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Simulating dynamic carrying capacity of the Icelandic environment for land use in relation to past and future climatic fluctuations

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Abstract

The presented paper aims at clarifying the complex interaction between biotic and abiotic factors influencing land cover changes in sub-arctic landscapes, especially issues regarding the carrying capacity of the ecosystem, such as land use pressure and grazing potential. This is important for the understanding of the land degradation processes and thus for the future land use and sustainability. The results indicate that the maximum sustainable population supported by the Icelandic environment from the beginning of the Viking settlement, thousand years ago, fluctuated between 30-60.000 inhabitants. This suggests that the pre-historical population overshoot the carrying capacity on several occasions.

Key words: *Dynamic modelling, vegetation cover, land-use, carrying capacity, Iceland.*

1. Introduction

One of the major environmental crises facing the present societies is depletion of natural resources and subsequence degradation of ecosystems. When looking at this global problem in a closer perspective it is often difficult to obtain a holistic view of the indicators involved in the degradation processes. Iceland has experienced extensive land degradation, which may be regarded as one of the most serious environmental problem facing the nation. Owing to the small size, Iceland gives researchers a great opportunity to study all the stages of the processes in a holistic view. Hence, the experience obtained in Iceland may be drawn upon when looking at other risk zones. Furthermore, the magnitude of expected climatic changes and the fragility of the environment make agricultural marginal lands in the Sub-Arctic a highly interested areas to study the effects of global change.

It is estimated that Iceland has lost over 50% of its vegetation cover, and over 90% of its forest cover from the time of its settlement, 1100 years ago (Bergþórsson, 1996; Þórarinsson, 1961; Einarsson, 1963; Þorsteinsson, 1972). Currently, vegetation is covering 25% of the country's total area. Only 1% is covered by forests (The Ministry of Agriculture, 1986; IGI, 1993; Arnalds, *et. al*. 1997; Sigurðsson, 1977; Bjarnason and Sigurðsson, 1977). The almost total lack of forest is a very striking feature, and so is the nakedness of the country, whereby waste areas are either devoid of vegetation or only have a very sparse vegetation cover and may be classified as deserts or semi-deserts. The upper limit of continuous vegetation cover is found on average at a fairly low elevation of 600-700 m a.s.l., and the average upper limit of the birch forest lies at 200-300 m (Sveinbjörnsson, 1993; Nordal & Kristinsson, 1996). The ecosystems are characterised by a short growing season and vulnerability to changes, such as in climate and anthropogenic pressure. The climate of Iceland is greatly marginal for vegetation growth, it has been estimated that a $1^{o}C$ decrease in annual mean temperature yields a 10-20% decrease in carrying capacity of the rangelands (Dýrmundsson & Jónmundsson 1987). The triggering factor for land degradation is, however, commonly believed to be anthropogenic.

The controversy whether the land degradation facing Iceland is mainly the result of inappropriate land use practices or if it is a natural process is extremely important for future land management practices in Iceland. It also has a much more universal importance for our understanding of land degradation processes. The complexity of the degradation processes requires a multi-disciplinary approach thorough integration of the involving factors. Here we use systemic approach to assess and analyse the natural and anthropogenic impact on land degradation processes. A special focus is given to the natural processes controlling vegetation cover changes before and after the settlement in the late 900 AD, and what possible increase in temperature might have in the nearest future. Such knowledge is crucial when determining the size of future land area that can be restored naturally or by artificial reclamation. Moreover, gives it a base to determine the amount of carbon stored in soil in the degradation process. Our objectives were to:

- ✓ Clarify the complex interplay between biotic and abiotic factors influencing land degradation and highlight the possible interaction between them
- ✓ Construct a long-term temperature driven dynamic model on past and future vegetation cover potential, in order to assess the impact of climate change
- ✓ Assess the carrying capacity of the Icelandic ecosystems regarding land use practices.

The term carrying capacity has been refined on a number of times. It is commonly defined as the maximum number or biomass of organisms that a given environment can support. The constrains of carrying capacity is determined by the interaction of the environmental potential biotic and the environmental resistance, which hampers further increase (Odum, 1996). The environmental resistance is the interplay of different feedback mechanism of biotic and abiotic forces that can vary between geographical regions. In sub-arctic and arctic environments, this interplay is very sensitive towards climatic fluctuations. Hence, climatic changes may sprout a new development to the ecosystems, which have to adapt towards the changes (Woodward, 1987).

2. Theoretical framework

In order to identify important factors and processes that lead to land degradation, and as such affecting the ecological sustainability, a conceptual model in the form of causal loop diagram (CLD) was developed (Figure 1). For construction and assessment of the model the methodology of system thinking was applied. System models are simple and useful tools of representing the natural and anthropogenic world. Their value is in their simplicity and in their ability to reveal the underlying nature of complex situations. The emphases are placed on broad viewpoints so that interrelationships and interconnectivity are the focus rather than a collection of complex variables. Often we tend to break up the complex environment into smaller, more manageable pieces, and believe that if we can understand the separate pieces, then we can put our separate understandings together to understand the whole. This works for simple things, but fails when addressed to complex problems because the connections and interactions between those parts get lost (e.g. Hitchins, 1992; Hannon, 2000; Roberts, *et al.*, 1983; Senge, 1990). By using system perspective details are analysed through a macroscopic perspective describing more thoroughly the history of land degradation.

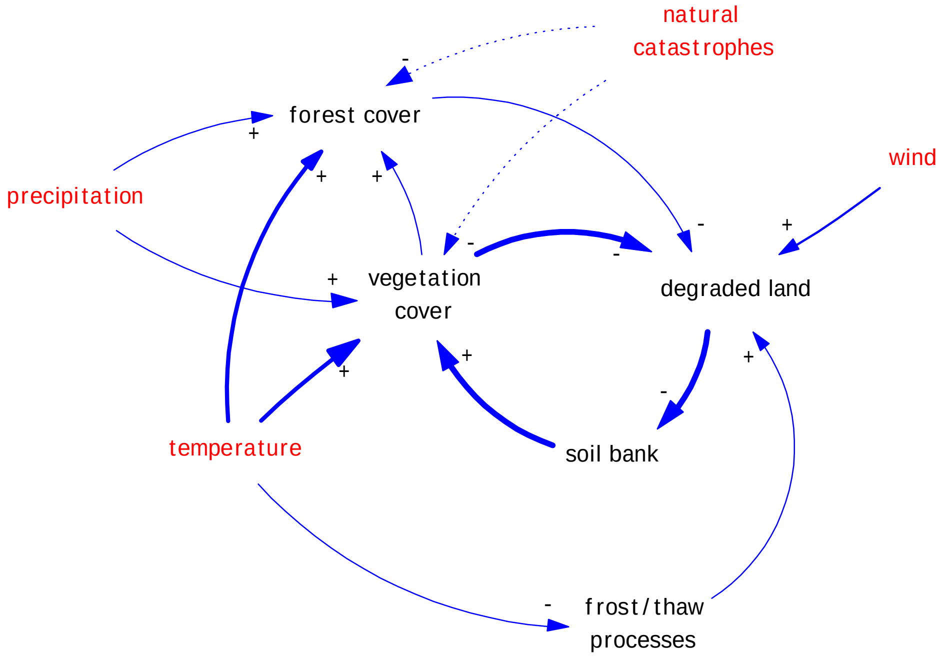

Figure 1. Natural factors influencing land degradation processes in Iceland. The arrows indicate influence of the parameters, either in the same direction (+) or opposite (-) direction. The system can be categorised as endogenous (black), i.e. variables that influence and are influenced by other variables, and as exogenous (red), i.e. parameters that influence the system but are not influenced by it.

