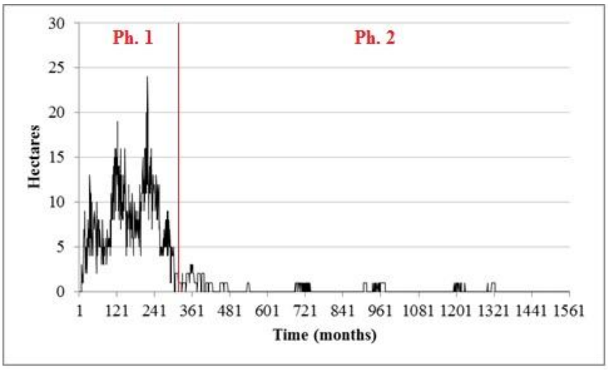


Figure 68. Total forest clearance in Mývatn. Scenario 2a. The outcomes of the single simulation run showing sporadic second phase of clearance. Note that the first phase includes both clearance for home-fields and pastures

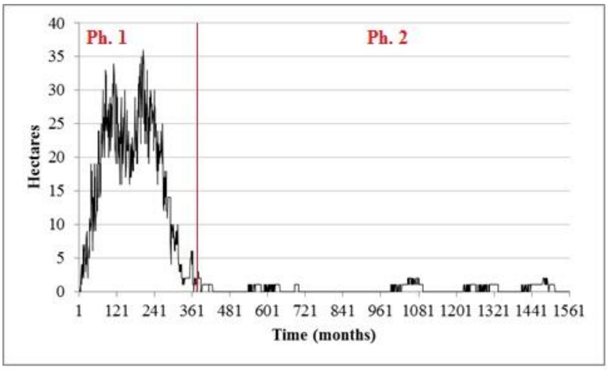


Figure 69. Total forest clearance in Borgarfjörður. Scenario 2b. The outcomes of the single simulation run showing sporadic second phase of clearance. Note that the first phase includes both clearance for home-fields and pastures

On the other hand, this phase can be regarded as very intense with great fluctuations in the rate of clearance (Figures 70 – 72, below). Twenty six runs of the model of Vestur-Eyjafjallahreppur (32.5 %) produced the outcomes of this kind; 35 runs of the Mývatn model (43.75 %) suggest that kind of dynamics of the second phase of deforestation while 29 runs of the Borgarfjörður model (36.25 %) correspond to this result.

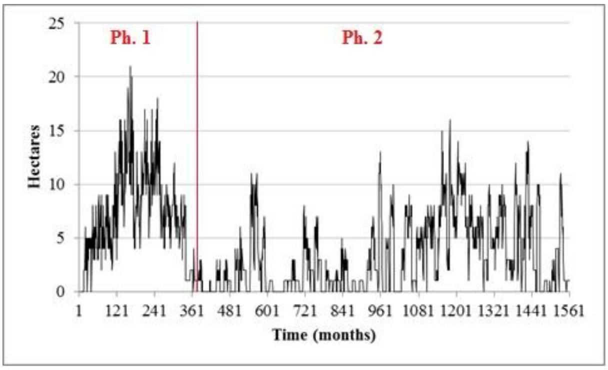


Figure 70. Total forest clearance in Vestur-Eyjafjallahreppur. Scenario 3. The outcomes of the single simulation run showing considerable fluctuations in the overall rate of clearance during the second phase of deforestation. Note that the first phase includes both clearance for home-fields and pastures

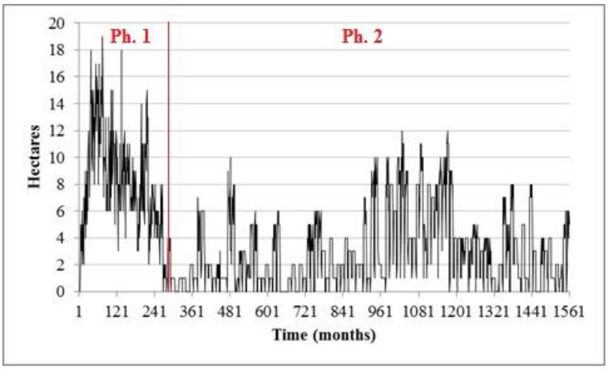


Figure 71. Total forest clearance in Mývatn. Scenario 2a. The outcomes of the single simulation run showing considerable fluctuations in the overall rate of clearance during the second phase of deforestation. Note that the first phase includes both clearance for home-fields and pastures

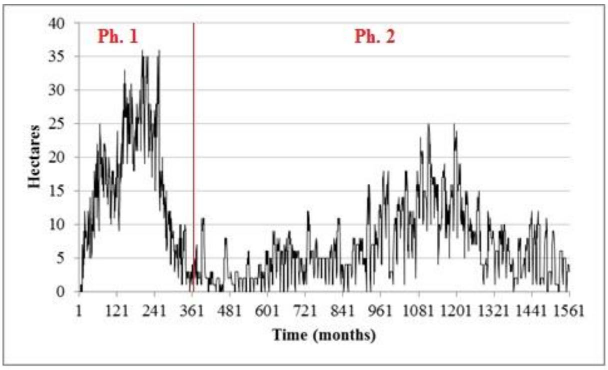


Figure 72. Total forest clearance in Borgarfjörður. Scenario 2b. The outcomes of the single simulation run showing considerable fluctuations in the overall rate of clearance during the second phase of deforestation. Note that the first phase includes both clearance for home-fields and pastures

Finally, some the simulation runs suggest that rates of clearance may have been increasing towards the end of the period under discussion (Figures 73 – 75, below), indirectly suggesting that the Icelandic environment witnessed a significant degree of deforestation at the beginning of the 11th century. In total, 26 runs of the model of Vestur-Eyjafjallahreppur (32.5 %), 15 runs of the model of Mývatn (18.75 %) and 13 runs of the Borgarfjörður model (16.25 %) correspond to this kind of outcome.

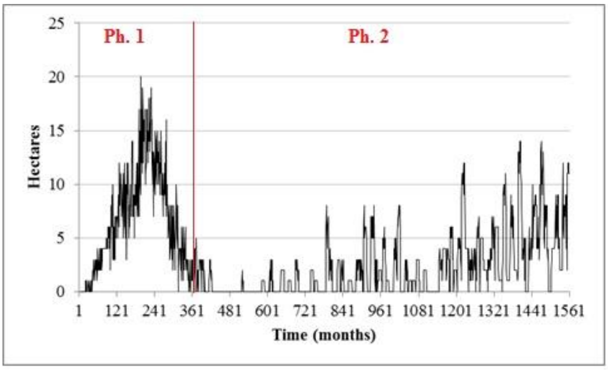


Figure 73. Total forest clearance in Vestur-Eyjafjallahreppur. Scenario 3. The outcomes of the single simulation run showing increase in the rates of clearance during the second phase of deforestation. Note that the first phase includes both clearance for home-fields and pastures

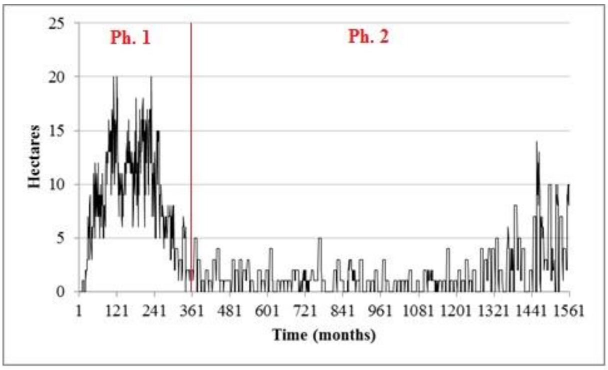


Figure 74. Total forest clearance in Mývatn. Scenario 2a. The outcomes of the single simulation run showing increase in the rates of clearance during the second phase of deforestation. Note that the first phase includes both clearance for home-fields and pastures

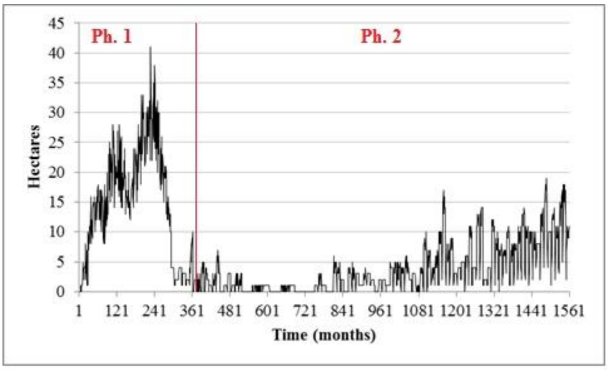


Figure 75. Total forest clearance in Borgarfjörður. Scenario 2b. The outcomes of the single simulation run showing increase in the rates of clearance during the second phase of deforestation. Note that the first phase includes both clearance for home-fields and pastures

Variations in the rates and degrees of clearance presented in the figures above can be generally explained by the combined effect of different input values (with regards to replacement effect, regrowth, timing of the establishment of farms etc.) but also values associated with the factors introduced during the simulation runs such as clearance-rate fluctuations (esp. at mid- and high-ranking farms), different periods of prevention of grazing and consequently different seasons of initation of grazing (summer as opposed to winter). Additionaly, differences in the numbers of simulation runs suggesting the increase in the rates of clearance by the end of the second phase of deforestation (32.5 % of the runs of the Vestur-Eyjafjallahreppur model, as opposed to 18.75 and 16.25 % of the runs of the Mývatn and Borgarfjörður model, respectively), clearly need to be brought into connection with the mentioned differences in the number of client farms in each of the regions.

Unfortunately, it is difficult to argue for either of the outcomes presented above and to suggest the actual course of this phase of deforestation, primarily because of the low resolution of the existing set of comparable empirical evidence that would eventually be used to suggest higher probability of one interpretation over another.

Finally, some of the outcomes of the single simulation runs which show the rates of clearance of the single independent farm units at Varmahlíð, Þorleifsstaðir and Oddstaðir (regions of Vestur-Eyjafjallahreppur, Mývatn and Borgarfjörður, respectively) suggest why the process of deforestation may be described as phased. Those outcomes reveal that the time-break between the intermittent periods of clearance during the second phase of deforestation (but also between the two major phases of deforestation) could have been up to several decades long (Figures 76 – 78, below).

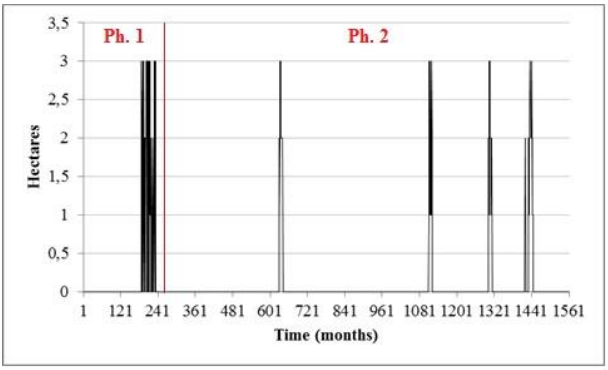


Figure 76. **Clearance of forest made by the farm of Varmahlíð. Scenario 3. The outcomes of the single simulation run. Note that the first phase includes both clearance for home-fields and pastures**

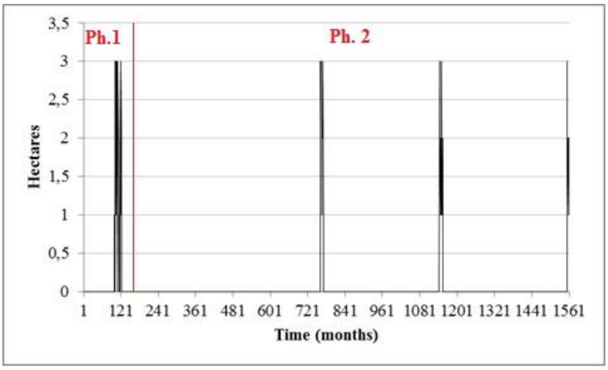


Figure 77. **Clearance of forests made by the farm of Þorleifsstaðir. Scenario 2a. The outcomes of the single simulation run. Note that the first phase includes both clearance for home-fields and pastures**

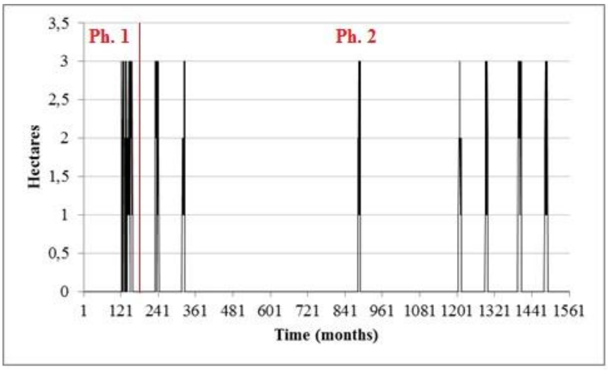


Figure 78. **Clearance of forests made by the farm of Oddstaðir. Scenario 3. The outcomes of the single simulation run. Note that the first phase includes both clearance for home-fields and pastures**

Still, some of the simulation outcomes (Figures 79 – 81) suggest the absence of reactive clearance during the later stages of the *landnám*. Twenty one runs of the model of Vestur-Eyjafjallahreppur (26.25 %), only 11 runs of the model of Borgarfjörður model (13.75 %) and 21 runs of the Mývatn model (26.25 %) suggest this possibility.

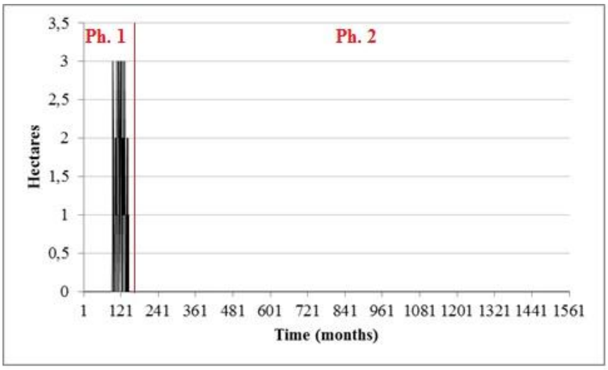


Figure 79. Clearance of forests made by the farm of Varmahlíð. Scenario 4. The outcomes of the single simulation run showing the absence of reactive clearance during the later stages of the *landnám*. Note that the first phase includes both clearance for home-fields and pastures

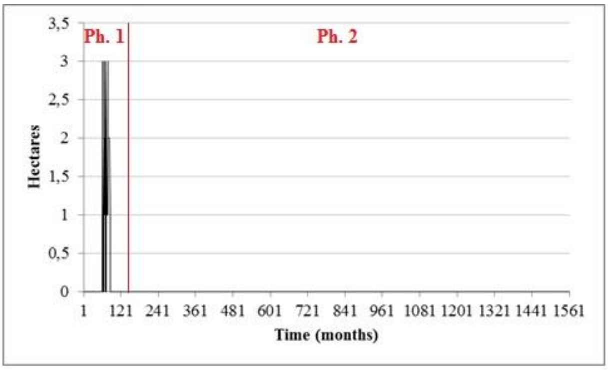


Figure 80. Clearance of forests made by the farm of Þorleifsstaðir. Scenario 3. The outcomes of the single simulation run showing the absence of reactive clearance during the later stages of the *landnám*. Note that the first phase includes both clearance for home-fields and pastures

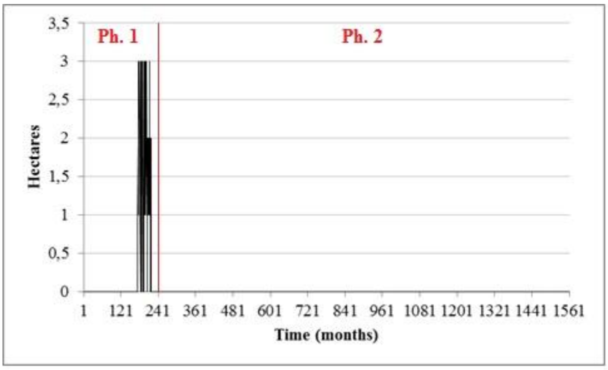


Figure 81. Clearance of forests made by the farm of Oddstaðir. Scenario 3. The outcomes of the single simulation run showing the absence of reactive clearance during the later stages of the *landnám*. Note that the first phase includes both clearance for home-fields and pastures

Although this situation therefore occurs only in the minor number of runs, it still needs to be taken into consideration as a possibility, especially if we take into account that there are no empirical evidence that can disprove its validity. One of the possible explanations for this type of outcomes lies in the combination of the timing of the establishment of settlements (summer/winter), the duration of the subsequent period of prevention of grazing (1 – 2 years) and the timing of the initiation of grazing, which, if set for the summer months could result in an insignificant degree of overgrazing and biomass loss in the initial stages of the *landnám*. A low degree of deterioration in the beginning of the *landnám* would in turn (at some locations) result in less dynamic environmental changes, or even stability during the later stages of the *landnám*, which in turn, would exclude the need for reactive clearance.

Dynamics in the second phase of deforestation, but also in the overall degree of degradation, also need to be brought into connection with the degree of increase in the existing population pressure. In the region of Vestur-Eyjafjallahreppur, an increased degree of dynamics is logical since c. 30 % of the total population could arrive during this phase. On the other hand, in the regions of Borgafjörður and Mývatn, only c. 7 % and 5 % of the total settler population (respectively) could arrive during the same period of time, which may have been one of the major reasons for less abrupt changes in the overall rate of deforestation and in general, the environmental degradation.

The idea that follows the outcomes of the simulations is that this phase resulted from a lack of awareness of the true nature of the local environmental potential. This would have been mostly a lack of awareness of the overgrazing, regrowth and replacement effect. All of these factors were diminishing the overall grazing biomass at the newly created pastures and as a result, there was a periodic need for re-clearance.

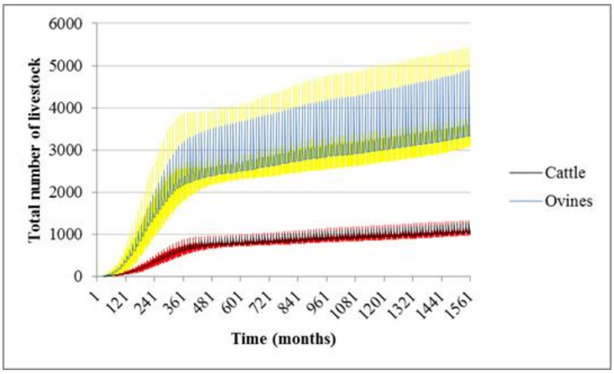
Because of the uncertainties about the actual rates and dynamics of these processes (caused by the lack of empirical studies that can be used to suggest a relevant set of parameters) but also other factors introduced during simulation runs (see section 8.3.6. below), the interpretations about this phase of deforestation (i.e. its degree, dynamics and consequences) need to be approached with reservations.

Finally, it may be said that while the first and second phases were most probably planned in accordance to projected livestock holdings, this last phase was most probably not planned.

8.3.3 Major drivers behind the deforestation dynamics

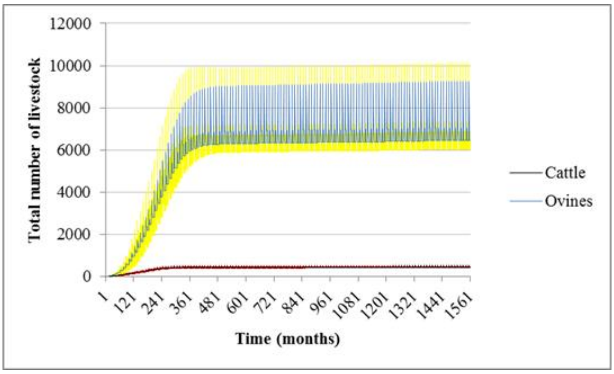
8.3.3.1 Growth of livestock population

One of the major drivers behind the deforestation dynamics was the growth of livestock population. The simulation runs suggested that most of the livestock population reached its maximum numbers already after c. 30 years of the Settlement (i.e. around AD 900). In the regions of Mývatn and Borgarfjörður (Figures 83 and 84, respectively), only minor increase in the number of cattle and ovines occurred throughout the 10th century while in Vestur-Eyjafjallahreppur (Figure 82) this increase appears to be noticeable, although at considerably lower rate than it was the case during the first stage of the *landnám*. Logically, this result can be brought into connection with the number of client farms arriving in each of the regions and introduction of their livestock herds during the second stage of the *landnám*. In general, these outcomes correspond to the previously presented „phasing" of the deforestation process but also to the idea that the major part of the animal husbandry economy was established pretty soon, i.e. already after three decades.



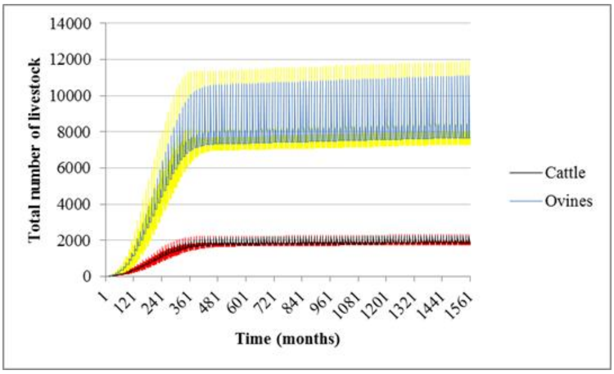
Note:—— average —— standard deviation; —— average —— standard deviation

Figure 82. Scenario 2a: Total number of livestock in Vestur-Eyjafjallahreppur



Note:—— average —— standard deviation; —— average —— standard deviation

Figure 83. Scenario 2b: Total number of livestock in Mývatn



Note:—— average —— standard deviation; —— average —— standard deviation

Figure 84. Scenario 3: Total number of livestock in Borgarfjörður

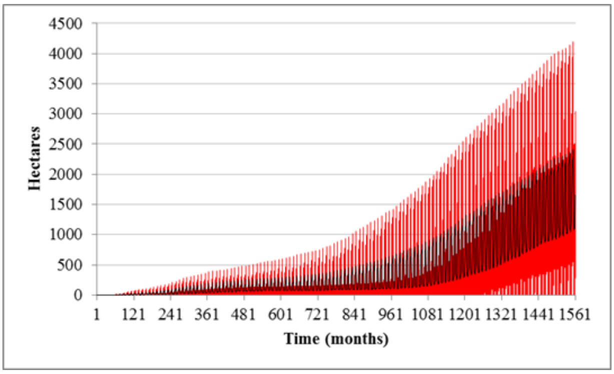
8.3.3.2 Overgrazing

The Figures 85 – 87 (showing the average values of 20 simulation runs) suggest that the exent of areas affected by overgrazing in each of the regions was generally increasing towards the end of the *landnám*.

Early stage of deforestation (pre- AD 900)

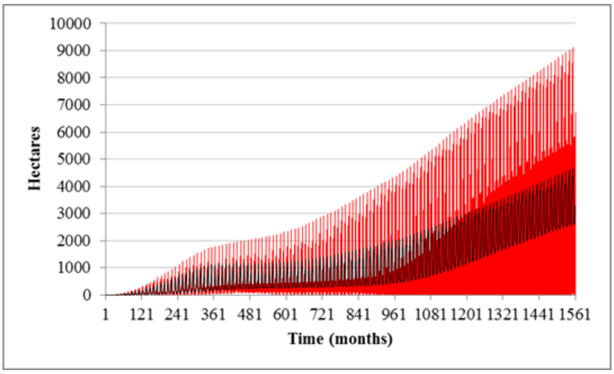
According to simulation runs, overgrazing (and hence possibly soil erosion) became apparent already during the early stage of deforestation. As the figures below show, in most of the cases, it occurred around c. AD 880, therefore after only a decade of settlement.

Most of the overgrazed areas appear to be close to home-field areas. A simple explanation for this is that during the initial stage of clearance, rates of clearance and thus creation of new pasturelands in the vicinity of the households, could not entirely follow demands for pastures of the initial livestock herds.



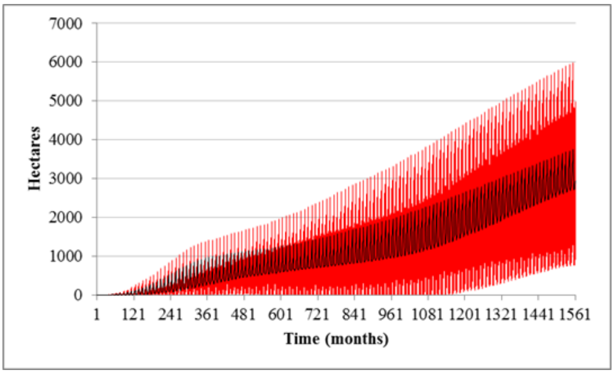
Note:—— **average** —— **standard deviation**

Figure 85. Scenario 3: Extent of areas affected by overgrazing in Vestur-Eyjafjallahreppur



Note:—— **average** —— **standard deviation**

Figure 86. Scenario 3: Extent of areas affected by overgrazing in Borgarfjörður



Note:—— **average** —— **standard deviation**

Figure 87. Scenario 2b: Extent of areas affected by overgrazing in Mývatn

Later stages of deforestation (post- AD 900)

During the last years of the 9th century and throughout the entire 10th century, overgrazing increased considerably in spite of continuation of woodland clearance. Primarily because of the replacement of grasses with grazing-tolerant vegetation but also because of the almost exponential growth of livestock numbers (which entailed increasing grazing pressure), the grassy biomass at the newly created pastures was in permanent decline. The rates of clearance were too low to compensate for the loss of biomass and as a result, frequent and increasing overgrazing was inevitable.