Figure 1 describes a system that is influenced only by natural processes. According to Bergþórsson *et al.* (1987), temperature is by far the most limiting climatic factor vegetation growth in Iceland. Hence, temperature has a strong positive effect on vegetation (i.e. heath- and grassland) and forest (birch) cover by increasing the potential area for establishment at higher elevation. This means that if all initial conditions regarding establishment are met these parameters will increase. This may be regarded as a higher carrying capacity of the environment owing to long term increase in annual temperature, which results in larger area covered by vegetation and forest. Increased vegetation cover also has a positive effect on the forest cover by adjusting the soil for forest establishment. Precipitation is similarly defined as the temperature, having positive effects on forest and vegetation cover. Vegetation cover has an opposite effect on land degradation, indicating that as more vegetation establishes the more area is reclaimed by vegetation cover. Land degradation may be defined as a reduction of the ability of the land to continue to produce that quality of a vegetative cover that makes it sustainable. Here it is considered eroded surfaces. With increased vegetation cover, we reduce land degradation and increase the organic carbon stored in the soil (indicated with opposite link), which in term enhances vegetation cover. The forest cover act similarly as the vegetation cover with regard to land degradation, however weaker due to the high requirements for establishment. Additionally, two more variables have a major influence on land degradation, i.e. wind and frost/thaw processes. These parameters enhance the land degradation when the vegetation cover retreats due to reduced carrying capacity of the environment. The relationship between occurrence of freeze/thaw and the initiation and rate of degradation is an interesting aspect that will considered later. Natural catastrophes, such as volcanic activities, are periodic events that influence the system adhoc by temporarily destroying the vegetation and forest cover, however, these factors may give a rise to severe long-term effects.

Prior to the Viking settlement, 1100 years ago, the Icelandic ecosystems were not at all adapted to grazing livestock, as became a large factor ever since. In Figure 2, the anthropogenic factor have been added to the CLD. Anthropogenic activities includes human population and its livestock. Since the Viking's introduction, livestock became an integral part of the Icelandic environment and served as a source of living for the people. At times, their impact on the environment is believed to have been very severe. For that reason livestock has been held responsible for destroying forest vegetation and leading to growing generation of desert patches and deserts consequently. It has even been speculated (Arnalds 1997) that land degradation gradually reduced Iceland’s carrying capacity leading to social unrest and serious consequences like the loss of independence in 1262. Agricultural and historical scientists (i.e. Júlíusson, 1998; Kristinsson 1998), on the other hand, have questioned this impact. However, human utilisation might have been above the regeneration capacity of the forest during the coldest time of the Little Ice Age period (LIA). As climate become cooler, the vegetation retreat faster than before due to the combination of anthropogenic activities and reduced forest cover that shelters the low vegetation. This is indicated with an opposite influence between forest cover and land degradation, which results in reduction in carrying capacity. The wind becomes a stronger influence factor on land degradation due to increased open spaces created by loss of forest, which allows the wind to become a more effective agent. Furthermore, vegetation is retreating relative faster due to cooler climate. Natural catastrophes have reducing effect on people and livestock but not significant as other factors since its adhoc and often localised.

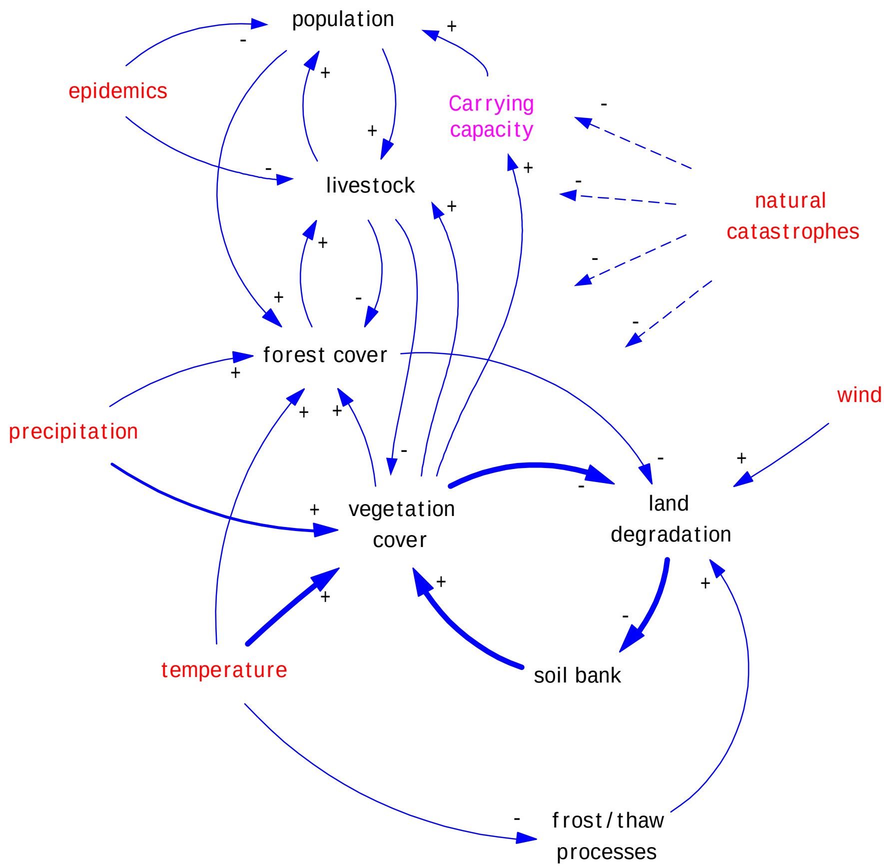

Figure 2. Integrated natural and anthropogenic factors influencing land degradation processes in Iceland.

3. Simulation structure and theory

To understand the natural variations and the anthropogenic effects on the vegetation cover there is a need to trace the dynamics "backward". If the environment has suffered similar fate of land degradation prior to Viking settlement then there is a risk that this is a cyclic event and thus natural. If the degradation is a unique event then there exists a possibility to estimate the threshold that limits the carrying capacity of land use. The dynamic model was constructed in the following sequence; 1) the vegetation model, 2) the population model and 3) the climatic change model.

3.1 The vegetation model

The Degree Days concept

The model makes use of long term temperature oscillations in order to simulate potential vegetation cover, based on the Degree Days concept. Temperature is by far the most limiting factor for vegetation development in Iceland (e.g. Friðriksson & Sigurðsson, 1983; Bergþórsson, 1985; Bergþórsson, *et al.* 1987). Moreover, the total heat needed for growth to occur depends entirely on the growing season length and temperature. According to Woodward (1992), these two factors, i.e. temperature and the length of the growing season, are combined in Degree-Days (DD). DD may be defined as the accumulated products of time and temperature above the developmental thresholds for each day (McGuffie & Henderson-Sellers, 1997). The basic concept is that actual photosynthesis will only occur if the temperature exceeds some minimum developmental threshold temperature (T_{base}) over its growing season. T_{base} for boreal regions in Scandinavia is generally considered to be 5°C (Prentice & Helmisaari, 1991). For the Icelandic maritime climatic conditions this number is recognised as 4°C (Friðriksson & Sigurðsson, 1983), which was used in the model.

The T_{base} for birch forest may be defined as the minimum mean summer temperature required for birch (here *betula pubecens*) to grow. For northern Scandinavia Prentice and Helmisaari (1991) imply 7°C (i.e. >450 DD above 4°C) as a threshold for birch during the growing season. Studies on treelines, i.e. upper margins of tree growth, in the southern part of the Swedish Scandes indicate the threshold for zero growth of birch, between the years 1972-1992, to be 7.3°C (Kullman, 1979; 1993), which coincides with the range 7.0-7.8°C in same areas observed by Kielland-Lund (1981). Woodward (1987) points out that birch establishment in the Scandes mountain range strongly correlates with increasing temperature above 5°C and markedly above 10°C. As T_{base} for Icelandic birch conditions Sigurðsson (1977) introduced 7.5°C (i.e. >525 DD above 4°C)**.** Another approach, where temperatures were used to determine the annual sum of growth indices of birch forest to develop in Iceland, reveal the T_{base} to be 8.5°C (i.e. >690 DD above 4°C) (Bergþórsson, 1985; 1995). From this it is obvious that values range between 7-8 °C, therefore Sigurðsson's (1977) value of 7.5°C does not seem unjustifiable.

Model equations

The simulation is entirely based on a reconstructed temperature curve from the Greenland Icecore Project (GRIP). The temperature curve represents annual temperature for the last 10.000 years. The reconstructed temperature was used to calculate the potential vegetation development constrained by number of DD. Calculation of DD requires daily measurements of maximum and minimum temperatures (T_{max} and T_{min}) and a base temperature (T_{base}). The DD figure for a given time is then the accumulated total of daily results over the period in question. The daily DD (equation 1) may be defined as follows:

$$DD_{day} = \left(\frac{(T_{max} + T_{min})}{2} \right) - T_{base} \qquad (1)$$

T_{base} used for vegetation growth in Iceland is + 4°C (Friðriksson & Sigurðsson, 1983). In case climate data lacks details on a daily basis, converting DD_{day} into annual DD (equation 2) may be done by using the average summer temperature of the expected annual growing season (GS), i.e. May – September or150 days (Botkin, 1993) as follows:

$$DD_{year} = (T_{mean} - T_{base}) \times GS_{(150\ days)} \qquad (2)$$

The GS mean temperature curve for the Holocene was obtained by applying linear regression between the annual mean (+3.59°C, std +0.84°C) and GS mean (+7.97°C, std

+1.07°C) acquired from a 100 year period (1890-1990) from the three selected climate stations, i.e. 5.08°C+0.8x, which gave the correlation coefficient (r) of 0.6. The DD for vegetation (equation 3) and forest (equation 4) were calculated using the following equations:

$$DD_{vegetation} = \left(\left(5.08 + 0.8T_{mean}\right) - T_{base}\right) \times GS_{(150\ days)} \qquad (3)$$

$$DD_{forest} = \left(\left(5.08 + 0.8T_{mean}\right) - T_{forest}\right) \times GS_{(150\ days)} \qquad (4)$$

To determine the treeline for birch forest, the T_{base} for forest (T_{forest}) was set to 7.5°C according to Sigurðsson (1977). A random normal distribution was used to simulate 200 Montecarlo runs with standard deviation (+1.07°C) in order to receive the range of temperature deviation through Holocene.The relationship between the measured temperature at a certain elevation and the equivalent at sea level is often described by the widely used standard atmosphere lapse rate of 6.5°C km^{-1} (McGuffie & Henderson-Sellers, 1997; Linacre, 1992). Observations from Iceland (Eyþórsson and Sigtryggsson, 1971) indicate similar results, or a mean temperature decrease of 0.6°C per 100m. That was chosen here to represent the relationship between elevation in meters and temperature. A histogram acquired from a digital elevation model (DEM) over Iceland gave the elevation interval in 100m. A polynomial fit of the DEM was used to acquire the area in km^2 at different elevations. The hypothetical area (equation 5) for potential vegetation and forest cover can be expressed as an area in km^2 (A_{potcov}):

$$A_{potcov} = \left(\frac{DD_X}{\left(6x10^{-3} * GS\right)} \right) * DEM \qquad (5)$$

where DD_x is degree days for either vegetation or forest and *lapse* is 0.006. The total vegetation and forest cover in km^2 over the Holocene was obtained by using the logistic growth function (dA_{potcov}/dt):

$$\frac{dA_{potcov}}{dt} = r \times A_{actcov} \left(\frac{A_{potcov} - A_{actcov}}{A_{potcov}} \right) \qquad (6)$$

where *r* is the growth establishment rate; A_{actcov} is the actual area cover according to the establishment rate *r*.

Reconstructed temperature and calibration model

The most accessible climate data for the northern Atlantic region over the Holocene (i.e. the last 10000 years) is gained from the Greenland Ice Core Projects (i.e. GRIP and GISP2). For the model's scenarios presented here, a time series for temperature conditions over the Holocene was obtained from the GRIP data (http://arcss.colorado.edu/Gispgrip/data). According to Einarsson (1993), monthly and annual temperatures during the period 1901-1990 reveal a general relationship between temperature conditions in Iceland and the North-Atlantic region. As calibration data over Iceland annual mean temperature over the last century in Iceland were obtained from three differently located climate stations, i.e. Stykkishólmur (65°05'N/22°44'W), being affected by the mild Irminger current at the west coast, Teigarhorn (64°41'N/14°21'W) located on the east cost and being rather under the influence of the cool East-Iceland current and Akureyri (65°41'N/18°05'W), located on the north coast affected by more contrasting temperature variations. The first source of daily temperature measurements in Iceland is from Stykkishólmur and dates back to 1846 AD. The observations started in 1874 at Teigarhorn and in 1882 at Akureyri (Bergþórsson, 1969b). Annual mean temperature (+3.59°C, std +0.84°C) from these stations over a hundred years period (1890-1990 AD) was used as a temperature index to evaluate and calibrate the model's results. The GRIP oxygen isotope data ($\delta^{18}O$) were calibrated into air surface temperature (T_S) by applying the following conversion factor (equation 7) introduced by Johnsen, *et al*. (1995).

$$T_S = 1.50\delta + 20.3 \qquad (7)$$

Calibration of the temperature in Greenland to Icelandic conditions was based on a regression of the Icelandic mean temperature and the $\delta^{18}O$ data over a 100 years period, i.e. 1880-1990. A weighted curve fit of least square error method was applied on both data sets to more clearly compare them. To reconstruct the Holocene temperature curve for whole Iceland the weighted curve fit was applied on the whole GRIP data (Figure 3).