Major remarks on the impact of grazing

A careful insight into the figures presented here also reveal great oscillations in the extent of overgrazed areas over the course of a single season. Those oscillations actually suggest the occurrence of overgrazing in January, with rapid increases in February and again in May, finally reaching its peak in June, after which it declined to its minimum (and in some cases, zero values). The results of the simulation runs therefore suggest that the late winter/early summer grazing pressure can be seen as the most impactful when it comes to degradation of the newly created pastures which probably resulted in soil erosion in many locations.

Furthermore, it may be said that it was precisely the removal of the ovine herds from the newly created pastures and their transfer to the natural highland pastures in early summer, combined with the increase in the biomass production in July and August, that resulted in almost immediate and significant decrease in the rate of overgrazing and hence possibly soil erosion at the newly created pastures.

At which particular locations soil erosion may have actually occurred throughout each of the regions is, unfortunately, hard to say since the overgrazed patches represented in the simulation outcomes do not necessarily imply soil erosion as such. Whether soil erosion actually occurred or not at a particular location, obviously depended on the duration of overgrazing and degree of biomass loss at those patches but also climate, vicinity to volcanic zones, elevation, soil texture and thickness as well as other local factors (Arnalds 2015). Since it is hard to specify all those details and implement them in the series of models, but also to determine what degree of biomass loss at certain locations (beyond the UB threshold value of 40 %; see section 7.7.5.3.) would actually imply soil erosion and/or what degree of soil erosion (comparable to stages of land condition and degradation, as defined by Aradóttir and others: Aradóttir *et al.* 1992), those estimates were not suggested here.

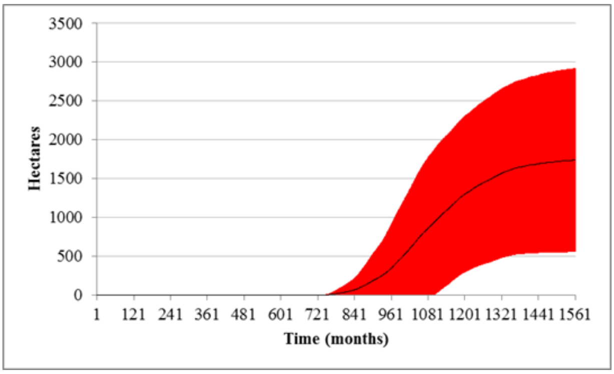
Eventually, a high resolution model, built with a sufficient amount of appropriate empirical data from specific locations and involving thorough information on the movement/distribution of livestock and dynamics of grazing, could suggest which particular locations suffered from soil erosion and also which form of erosion (e.g. erosion spots which at some point could expand and develop into rofabards: Dugmore *et al.* 2009).

The simulation runs also suggest that, in most cases, the degree of overgrazing and hence soil erosion (regional scale figures) could change abruptly primarily because of the combined effect of two factors: the arrival of the client farms (and introduction of their livestock herds) and the dynamics in the increase of overgrazing developed around the high-ranking farms, which in turn was a result of the interrelationship between their clearance potential and environmental response (see section 8.2.2.2.). It is exactly the high number of client-farms that appears to be a decisive factor in this regard in Vestur-Eyjafjallahreppur and up to certain extent in Borgarfjörður (8 and 6 high-ranking farms, respectively) and can explain more or less the sudden changes in the rates of ovegrazing in those regions. On the other hand, the reason for (broadly speaking) the gradual increase in overgrazing in the region of Mývatn is to be found in the small number of client farms (only 2).

Also, based upon the outcomes of the simulation runs, it may be said that scenario 1 would have left a less negative environmental signature, in terms of overgrazing and possibly soil erosion, than the other three scenarios. Because of uncontrolled/unlimited clearance, the ratio between the overall extent of cleared areas and the number of livestock was increasing. As a result there could have been larger areas of pastures that did not suffer from overgrazing, compared to other scenarios, which allow for clearance limited by livestock needs. Therefore, although it may sound surprising, this scenario would have produced more successful, i.e. less environmentally damaging, outcomes than the others.

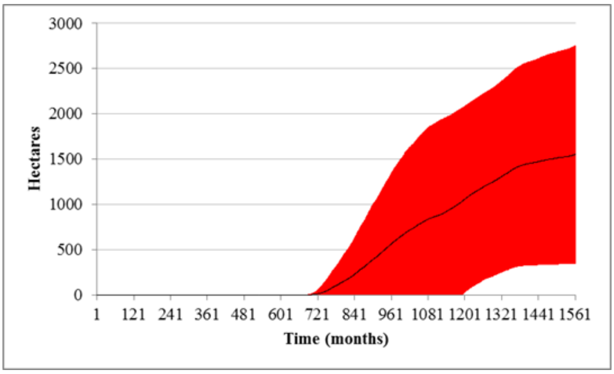
8.3.3.3 Replacement of grasses by grazing-tolerant vegetation

Another factor that obviously shaped the dynamics and degree of deforestation is the replacement of grasses by grazing-tolerant vegetation. As can be seen from the simulation outcomes in each of the regions it became apparent after c. AD 930, or after c. 60 years of settlement. In general, it increased at different rates towards the end of the period although at some occasions it showed a trend towards stabilisation from around c. AD 980 (Figures 88 – 90, below). That trend can be brought into connection with the possible increase in the rates of clearance during the later stages of the *landnám* (Figures 73 – 75, section 8.3.2.3.), which may have resulted in decrease in the grazing pressure and thus reduced spread of the grazing-tolerant vegetation. Finally, the outcomes of the simulation runs also suggested that the replacement effect continued to be significant in the first stages of the subsequent 11th century.



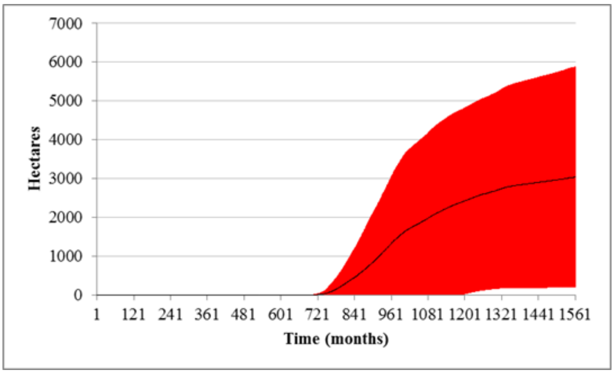
Note:—— average —— standard deviation

Figure 88. Scenario 3: Extent of areas with more than 50 % of grazing-tolerant vegetation in Vestur-Eyjafjallahreppur



Note:—— average —— standard deviation

Figure 89. Scenario 2a: Extent of areas with more than 50 % of grazing-tolerant vegetation in Mývatn

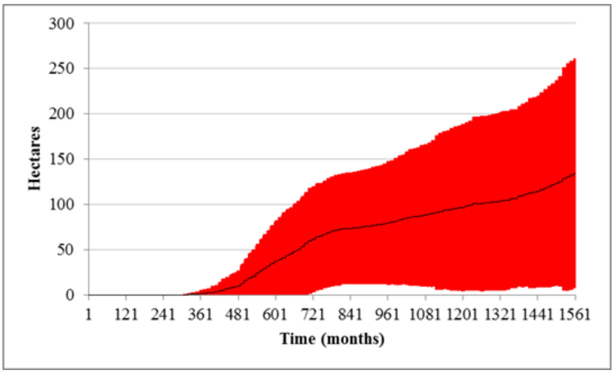


Note:—— average —— standard deviation

Figure 90. Scenario 4: Extent of areas with more than 50 % of grazing-tolerant vegetation in Borgarfjörður

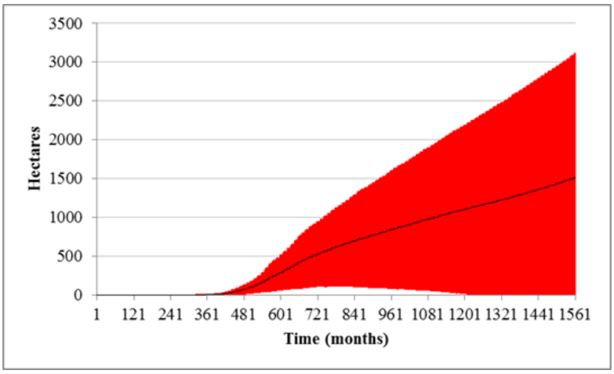
8.3.3.4 Regrowth effect

The simulation outcomes shown in Figures 91 – 93 below, suggested that the regrowth of birch played an important role in the deforestation process. Still, it was less significant than other factors. Judging from the regional-scale figures, in most of the cases, regrowth of birch became apparent after c. 30 years, i.e. after AD 900. A minor degree of regrowth obviously occurred at the beginning of the deforestation process, during the periods of prevention of grazing at the newly created pastures. Most of the regrowth that occurred throughout the *landnám* actually resulted from the termination of grazing which happened at many locations due to the loss of biomass. Finally, the simulation runs also suggested that the regrowth of birch continued to be obvious in the first stages of the 11th century.



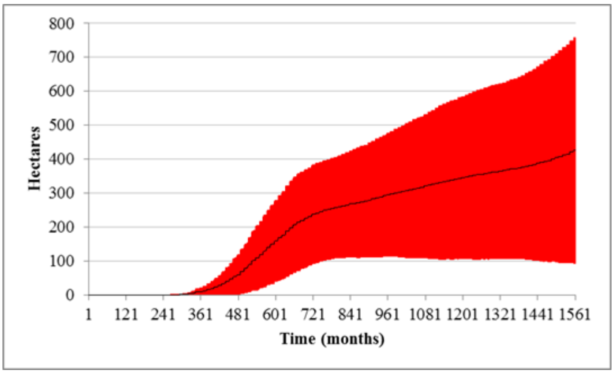
Note:—— average —— standard deviation

Figure 91. Scenario 3: Extent of areas with more than 50 % of regrown birch cover in Vestur-Eyjafjallahreppur



Note:—— average —— standard deviation

Figure 92. Scenario 2a: Extent of areas with more than 50 % of regrown birch cover in Mývatn



Note:—— average —— standard deviation

Figure 93. Scenario 3: Extent of areas with more than 50 % of regrown birch cover in Borgarfjörður

8.3.4 Extent and condition of the newly created pastures

The *ICELANDEF* models suggest that only a part of the land that was cleared was actually used as pastureland, since some parts of it were damaged and practically useless for grazing due to overgrazing and effects of replacement and regrowth. In particular, the areas close to households, were only of a „spotty“/„patchy“ character and there were no continuously large pastures with a sufficient amount of utilisable biomass close to home-fields. On the other hand, the newly created pastureland areas established further away from the households were of much higher quality (Figures 94 – 96 below). Precisely this situation suggests that, at a certain point, most likely by the end of the *landnám*, settlers had to move their livestock further away from the home-field areas which can be interpreted as a first step towards adequate shepherding introduced in the subsequent centuries.

On average, a farm in Vestur-Eyjafjallahreppur cleared between c. 87 (scenario 2a) – 106 ha (scenario 4) for pastures. Between c. 26 (sc. 2a) – 48 ha (sc. 4) of each farm’s pastureland was probably overgrazed at the very end of the period under discussion. Furthermore, at between c. 3 (sc. 3) – 17 ha-cells (sc. 4) of each farm’s pastureland there was more than 50 % of regrown birch cover, while at between c. 23 (sc. 2b) – 40 (sc. 3) ha-cells more than 50 % of the surface was covered with grazing-tolerant vegetation (Table 28).

Table 28. Degrees of deforestation, overgrazing, birch regrowth and replacement effect in Vestur-Eyjafjallahreppur (per farm). Average outcomes of 20 simulation runs

Deforested	Overgrazed (AD 1001)	Regrowth (› 50 %)	Replacement (› 50 %)
87 – 106 ha	26 – 48 ha	3 – 17 ha	23 – 40 ha

On average, a single farm at Mývatn cleared between c. 63 (sc. 3) – 85 ha (sc. 2a) for pastures, and c. 25 (sc. 3) – 46 ha (sc. 2a) of their pastureland was most likely overgrazed. At between c. 12 (sc. 3) – 22 ha-cells (sc. 2a) birch cover regained more than 50 % of the original extent, while at between c. 15 (sc. 3) – 26 ha-cells (sc. 2b) grazing-tolerant vegetation constituted more than 50 % of the ground cover (Table 29).

Table 29. Degree of deforestation, overgrazing, birch regrowth and replacement effect in Mývatn (per farm). Average outcomes of 20 simulation runs

Deforested	Overgrazed (AD 1001)	Regrowth (› 50 %)	Replacement (› 50 %)
63 – 85 ha	25 – 46 ha	12 – 22 ha	15 – 26 ha

In Borgarfjörður, the average extent of clearance for pastures per farm was between c.79 (sc. 2b) – 87 ha (sc. 2a), while c. 30 (sc. 2b) – 36 ha (sc. 2a) of each farm's pastureland suffered some degree of overgrazing. On average, at between c. 4 (sc. 3) – 12 ha-cells (sc. 2a) of their pasturelands, birch cover regained more than 50 % of the original extent, while at between c. 26 (sc. 2a) – 32 ha-cells (sc. 3) grazing-tolerant species constituted more than 50 % of the ground cover (Table 30).

Table 30. Degrees of deforestation, overgrazing, birch regrowth and replacement effect in Borgarfjörður (per farm). Average outcomes of 20 simulation runs

Deforested	Overgrazed (1001)	Regrowth (› 50 %)	Replacement (› 50 %)
79 – 87 ha	30 – 36 ha	4 – 12 ha	26 – 32 ha

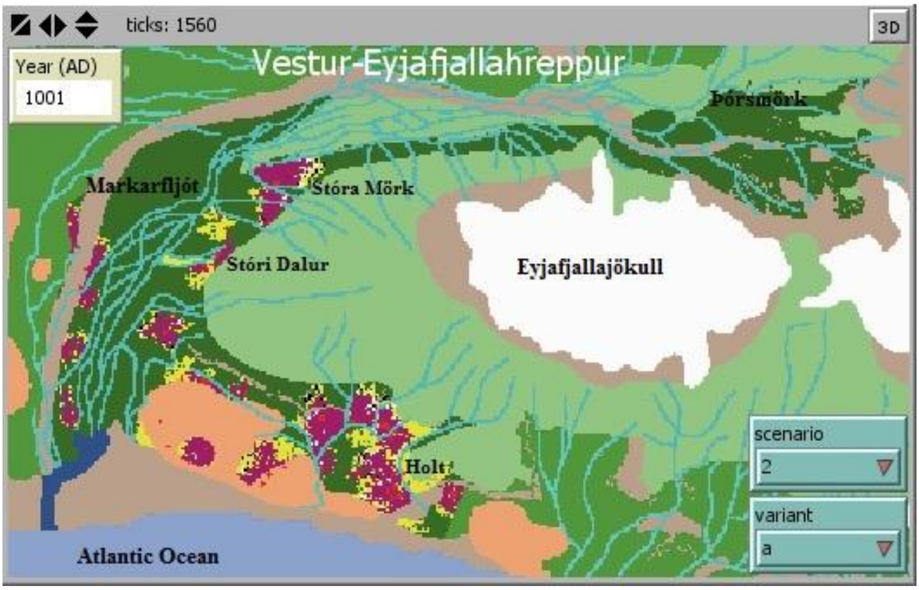
The tables above suggest that the smallest variation in the possible conclusive extent of deforested areas but also areas affected by overgrazing, replacement and regrowth (per farm) is to be found in the region of Borgarfjörður. According to the *ICELANDEF* models, this variation appeared to be much higher in the regions of Mývatn and Vestur-Eyjafjallahreppur. The differences in degrees of uncertainty with regards to these particular outcomes can be explained by the combination of various factors – logically, different input values (e.g. degrees of replacement and regrowth), previously mentioned factors introduced during the simulation runs (section 8.2.2.1.), but also by the timing of the establishment of client-farms and their numbers as well as uncertainties about the livestock numbers (Table 10, Chapter 7).

It is important to note that the early arrival of the client population and their long-term exploitation of the newly created pastures would almost certainly result in a reactive clearance during the later stages of the *landnám*. Consequently, the ending degree of deforestation would be high, and frequently, overgrazing, replacement and regrowth would also reach noticeable degrees. On the other hand, the late arrival of the client population (c. post- AD 950) would generally diminish or even exclude the need for reactive clearance before AD 1000; needless to say, overgrazing, replacement effect and regrowth, would also have been low. Therefore, it is clear that the variations in the final outcomes originate from differences in the duration of presence of client farms in each of the regions. Logically, those differences would have been smaller in the regions with few client farms (Mývatn: 3 out of 69 farms in total, and Borgarfjörður: 10 out of 110 farms in total) than in the regions with high number of client farms (Vestur-Eyjafjallahreppur: 20 out of 44 farms in total). This is one of the major reasons for the high-level of uncertainty in the conclusive degrees of deforestation, overgrazing, replacement effect and regrowth in the region of Vestur-Eyjafjallahreppur. By following this explanation one would expect a low level of uncertainties for the regions of Borgarfjörður and Mývatn. While the outcomes of the Borgarfjörður model do correspond to this explanation, uncertainties about these specific final outcomes of the Mývatn model are, at first glance, surprisingly high. However, uncertainties for the region of Mývatn actually originate from another factor – high uncertainties in the number of animals. At 32 (out of 69) farms in Mývatn, livestock numbers were not fully determined (Table 10) and were therefore randomly chosen, prior to every simulation run, from the range of livestock numbers available for other sites of comparable rank and status (with regards to ovine population: 12 – 192, 119 – 162 and 25 – 204; cattle population: 2 – 12, 2 – 14, 9 – 12). Clearly, those numbers suggest that there were high differences in the number of animals in every separate simulation run – consequently, there were high differences in the final outcomes. On the other hand, in the regions of Vestur-Eyjafjallahreppur and Borgarfjörður, uncertainties about the number of animals were present at a small number of farms (2 and 6, respectively), meaning that the corresponding variation cannot be as significant as it was in the region of Mývatn.

Surely, further clarification of the timing of the client population‘s arrival (i.e. reduction of the possible time-span of their arrival in Iceland) and estimates about the size of their livestock herds, would help us improve the models and reduce the uncertainty in the outcomes. Unfortunately, at present, there are no research studies that can be used to improve the models in those regards. Hopefully, they will be produced in the near future.

8.3.5 Distribution of clearance

In Vestur-Eyjafjallahreppur, only a minor part of the clearance activities took place in the areas west of the cluster of river streams around Markarfljót. This is a more or less expected outcome that can be explained by the distribution of farmsteads. Also, most of the woodland cover in the north of this area, from the pasturelands of Stóra-Mörk all the way to Þórsmörk (almost the entire area north of Eyjafjallajökull), was left undisturbed (Figure 94 below).


ticks: 1560

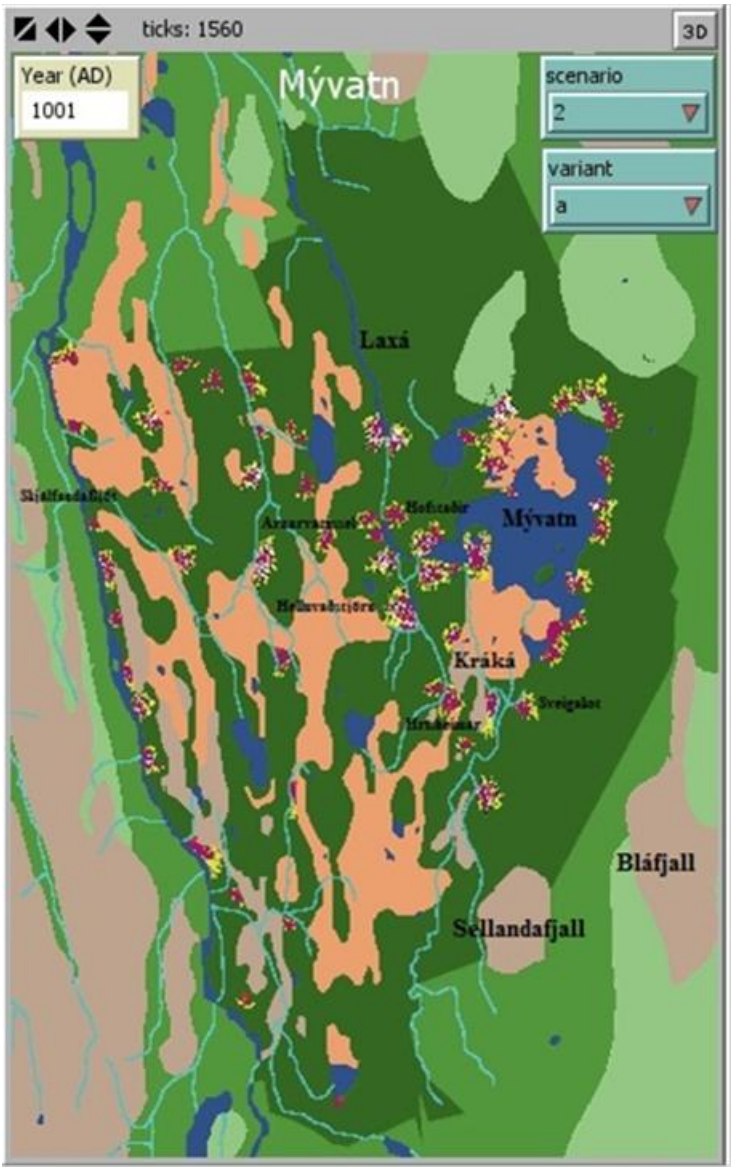
Year (AD) 1001

scenario 2

variant a

Figure 94. Vestur-Eyjafjallahreppur: Visual output from single simulation run (Scenario 2a - at AD 1001). Note that more than 50 % of the surface of magenta-coloured ha-cells is covered with grazing-tolerant vegetation. White-coloured ha-cells (only 115 of those according to this simulation run; excluding the glaciers) have more than 50 % of regrown birch cover. Yellow-coloured ha-cells represent high-quality pastures.

In the Mývatn area (Figure 95 below), deforestation occurred throughout the region, with a concentration around the lake Mývatn. Minor woodland loss occurred in the north-central part of the region and along the river Skjálfandafljót in the west, which is a logical and more or less expected distribution if we take the distribution of farmsteads into account. Large areas in the north and south were simulated as being left undisturbed, at least until the end of the 10th century. As established earlier, the degree of deforestation (and overgrazing of new pastures), which is somewhat lower than in other study areas, may be attributed to smaller livestock herds with lower demands for pastures and in general less impact on woodlands.



ticks: 1560

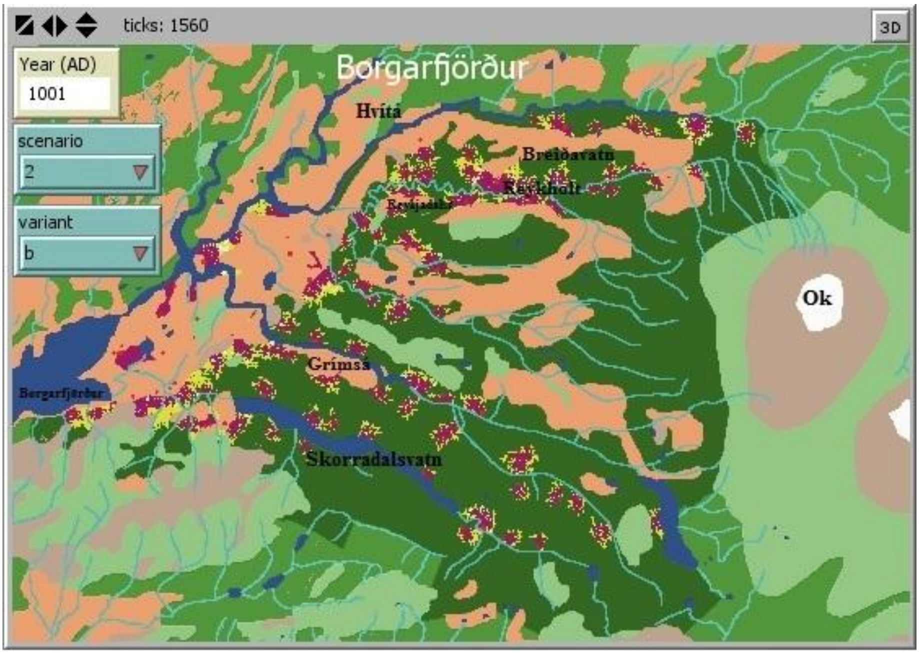
Year (AD) 1001

scenario 2

variant a

Figure 95. Mývatn: Visual output from a single separate simulation run (Scenario 2a – at AD 1001). Note that more than 50 % of the surface of magenta-coloured ha-cells is covered with grazing-tolerant vegetation. White-coloured ha-cells have more than 50 % of regrown birch cover. Yellow-coloured ha-cells represent high-quality pastures.

In Borgarfjörður (Figure 96 below), deforestation was concentrated in Hálsasveit, in the valley of Reykholtsdalur, around the rivers of Flókadalsá and Grímsá and in between Grímsá and the lake Skorradalsvatn as well as around the river of Andakílsá. As for the other regions, distribution of clearance in Borgarfjörður can be explained by the location of farmsteads and the policy of locating pastures in the immediate vicinity of the households. The outcomes of simulation runs suggest that vast areas in the east and the interior of the region were left wooded.



ticks: 1560

Year (AD)
1001

scenario
2

variant
b

Figure 96. Borgarfjörður: Visual output from a single separate simulation run (Scenario 2b – at AD 1001). Note that more than 50 % of the surface of magenta-coloured ha-cells is covered with grazing-tolerant vegetation. White-coloured ha-cells (excluding the glaciers) have more than 50 % of regrown birch cover. Yellow-coloured ha-cells represent high-quality pastures.