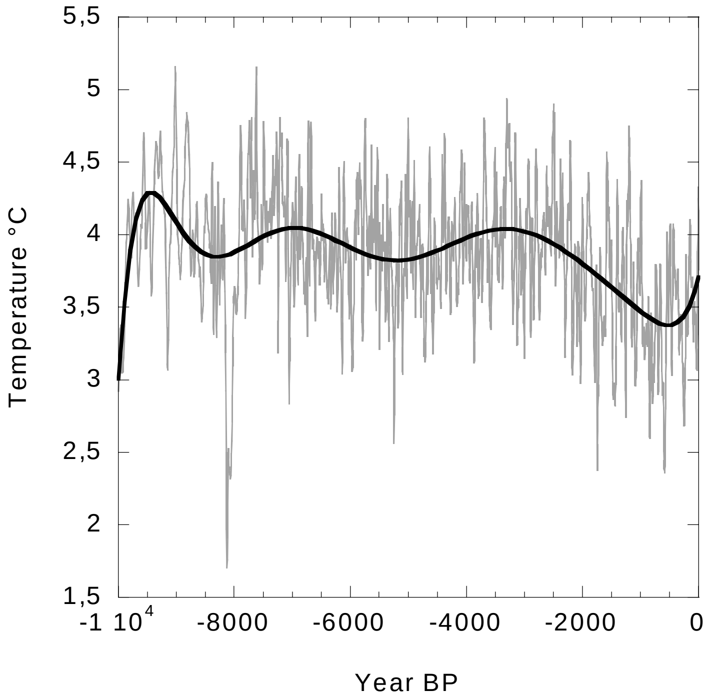

Figure 3. A smoothed version of the GRIP $\delta^{18}O$ records, interpreted in terms of mean annual temperature.

Assumptions and limitations strategy for vegetation development

Since the theoretical framework of the model is on a high observation level the model reflects hypothetical development of potential vegetation in Iceland based on temperature thresholds for vegetation developments. Elevation and temperature are assumed the primary limitations to vegetation growth and possible variations of changes owing to latitude or microclimate are not taken into account. Such knowledge requires more detailed knowledge on local sites and thus spatial application, which is not covered here. The following assumption and limitations where developed for the vegetation and forest cover simulation:

- Precipitation is treated as constant in the model and unchanged.
- The annual mean temperature at three climate locations, i.e. Stykkishólmur (65°05'N/22°44'W), Teigarhorn (64°41'N/14°21'W) and Akureyri (65°41'N/18°05'W), represents the DD development for the whole country through the observation period. The summer mean temperature from respective stations is estimated to coincide linearly with the annual mean temperature.
- The growing season is assumed to be five months (i.e. from May-September).
- Birch (*betula pubescens)* is the only tree class modelled. Other vegetation is considered various heath and grass species. Birch that is lower than two meters in height is classified with other vegetation. Moss and lichen are excluded from the model.
- The model uses 4°C as a T_{base} for vegetation. All DD numbers in the model are calculated using this base.
- The value 7.5°C is used as T_{base} for birch forest, denoting establishment conditions for birch to start at >525 DD above 4°C.
- The establishment and decline rates for total vegetation cover and for forest cover is assumed to be 1%. This number is an arbitrational number since physical factors, such as climate conditions and soil, vary between regions in Iceland.
- Since insufficient data exists on vegetation decline, the T_{base} threshold for vegetation and birch forest is used as a limiting factor.

3.2 The population model

The land-use model is based on the crop/yield concept, i.e. the annual harvestable hay on cultivatable land area. Historical records are used to estimate the population size in the early colonisation period and to create the ratio of domestic animals per person (Kristinsson, 1998) and furthermore the hay yields per hectare land (Bergþórsson, 1982). The beginning of the colonisation in Iceland is set to AD 874 and the following 100 years are assumed the colonisation period. The population size is believed to have fluctuated around 50.000 inhabitants until the 18th century where it progressively increased to the present level of 270.000 (Júliusson, 1990). The following assumption and limitation strategy was used for land-use and degradation:

- The model uses livestock (sheep, cows and horses) as a limiting factor on population size.
- The available grass from the highlands for the sheep is 25% of the total yield over the growing season. This is considered as sustainable use (Þorsteinsson, 1972).
- Lowland is all the area below 300 meters and highland is all the area above 300 meters.
- Highest estimates on farming land are 10% of the country's total area (Ministry of Agriculture, 2000). By subtracting wetlands and lakes, the maximum area cultivatable is 600.000 hectares (Kristinsson, 1998).

- The harvestable hay on lowlands is a triangular function, allowing highest yield at sea level and close to zero at the transitional zone between barren land and vegetation cover. The yield is a function of annual temperature, ($9.5x10^{-3}$ * (Degree Days)-2.04) which is derived and modified from Þorsteinsson (1972).
- Each individual requires 32 livestock equivalents in order to survive in the long-term. The model uses sheep equivalents which are calculated as followed: 1 cow = 20 sheep, 1 horse = 7 sheep (Þorsteinsson, 1972).
- Annual produced biomass per hectare is converted into annual hay yields. Hay requirements for cow are 6.5 tonnes/year, for horse 4.0 tonnes/year and for sheep 0.75 tonnes/year (Harlin, 1998).
- 20% is subtracted from the total harvested hay due to loss of nutrition in the storing process.
- Annual degradation has been measured to be 0.35-0.8% in Iceland (Arnalds et al, 1997; Þorsteinsson, 1972). The extreme scenario of 1% annual degradation is used in the model, which is randomly varied by 50%.
- Forest is excluded, but the rate of use is set 0.15% per year.

The land use model is divided into five sections that represent different elevation intervals. Since the area km^2 is known under different elevations, it was possible to estimate the biomass from each categorised elevation segment. The figure 4 shows the basic structure of the climatic and the land-use model combined.

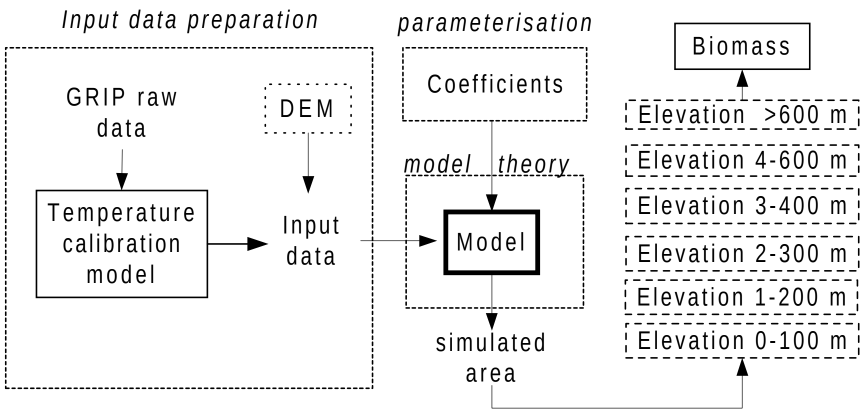

Figure 4. A flow chart of the model procedure. Long term temperature data is used to simulate potential area of vegetation cover, which is converted into biomass according to yields at each elevation segment.

3.3 The climate change model

The temperature fluctuation due to climatic change according to IPCC (1996) for the next several 100 years can be described as the function ($T_{increase}$) (equation 8):

$$T_{increase} = \frac{a}{\left(1 + b * \exp(-c * D_{100\,year}\right)} \quad T_{increase} = \frac{a}{\left(1 + b * \exp(-c * D_{100\,year}\right)} \qquad (8)$$

Where a (0.02), and b (1138), and c (23.2) are constants. $D_{100\ year}$ is a temperature, resulting from a linear increase for a one hundred year period. Temperature scenarios, 1-3°C where used to represented an increase in atmospheric temperature for the next centuries. The assumption is made that expected release is linear and will cease after 100 years from the year 2000.

4. Results and discussion

4.1 Changes in vegetation and forest cover during the Holocene

According to Haraldsson and Ólafsdóttir (2001), during the Holocene the potential vegetation range limits are characterised by active oscillations back and forth, until c. 2500 BP when actual degradation in vegetation cover began and accelerated greatly after c. 1150 BP (AD 800) (Figure 6).

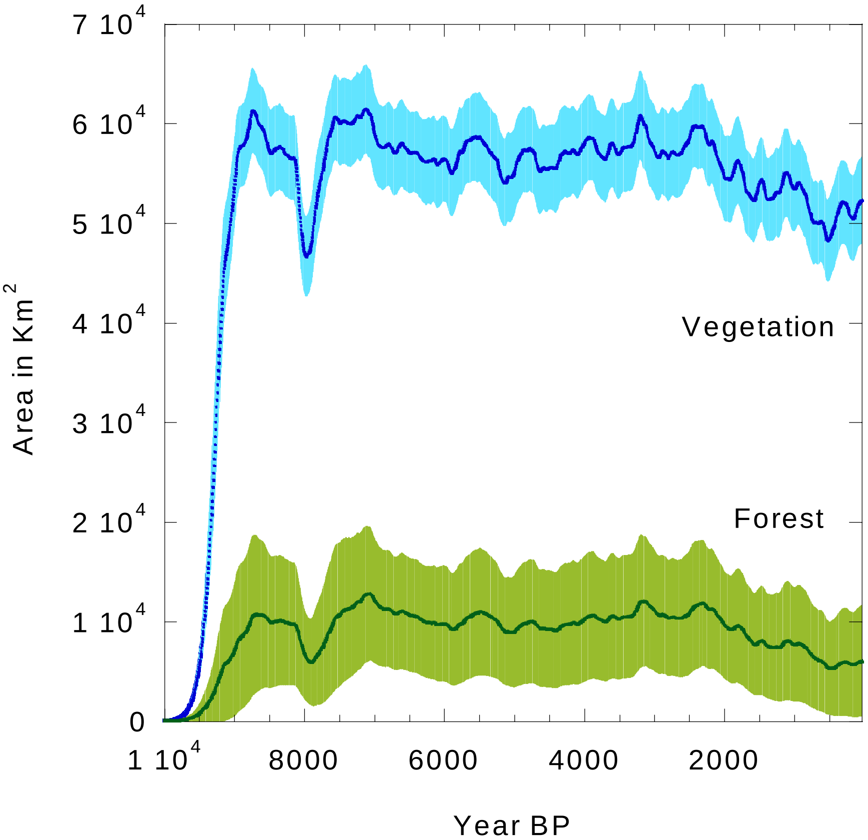

Figure 5. The simulation results of potential vegetation cover as well as forest cover (in km^2) over the Holocene in Iceland. The shaded areas indicate the maximum and minimum spread of vegetation cover by when all the input parameters are varied by 10% and run 200 cycles. (adapted from Haraldsson and Ólafsdóttir, 2001).

In the light of these long-term simulations of vegetation cover it is of interest to look at the question, whether the severe land degradation occurring in Iceland today is initiated by natural factors or anthropogenic exploitation. The results indicate that a 45-55% of the total land area should currently be vegetated and 1-10% covered by natural birch forest (figure 5). This is in contrast with the current situation (Figure 6), since today 27% of Iceland has vegetation cover but forest occupy less than 1% of the total land area (IGI 1993). It is tempting to interpret this difference as an anthropogenic cause, it is however important to note that the temperature drop during the LIA resulted in the coldest period throughout the Holocene. Such a decrease is likely to weaken the vegetation cover and make it more vulnerable toward the degradation processes. The human intervention possibly played a significant part in disturbing the natural vegetation and forest cover and thus in combination with climatic deterioration during the LIA period, it most likely set the stage for the accelerated land degradation observed today despite seven decades of relatively warm climate.

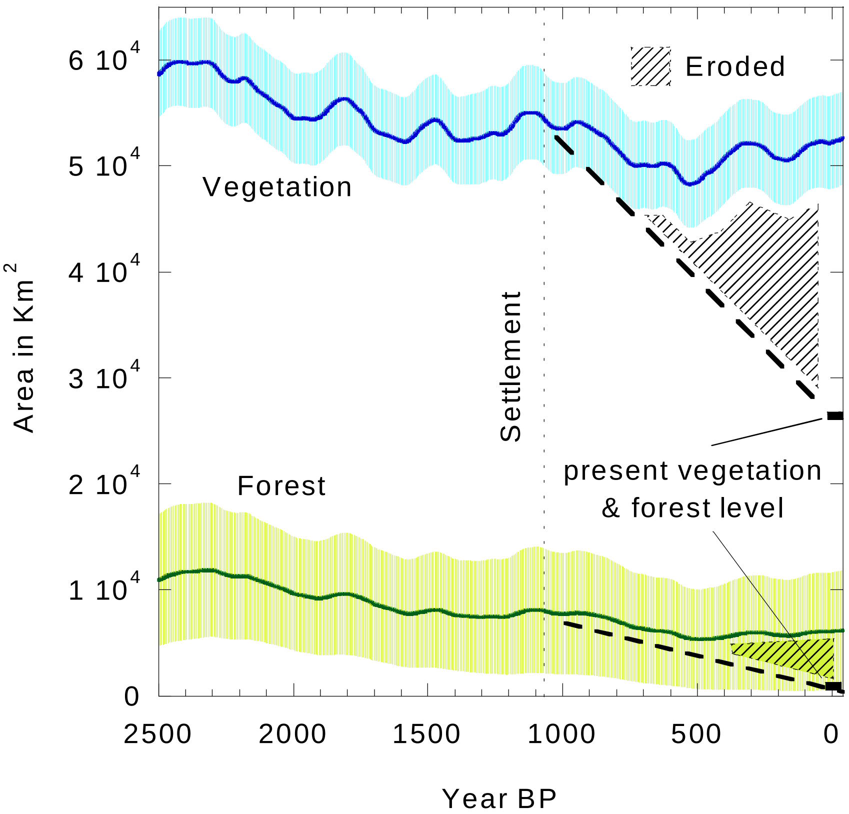

Figure 6. Modelled area cover of vegetation versus present level of vegetation (adapted from Haraldsson & Ólafsdóttir, 2001).

A natural decrease of ~10% in vegetation cover from the beginning of the settlement period could represent a similar reduction in the sustainable yield of these resources. The regeneration capacity in the early settlement period may have been higher than during the colder periods of LIA, even if the rate of harvest was the same. A continuous vegetation cover has a different yield factors, depending on the temperature at any given time. It was observed in the simulations as a downward trend in harvestable vegetation occurred during the LIA (Figure 7).