The model of Vestur-Eyjafjallahreppur suggests that many of the settlers, during the process of clearance for their own pastures, also cleared areas in which later on, other farms were established. This situation is associated with Scenario 3 and suggests that clearance was made prior to the establishment of newcoming, client farms, as a sort of a „preparation of the ground“ prior to their arrival. However, the simulation outcomes suggest that this type of clearance also happened outside of the context of patron-client relationships, that is, that independent or patron settlers cleared the areas which were simply rented or sold out later on to another independent settler or patron. This could have been the case with farms that were situated very close to one another, for instance the farms of Hamragarðar and Seljaland, that were both independent settler units. It is tempting to assume that this type of clearance could have been frequently practiced simply because that way, farms that were established earlier would have enjoyed the benefit of having much higher rent-income than would have been the case if the areas that were rented out (or sold) were fully forested.

8.3.6 A note on equifinality

The figures shown in the pages above and in the Appendix 1 of this dissertation reveal broad similarities between the outcomes of different scenarios. At first glance, it may be said that the major reason why the outcomes of different scenarios are sometimes so similar is the high number of independent farms (compared to the number of cluster-farms; especially in Mývatn and Borgarfjörður) and the fact that the course of their clearance for pastures (autonomous and self-governing) was same for each scenario. Another reason for this similarity is the fact that the simulated environmental dynamics and response to deterioration broadly overshadowed, i.e. exceeded in significance, differences between considered scenarios, or more precisely, differences between various clearance-strategies applied by cluster-farms.

A detailed analysis of the simulation runs and their outcomes also suggests that this similarity can be brought into connection with equifinality, i.e. the principle by which the same or similar results may be reached in different ways and with the use of a different set of starting parameters (i.e. initial conditions). In recent years, the concept of equifinality in archaeology-related modelling studies has been given considerable attention and a number of scholars have recognised it as a significant problem in the overall simulation-based research, urging for further systematic exploration of the model outcomes (e.g. Lake 2015, pp. 23 – 24). While some authors have proposed particular ways to solve the problem of equifinality (Premo 2008, p. 48), others have stressed that certain levels of equifinality should be expected regardless of the analytical tools we use (Crema *et al.* 2014, p. 298).

However, equifinality, in particular with regards to analyses of the archaeology- but also palaeoecology-related agent-based models, should not necessarily be seen as a problem. In fact it may even be seen as a desired outcome since for many of the processes that occurred in the past it is more reasonable, and in the end realistic, to suggest a variety of possible explanations (and/or starting conditions) and not a single one which would then eventually be presented in the form of an assertion – especially if we know that even modern societies (Grabowski 2014, p. 281) and environmental processes (e.g. Savenije 2001) are also characterised by equifinality.

The examples discussed in sections 8.2.2.1. and 8.2.3.1. show the nature of equifinality that emerge in the *ICELANDEF* simulations models. A logical explanation for its emergence lies in the combined effect of the factors described in Chapter 7 which are introduced during the simulation runs and which are independent of the initial conditions: decision-making with regards to spatial distribution of clearance (section 7.5.4.), clearance-rate fluctuations (esp. at mid- and high-ranking farms: section 7.5.9.4.) and different periods of prevention of grazing (section 7.7.4.) and consequently, different seasons of initation of grazing (summer as opposed to winter). Unfortunately, for those factors we have only very limited knowledge and/or insufficient amount of information which clearly implies the need for further research. Finally, it is important to stress that primarily because of the emergence of equifinality in the *ICELANDEF* models, applied starting parameters need to be recognised as only contingent initial conditions.

9 Final remarks and conclusions

The following paragraphs provide the final remarks about the results presented and discussed in the previous chapters and suggest the major conclusions of this study.

9.1 Strategy and mismanagement

The discussion of the simulation outcomes presented in the previous chapter suggests that the answer to the principal question behind this dissertation is obviously positive – the country-wide reduction of forest cover, which was significant but not catastrophic, was the result of a deliberate strategy by the settlers to establish and sustain their animal husbandry economy. The animal husbandry required considerable extent of pastures – therefore, at many locations in the absence of appropriate natural treeless pasturelands, the clearance of woodlands by cutting was an obvious choice and the most efficient way of their use since the floor of the original birch forests could provide sufficient amount of utilisable biomass. Woodland clearance was therefore carried out for practical reasons and it was intentional.

However, the application of this strategy was not completely successful. Firstly, the process of deforestation, destructive *per se*, had another negative environmental effect: the overgrazing of new pastures which in many cases may have resulted in soil erosion. Secondly, due to the replacement of grasses by grazing-tolerant vegetation and the regrowth of birch, clearance work became much more extended than the settler population probably expected at first. Both the overgrazing and the continued need for clearance and re-clearance are the results of mismanagement, arising from incomplete understanding of environmental potential and fragility.

In any case, there would have been considerably more limited environmental degradation if the settlers had been fully aware of the seasonal variation in utilisable biomass (Ogilvie and McGovern 2000) and if winter-grazing had not been practiced. Prevention of grazing in the months of low grass growth would have resulted in less overgrazing damage and less overall browsing of woody vegetation. A much smaller land area would have been impacted, and the need for additional clearance for pastures would have been reduced (although more hay production would have been required). Also, reduction of grazing pressure would have resulted in a lower degree of the replacement of grasses by grazing-tolerant species. Again, a need for extra clearance would have been diminished.

It may also be said that overgrazing, significant replacement effect and extended clearance actually resulted from insufficient clearing during the initial stages of the Settlement. If the settlers would have cleared more than they estimated they needed and than they did at first, the overall grazing pressure per ha and consequently the rate of replacement of grasses by grazing-tolerant vegetation would have been lower than they actually were. In that case, the need for re-clearance would have been diminished and the overall landscape degradation would have been reduced.

In general, it may be said that an awareness of the potential and limits of the environment and appropriate management would have considerably reduced the overall damage and in general, the overall need for clearance. Unfortunately, the settlers were unaware of the environmental potential (Ogilvie and McGovern 2000, McGovern *et al.* 2007) – *nihil nuovo sub sole*, since even today we are neither fully aware of the potential and the limits of our own environment, nor do we manage it efficiently.

The size of the initial animal husbandry economy and the rate of its development can be regarded as equally significant factors in the process of environmental degradation during the *landnám*. It is clear that with smaller initial livestock herds, higher degree of culling and / or a lower intrinsic rate of growth, the overall negative environmental impact would have been considerably smaller. However, in that case, the rate of growth of the animal husbandry economy, at least from the perspective of a Viking Age settler, would have been remarkably slow and thus probably unacceptable. Instead, the fast rate of development was chosen and as a result, considerable, yet not extreme degradation of the natural environment was inevitable.

In general, it may be said that there were two distinct phases of woodland clearance during the age of Settlement:

a) the initial phase of clearance (pre- c. AD 900), during which the baseline extent of required pastures was reached; this phase reflects development and establishment of the major part of the animal husbandry based economy, and

b) the second phase of clearance (post- c. AD 900) which resulted from the mentioned lack of awareness of the environmental potential and its response to deterioration and which can be brought into connection with the maintenance of the animal husbandry based economy.

The second phase of deforestation can best be comprehended through analyses of the single farm clearance activities (section 8.3.2.3.). As the outcomes of the simulation runs suggested (Figures 76 – 78), those activities were only intermittent and were the result of a combination of the simple pursue for pastures and corresponding environmental response. It is important to underline that the time-breaks between the clearance activities should not be associated with eventual application of management and/or certain restraints in the process of exploitation of natural resources. Rather, it seems that if any management or restraint would have been applied at all, it would happen either during the later periods[66], or only at rare locations with extreme degradation of environment but certainly not around the majority of the *landnám* farms

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[66] Which, in the end, has been confirmed by some of the research studies (e.g. Church *et al.* 2007).

where environment was, although deteriorated, still in decent condition and where there were still sufficient resources to support the livestock herds.

Finally, it is clear that the different settlement patterns obviously affected pristine Icelandic environment in different ways – the regions with the high number of clusters of farms (e.g. Vestur-Eyjafjallahreppur), having repetitive environmental impact concentrated in relatively small areas frequently bounded by the natural features, suffered from higher degrees of deterioration than the areas where most of the settlements were independent and spread throughout the landscape (e.g. Mývatn and up to a certain extent Borgarfjörður). It may even be said that this result and the fact that most of the Icelandic settlements were spread throughout the country (thus having only limited pressure on local environments) can explain, along with other reasons (e.g. landscape resilience), why the Icelandic environment endured for centuries.

9.2 Major limitations and benefits of the present study

9.2.1 Limitations

This study and the series of models have limitations which were caused by the lack of relevant datasets; consequently it may be said, that the question is far from being settled. Firstly, the map that was used as a reference basis to quantify the impact on the woodlands and for modelling is still only conjectural due to the lack of empirical research needed to establish accurately the distribution of woodland cover before the arrival of the first settlers. Secondly, the quantification of woodland loss to meet the various needs of the settler population was based on studies which do not cover the whole issue in sufficient detail.

The simplification of the replacement of grasses by grazing-tolerant vegetation and the regrowth of birch can be seen as another major limitation. As noted in the sections 5.2.5.3. and 5.2.5.4., those processes were more complex in reality – they differed from one region of the country to another, depending on the state of local ecosystems and variety of circumstances. Consequently, they may have resulted in a variety of outcomes and hence effects on the deforestation process.

Uncertainties about the sets of parameters associated with those and other factors can be seen as another major weakness of the simulation models. As discussed in Chapter 8, those uncertainties resulted in a high degree of variations in the conclusive degrees of deforestation, overgrazing, replacement and regrowth, thus complicating the establishment of an accurate interpretation of this environmental change.

Furthermore, failure to include estimates of the impact of volcanic eruptions and climatic changes on the process of deforestation and especially on the subsequent grazing of the newly created pastures can be seen as another significant flaw in the structure of the models. Today, we know that those factors may have contributed significantly to the environmental degradation in the past, for instance by worsening the negative effects of grazing (Arnalds 2015). Finally, the resolution of the series of models can be seen as yet another weakness, which may have affected the precision of the final outcomes. These limitations and weaknesses suggest that the *ICELANDEF* models therefore do not explain the process of deforestation in the closest possible detail. Still, they do provide a generalised and reasonable depiction of this environmental change.

9.2.2 Benefits

Like other studies already made on the topic of the *landnám* deforestation, this one aimed to clarify the degree of change that the woodlands underwent during the age of Settlement. Also, like many others, this study suggests that it was the human factor which played the principal role in this process.

However, unlike other studies, this one has improved the knowledge about the anthropogenic side of this environmental change. Hence, reasonable estimates of the degree of intentional human impact on woodlands have been given. Also, this study has identified the essence of this environmental change – clearance for home-fields and pastures which were crucial for the growth of the *landnám* animal husbandry based economy. Furthermore, the *ICELANDEF* series of models offer new insights on the rates and spatial distribution of human-induced clearance as well as on the degree of deforestation and environmental degradation (i.e. overgrazing) at the initial, mid- and final stages of the period under discussion. As a result, it was possible to get a comprehensive view of the process of deforestation – its start, continuation and consequences and, on those grounds, to better understand its dynamics and nature.

One of the additional benefits of this series of models is that they can eventually suggest which locations and areas may be of particular interest for future empirical studies. As described in Chapter 2, the lack of empirical research is one of the major weaknesses of the overall state of knowledge on this subject. The available empirical studies confirm the type and rate of vegetation changes only in a very limited number of locations while extensive areas have not been the subject of any sort of systematic empirical research and the knowledge of environmental changes in those locations is very limited or does not exist at all. The outcomes of a series of models like this one can considerably improve this situation. They can indicate which particular locations were the epicentres of highly dynamic human-environment interactions, thus opening the way for a variety of future empirical studies.

The outcomes of the *ICELANDEF* series of models also point to further questions about how the environmental degradation of the *landnám* affected the development of livestock management and the utilisation of natural resources during the subsequent periods. Those and many other questions may fuel future research studies that can improve our understanding of the human-environment interactions during the post-*landnám* periods.

Finally, the results of this study and the series of models also contribute to our understanding of the colonisation processes and accompanying environmental changes

– they help answering questions such as how long it took colonising populations to significantly alter pristine landscapes, how intense the contemporary interaction between humans and their environments was but also what were the consequences of large-scale human-induced environmental changes during the colonisation processes.

9.3 Conclusions

The results presented in this dissertation suggest the following conclusions:

1) The extent of birch forest cover before the arrival of the first settlers around AD 871 was most probably little less than 23,844 km^2. Given the size of the total area of the country (103,001 km^2) this represents 23.14 %. For reasons outlined in the dissertation this figure, however, should be taken with caution.
2) The clearance for pastures, but also for home-fields, should be seen as the essence of the process of deforestation. Such clearances also fulfilled the requirements for fuel and building material which were insignificant factors in the overall deforestation process. The baseline calculations suggest that in an ideal situation, clearance for pastures and home-fields should not have resulted in massive deforestation. However, due to overgrazing damage and effects of replacement of grasses by grazing-tolerant species as well as regrowth of birch, the extent of clearance was much greater and the entire process of deforestation lasted much longer than initially expected by the landnám farmers.
3) The outcomes of the series of agent-based simulations suggest that there were regional differences in dynamics and distribution of the forest clearance which originate from different livestock numbers from one region to another, but also differences in the concentration and interrelationships of farms in each of the regions.
4) In most cases, it seems likely that clearance was an autonomous and self-governing activity, where each farm, regardless of its hierarchical position and/or status, cleared woodlands for its own benefits and according to needs of its livestock herds. At a small number of cluster-farm localities (e.g. Holt), clearance was most probably a collective endeavour directed by patrons. Unfortunately, due to scarcity of empirical studies, at many locations it is impossible to suggest which particular scenario took place (apart from the disregarded scenario 1, whose evaluation still produced useful comprehension of this environmental change). Nevertheless, the outcomes of the considered scenarios provide important information about the possible courses of deforestation in each of the regions, in particular its timing, degree and distribution.
5) The deforestation during the late 9th and 10th centuries was a result of the application of a deliberate strategy to establish and develop an animal husbandry economy as soon as possible. The strategy was applied without a full awareness of the potential of local environments and as a result, huge areas of land suffered from extensive degradation and deforestation reached a considerable degree.

Bibliography

Adam, N.R. 1983. Achieving a confidence interval for parameters estimated by simulation. Management Science 29, pp. 856 – 866.

Adderley, P.W., Simpson, I.A., Vésteinsson, O. 2008. Local-scale adaptations: A modeled assessment of soil, landscape, microclimatic, and management factors in Norse home-field productivities. Geoarchaeology 23 (4), pp. 500 – 527.

Agate, E. 1986, Fencing: A Practical Conservation Handbook. British Trust for Conservation Volunteers, Wallingford.

Aldred, O. 2008. Unfamiliar landscapes: infields, outfields, boundaries and landscapes in Iceland. In: Chadwick A.M. (ed.) Recent approaches to the archaeology of land allotment, BAR Series 1875, pp. 299 – 321. Archaeopress, Oxford.

Alvard, M.S. and Kuznar, L. 2001. Deferred Harvests: The Transition from Hunting to Animal Husbandry. American Anthropologist 103 (2), pp. 295 – 311.

Aradóttir A.L., Arnalds Ó, Archer, S. 1992. Degradation of vegetation and soils (Hnignun grodurs og jardvegs). Græðum Island, Soil conservation Service yearbook 1991 – 1992, pp. 73 – 82.

Aradóttir, Á.L., Þorsteinsson, I., Sigurðsson, S. 2001. Distribution and characteristics of birch woodlands in North – Iceland. In: Wielgolaski, F. E. (ed.) Nordic Mountain Birch Ecosystems, pp. 51 – 61, UNESCO, Paris.

Arnalds, A. 1987. Ecosystem destruction in Iceland. Arctic and Alpine Research 19, pp. 508 – 513.

Arnalds, Ó. 2015. The Soils of Iceland. Springer, Netherlands.

Austad, I. and Hauge, L. 2006. Pollarding in western Norway. 1er colloque européen sur les trognes, Vendome, 26, 27, 28. octobre 2006; pdf file available at: http://www.maison botanique.com/dyn/14acte_4_austad_hauge.pdf. Last consulted on 08.04. 2010.

Barger, N.N., Archer,S.R., Campbell, J.L., Huang, C., Morton,J.A., Knapp, A.K. 2011. Woody plant proliferation in North American drylands: A synthesis of impacts on ecosystem carbon balance, Journal of Geophysical Research 116, pp. 1 – 17.

Barton, C.M., Riel-Salvatore, J., Anderies, J.M., Popescu, G. 2011. Modeling Human Ecodynamics and Biocultural Interactions in the Late Pleistocene of Western Eurasia, Human Ecology 39, pp. 705 – 725.

Benavides Calvo, R. 2008. Knowledge and experiences for the development of sustainable silvopastoral systems in heathlands in Asturias. Doctoral Thesis, University of Santiago de Compostela, Santiago de Compostela. Available at: http://dspace.usc.es/handle/10347/2466. Last consulted on 11.05.2016.

Benediktsson, J. 1968. (ed.) Íslenzk fornrit I. Íslendingabók – Landnámabók. Hið íslenzka fornritfélag, Reykjavík.

Berson, B. 2002. A contribution to the study of the medieval Icelandic farm: the byres. Archaeologia Islandica 2, pp. 37 – 64.

Bishop, R.R., Church, M.J., Dugmore, A.J., Koch Madsen, C., Møller, N.A. 2013. A charcoal rich horizon at Ø69, Greenland: evidence for vegetation burning during the Norse landnám? Journal of Archaeological Science 40, pp. 3890 – 3902.

Bjarnason, H. 1971. Um friðun lands og frjósemi jarðvegs. Ársrit Skógræktarfélags Íslands 1971, pp. 4 – 19.

Bjarnasson, H. 1974. Athugasemdir við sögu Íslendinga í sambandi við eyðingu skóglendis. Ársrit Skógræktarfélags Íslands 1974, pp. 30 – 43.

Blondel, J. and Aronson, J. 1995, Biodiversity and ecosystem function in the Mediterranean basin: Human and non-human determinants. In: Davis, G.W. and Richardson, D. M (eds.): Mediterranean-Type Ecosystem: Functions of Biodiversity, pp. 43 – 119. Springer, Heidelberg.

Box, G.E.P. 1979. Robustness in the strategy of scientific model building. In: Launer R.L, Wilkinson G.N. (eds.) Robustness in statistics, pp. 201 – 236. NY Academic Press, New York.

Briggs, J.M., Knapp, A.K., Blair, J.M, Heisler, J.L., Hoch, G.A., Lett, M.S., McCarron, J.K. 2005. An Ecosystem in Transition: Causes and Consequences of the Conversion of Mesic Grassland to Shrubland. BioScience 55 (3), pp. 243 – 254.

Bryson, J.J., Ando, Y., Lehmann, H. 2007. Agent based modelling as scientific method: a case study analysing primate social behaviour. Philosophical Transactions of the Royal Society, B – Biology 362, pp. 1685 – 1698.

Buckland, P.C. 2000. The North Atlantic Environment. In: Fitzhugh, W.W., Ward, E.I. (eds.) Vikings: The North Atlantic Saga., pp. 146 – 153. Smithsonian Institution, Washington.

Buckland, P.C., Dugmore, A.J., Perry, D.W., Savory, D., Sveinbjarnardóttir, G. 1991a. Holt in Eyjafjallasveit, Iceland: A paleoecological study of the impact of Landnám. Acta Archaeologica 61, pp. 252 – 270.

Buckland, P., Dugmore, A., Sadler, J. 1991b. Faunal change or taphonomic problem? A comparison of modern and fossil insect faunas from southeast Iceland. In: Maizels, J. K., Caseldine, C. (eds.) Environmental Change in Iceland: Past and Present. Glaciology and Quaternary Geology 7, pp. 127 – 146. Kluwer Academic Publishers, Dordrecht.

Buckland, P.C., Edwards, K.J., Blackford, J.J., Dugmore, A.J., Sadler, J.P., Sveinbjarnardóttir, G. 1995. A question of Landnám: Pollen, charcoal and insect studies on Papey, eastern Iceland. In: Butlin, R.A., Roberts, N. (eds.) Ecological Relations in Historical Times: Human Impact and Adaptation. The Institute of British Geographers special publications series: 32, pp. 245 – 64. Blackwell, Oxfrod.

Burton, A., Altman, D.G., Royston, P., Holder, R.L. 2006. The design of simulation studies in medical statistics, Statistics in medicine 25, pp. 4279 – 4292.

Byock, J. 2001. Viking Age Iceland, Penguin, London.

Carter, T.D. 2010. Rethinking Secondary State Formation in Medieval Iceland: Trade and Social Connectivity in the Norse Economic Territory. Ph.D. thesis. University of California, San Diego.

Castle, C.J.E. and Crooks, A.T. 2006. Principles and Concepts of Agent-Based Modelling for Developing Geospatial Simulations. Centre for Advanced Spatial Analysis, University College London, London.

Chepstow-Lusty, A. 2001. Pollen analyses, Hofstaðir 2000. Framvinduskýrslur/Interim Report, pp. 55 – 61. Fornleifastofnun Íslands, Reykjavík.

Church M. J., Vésteinsson O., Einarson Á., McGovern T. H. 2006. Charcoal production pits at Höskuldsstaðir, Mývatnsveit. Unpublished report for the National Museum of Iceland.

Church, M.J., Dugmore, A.J., Mairs, K.A., Millard, A. R., Cook, G.T., Sveinbjarnardóttir, G., Ascough, P.A., Roucoux, K.H. 2007. Charcoal production during the Norse and Early Medieval periods in Eyjafjallahreppur, Southern Iceland. Radiocarbon 49 (2), pp. 659 – 672.

Crema, E.R., Kerig, T., Shennan, S. 2014. Culture, space, and metapopulation: a simulation-based study for evaluating signals of blending and branching. Journal of Archaeological Science 43, pp. 289 – 298.

Dennis, A. (ed. and trans.) 1980. Laws of early Iceland: Grágás, the Codex Regius of Grágás, with material from other manuscripts. University of Manitoba, Winnipeg.

Desch, H.E. 1973, Timber: Its Structure and Properties. Macmillan, London.

Díaz-Emperanca, I. 1996. Selecting the number of replications in a simulation study. Working Paper 1996-1. Available at SSRN: http://ssrn.com/abstract=1582 or http://dx.doi.org/10.2139/ssrn.1582. Last consulted on 14.03.2015.

Dugmore, A.J. and Buckland, P.C. 1991. Tephrochronology and late Holocene soil erosion in south Iceland. In: Maizels, J.K., Caseldine, C. (eds.) Environmental Change in Iceland: Past and Present. Glaciology and Quaternary Geology 7, pp. 147 – 161. Kluwer Academic Publishers, Dordrecht.

Dugmore, A.J. and Erskine, C.C. 1994. Local and regional patterns of soil erosion in southern Iceland. Münchener Geographische Abhandlungen 12, pp. 63 – 79.

Dugmore, A. and Vésteinsson, O. 2012. Black Sun, High Flame and Flood: Volcanic Hazards in Iceland. In: Cooper, J. and Sheets, P. (eds.) Surviving Sudden Environmental Change. Answers from Archaeology, pp. 67 – 90. University Press of Colorado, Boulder.

Dugmore, A.J., Newton, A.J., Larsen, G., Cook, G.T. 2000. Tephrochronology, environmental change and the Norse colonisation of Iceland. Environmental Archaeology 5, pp. 21 – 34.

Dugmore, A.J., Church, M.J., Buckland, P.C, Edwards, K.J., Lawson, I.T., McGovern, T.H., Panagiotakopulu, E., Simpson, I.A., Skidmore, P., Sveinbjarnardóttir, G. 2005. The Norse landnám on the North Atlantic islands: an environmental impact assessment. Polar record 41 (1). pp. 21 – 37.

Dugmore, A.J., Church, M.J., Mairs, K.A., McGovern, T.H., Newton, A.J., Sveinbjarnardóttir, G. 2006. An over-optimistic pioneer fringe? Environmental perspectives on medieval settlement abandonment in Þórsmörk, south Iceland. In: Arneborg, J., Grønnow, B. (eds.) Dynamics of Northern Societies. Proceedings of the SILA/NABO conference on Arctic and North Atlantic Archaeology, Copenhagen, May 10th – 14th, 2004 (Publications of the National Museum. Studies in archaeology and history 10), pp. 335 – 45. National Museum, Copenhagen.

Dugmore, A.J., Gísladóttir, G., Simpson, I.A., Newton, A. 2009. Conceptual Models of 1200 years of Icelandic Soil Erosion Reconstructed Using Tephrochronology. Journal of the North Atlantic 2, pp. 1 – 18.

Durrenberger, E.P. 1988. Stratification Without a State: The Collapse of the Icelandic Commonwealth. Ethnos 53(III-IV), pp. 239 – 265.

Durrenberger, E.P. 1990. Production in Medieval Iceland, Acta Archaeologica 61, pp. 14 – 21.

Eckmeier, E., Rösch, M., Ehrmann, O., Schmidt, M.W.I., Schier, W., Gerlach, R. 2007. Conversion of biomass to charcoal and the carbon mass balance from a slash-and-burn experiment in a temperate deciduous forest, Holocene 17 (4), pp. 539 – 542.