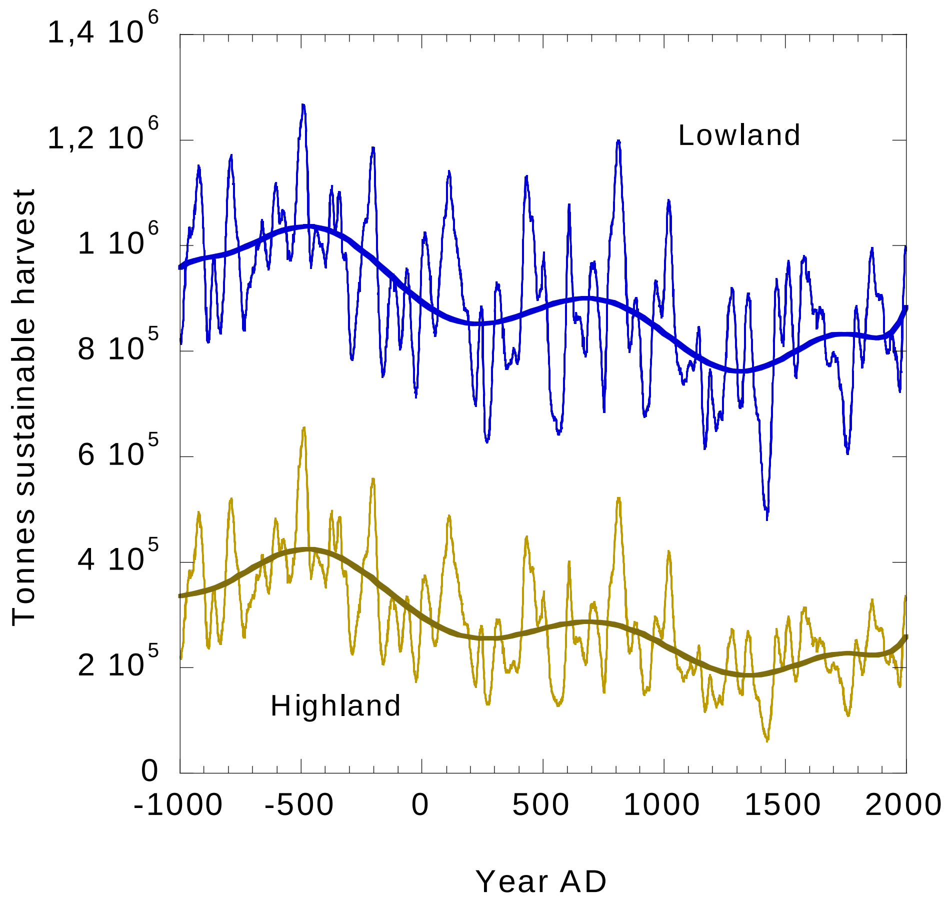

Figure 7. Fluctuation in potential yields in lowlands (<300m) and highlands (>300m) respectively. It is noticeable that during the simulated period, the yield from cultivatable lowlands is 30% lower during the LIA, and 50% reduction is seen in the potential highlands yields during the LIA.

Figure 7 shows the sustainable harvest of vegetation, i.e. the amount of biomass removed that does not affect the natural development of the vegetation cover. The yields from lowlands obtained the maximum possible land area suitable for hey cultivation, which is 600.000 hectares. This is probably not an underestimate since the area used today for hey cultivation is 150.000 hectares. All hey harvest needed during the wintertime for livestock could only come from these sources unless winter grazing was practiced. What is interesting is that the sustainable harvest from the highlands is only ~25% of the cultivated land area. This is the amount available for grazing without hampering vegetation development and triggering eventual degradation (Þorsteinsson, 1972).

4.2 Pre-industrial land-use

An attempting question from the above content is what can the expected population carrying capacity of the ecosystem be if all the available land areas are harvested? Figure 8 shows the maximum population sustained under the assumption that each inhabitant requires 32 livestock equivalents (see assumption chapter).

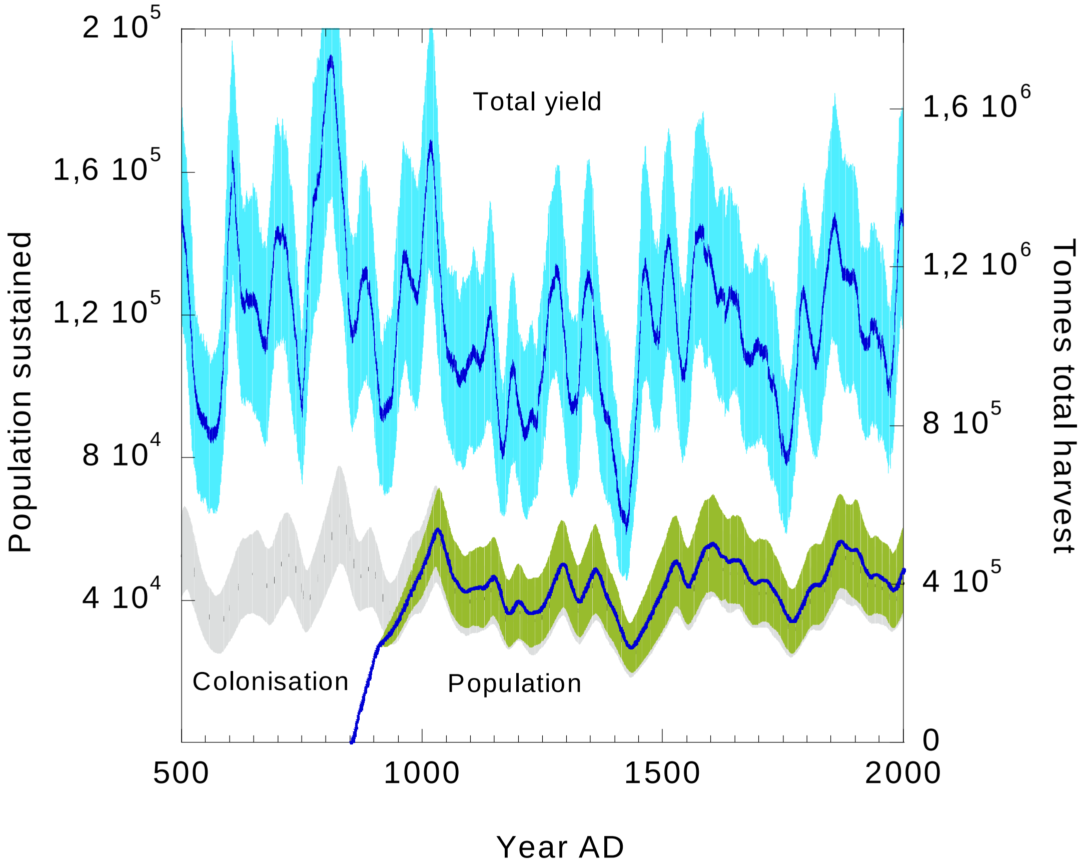

Figure 8. If all cultivatable land area is used and harvestable resources from the highlands are used sustainable, then the environment could support between 30-60.000 inhabitants from the start of the settlement period.

The maximum population sustained by the Icelandic environment is between 30.000-60.000, given that all of the easily accessible land (i.e. 600.000 hectares) for hay cultivation is utilized and the highlands are used sustainable. According to Júlíusson (1998), the pre-historic population fluctuated between 50-60.000. This would result in a periodical overshoot in natural resource use (Figure 9). In colder periods the vegetation cover was under much stress, especially when livestock was winter grazed. Sub-arctic environments are fragile and possibly less resilient toward grazing pressure than other areas. Pollen analytical studies indicate (Hallsdóttir, 1987) that soon after the colonisation soil erosion on a large scale started to reduce the vegetation cover in the transitional area to the barren highlands.

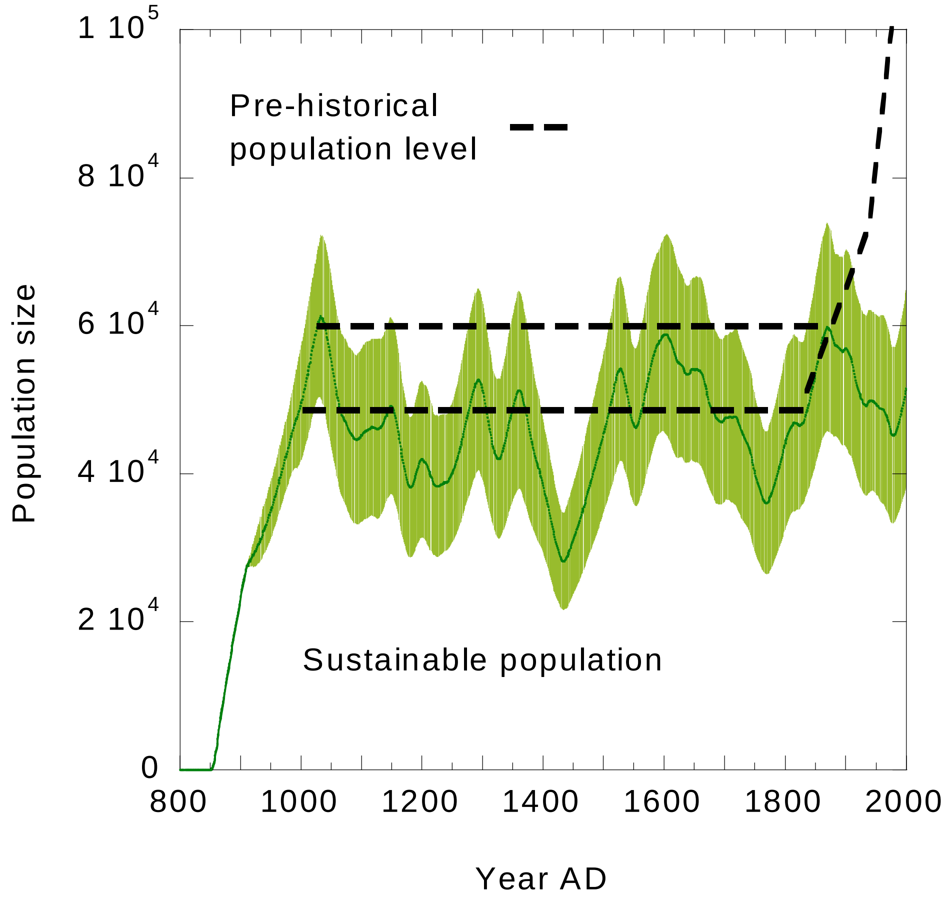

Figure 9. The pre-historical population in Iceland fluctuated between 50-60.000 inhabitants, which was periodically over the size of the simulated sustainable population.

4.3 The relationship between land degradation and carrying capacity

It is generally thought that land degradation and soil erosion has kept the population around the 50-60.000 limits, due to the loss of habitat for grazers (Hallsdóttir, 1987).

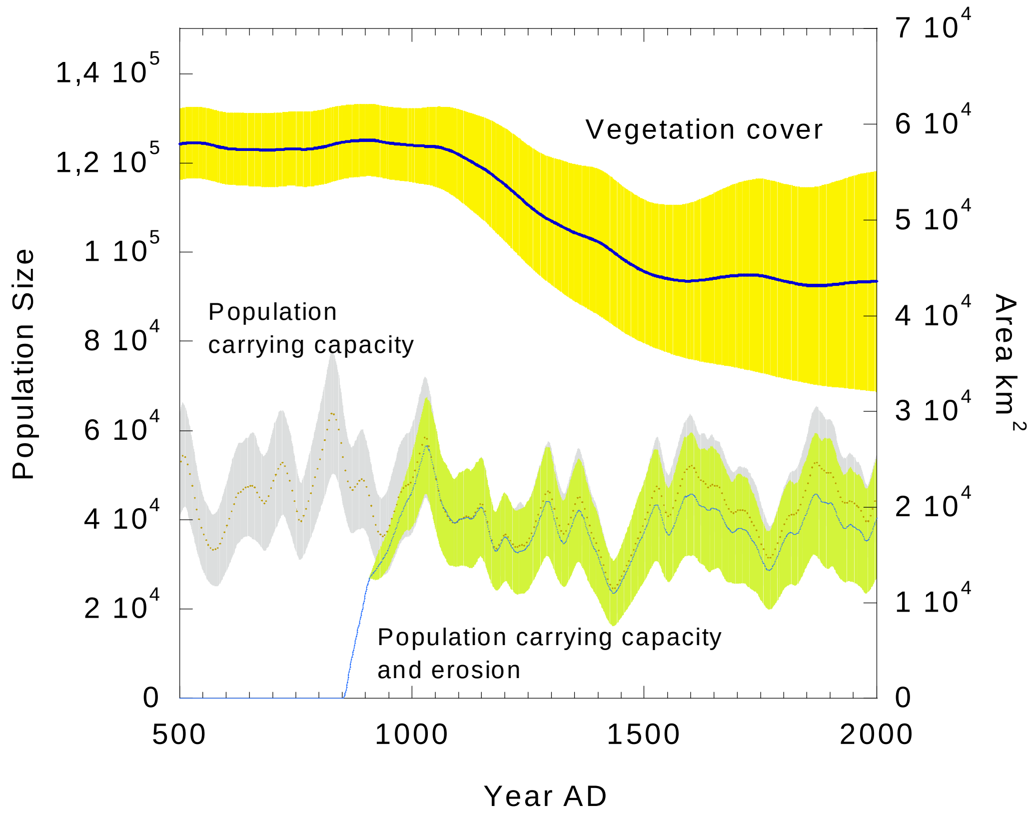

Figure 10. A scenario of extreme land degradation. When the pre-historical population size surpasses the simulated population size, degradation is imposed on the highland vegetation cover. By using 1% degradation (varied 50% during 200 simulations) the carrying capacity of the population is reduced by ~10% by the erosion.

Figure 11 shows a scenario of extreme land degradation, based on overshoot of the actual population in relation to the simulated one, where 1% annual degradation decreases the vegetation cover. The total harvest from the highlands decreases and results in a 10% reduction in population carrying capacity. Livestock is depended on the hay harvested for winter-feed. Since only 25% of the lowland area is cultivatable, the rest of the lowland can act as buffer when the highlands are being eroded. Even if the highland vegetation cover is reduced, it does not affect the hay yields in the lowlands. Even if the vegetation cover is decreasing in the highland, the population can remain fairly constant. The natural capital can be degraded and not show any symptoms on reduced yields in the lowlands.