Edblom, L. 2004. Långhus i Gene. Studia Archaeologica Universitatis Umensis 18, University of Umeå, Umeå.

Edwards, K.J., Lawson, I.T., Erlendsson, E., Dugmore, A.J. 2005. Landscapes of contrast in Viking Age Iceland and the Faroe Islands. Landscapes, 6 (2), pp. 61 – 79.

Einarsson, B. 1995. The Settlement of Iceland; A Critical Approach: Granastaðir and the ecological heritage. Hið íslenska bókmenntafélag, Reykjavík.

Einarsson, Þ. 1957. Tvö frjólínurit úr íslenzkum myrum. Ársrit Skógræktarfélags Íslands 1957, pp. 89 – 97.

Einarsson, Þ. 1962. Vitnisburður frjógreiningar um gróður, veðurfar og landnám á Íslandi. Saga 24: tímarit Sögufélags, pp. 442 – 469.

Eldjárn, K. 1961. Bær í Gjáskógum. Árbók Hins íslenzka fornleifafélags 1961, pp. 7 – 46.

Elmarsdóttir, A., Fjellberg, A., Halldórsson, G., Ingimarsdóttir, M., Nielsen, O.K., Nygaard, P., Oddsdóttir, E.S. and Sigurðsson, B.D. 2008. Effects of afforestation on biodiversity. Affornord. Effects of afforestation on ecosystems, landscape and rural development. TemaNord 2008 562, pp. 37 – 47.

Erlendsson, E. 2007. Environmental Change Around the Time of the Norse Settlement of Iceland. Ph.D. thesis. University of Aberdeen, Aberdeen.

Erlendsson, E. and Edwards, K.J. 2009. The timing and causes of the final pre-settlement expansion of Betula pubescens in Iceland. The Holocene 19 (7), pp. 1083 – 1091.

Erlendsson, E., Edwards, K.J., Buckland, P.C. 2009. Vegetational response to human colonisation of the coastal and volcanic environments of Ketilsstaðir, southern Iceland. Quaternary Research 72, pp. 174 – 187.

Eysteinsson, Þ. 2004. Forestry in a tree-less land. Lustgarden. Available at: http://www.skogur.is/english/forestry-in-a-treeless-land. Last consulted on 03.06.2010.

Eysteinsson, Þ. 2012. Regeneration after clear-felling and selection-felling in an Icelandic birch forest. Icelandic Agricultural Sciences 25, pp. 37 – 40.

Feldman, L.H. 1974. Axes of stone and metal indices for a time of transition. American Antiquity 39 (1).

Findlay, W. P.K. 1962. The Preservation of Timber. Adam & Charles Black, London.

Fredskild, B. 1978. Paleobotanical Investigations of some Peat Deposits of Norse Age at Qagssiarssuk, South Greenland. Meddelelser om Grønland 204 (5).

Fredskild, B. 1992. Erosion and vegetation change in south Greenland caused by agriculture. Geografisk Tidsskrift 92, pp. 14 – 21.

Friðriksson, S. 1967. Gras og grasnytjar. Andvari, pp. 198 – 221.

Friðriksson, S. 1972. Grass and grass utilization in Iceland. Ecology 53, pp. 785 – 796.

Friðriksson, S. 1987. Gróðurfar við upphaf landnáms. In Johansson, F. F. (ed.) Íslensk Þjóðmenning I – Uppruni og Umhverfi, pp. 167 – 179. Bókaútgáfan Þjóðsaga, Reykjavík.

Gathorne-Hardy, F.J., Erlendsson, E., Langdon, P.J., Edwards, K.J. 2009. Lake sediment evidence for late Holocene climate change and landscape erosion in western Iceland. Journal of Palaeolimnology, pp. 413 – 426.

Gilbert, N. 2008. Agent-Based Models. Series: Quantitative Applications in the Social Sciences 153.

Gimblett, H.R. (ed.) 2002. Integrating Geographic Information Systems and Agent-Based Modelling Techniques for Simulating Social and Ecological Processes. Oxford University Press, London.

Gísladóttir, G., Erlendsson, E., Lal, R. 2011. Soil evidence for historical human-induced land degradation in West Iceland. Applied Geochemistry 26, pp. 28 – 31.

Gíslason, G.M. and Ólafsson, E. 1989. Entomology in Iceland. Fauna Norvegica, Norwegian Journal of Entomology, Ser. B, 36 (1)., pp. 11 – 16.

Gjerløff, A.K. and Sørensen, H. 1997. Fuel for the Fire: Wood vs. Charcoal in Iron Production. In: Nørbach, L.C. (ed.). Early Iron Production: Archaeology, Technology and Experiments. Denmark: Historisk-Archaeologisk Forgoscenter Lejre, pp. 67 – 71.

Grabowski, D. 2014. Cultural Factors of Economic Effectiveness and Innovation: Organizational Psychology of Innovation. In: Marek, T., Karwowski, W., Frankowicz, M., Kantola, J., Zgaga, P. (eds.) Human Factors of a Global Society. CRC Press, Taylor and Francis Group, Boca Raton.

Griffith, C.S., Long, B.L., Sept, J.M. 2010. HOMINIDS: An agent-based spatial simulation model to evaluate behavioral patterns of early Pleistocene hominids. Ecological Modelling 221, pp. 738 – 760.

Grimm, V. and Railsback, S.F. 2005. Individual-Based Modeling and Ecology. Princeton University Press, Princeton.

Grimm V., Berger U., Bastiansen F., Eliassen S., Ginot V., Giske J., Goss-Custard J., Grand T., Heinz S.K., Huse G., Huth A., Jepsen J.U., Jørgensen C., Mooij W.M., Müller B., Pe‘er G., Piou C., Railsback S.V., Robbins A.M., Robbins M.M., Rossmanith E., Rüger N., Strand E., Souissi S., Stillman, R.A., Vabø R., Visser U., DeAngelis D.L. 2006. A standard protocol for describing individual-based and agent-based models. Ecological Modelling 198, pp. 115 – 126.

Grimm V., Berger U., DeAngelis D.L., Polhill J.G., Giske J., Railsback S.F. 2010. The ODD protocol: A review and first update. Ecological Modelling 221, pp. 2760 – 2768.

Grönvold, K., Óskarsson, K., Johnsen, S.J., Clausen, H.B., Hammer, C.U., Bond, G., Bard, E. 1995. Ash layers from Iceland in the Greenland GRIP ice core correlated with oceanic and land sediments. Earth and Planetary Science 135, pp. 149 – 155.

Guðbergsson, G. 1996. Í norðlenskri vist. Um gróður, jarðveg, búskaparlög og sögu. Búvísindi, Icel. Agr. Sci. 10, pp. 31 – 89.

Guðbergsson, G. and Einarsson, Þ. 1996. Landið við landnám. In: Grímsdóttir G.Á (ed.) Um landnám á Íslandi, pp. 191 – 200. Vísindafélag Íslending, Reykjavík.

Guðmundsson, G. 1996. Gathering and processing of lyme-grass (Elymus Arenarius L.) in Iceland: an ethnohistorical account. Vegetation History and Archaeobotany 5, pp. 13 – 23.

Guðmundsson, G. 2001. The Environmental Evidence. Interim report on Sampling and analysis. In: Roberts, H. M. (ed.) Fornleifarannsókn á lóðunum/Archaeological Excavations at Aðalstræti 14 – 18, 2001, A Preliminary Report/Framvinduskýrslur, pp. 83 – 90. Fornleifastofnun Íslands, Reykjavík.

Gunnarsdóttir, B. 2001. Gróðurfarslýsingar í Íslendingasögunum bornar saman við núverandi gróðurfar. Skógræktarritið 2001 (2), pp. 63 – 77.

Hallsdóttir, M. 1984. Frjógreining tveggja jarðvegssniða á Heimaey. Árbók Hins íslenzka fornleifafélags 1983, pp. 48 – 68.

Hallsdóttir, M. 1987. Pollen Analytical Studies of Human Influence on Vegetation in Relation to the Landnam Tephra Layer in Southwest Iceland. Lundqua thesis, volume 18, Lund University, Sweden.

Hallsdóttir, M., 1993. Frjórannsókn á mósniðum úr Viðey. Raunvísindastofnun og Árbæjarsafn, Reykjavík.

Hallsdóttir, M. 1995. On the pre-settlement history of Icelandic vegetation. Búvísindi 9, pp. 17 – 29.

Hallsdóttir, M. 1996. Frjógreining. Frjókorn sem heimild um landnámið. In: Grímsdóttir, G. A. (ed.) Um landnám á Íslandi, pp. 123 – 34. Vísindafélag Íslending, Reykjavík.

Hamilton, H. 1997. Slash-and-Burn in the History of the Swedish Forests. Rural Development Forestry Network Paper 21f. ODI, London.

Hardin, G. 1968. Tragedy of Commons. Science 162 (3859), pp. 1243 – 1248.

Harju, A., 1996. Effect of birch (Betula pendula) bark and food protein level on root voles (Microtus oeconomus): II. Detoxification capacity. Journal of Chemical Ecology 22 (4), pp. 719 – 728.

Hidalgo, L.G. and Cauhépé, M.A. 1991. Effects of seasonal rest in aboveground biomass for a native grassland of the flood Pampa, Argentina. Journal of Range Management 44 (5), pp. 471 – 475.

Highley, T.L. 1995. Comparative Durability of Untreated Wood in Use Above Ground. International Biodeterioration and Biodegradation, pp. 409 – 419.

Holtmeier, F.K. 2003. Mountain timberlines – ecology, patchiness, and dynamics. Kluwer Academic Publishers, Dordrecht.

Innes, J.B. and Blackford, J.J. 2003. The Ecology of Late Mesolithic Woodland Disturbances: Model Testing with Fungal Spore Assemblage Data. Journal of Archaeological Science 30, pp. 185 – 194.

Jakobsen, B.H. 1991, Soil resources and soil erosion in the Norse settlement area of Østerbygden in Southern Greenland. Acta borealia 1, pp. 56 – 68.

Johnsen, J. 1847, Jarðatal á Íslandi. S.Trier, Kaupmannahöfn.

Jónsson, Þ.H. 2004. Stature of Sub-arctic Birch in Relation to Growth Rate, Lifespan and Tree Form. Annals of Botany 94, pp. 753 – 762.

Kaplan, J.O., Krumhardt, K.M., Zimmermann, N. 2009. The prehistoric and preindustrial deforestation of Europe. Quaternary Science Reviews 28, pp. 3016 – 3034.

Karlsdóttir, L., Hallsdóttir, M., Thórsson, Æ.Th., Anamthawat-Jónsson, K. 2009. Evidence of hybridisation between Betula pubescens and B. nana in Iceland during the early Holocene. Review of Palaeobotany and Palynology 156, pp. 350 – 357.

Kennett, D.J. and Winterhalder, B. (eds.) 2005. Behavioral ecology and the transition to agriculture. University of California Press, Berkeley and Los Angeles.

Kohler, T.A., Gumerman, G.J., Reynolds, R.G. 2005. Simulating ancient societies. Scientific American 293 (1), pp. 76 – 82.

Kristinsson, A. 2000. Productivity and Population in Pre-Industrial Iceland. In: Sigurðsson, I. and Skaptason J. (eds.) Aspects of Arctic and Sub-Arctic History. Proceedings of the International Congress on the History if the Arctic and Sub-Arctic Region, Reykjavík, 18 – 21 June 1998, pp. 270 – 278. University of Iceland, Reykjavík.

Lake, M.W. 2015. Explaining the Past with ABM: On Modelling Philosophy. In: Wurzer, G. and Kowarik, K., Reschreiter, H, (eds.) Agent-Based Modeling and Simulation in Archaeology, pp. 3 – 35. Springer International Publishing, Switzerland.

Larsen, G. 1993. Tephra layer from the 10th century Eldgjá fissure eruption, South Iceland. EOS 74 (43, supplement): 132. AGU Fall Meeting, December 6-10, San Francisco.

Lawson, I.T., Gathorne-Hardy, F.J., Church, M.J., Newton, A.J., Edwards, K.J., Dugmore, A. J., Einarsson, Á. 2007. Environmental impacts of the Norse settlement: palaeoenvironmental data from Mývatnssveit, northern Iceland. Boreas 36, pp. 1 – 19.

Lawson, I.T. with contributions of Milek, K.B., Adderley, W.P., Casely, A.F., Church, M.J., Duarte, L., Dugmore, A.J., Edwards, K.J., Gathorne-Hardy, F.J., Guðmundsson, G., Morrison, S., Newton, A.J., Simpson, I.A. 2009. The Palaeoenvironment of Mývatnssveit During the Viking Age and Early Medieval Period, pp. 26 – 54. In: Lucas, G. (ed.) 2009. Hofstadir: excavations of a Viking Age feasting hall in north-eastern Iceland. Fornleifastofnun Íslands, Reykjavík.

Lárusson, B. 1967. The Old Icelandic Land Register. Institute of Economic History, Lund University.

Lehtilä, K., Haukioja, E., Kaitaniemi, P., Laine K.A. 2000. Allocation of resources within mountain birch canopy after simulated winter browsing. OIKOS 90, pp. 160 – 170.

Levanič, T. and Eggertsson O. 2008. Climatic Effects on birch (Betula pubescens Ehrh.) growth in Fnjoskadalur valley, northern Iceland. Dendrochronologia 25, pp. 135 – 143.

Lucas, G. (ed.) 2009. Hofstadir: excavations of a Viking Age feasting hall in north-eastern Iceland. Fornleifastofnun Íslands, Reykjavík.

Magnússon, Á. and Vídalín, P. 1980. Jarðabók Árna Magnússonar og Páls Vídalín. Farm account by Árni Magnússon and Páll Vídalín (information gathered in 1702 – 1714), Vol. 1 – 13, second edition. Hið íslenzka fræðafélag, Reykjavík.

Mairs, K., Church, M.J., Dugmore, A.J., Sveinbjarnardóttir, G. 2006. Degrees of success: Evaluating the environmental impacts of long term settlement in South Iceland. In: Arneborg, J., Grønnow, B. (eds.) Dynamics of Northern Societies. Proceedings of the SILA/NABO conference on Arctic and North Atlantic Archaeology, Copenhagen, May 10th - 14th, 2004, pp. 365 – 374. Publications from the National Museum, Studies in Archaeology and History, Vol. 10. National Museum, Copenhagen.

Marteinsdóttir, B., Svavarsdóttir, K., Þórhallsdóttir, Þ.E. 2007. Landnám birkis á Skeiðarársandi. Náttúrufræðingurinn 75, pp. 123 – 129.

Martin, R.M., Kneeland, D., Brooks, D., Matta, R. 2012 (eds). FAO: 2012. State of World’s Forests 2012. Food and Agriculture Organization of the United Nations, Rome.

Mathieu, J.R. and Meyer, D.A. 1997. Comparing Axe Heads of Stone, Bronze, and Steel: Studies in Experimental Archaeology. Journal of Field Archaeology 24 (3), pp. 333 – 351.

McEvoy, P. and McAdam, J. 2008. Sheep grazing in young oak Quercus spp. and ash Fraxinus excelsior plantations: vegetation control, seasonality and tree damage. Agroforestry Systems 74, 199 – 211.

McGovern, T. and Woollett, J. 2003. Midden Investigations at Hrísheimar, N. Iceland 2003, Norsec Field Report 03/6. CUNY Northern Science and Education Center, New York.

McGovern, T.H., Bigelow, G.F., Amorosi, T., and Russell, D. 1988. Northern islands, human error, and environmental degradation: A preliminary model for social and ecological change in the medieval North Atlantic. Human Ecology 16, pp. 225 – 270.

McGovern, T.H., Friðriksson, A., Vésteinsson, O., Church, M.J., Lawson, I., Simpson, I.A., Einarsson, Á, Dugmore, A.J., Cook, G., Perdikaris, S., Edwards, K.J., Thomson, A.M., Adderley, W.P., Newton, A., Lucas, G., Aldred, O. 2007. Landscapes of settlement in Northern Iceland: Historical ecology of human impact and climate fluctuation on the millennial scale. American Anthropologist 109 (1), pp. 27 – 51.

McGuire, E.L.H. 2006. Archaeology in Iceland: Recent Developments. Scandinavian-Canadian Studies Volume 16, Études Scandinaves au Canada 2005 – 2006, pp. 10 – 26.

Milek, K. 2006. Houses and households in early Icelandic Society. Ph.D. thesis. University of Cambridge, Cambridge.

Mosley, S. 2010. The Environment in World History. Routledge, London.

Ngo, T.A. and See, L. 2012. Calibration and Validation of Agent-Based Models of Land Cover Change. In: Heppenstall, A.J., Crooks, T.A., See, M.L., Batty, M. (eds.) Agent-Based Models of Geographical Systems, pp. 181 – 196. Springer, Netherlands.

Niamir, M. 1990. Traditional woodland management techniques of African pastoralists. In: Dembner, S.A. (ed.) Unasylva – Forestry and Food Security, An international journal of forestry and forest industries 160 (41), 1990/1. Food and Agriculture Organization of the United Nations, Rome. Available at: http://www.fao.org/docrep/t7750e/t7750e00.htm#Contents. Last consulted on 20.02.2016.

Nielsen, A.B. and Sugita, S. 2005. Estimating relevant source area of pollen for small Danish lakes around AD 1800. The Holocene 15, pp. 1006 – 1020.

Ogilvie, A.E.J. and McGovern, T.H. 2000. Sagas and Science: Climate and Human Impacts in the North Atlantic. In: Fitzhugh, W.W. and Ward, E.I. (eds.) Vikings: The North Atlantic Saga, pp. 385 – 393. DC: Smithsonian Institution Press, Washington.

Oreskes, N., Shrader-Frechette, K., Belitz, K. 1994. Verification, validation and confirmation of numerical models in the earth sciences. Science 263, pp. 641 – 646.

Ólafsdóttir, R., Schlyter, P., Haraldsson, H. 2001, Simulating Icelandic Vegetation Cover during the Holocene: Implications for Long-term Land Degradation. Geografiska Annaler, Series A. Physical Geography 83A, pp. 203 – 215.

Ólafsson, G., Smith, K.P., Stefánsdóttir, A. 2004. Rannsókn á minjum í Surtshelli. Rannsóknaskýrslur Þjóðminjasafns 2001, VIII. Reykjavík.

Ólafsson, S. 2012. Smávegis um rústaþyrpingar í Kelduhverfi. Master thesis, University of Iceland, Reykjavík.

Pálsson, H. (transl.) 1987. Hrafnkel's saga and other stories. Penguin, London.

Poole, H. 2009. The Calorific Power of Fuels. BiblioBazaar, Charleston.

Premo, L.S. 2008. Exploring behavioural terra incognita with archaeological agent-based models. In: Frischer, B. and Dakouri-Hild, A. (eds.) Beyond illustration: 2D and 3D digital technologies as tools for discovery in archaeology, pp. 46 – 56. Archaeopress, Oxford.

Price, T.D. and Gestsdóttir H. 2006. The first settlers of Iceland: an isotopic approach to colonisation. Antiquity, 80 (307), pp. 130 – 144.

Railsback, S.F. 2001. Concepts from complex adaptive systems as a framework for individual-based modelling. Ecological Modeling 139, 47 – 62.

Riipi, M., Lempa, K., Haukioja, E., Ossipov, V., Pihlaja, K. 2005. Effects of simulated winter browsing on mountain birch foliar chemistry and on the performance of insect herbivores. OIKOS 111, pp. 221 – 234.

Roberts, H.M., Snæsdóttir, M and Vésteinsson, O. (eds.) 2002. Archaeological investigations in Aðalstræti 2001, Interim report, Fornleifastofnun Íslands, June 2002, unpublished.

Roques, K.G., O'Connor, T.G., Watkinson, A.R. 2001. Dynamics of shrub encroachment in an African savanna: relative influences of fire, herbivory, rainfall and density dependence. Journal of Applied Ecology 38 (2), pp. 268 – 280.

Rykiel, E.J., Jr. 1996. Testing ecological models: the meaning of validation. Ecological Modeling, 90, pp. 229 – 244.

Rösch, M., Ehrmann, O., Herrmann, L., Schulz, E., Bogenrieder, A. 2004. Slash-and-Burn Experiments to Reconstruct Late Neolithic Shifting Cutivation. International Forest Fire News 30, pp. 70 – 74.

Saraydar, S. and Shimada, I. 1971. A Quantitative Comparison of Efficiency Between A Stone Axe and A Steel. American Antiquity 36, pp. 216 – 217.

Savenije, H.H.G. 2001. Equifinality, a blessing in disguise? Hydrological Processes 15, pp. 2835 – 2838.

Sée, H. 2004. Economic and Social Conditions in France During the Eighteenth Century. Batoche Books, Kitchener.

Short, W. 2010. Icelanders in the Viking Age: The People of the Sagas.McFarland & Company, Inc. Publishers, Jefferson.

Sigurðsson, B.D., Magnússon, B., Elmarsdóttir, A., Bjarnadóttir, B. 2005. Biomass and composition of understory vegetation and the forest floor carbon stock across Siberian larch and mountain birch chronosequences in Iceland. Annals of Forest Science 62, pp. 881 – 888.

Sigurðsson, S. 1990. Birki á Íslandi. In: Ragnarsson, H. (ed.) Skógræktarbókin, pp. 105 – 114. Skógræktafélag Íslands, Reykjavík.

Simpson, I.A., Dugmore, A.J., Thomson, A.M. and Vésteinsson, O. 2001. Crossing the thresholds: Human ecology and historical patterns of landscape degradation. CATENA 42, pp. 176 – 192.

Simpson, I.A., Adderley, P., Guðmundsson, G., Hallsdóttir, M., Sigurgeirsson, M.Á., Snæsdóttir, M. 2002. Soil limitations to agrarian production in premodern Iceland. Human ecology 30 (4), pp. 423 – 443.

Simpson, I.A., Vésteinsson, O., McGovern, T.H. 2003. Fuel resource utilisation in landscapes of settlement. Journal of Archaeological Science 30, pp. 1401 – 1420.

Simpson, I.A., Guðmundsson, G., Thomson, A.M., and Cluett, J. 2004. Assessing the Role of Winter Grazing in Historic Land Degradation, Mývatnssveit, North-East Iceland. Geoarchaeology 19, pp. 471 – 503.

Skov, H., Christenssen C.S., Fenger, J., Essenbæk, M., Larsen, D., Sørensen, L. 2000. Exposure to indoor air pollution in a reconstructed house from the Danish Iron Age. Atmospheric Environment 34, pp. 3801 – 3804.

Smith, K.P. 1995. Landnám: the settlement of Iceland in archaeological and historical perspective. World Archaeology 26 (3), pp. 319 – 347.

Smith, K.T. and Dugmore, A.J. 2006. Jökulhlaups Circa Landnám: Mid- to late first millennium AD floods in South Iceland and their implications for landscapes of settlement. Geografiska Annaler 88 A (2), pp. 165 – 176.

Speed, J.D.M., Austrheim, G., Hester, A.J., Mysterud, A. 2011. Growth limitation of mountain birch caused by sheep browsing at the altitudinal treeline. Forest Ecology and Management 261, pp. 1344 – 1352.

Steinberg, J.M. 2006. A Political Economy from Increasing Marginal Returns to Labor: An Example from Viking Age Iceland. In: Durrenberger, E.P. and Martí, J. (eds.) Labor in Cross-cultural Perspective, pp. 217 – 244. Society for Economic Anthropology Monograph 23. Altamira Press, Lanham.

Stenberger, M. 1943. Ísleifsstaðir, Borgarfjarðarsýsla. In: Stenberger, M. (ed.) Forntida gårdar i Island: meddelanden från der nordiska arkeologiska undersökningen i Island sommaren 1939, pp. 145 – 170. Munksgaard, København..

Sugita, S. 1993. A Model of Pollen Source Area for an Entire Lake Surface. Quaternary Research 39, pp. 239 – 244.

Sugita, S. 1994. Pollen representation of vegetation in quaternary sediments: theory and method in patchy vegetation. Journal of Ecology 82, pp. 881 – 897.

Sveinbjarnardóttir, G. 1992. Farm abandonment in Medieval and Post-Medieval Iceland; An Interdisciplinary study. Oxbow books, Oxford.

Sveinbjarnardóttir, G., Erlendsson, E., Vickers, K., McGovern, T.H., Milek, K.B., Edwards, K.J., Simpson, I.A., Cook, G. 2007. The palaeoecology of a high status Icelandic farm. Environmental Archaeology 12 (2), pp. 187 – 206.

Thomson, A.M. 2003. A modelling approach to farm management and vegetation degradation in pre-modern Iceland. Ph.D. dissertation. University of Stirling, Stirling.

Thomson, A.M. and Simpson, I.A. 2007. Modeling Historic Rangeland Management and Grazing Pressures in Landscapes of Settlement. Human Ecology 35, pp. 151 – 168.

Thorarinsson, S. 1979. On the Damage Caused by Volcanic Eruptions with Special Reference to Tephra and Gases. In: Sheets, P.D. and Grayson, D.K. (eds.) Volcanic Activity and Human Ecology, pp. 125 – 160. Academic Press, London.

Thoroddsen, Þ. 1884. Explorations in Iceland: the lava desert Ódáðahraun. Nature 30, pp. 584 – 585.

Thoroddsen, Þ. 1891. Ferð um Snæfellsnes sumarið 1890. Andvari 17, pp. 27 – 118.

Thoroddsen, Þ. 1901. Geological map of Iceland; surveyed in 1881 – 1898. Carslbergfondet, Copenhagen.

Thoroddsen, Þ. 1912. An account of the physical geography of Iceland. In: Rosenvinge, L. K., Warming, E. (eds.) The Botany of Iceland Úrval, Vol. 1 (1912 – 1918). Frimodt, J., Copenhagen.

Thoroddsen, Þ. 1933. Lýsing Íslands I-IV. Sjóður Þorvaldar Thoroddsen, Reykjavík.

Thorsteinsson, I. 1980. Environmental data, botanical composition and production of plant communities and the plant preference of sheep. Íslenzkar Landbúnaðarrannsóknir, 12(2), pp. 85 – 99.

Thorsteinsson, I., Ólafsson, G., Van Dyme, G.M. 1971. Range resources of Iceland. Journal of Range Management 24 (2), pp. 86 – 93.

Tinner W. 2007. Treeline studies. In: Elias S.A. (ed.) Encyclopedia of Quaternary Science, pp. 2374 – 2383. Elsevier, Amsterdam.

Tisdall, E. and Verril, L. 2009. Pollen analysis from archaeological samples, Sveigakot, Northern Iceland. Unpublished report.

Tomasson, R.F. 1980. Iceland, The First New Society. University of Minnesota, Minneapolis.

Trbojević, N., Mooney, D.E., Bell, A. J. 2011. A Firewood experiment at Eiríksstaðir, A step towards quantifying the use of firewood for daily houshold needs in Viking Age Iceland, Archaeologia Islandica 9, pp. 29 – 41.

Trechsel, H.R. 2001. Moisture analysis and condensation control in building envelopes. American Society for Testing and Materials, Philadelphia.

Vésteinsson, O. 1998. Patterns of Settlement in Iceland. A Study in Pre-History. Saga-Book of the Viking Society 25, pp. 1 – 29.

Vésteinsson, O. 2000a. The Christianization of Iceland: Priests, Power and Social Change 1000 – 1300. Oxford University Press, Oxford .

Vésteinsson, O. 2000b. The Archaeology of Landnám Icelandic Early Settlement. In: Fitzhugh, W. W., Ward, E. (eds.) Vikings: The North Atlantic Saga, pp. 164 – 174. Smithsonian Institution, Washington.

Vésteinsson, O. 2002. Hrísheimar – the structures. In: Vésteinsson O. (ed.) Archaeological Investigations at Sveigakot 2001, with reports on preliminary investigations at Hrísheimar, Selhagi and Ytri Tunga, pp. 59 – 63. Fornleifastofnun Íslands, Reykjavík.

Vésteinsson, O. 2004. Archaeological investigations at Oddastaðir. In: Vésteinsson, O. (ed.) 2004, Landscapes of Settlement 2002, Reports on investigations at five medieval sites in Mývatnssveit, pp. 58 – 69. Fornleifastofnun Íslands, Reykjavík.

Vésteinsson, O. 2006. Communities of Dispersed Settlements: Social Organization at the Ground Level in Tenth- to Thirteenth-Century Iceland. In: Davies, W., Halsall, G., Reynolds, A. (eds.) People and space in the Middle Ages, 300-1300, pp. 87 – 113. Brepols Publishers, Turnhout.

Vésteinsson, O. 2008. Archaeological investigations in Mývatnssveit 2007 – Discussion. In: Vésteinsson, O. 2008 (ed.) Archaeological investigations in Mývatnssveit 2007, pp. 64 – 74. Fornleifastofnun Íslands, Reykjavík.

Vésteinsson, O. and Simpson, I. A. 2004. Fuel utilisation in pre-industrial Iceland: A micromorphological and historical analysis. In: G. Guðmundsson (ed.) Current Issues in Nordic Archaeology, pp. 181 – 187. Society of Icelandic Archaeologists, Reykjavík.

Vésteinsson, O. and McGovern, T.H. 2012. The Peopling of Iceland. Norwegian Archaeological Review 45 (2), pp. 206 – 218.

Vésteinsson, O. and Gestsdóttir, H. (forthcoming). The colonisation of Iceland in light of isotope analyses. Viking Settlers of the North Atlantic: An Isotopic Approach. Journal of the North Atlantic, Special volume 7.

Vésteinsson, O., McGovern, T.H., Keller. C. 2002. Enduring impacts: Social and environmental aspects of Viking Age settlement in Iceland and Greenland. Archaeologia Islandica 2, pp. 98 – 136.

Vickers, K., Erlendsson, E., Church, M.J., Edwards, K.J., Bending, J. 2011. 1000 years of environmental change and human impact at Stóra-Mörk, southern Iceland: A multiproxy study of a dynamic and vulnerable landscape. Holocene 21 (6), pp. 979 – 995.

Wilensky, U. 1999. NetLogo http://ccl.northwestern.edu/netlogo/ - Center for Connected Learning and Computer-Based Modeling. Northwestern University, Evanston.

Williams, M. 2000. Dark ages and dark areas: global deforestation in the deep past. Journal of historical geography 26 (1), pp. 28 – 46.

Wilson, A.D., Leigh, J.H., Hindley, N.L., Mulham,W.E. 1975. Comparison of the diets of goats and sheep on a Casuarina cristata–Heterodendrum oleifolium woodland community in western New South Wales. Australian Journal of Experimental Agriculture 15, 45 – 53.

Woodward, F.I. 1992. A review of the effects of climate on vegetation:ranges, competition and composition. In: Robert L. Peters and Thomas E. Lovejoy (eds) Global warming and biological diversity, pp. 105 – 123. Yale University Press, New Haven.

Wöll, C. 2008. Treeline of mountain birch (Betula pubescens Ehrh.) in Iceland and its relationship to temperature. Diploma thesis in Forest Botany. Technical University Dresden, Department of Forestry, Dresden.

Zamora, R., Gómez, J.M., Hódar, J.A., Castro, J., García, D. 2001. Effect of browsing by ungulates on sapling growth of Scots pine in a Mediterranean environment: consequences for forest regeneration. Forest Ecology and Management 144, 33 – 42.

Zeigler, B.P. 1976. Theory of modelling and simulation. Wiley, New York.

Þorsteinsson, I. 1972. Gróðurvernd: byggð á hóflegri nýtingu og ræktun lands. Rit Landvenrdar, 2. Landvernd, Reykjavík.

Þórarinsson, S. 1943. Þjórsárdalur och dess förödelse. In: Stenberger, M. (ed.) Forntida gårdar i Island: meddelanden från der nordiska arkeologiska undersökningen i Island sommaren 1939, pp. 9 – 52. Munksgaard, København.

Þórarinsson, S. 1944. Tefrokronologiska studier på Island. Geografiska Annalen 26, pp. 1 – 217.

Þórarinsson, S. 1949. Örlög byggðarinnar á Hrunamannaafrétti í ljósi öskulagarannsókna. Árbók Hins íslenzka fornleifafélags 1943 – 48, pp. 44 – 65.

Þórarinsson, S. 1961. Uppblástur á Íslandi í ljósi öskulagarannsókna. Ársrit Skógræktafélags Íslands, pp. 17 – 54.

Þórarinsson, S. 1977. Gjóskulög og gamlar rústir. Brot úr íslenskri byggðasögu. Árbók Hins íslenzka fornleifafélags 1976, pp. 5 – 38.

Þórarinsson, Þ. 1974. Þjóðin lifði en skógurinn dó. Ársrit Skógræktarfélags Íslands 1974, pp. 16 – 29.

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Web links:

1) web link 1: http://www.ucdblogs.org/buildingmesolithic/tree-felling/ - last consulted on 09.10.2013.

2) web link 2: http://www.youtube.com/watch?v=lJd8Qo4TRag - last consulted on 17.04.2013.

Additional references:

1) FRA 2010, Global Forest Resources Assessment 2010. Country Report: Iceland, Rome 2010. Available at: http://www.fao.org/docrep/013/al529E/al529e.pdf. Last consulted on 25.09.2014.

2) Icelandic Agriculture 1997, Text written by the Icelandic Agricultural Information Service. Neither the name of the author(s) or the editor(s) of the edition are stated. Available at the Library of the University of Iceland.

3) Ísleif: Sites and monuments database. Institute of Archaeology, Iceland (*Fornleifastofnun Íslands*).

4) Túnakort 1918. Skilmannahreppur. Þjóðskalasafn Íslands, Reykjavík.

5) Map of vegetation in Iceland at the age of Settlement. Icelandic Institute of Natural History (*Náttúrufræðistofnun Íslands*) 2001.

6) Map of the property boundaries. Agricultural Research Institute of Iceland (*Rannsóknastofnunar landbúnaðarins*, abbrev. RALA; now Agricultural University of Iceland, *Landbúnaðarháskóli íslands*) 2005.

7) Map of the place names. National Land Survey of Iceland (*Landmælingar Íslands*).

8) The complete instructions for importing and using GIS data in a NetLogo environment can be found in the user manual, pp. 279 – 299, available at: http://ccl.northwestern.edu/netlogo/docs/NetLogo%20 User% 20 Manual.pdf Last consulted on 28.07.2011.

Appendix 1

Modelling outcomes: Vestur-Eyjafjallahreppur

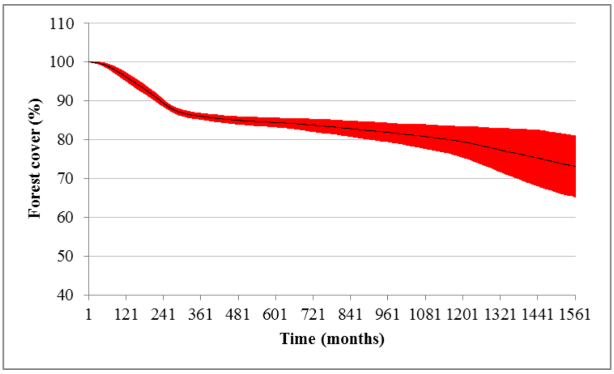
The starting parameters of the simulation runs for the region of Vestur-Eyjafjallahreppur are presented in the tables and figures below.

Scenario 2a:

Table 31. („a“, above and „b“, below) Vestur-Eyjafjallahreppur: Average values and standard deviations of starting parameters of 20 simulation runs of Scenario 2a

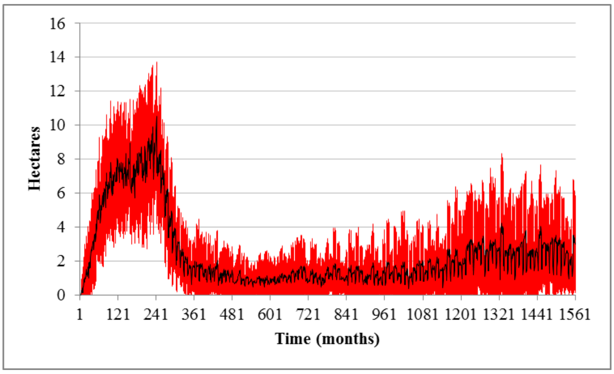
Starting parameters	Cattle cull	Ovines cull	Cattle growth	Ovines growth
AVG	5.35 %	7.9 %	22.79 %	46.76 %
SD	3.15	4.84	1.44	8.55

Starting parameters	Starting cattle	Starting ovines	Initiation of replacement	Replacement (heavy grazing)	Replacement (light grazing)
AVG	3.4	6.4	87.45	0.23 %	0.04 %
SD	1.14	2.16	21.32	0.08	0.02



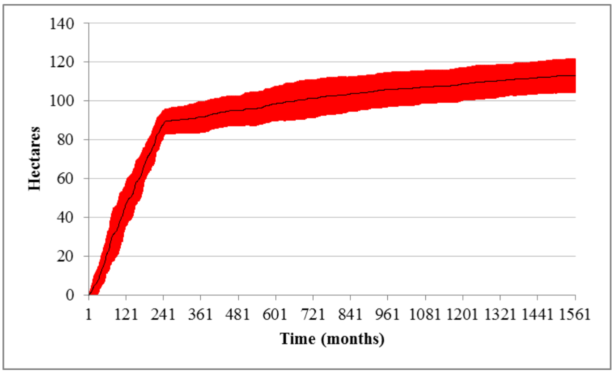
Note: —— **average** —— **standard deviation**

Figure 97. Scenario 2a: Extent of forest cover in Vestur-Eyjafjallahreppur



Note:—— average —— standard deviation

Figure 98. Scenario 2a: Total forest clearance in Vestur-Eyjafjallahreppur



Note:—— average —— standard deviation

Figure 99. Scenario 2a: Extent of areas cleared for home-fields in Vestur-Eyjafjallahreppur

Note:—— average —— standard deviation

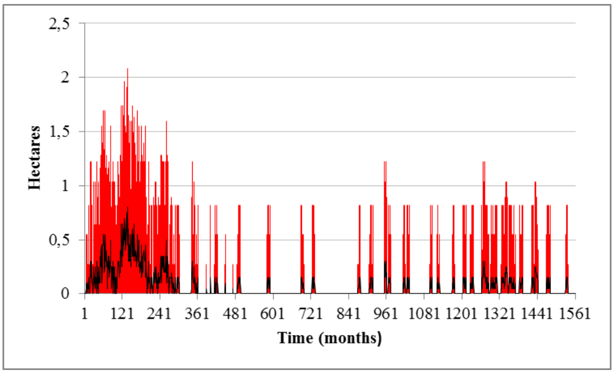
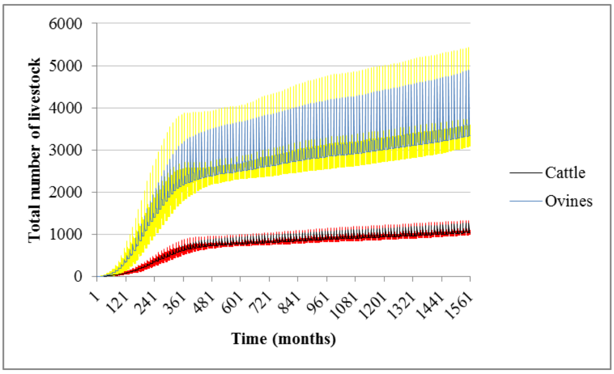
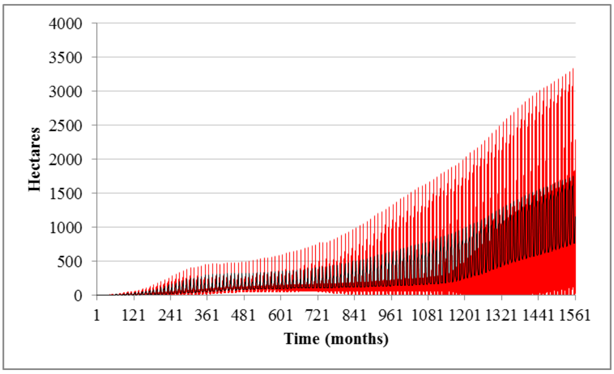


Figure 100. Scenario 2a: Clearance of forests made by the farm of Varmahlíð



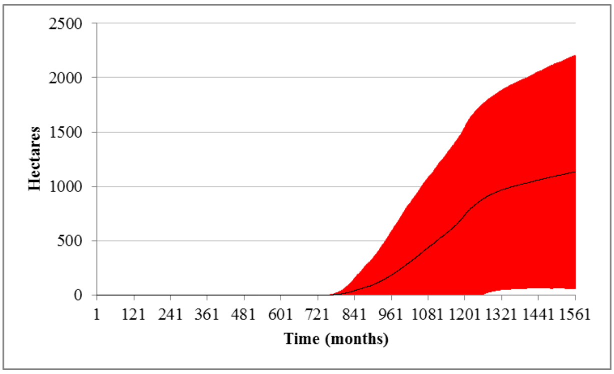
Note:—— average —— standard deviation; —— average —— standard deviation

Figure 101. Scenario 2a: Total number of livestock in Vestur-Eyjafjallahreppur



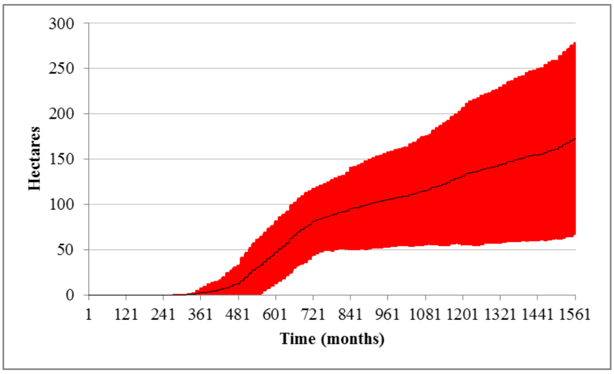
Note:—— average —— standard deviation

Figure 102. Scenario 2a: Extent of areas affected by overgrazing in Vestur-Eyjafjallahreppur



Note:—— average —— standard deviation

Figure 103. Scenario 2a: Extent of areas with more than 50 % of grazing-tolerant vegetation in Vestur-Eyjafjallahreppur



Note:—— average —— standard deviation

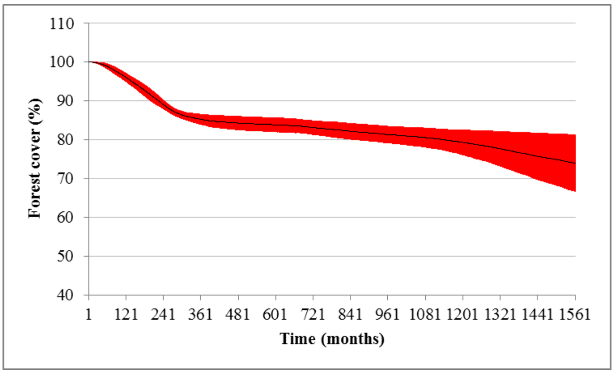
Figure 104. Scenario 2a: Extent of areas with more than 50 % of regrown birch cover in Vestur-Eyjafjallahreppur

Scenario 2b:

Table 32. („a“, above and „b“, below). Vestur-Eyjafjallahreppur: Average values and standard deviations of starting parameters of 20 simulation runs of Scenario 2b

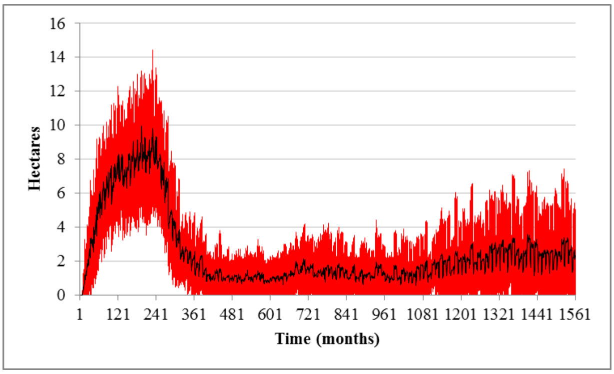
Starting parameters	Cattle cull	Ovines cull	Cattle growth	Ovines growth
AVG	5.4 %	6.15 %	22.97 %	44.34 %
SD	2.7	4.47	1.6	9.42

Starting parameters	Starting cattle	Starting ovines	Initiation of replacement	Replacement (heavy grazing)	Replacement (light grazing)
AVG	3.65	7.2	82	0.22 %	0.03 %
SD	1.03	2.23	15.94	0.08	0.02



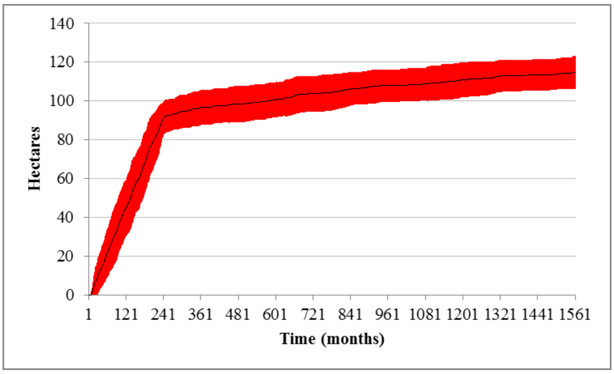
Note:—— average —— standard deviation

Figure 105. Scenario 2b: Extent of forest cover in Vestur-Eyjafjallahreppur



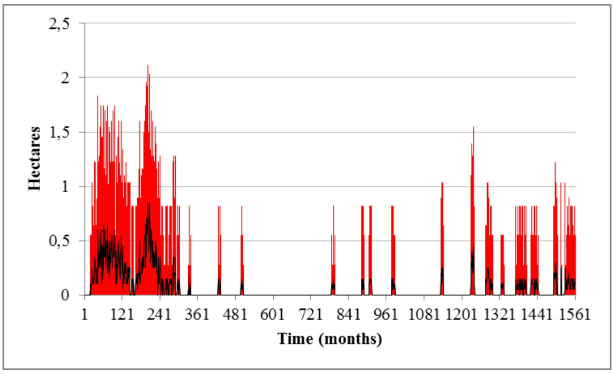
Note:—— average —— standard deviation

Figure 106. Scenario 2b: Total forest clearance in Vestur-Eyjafjallahreppur



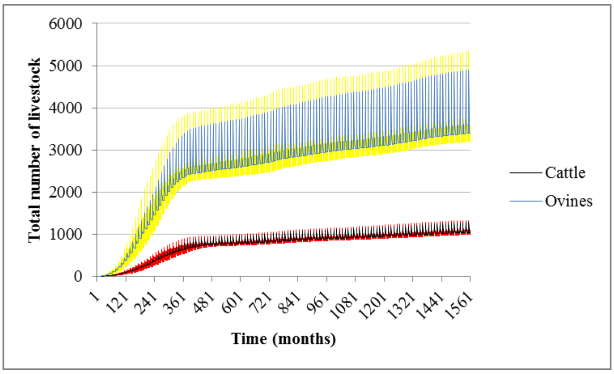
Note:—— average —— standard deviation

Figure 107. Scenario 2b: Extent of areas cleared for home-fields in Vestur-Eyjafjallahreppur



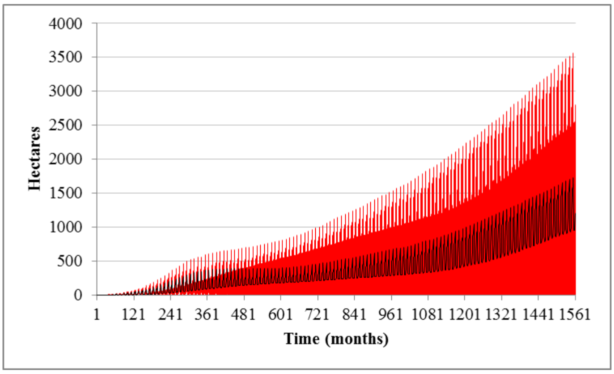
Note:—— average —— standard deviation

Figure 108. Scenario 2b: Clearance of forests made by the farm of Varmahlíð



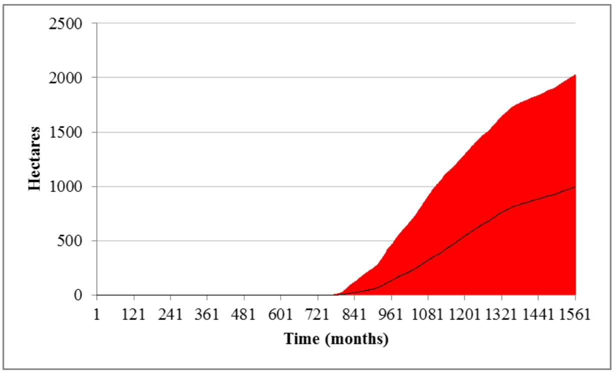
Note:—— average —— standard deviation; —— average —— standard deviation

Figure 109. Scenario 2b: Total number of livestock in Vestur-Eyjafjallahreppur



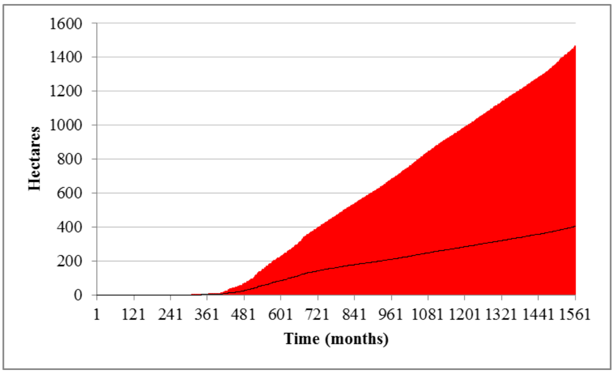
Note:—— average —— standard deviation

Figure 110. Scenario 2b: Extent of areas affected by overgrazing in Vestur-Eyjafjallahreppur



Note:—— average —— standard deviation

Figure 111. Scenario 2b: Extent of areas with more than 50 % of grazing-tolerant vegetation in Vestur-Eyjafjallahreppur



Note:—— average —— standard deviation

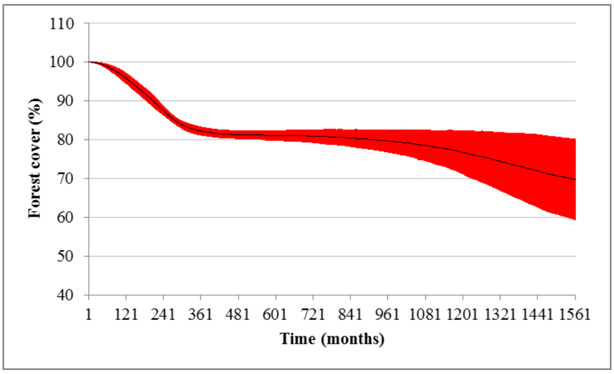
Figure 112. Scenario 2b: Extent of areas with more than 50 % of regrown birch cover in Vestur-Eyjafjallahreppur

Scenario 3:

Table 33. („a“, above and „b“, below). Vestur-Eyjafjallahreppur: Average values and standard deviations of starting parameters of 20 simulation runs of Scenario 3

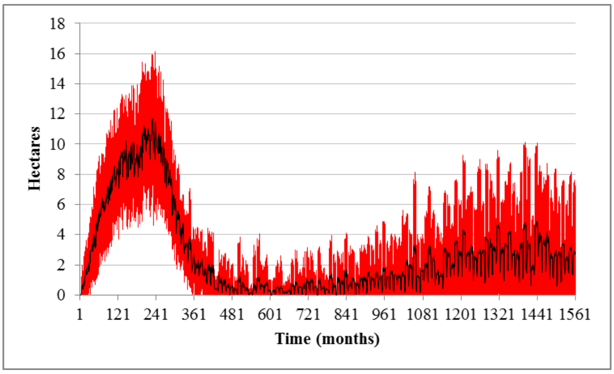
Starting parameters	Cattle cull	Ovines cull	Cattle growth	Ovines growth
AVG	5.95 %	8.5 %	23 %	42.23 %
SD	2.78	4.04	1.55	9.28

Starting parameters	Starting cattle	Starting ovines	Initiation of replacement	Replacement (heavy grazing)	Replacement (light grazing)
AVG	3.05	6.4	89.1	0.28 %	0.05 %
SD	0.94	2.77	16.95	0.09	0.02



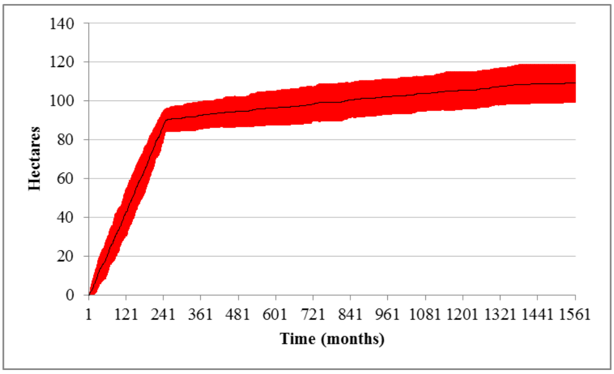
Note:—— average —— standard deviation

Figure 113. Scenario 3: Extent of forest cover in Vestur-Eyjafjallahreppur



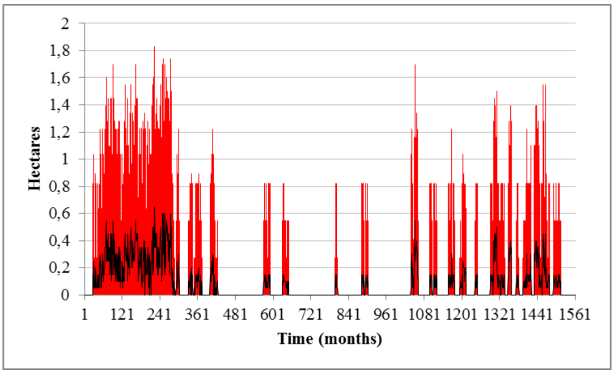
Note:—— average —— standard deviation

Figure 114. Scenario 3: Total forest clearance in Vestur-Eyjafjallahreppur



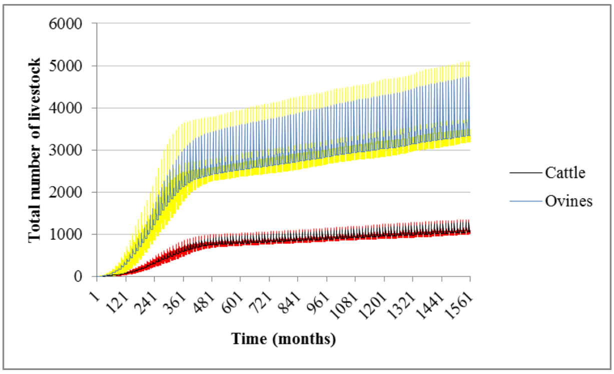
Note:—— average —— standard deviation

Figure 115. Scenario 3: Extent of areas cleared for home-fields in Vestur-Eyjafjallahreppur



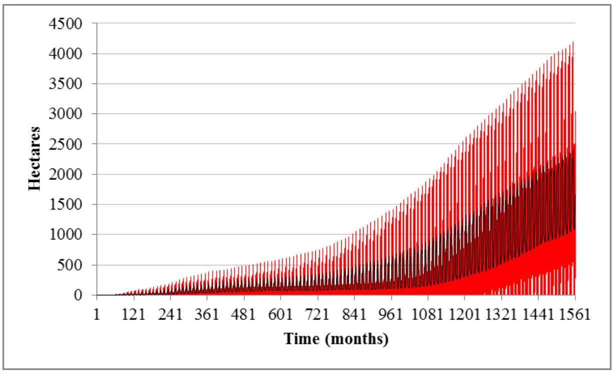
Note:—— average —— standard deviation

Figure 116. Scenario 3: Clearance of forests made by the farm of Varmahlíð



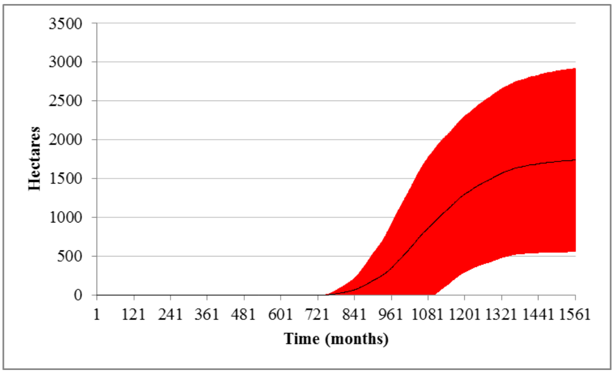
Note:—— average —— standard deviation; —— average —— standard deviation

Figure 117. Scenario 3: Total number of livestock in Vestur-Eyjafjallahreppur



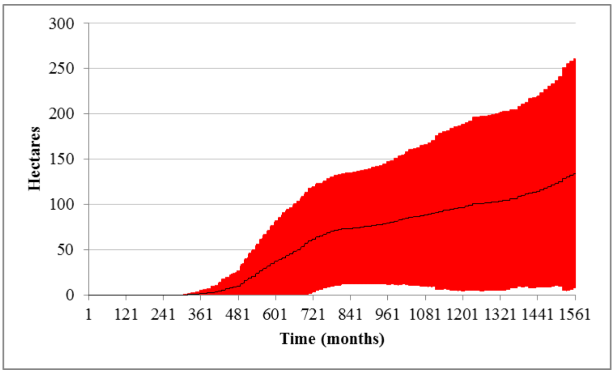
Note:—— average —— standard deviation

Figure 118. Scenario 3: Extent of areas affected by overgrazing in Vestur-Eyjafjallahreppur



Note:—— average —— standard deviation

Figure 119. Scenario 3: Extent of areas with more than 50 % of grazing-tolerant vegetation in Vestur-Eyjafjallahreppur



Note:—— average —— standard deviation

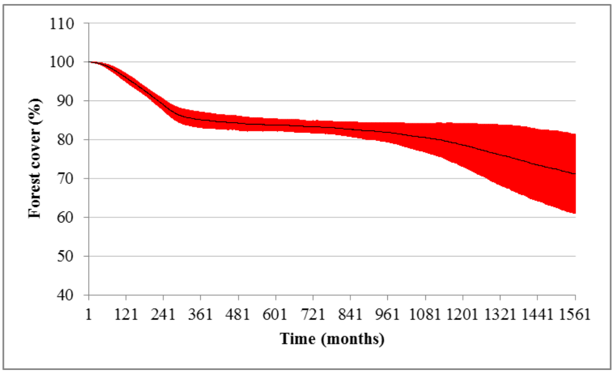
Figure. 120. Scenario 3: Extent of areas with more than 50 % of regrown birch cover in Vestur-Eyjafjallahreppur

Scenario 4:

Table 34. („a“, above and „b“, below). Vestur-Eyjafjallahreppur: Average values and standard deviations of starting parameters of 20 simulation runs of Scenario 4

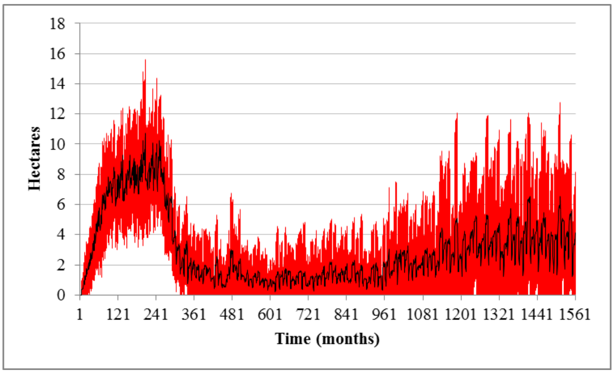
Starting parameters	Cattle cull	Ovines cull	Cattle growth	Ovines growth
AVG	5.9 %	7.95 %	23.61 %	50.84 %
SD	2.97	4.17	1.62	7.17

Starting parameters	Starting cattle	Starting ovines	Initiation of replacement	Replacement (heavy grazing)	Replacement (light grazing)
AVG	3.16	6.15	86.6	0.23 %	0.04 %
SD	1.14	2.43	19.43	0.09	0.02



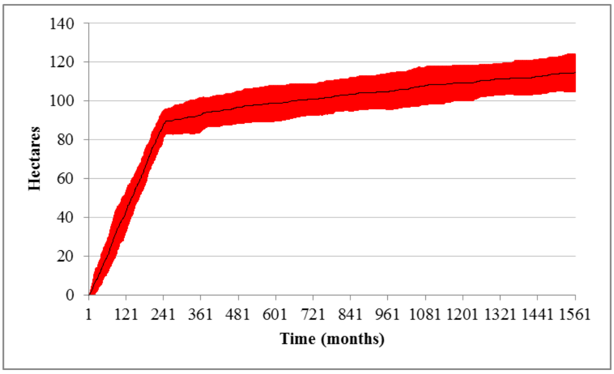
Note:—— average —— standard deviation

Figure 121. Scenario 4: Extent of forest cover in Vestur-Eyjafjallahreppur



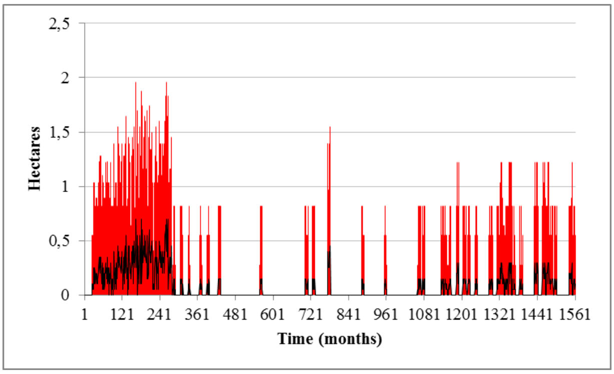
Note:—— average —— standard deviation

Figure 122. Scenario 4: Total forest clearance in Vestur-Eyjafjallahreppur



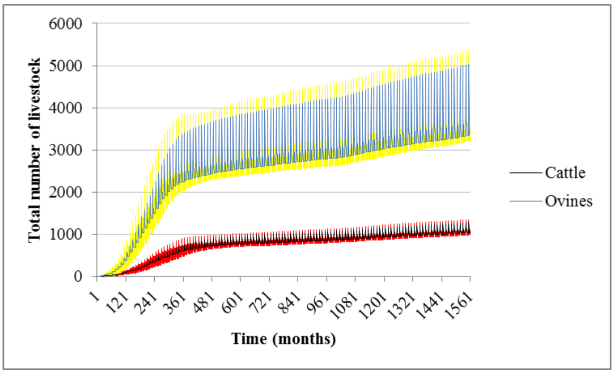
Note:—— average —— standard deviation

Figure 123. Scenario 4: Extent of areas cleared for home-fields in Vestur-Eyjafjallahreppur



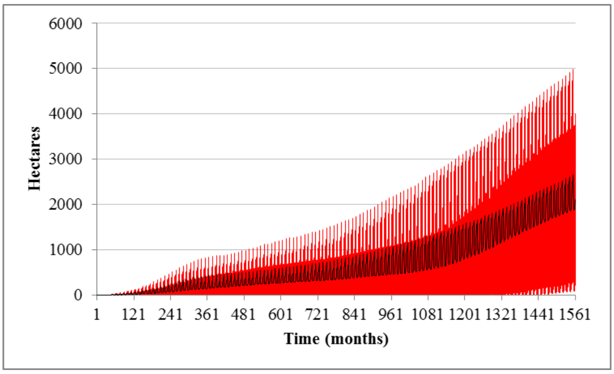
Note:—— average —— standard deviation

Figure 124. Scenario 4: Clearance of forests made by the farm of Varmahlíð



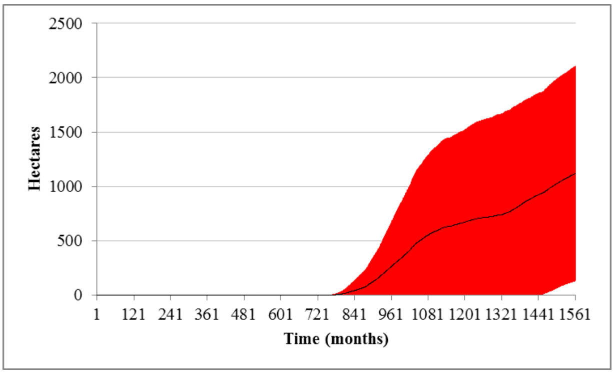
Note:—— **average** —— **standard deviation;** —— **average** —— **standard deviation**

Figure 125. Scenario 4: Total number of livestock in Vestur-Eyjafjallahreppur



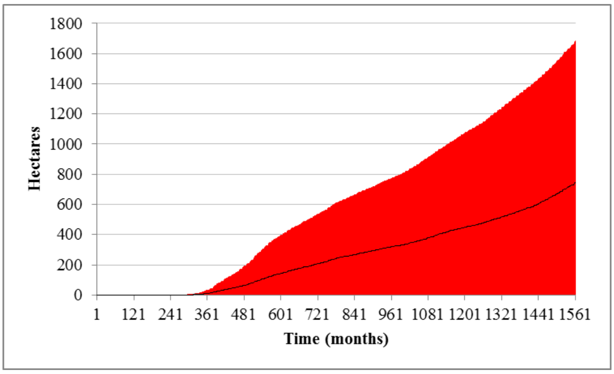
Note:—— average —— standard deviation

Figure 126. Scenario 4: Extent of areas affected by overgrazing in Vestur-Eyjafjallahreppur



Note:—— average —— standard deviation

Figure 127. Scenario 4: Extent of areas with more than 50 % of grazing-tolerant vegetation in Vestur-Eyjafjallahreppur



Note:—— average —— standard deviation

Figure 128. Scenario 4: Extent of areas with more than 50 % of regrown birch cover in Vestur-Eyjafjallahreppur

Modelling outcomes: Mývatn

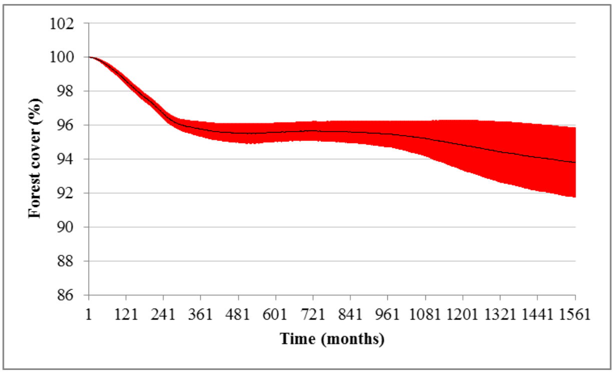
The starting parameters of the simulation runs for the region of Mývatn are presented in the tables and figures below.

Scenario 2a:

Table 35. („a“, above and „b“, below). Mývatn: Average values and standard deviations of starting parameters of 20 simulation runs of Scenario 2a

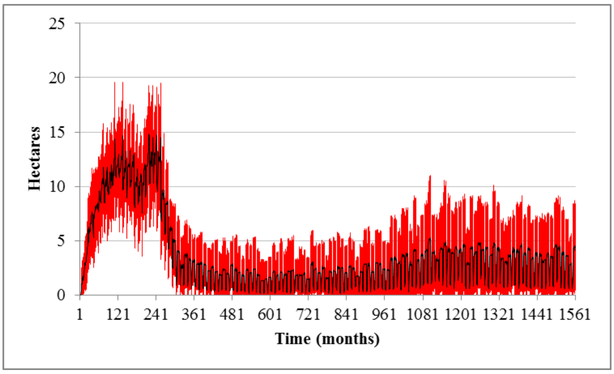
Starting parameters	Cattle cull	Ovines cull	Cattle growth	Ovines growth
AVG	4.7 %	7.25 %	22.67%	46.08%
SD	3.19	3.44	1.57	9.6

Staring parameters	Starting cattle	Starting ovines	Initiation of replacement	Replacement (heavy grazing)	Replacement (light grazing)
AVG	3.2	6.25	91.15	0.2 %	0.05 %
SD	0.95	2.61	18.18	0.08	0.02



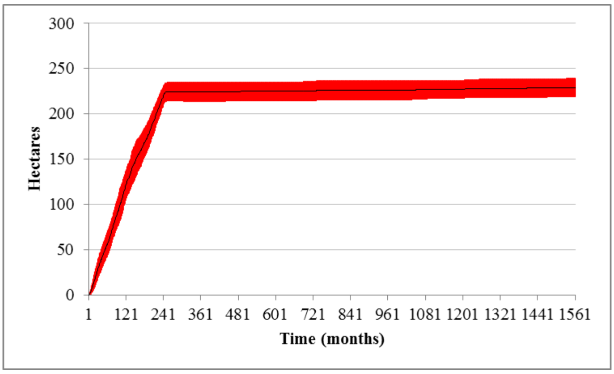
Note:—— average —— standard deviation

Figure. 129. Scenario 2a: Extent of forest cover in Mývatn



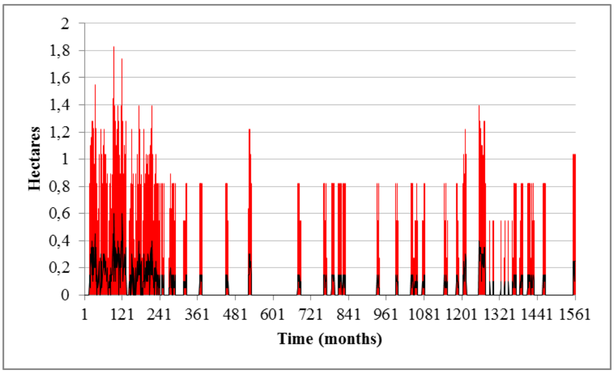
Note:—— average —— standard deviation

Figure 130. Scenario 2a: Total forest clearance in Mývatn



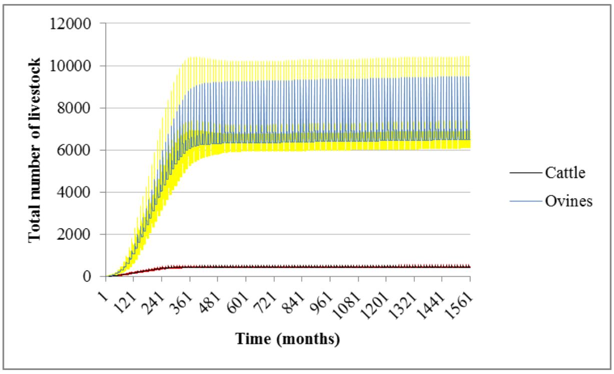
Note:—— average —— standard deviation

Figure 131. Scenario 2a: Extent of areas cleared for home-fields in Mývatn



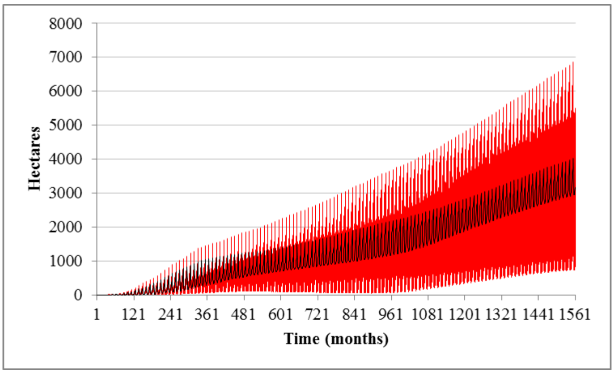
Note:—— average —— standard deviation

Figure 132. Scenario 2a: Clearance of forests made by the farm of Þorleifsstaðir



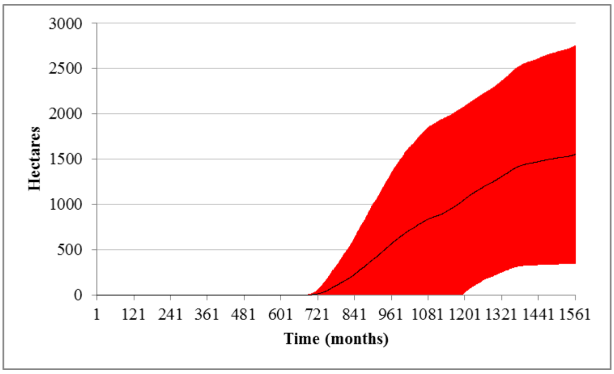
Note:—— average —— standard deviation; —— average —— standard deviation

Figure 133. Scenario 2a: Total number of livestock in Mývatn



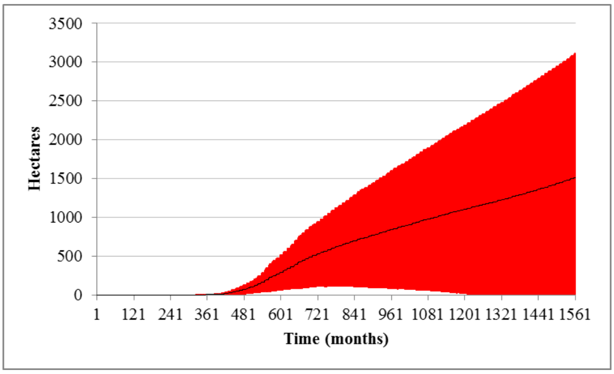
Note:—— average —— standard deviation

Figure 134. Scenario 2a: Extent of areas affected by overgrazing in Mývatn



Note:—— average —— standard deviation

Figure 135. Scenario 2a: Extent of areas with more than 50 % of grazing-tolerant vegetation in Mývatn



Note:—— **average** —— **standard deviation**

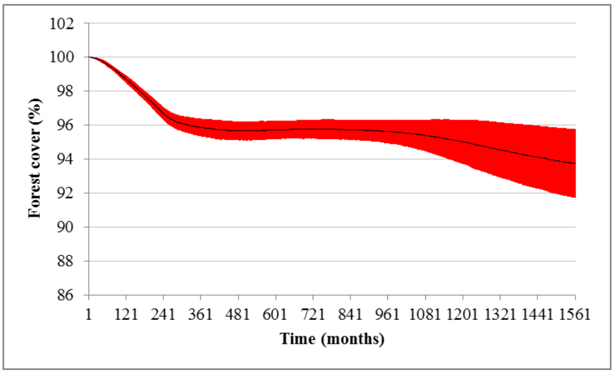
Figure 136. Scenario 2a: Extent of areas with more than 50 % of regrown birch cover in Mývatn

Scenario 2b:

Table 36. („a“, above and „b“, below). Mývatn: Average values and standard deviations of starting parameters of 20 simulation runs of Scenario 2b

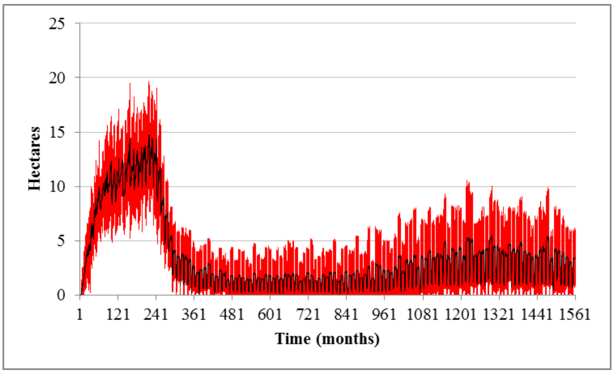
Starting parameters	**Cattle cull**	**Ovines cull**	**Cattle growth**	**Ovines growth**
AVG	4.95 %	8.5 %	23.01 %	43.57 %
SD	2.81	4.48	1.86	9.84

Starting parameters	**Starting cattle**	**Starting ovines**	**Initiation of replacement**	**Replacement (heavy grazing)**	**Replacement (light grazing)**
AVG	3.3	6.85	99.3	0.24 %	0.05 %
SD	0.97	2.6	18.09	0.11	0.02