What implication do such simulations give us for future prognosis of vegetation distribution? As clearly shown in the CDL, the temperature is not the only factor controlling the environment. Furthermore, morphology, giving rise to favourable local conditions, and varying precipitation are elements that influence the ecosystem development in Iceland. Another important aspect is annual fluctuation in temperature. According to Bergþórsson (1996), summer days that are "very warm" are important to facilitate growth and often the number of such days is more important than the average temperature of the month. These components are not included in our model but could give some different results if considered.

4.4 Potential of revegetation and carrying capacity

One aspect of human imposed action on the environment is to determine its impact on vegetation development in Iceland. The anthropogenic emission of CO_2 is believed to be the main cause for an increase of the average global temperature for the past decades (IPCC 1996). The international panel on climate change (IPCC) predicts an average increase of an average of global temperature between 1°C and 3°C over the next 100 years. An increase of global temperature is expected to have a profound effect on vegetation development around the globe. In Iceland, such development could lead to an increase in the potential vegetation cover. The IPCC expects that the lag time of CO_2 in the atmosphere, from the time emissions stop to a new equilibrium to be 100-500 years, where a decrease is most rapid during the first 100 years but acquires a new equilibrium 15% higher than the current one. This scenario was run in the model to see the effects on the Icelandic vegetation cover (figure 11).

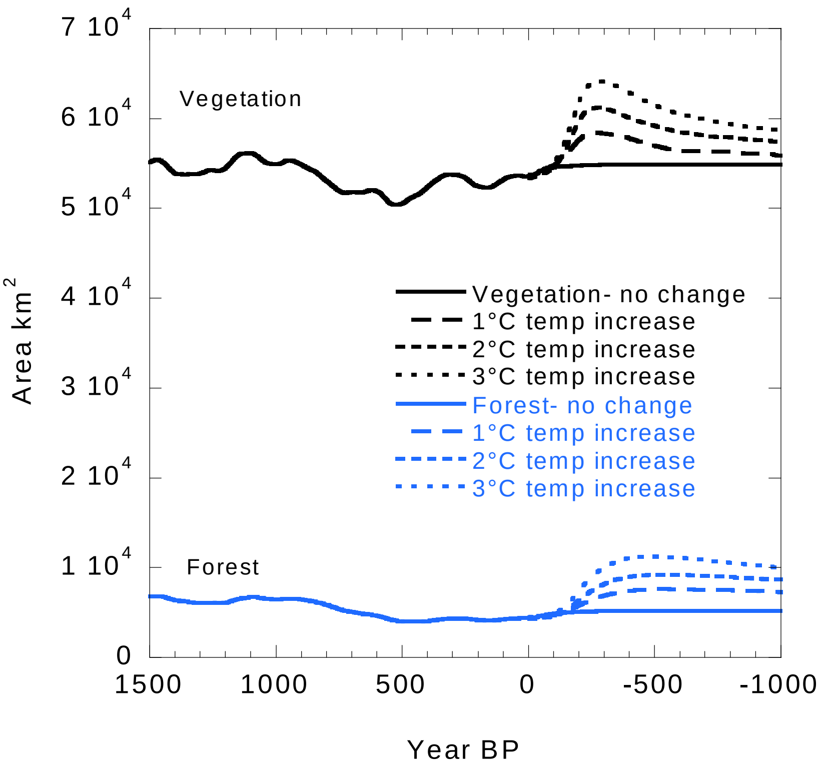

Figure 11. Modelled increase in vegetation cover due to increased temperature and excluding land-use.

Figure 11 shows the potential vegetation and forest cover from a simulated increase (i.e. 1°C -3°C increase) in temperature due to climatic change over the next 150 years. The area covered with vegetation and forest increases but levels out as the effect of climate change wears out. Even a small increase in temperature is expected to have an impact on vegetation and forest development. If climatic changes give a rise to 3°C increase in temperature in the nearest future the natural increase in vegetation and forest cover from the present level will be much faster than we may expect according to normal conditions (Figure 12).

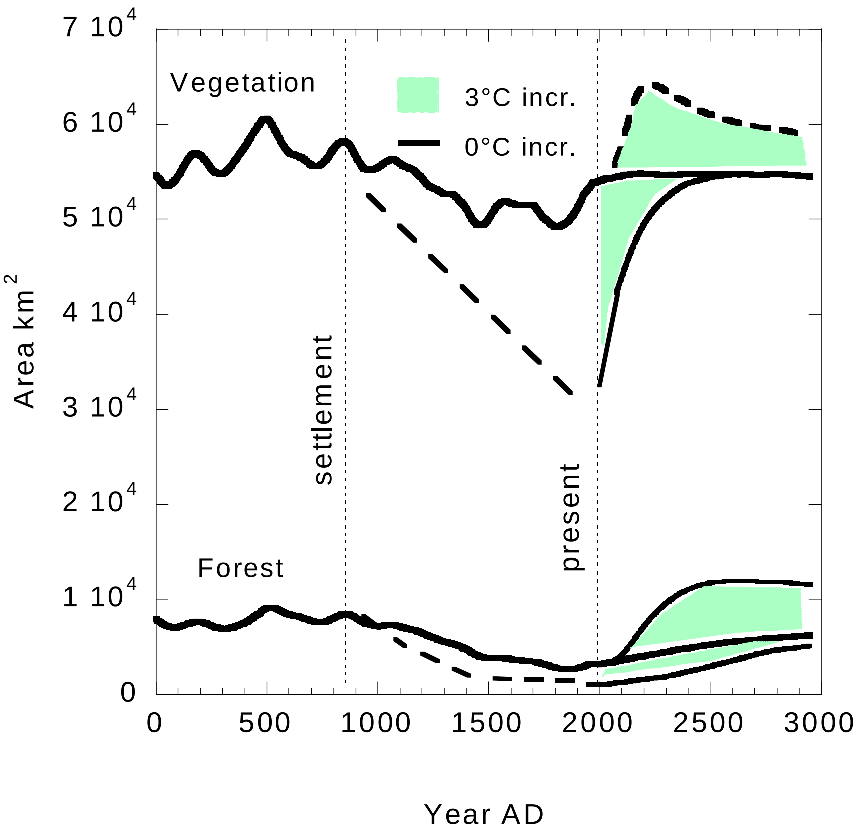

Figure 12. Vegetation development over the next millennia with current annual temperature and with a 3°C increase. Dashed line shows the vegetation development from the time of settlement.

The carrying capacity can be described as the percent area covered with vegetation. Hence, the implication could temporarily result in higher carrying capacity but only as long as the climatic effects last. In the short term, it could mean that areas currently barren may be reclaimed by the vegetation and boost land-use possibilities. However, looking at the long-term perspective such efforts will probably be reversed and produce similar problems we deal with today. Knowledge on carrying capacity can aid us to steer management and reclamation practices towards more reasonable goals, where we are aware of the consequences of our actions.

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