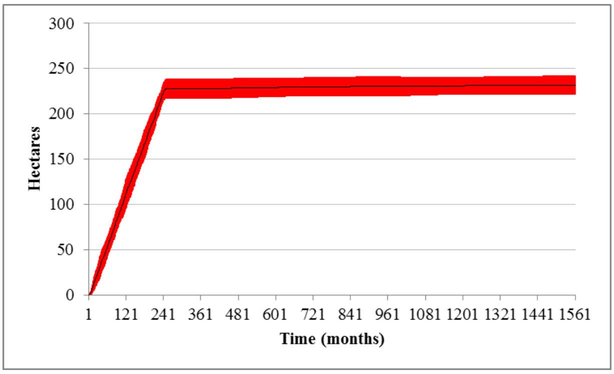
Note:—— average —— standard deviation

Figure 137. Scenario 2b: Extent of forest cover in Mývatn



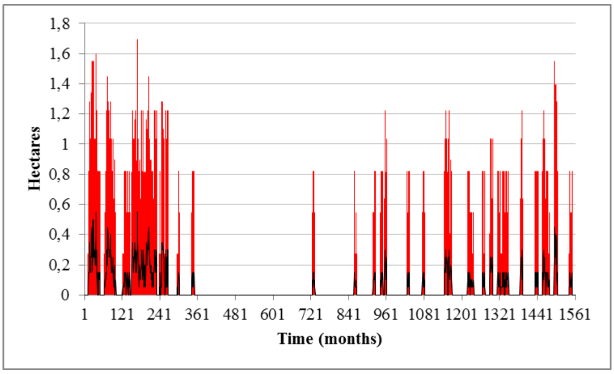
Note:—— average —— standard deviation

Figure 138. Scenario 2b: Total forest clearance in Mývatn



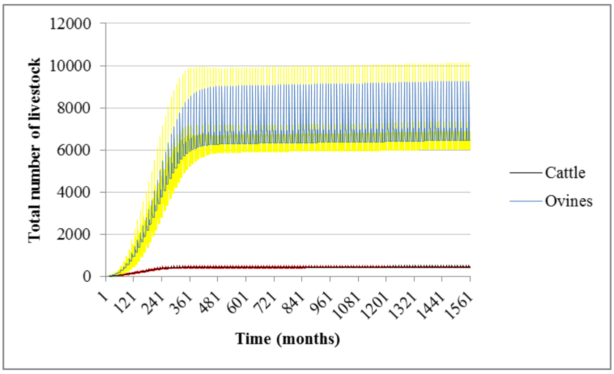
Note:—— average —— standard deviation

Figure 139. Scenario 2b: Extent of areas cleared for home-fields in Mývatn



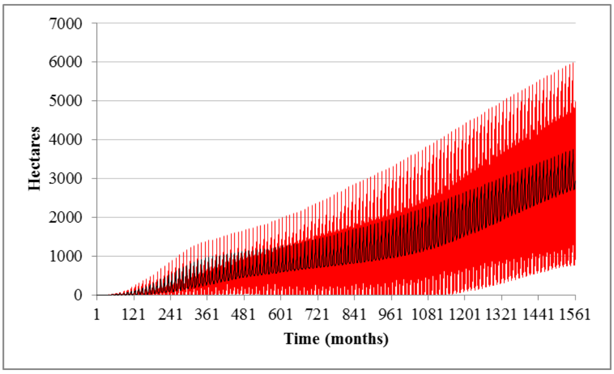
Note:—— average —— standard deviation

Figure 140. Scenario 2b: Clearance of forests made by the farm of Þorleifsstaðir



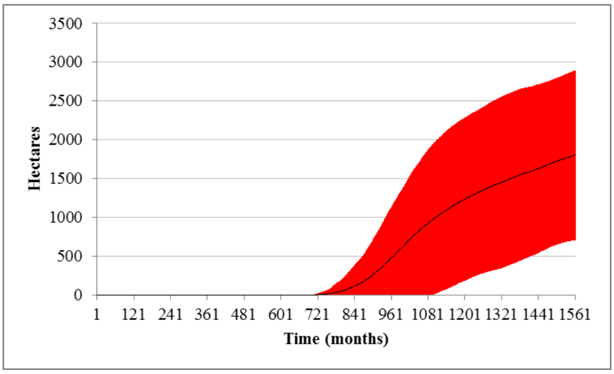
Note:—— **average** —— **standard deviation;** —— **average** —— **standard deviation**

Figure 141. Scenario 2b: Total number of livestock in Mývatn



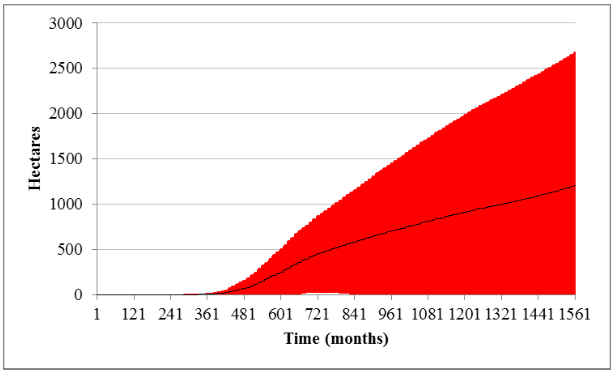
Note:—— **average** —— **standard deviation**

Figure 142. Scenario 2b: Extent of areas affected by overgrazing in Mývatn



Note:—— **average** —— **standard deviation**

Figure 143. Scenario 2b: Extent of areas with more than 50 % of grazing-tolerant vegetation in Mývatn



Note:—— average —— standard deviation

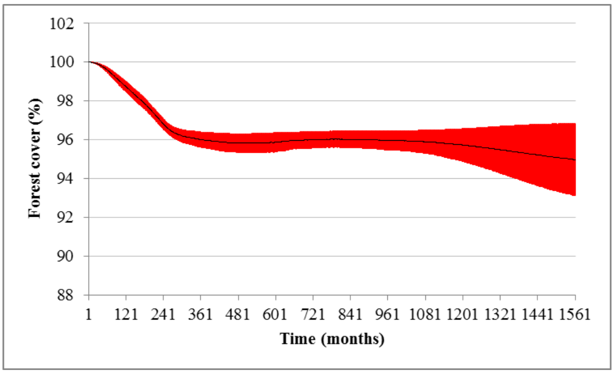
Figure 144. Scenario 2b: Extent of areas with more than 50 % of regrown birch cover in Mývatn

Scenario 3:

Table 37. („a“, above and „b“, below). Mývatn: Average values and standard deviations of starting parameters of 20 simulation runs of Scenario 3

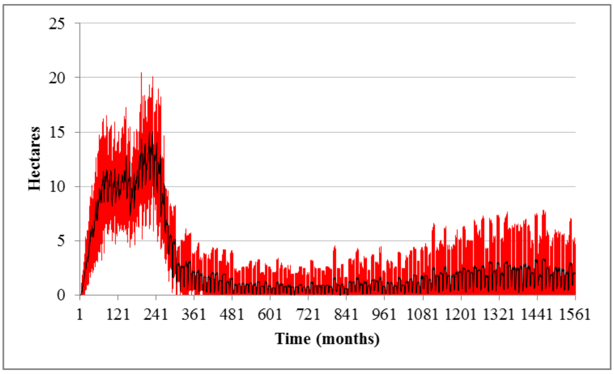
Starting parameters	Cattle cull	Ovines cull	Cattle growth	Ovines growth
AVG	5.2 %	8.3 %	23.2 %	42.49 %
SD	2.89	5.1	1.65	8.22

Starting parameters	Starting cattle	Starting ovines	Initiation of replacement	Replacement (heavy grazing)	Replacement (light grazing)
AVG	3.7	5.15	86.45	0.26 %	0.03 %
SD	1.3	2.2	21.98	0.1	0.02



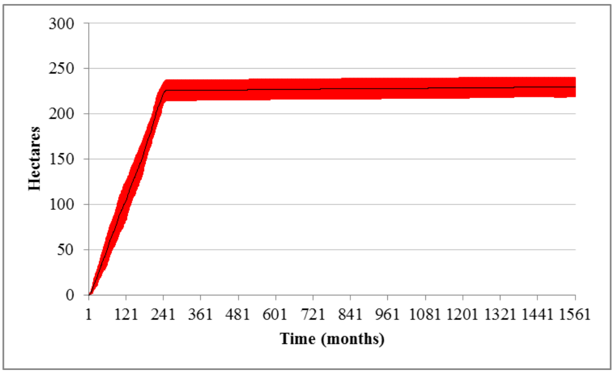
Note:—— average —— standard deviation

Figure 145. Scenario 3: Extent of forest cover in Mývatn



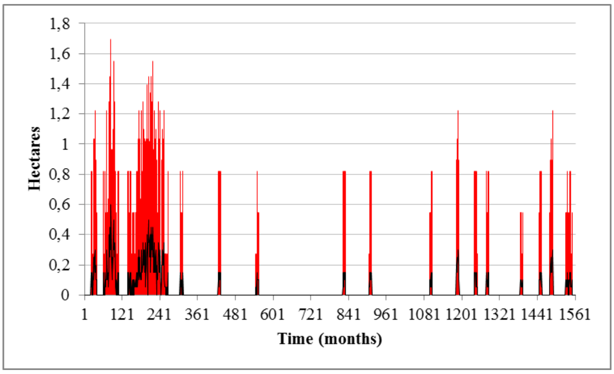
Note:—— average —— standard deviation

Figure 146. Scenario 3: Total forest clearance in Mývatn



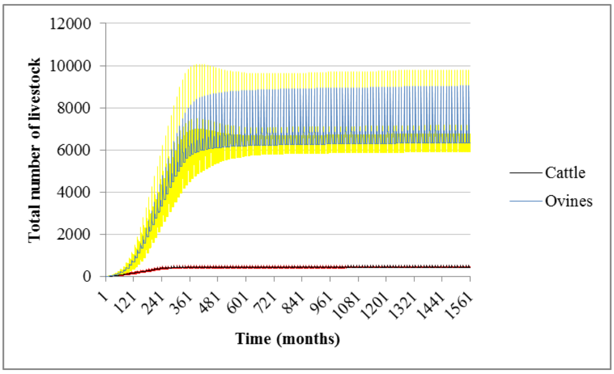
Note:—— average —— standard deviation

Figure 147. Scenario 3: Extent of areas cleared for home-fields in Mývatn



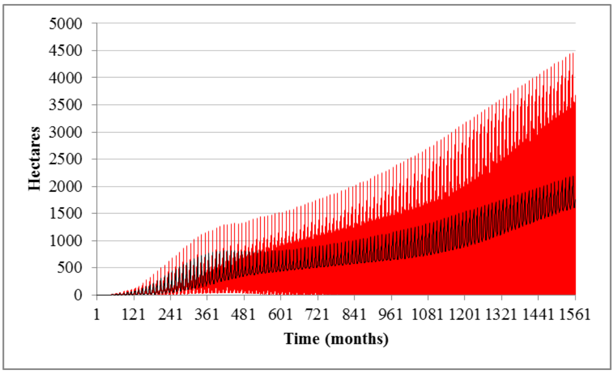
Note:—— average —— standard deviation

Figure 148. Scenario 3: Clearance of forests made by the farm of Þorleifsstaðir



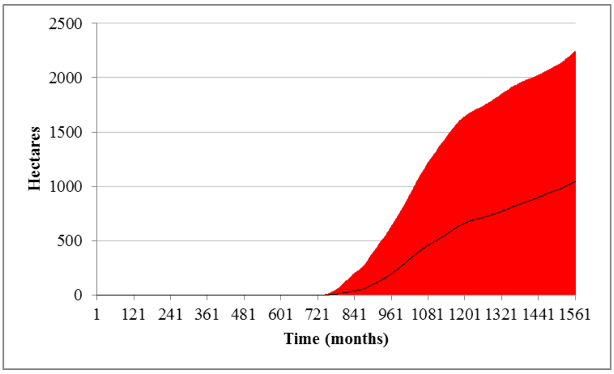
Note:—— **average** —— **standard deviation;** —— **average** —— **standard deviation**

Figure 149. Scenario 3: Total number of livestock in Mývatn



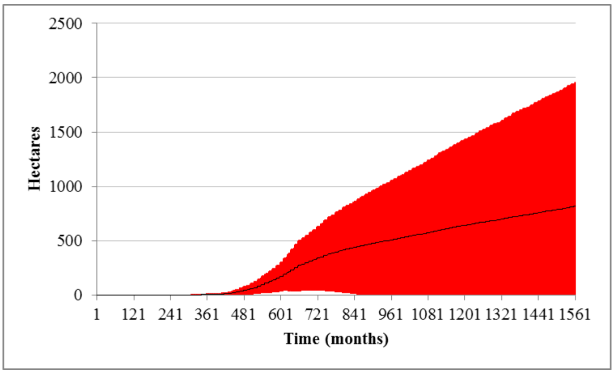
Note:—— **average** —— **standard deviation**

Figure 150. Scenario 3: Extent of areas affected by overgrazing in Mývatn



Note:—— **average** —— **standard deviation**

Figure 151. Scenario 3: Extent of areas with more than 50 % of grazing-tolerant vegetation in Mývatn



Note:—— **average** —— **standard deviation**

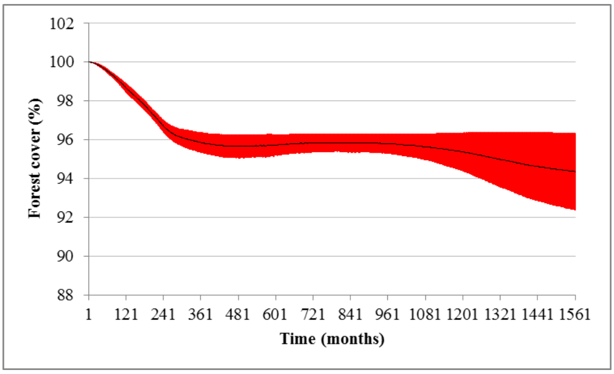
Figure 152. Scenario 3: Extent of areas with more than 50 % of regrown birch cover in Mývatn

Scenario 4:

Table 38. („a“, above and „b“, below). Mývatn: Average values and standard deviations of starting parameters of 20 simulation runs of Scenario 4

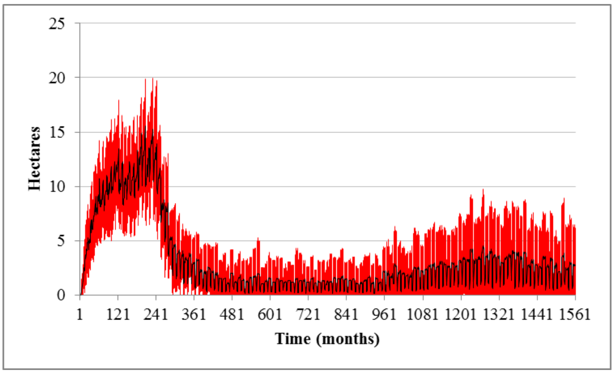
Starting parameters	Cattle cull	Ovines cull	Cattle growth	Ovines growth
AVG	5 %	8.35 %	23.13 %	44.84 %
SD	2.95	3.64	1.62	9.09

Starting parameters	Starting cattle	Starting oviness	Initiation of replacement	Replacement (heavy grazing)	Replacement (light grazing)
AVG	3.1	5.8	83.25	0.29 %	0.04 %
SD	1.2	3	20.13	0.1	0.02



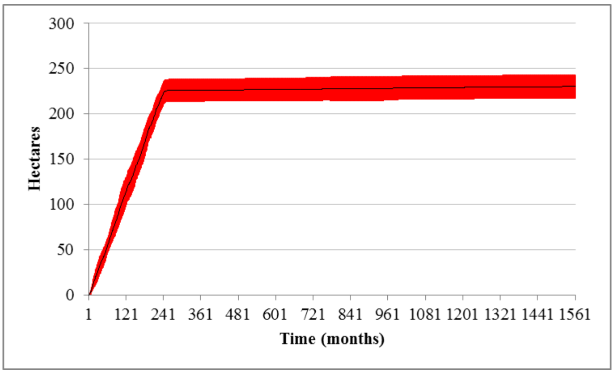
Note:—— average —— standard deviation

Figure 153. Scenario 4: Extent of forest cover in Mývatn



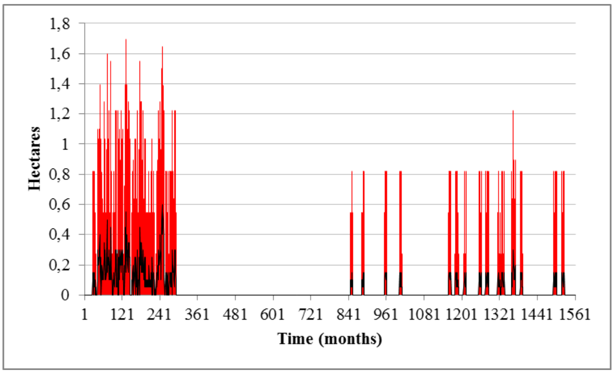
Note:—— average —— standard deviation

Figure 154. Scenario 4: Total forest clearance in Mývatn



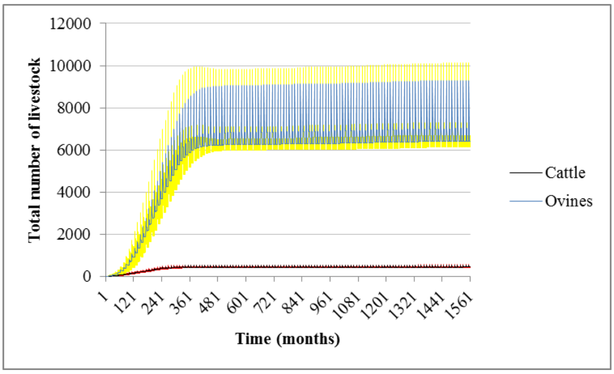
Note:—— average —— standard deviation

Figure 155. Scenario 4: Extent of areas cleared for home-fields in Mývatn



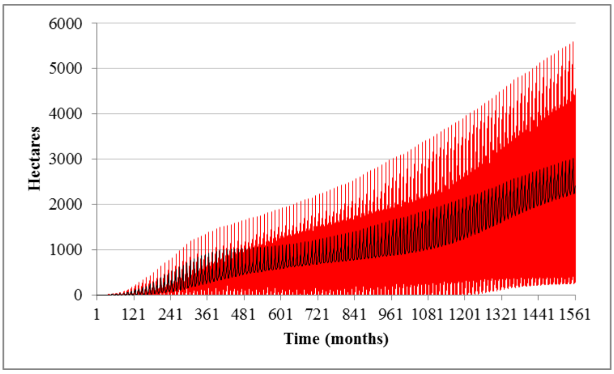
Note:—— average —— standard deviation

Figure 156. Scenario 4: Clearance of forests made by the farm of Þorleifsstaðir



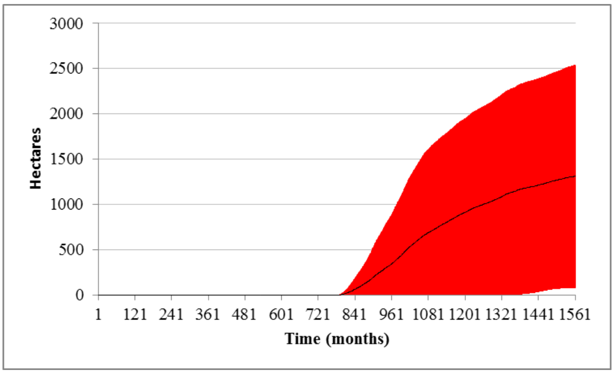
Note:— average — standard deviation; — average — standard deviation

Figure 157. Scenario 4: Total number of livestock in Mývatn



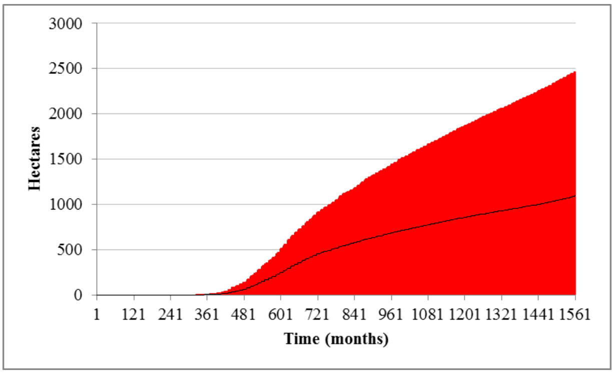
Note:— average — standard deviation

Figure 158. Scenario 4: Extent of areas affected by overgrazing in Mývatn



Note:— average — standard deviation

Figure 159. Scenario 4: Extent of areas with more than 50 % of grazing-tolerant vegetation in Mývatn



Note:—— **average** —— **standard deviation**

Figure 160. Scenario 4: Extent of areas with more than 50 % of regrown birch cover in Mývatn

Modelling outcomes: Borgarfjörður

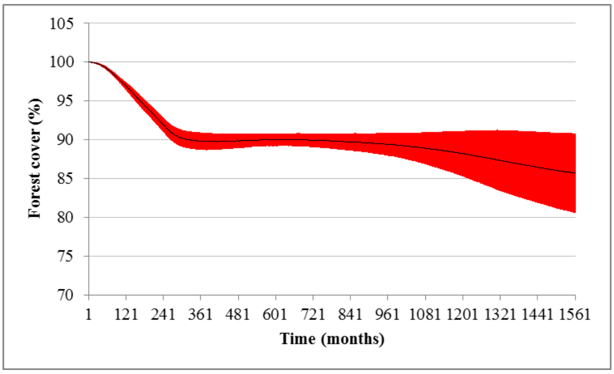
The starting parameters of the simulation runs for the region of Borgarfjörður are presented in the tables and figures below.

Scenario 2a:

Table 39. („a“, above and „b“, below). Borgarfjörður: Average values and standard deviations of starting parameters of single simulation runs of Scenario 2a

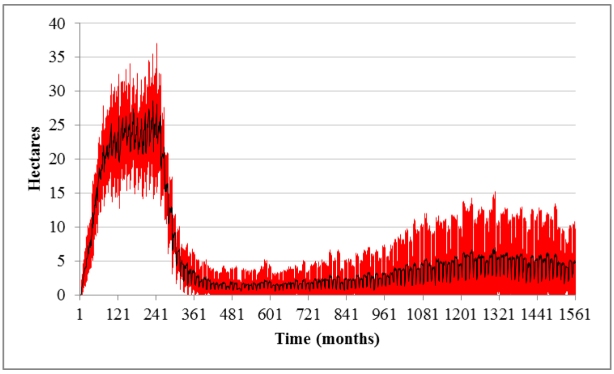
Starting parameters	Cattle cull	Ovines cull	Cattle growth	Ovines growth
AVG	5.1 %	7.55 %	22.48 %	49.74 %
SD	3.16	4.92	1.22	7.05

Starting parameters	Starting cattle	Starting ovines	Initiation of replacement	Replacement (heavy grazing)	Replacement (light grazing)
AVG	3.8	6.8	85.9	0.23 %	0.04%
SD	1.28	2.58	14.71	0.08	0.02



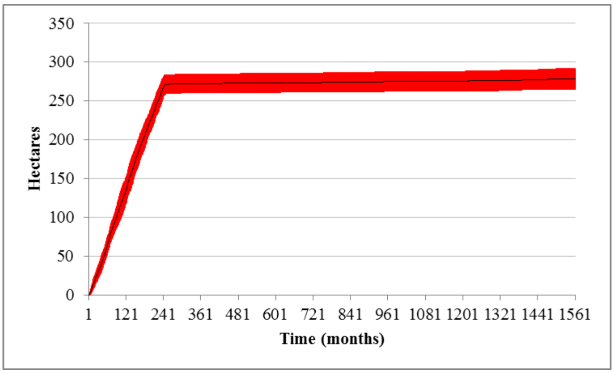
Note:—— average —— standard deviation

Figure 161. Scenario 2a: Extent of forest cover in Borgarfjörður



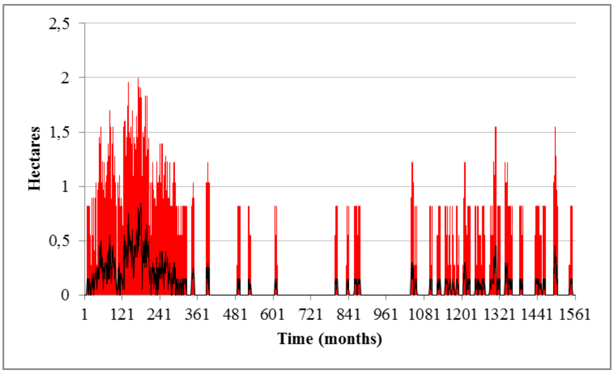
Note:—— average —— standard deviation

Figure 162. Scenario 2a: Total forest clearance in Borgarfjörður



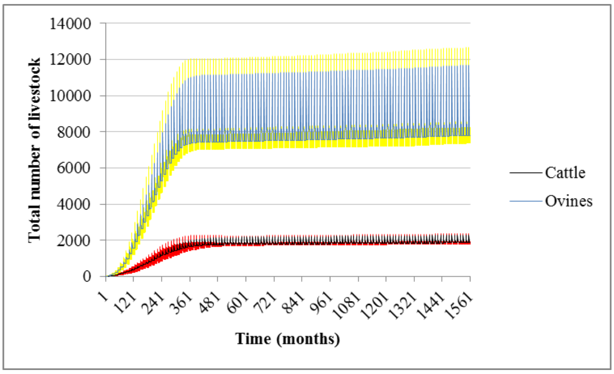
Note:—— average —— standard deviation

Figure 163. Scenario 2a: Extent of areas cleared for home-fields in Borgarfjörður



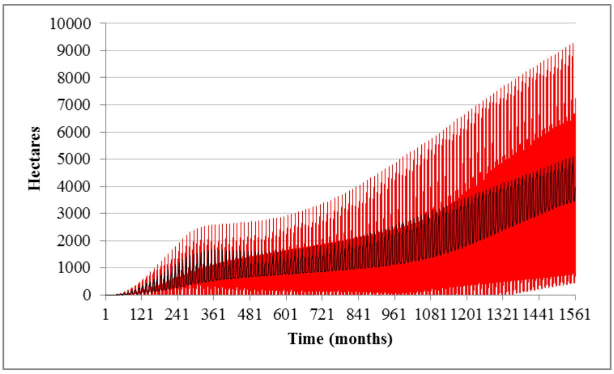
Note:—— average —— standard deviation

Figure 164. Scenario 2a: Clearance of forests made by the farm of Oddstaðir



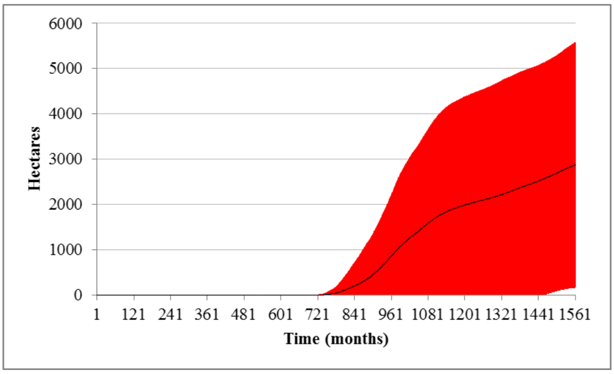
Note:—— average —— standard deviation; —— average —— standard deviation

Figure 165. Scenario 2a: Total number of livestock in Borgarfjörður



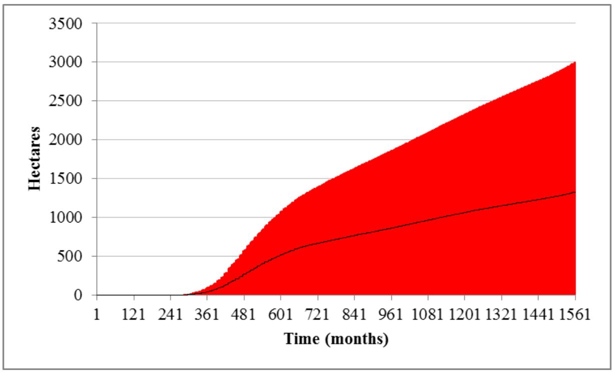
Note:—— average —— standard deviation

Figure 166. Scenario 2a: Extent of areas affected by overgrazing in Borgarfjörður



Note:—— average —— standard deviation

Figure 167. Scenario 2a: Extent of areas with more than 50 % of grazing-tolerant vegetation in Borgarfjörður



Note:—— **average** —— **standard deviation**

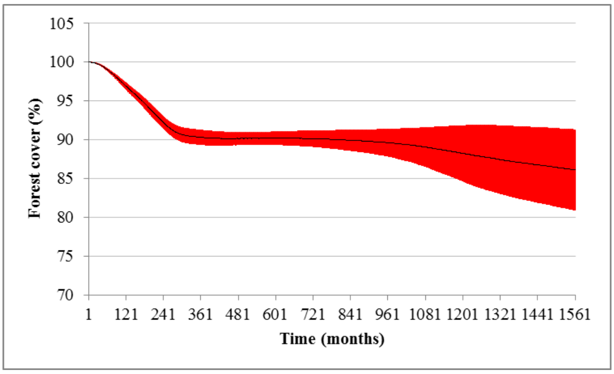
Figure 168. Scenario 2a: Extent of areas with more than 50 % of regrown birch cover in Borgarfjörður

Scenario 2b:

Table 40. („a“, above and „b“, below). Borgarfjörður: Average values and standard deviations of starting parameters of 20 simulation runs of Scenario 2b

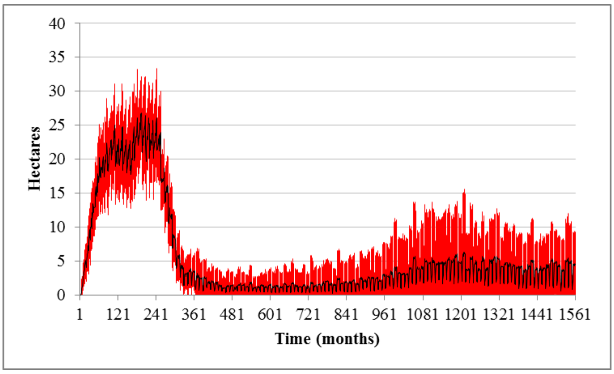
Starting parameters	Cattle cull	Ovines cull	Cattle growth	Ovines growth
AVG	4.45 %	8.1 %	22.64 %	45.06 %
SD	3.03	4.51	1.73	8.9

Starting parameters	Starting cattle	Starting ovines	Initiation of replacement	Replacement (heavy grazing)	Replacement (light grazing)
AVG	4	6	91.45	0.26 %	0.04 %
SD	0.44	1.27	18.54	0.1	0.02



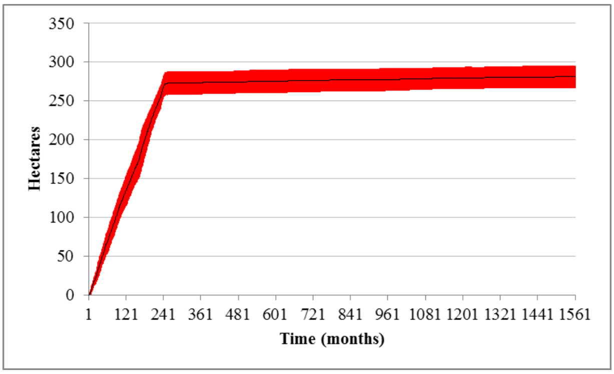
Note:—— average —— standard deviation

Figure 169. Scenario 2b: Extent of forest cover in Borgarfjörður



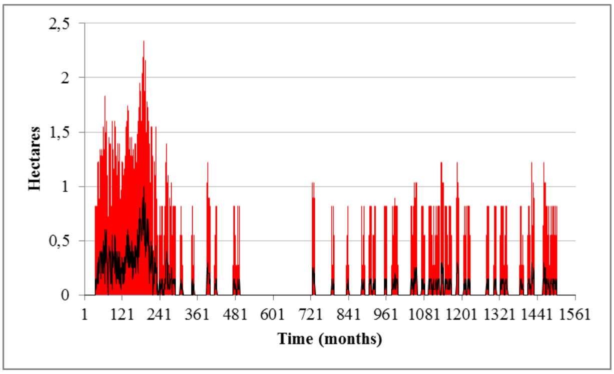
Note:—— average —— standard deviation

Figure 170. Scenario 2b: Total forest clearance in Borgarfjörður



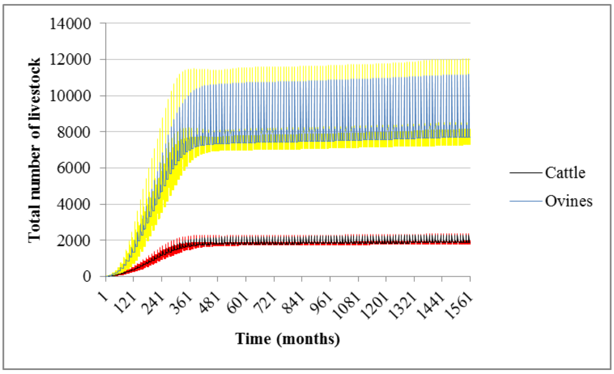
Note:—— average —— standard deviation

Figure 171. Scenario 2b: Extent of areas cleared for home-fields in Borgarfjörður



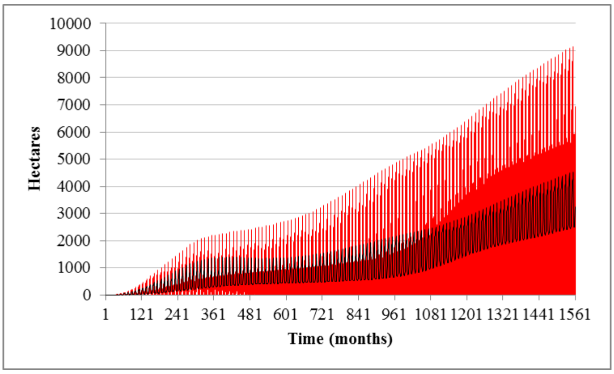
Note:—— average —— standard deviation

Figure 172. Scenario 2b: Clearance of forests made by the farm of Oddstaðir



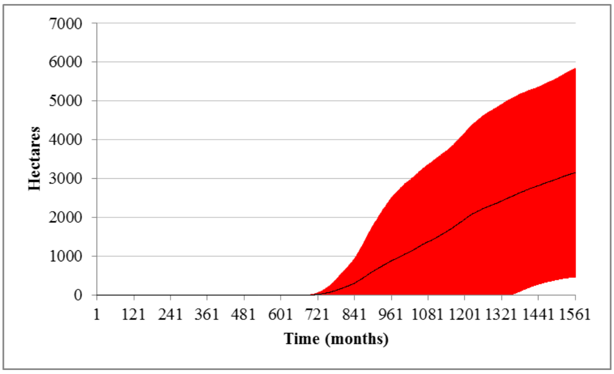
Note:—— average —— standard deviation; —— average —— standard deviation

Figure 173. Scenario 2b: Total number of livestock in Borgarfjörður



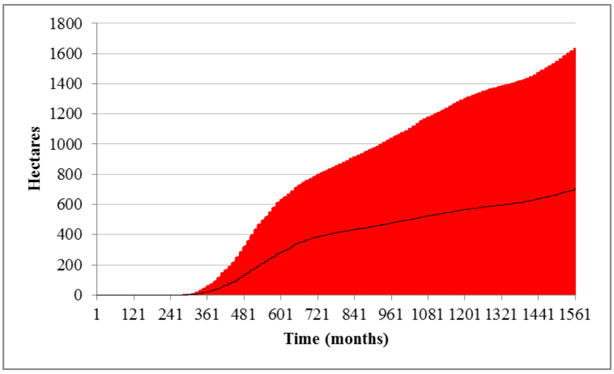
Note:—— average —— standard deviation

Figure 174. Scenario 2b: Extent of areas affected by overgrazing in Borgarfjörður



Note:—— average —— standard deviation

Figure 175. Scenario 2b: Extent of areas with more than 50 % of grazing-tolerant vegetation in Borgarfjörður



Note:—— average —— standard deviation

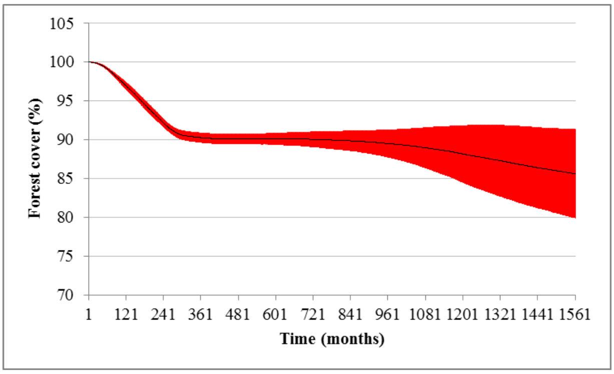
Figure 176. Scenario 2b: Extent of areas with more than 50 % of regrown birch cover in Borgarfjörður

Scenario 3:

Table 41. („a“, above and „b“, below). Borgarfjörður: Average values and standard deviations of starting parameters of 20 simulation runs of Scenario 3

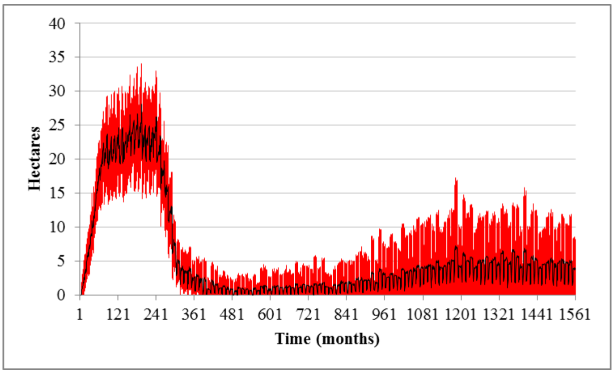
Starting parameters	Cattle cull	Ovines cull	Cattle growth	Ovines growth
AVG	6 %	8.65 %	23.05 %	44.84 %
SD	3.12	4.45	1.52	9.01

Starting parameters	Starting cattle	Starting ovines	Initiation of replacement	Replacement (heavy grazing)	Replacement (light grazing)
AVG	3.55	5.45	85.65	0.29 %	0.04 %
SD	1.14	2.78	16.88	0.09	0.02



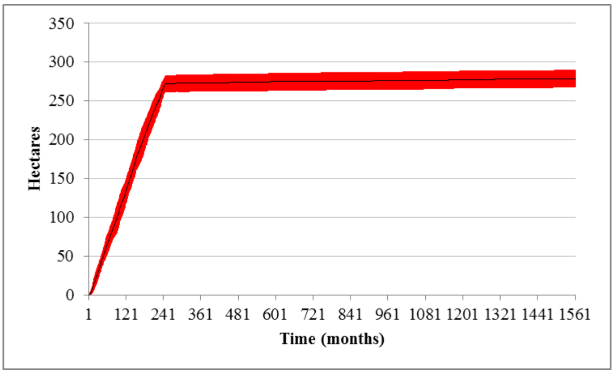
Note:—— average —— standard deviation

Figure 177. Scenario 3: Extent of forest cover in Borgarfjörður



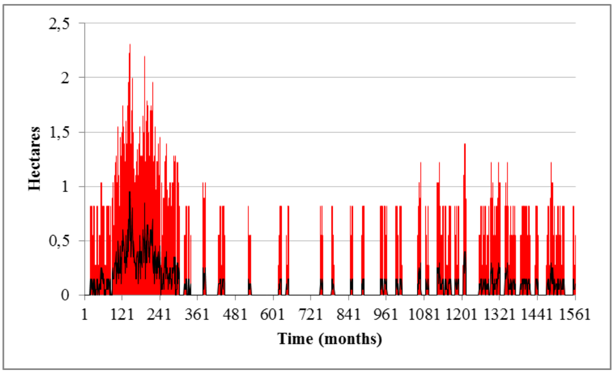
Note:—— average —— standard deviation

Figure 178. Scenario 3: Total forest clearance in Borgarfjörður



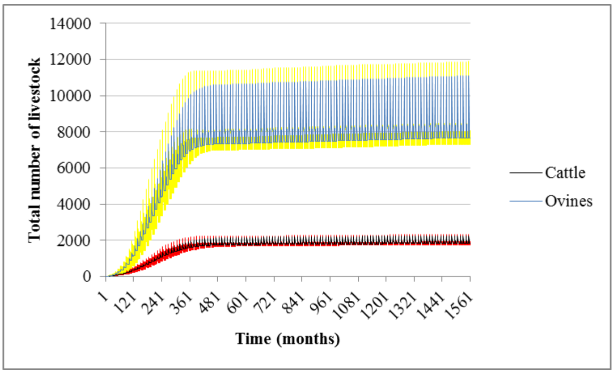
Note:—— average —— standard deviation

Figure 179. Scenario 3: Extent of areas cleared for home-fields in Borgarfjörður



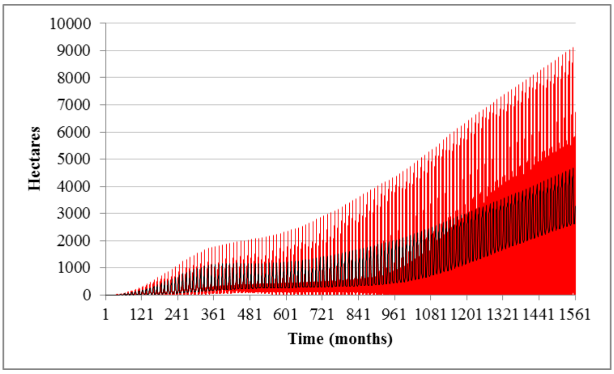
Note:—— average —— standard deviation

Figure 180. Scenario 3: Clearance of forests made by the farm of Oddstaðir



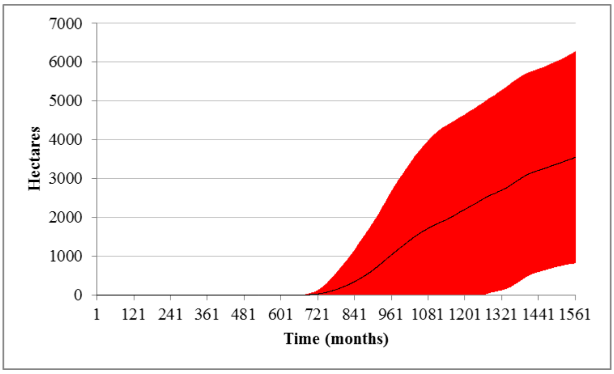
Note:—— **average** —— **standard deviation;** —— **average** —— **standard deviation**

Figure 181. Scenario 3: Total number of livestock in Borgarfjörður



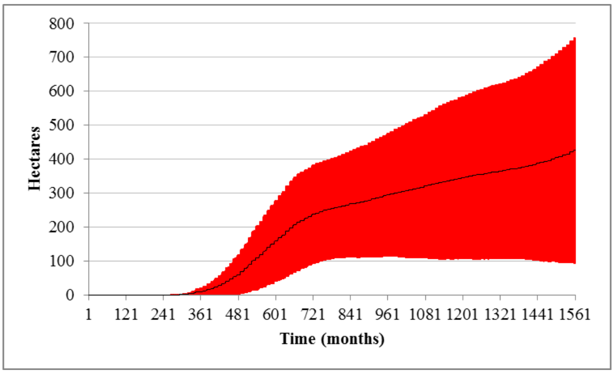
Note:—— average —— standard deviation

Figure 182. Scenario 3: Extent of areas affected by overgrazing in Borgarfjörður



Note:—— average —— standard deviation

Figure 183. Scenario 3: Extent of areas with more than 50 % of grazing-tolerant vegetation in Borgarfjörður



Note:—— average —— standard deviation

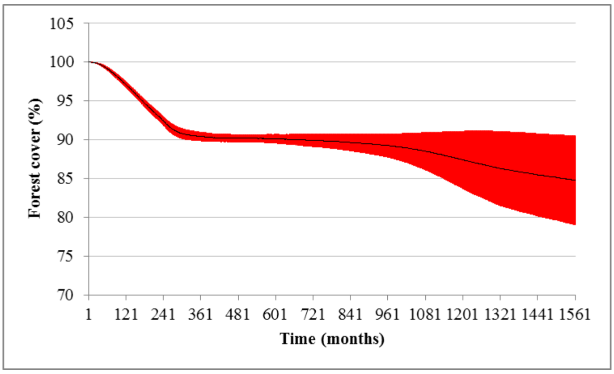
Figure 184. Scenario 3: Extent of areas with more than 50 % of regrown birch cover in Borgarfjörður

Scenario 4:

Table 42. („a“, above and „b“, below). Borgarfjörður: Average values and standard deviations of starting parameters of 20 simulation runs of Scenario 4

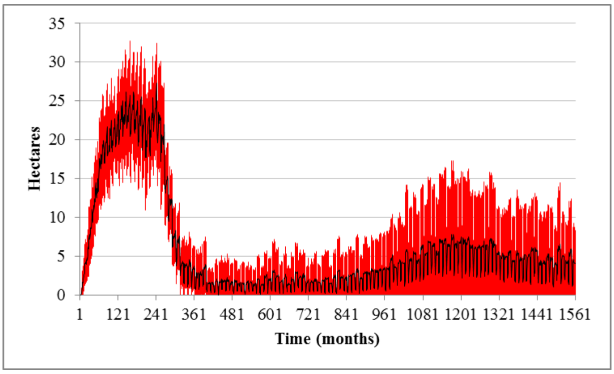
Starting parameters	**Cattle cull**	**Ovines cull**	**Cattle growth**	**Ovines growth**
AVG	5.8 %	6.25 %	23.33 %	46.69 %
SD	2.93	3.47	1.55	6.99

Starting parameters	**Starting cattle**	**Starting ovines**	**Initiation of replacement**	**Replacement (heavy grazing)**	**Replacement (light grazing)**
AVG	3.35	5.6	92.9	0.25 %	0.05 %
SD	1.3	3.01	20.12	0.11	0.02



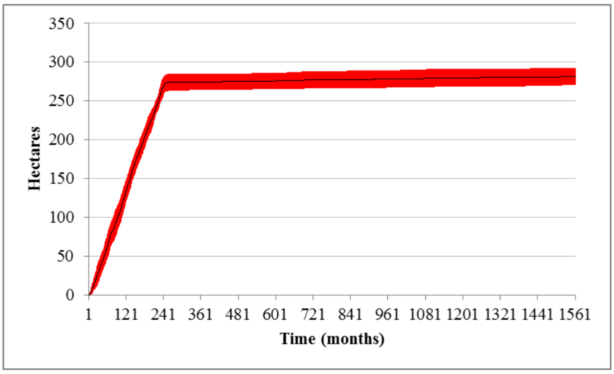
Note:—— average —— standard deviation

Figure 185. Scenario 4: Extent of forest cover in Borgarfjörður



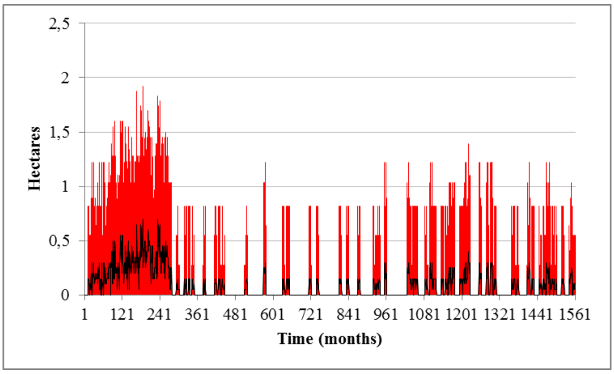
Note:—— average —— standard deviation

Figure 186. Scenario 4: Total forest clearance in Borgarfjörður



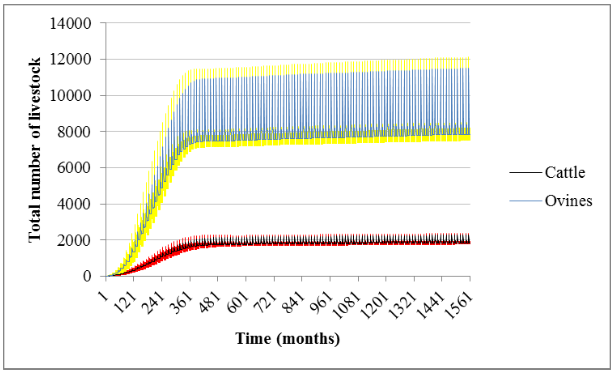
Note:—— average —— standard deviation

Figure 187. Scenario 4: Extent of areas cleared for home-fields in Borgarfjörður



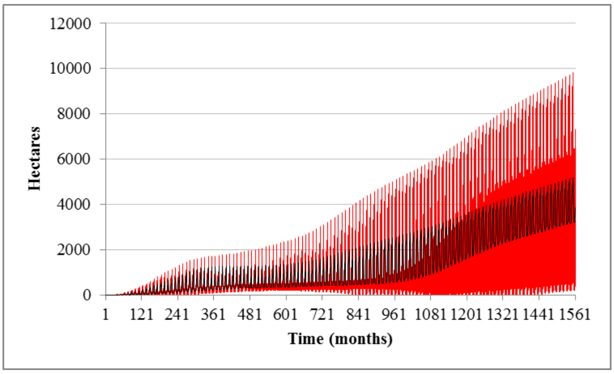
Note:—— average —— standard deviation

Figure 188. Scenario 4: Clearance of forests made by the farm of Oddstaðir



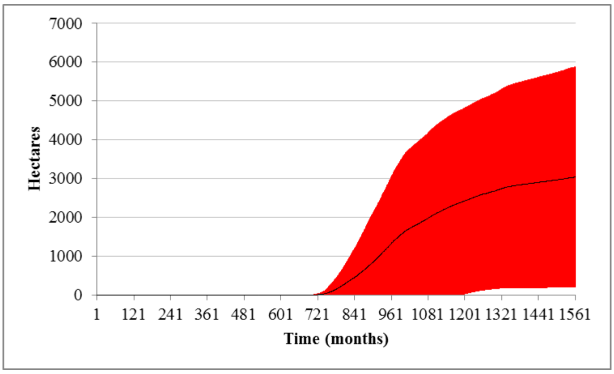
Note:—— average —— standard deviation; —— average —— standard deviation

Figure 189. Scenario 4: Total livestock number in Borgarfjörður



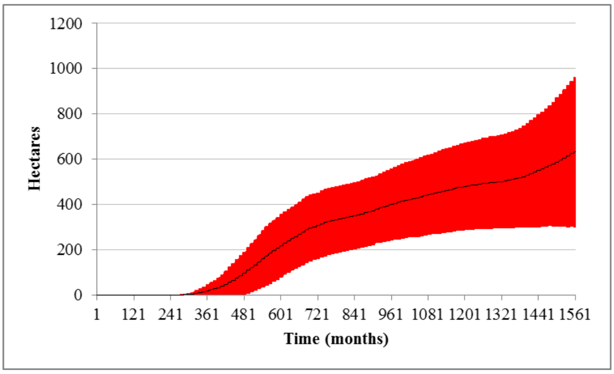
Note:—— average —— standard deviation

Figure 190. Scenario 4: Extent of areas affected by overgrazing in Borgarfjörður



Note:—— average —— standard deviation

Figure 191. Scenario 4: Extent of areas with more than 50 % of grazing-tolerant vegetation in Borgarfjörður



Note:—— average —— standard deviation

Figure 192. Scenario 4: Extent of areas with more than 50 % of regrown birch cover in Borgarfjörður