A modelling approach for evaluate the pre-industrial natural carrying capacity of human population in Iceland

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Abstract

A simple approach was used to evaluate the potential human population that the pre-industrial Icelandic environment could sustain. A model was constructed that simulated the population size according to potential biological production available for livestock. Biological production was determined by the extent of the total potential vegetation cover based on the Degree-day concept. Fluctuations in the mean annual temperature cause changes in the potential vegetation cover and as a consequence change the biological production sustaining livestock and ultimately human population. The simulation's results indicate that the potential population that the environment could sustain during the pre-industrial period fluctuated around 40-80 thousand. The results further indicate that the severe land degradation experienced after the settlement period had a marginal impact on the population size. The prehistorical population did however overshoot the natural sustainability on few occasions.

Key words: *Systemic, vegetation cover, sustainable population, carrying capacity, pre-industrial, climate change, Iceland*

1 Introduction

To increase our understanding of the factors affecting natural sustainability, understanding the past is critical. Iceland is currently facing severe land degradation. It is generally believed that the Icelandic ecosystems have lost half of its vegetation cover and nearly all of its forest cover since the recorded Viking settlement in AD 874 (Þórarinsson, 1961; Einarsson, 1963; Þorsteinsson, 1972; Bergþórsson, 1996). Many factors are likely to have contributed to these changes, such as harsh climate, natural catastrophes, fragile ecosystems and human settlement. Changes in mean temperature are believed to be the largest factor attributed to long term changes in the vegetation cover (Bergþórsson, 1985; Bergþórsson *et al.*, 1987; Bergþórsson, 1996).

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2 Objectives and aims

This study attempts to assess the carrying capacity (CC) of the Icelandic ecosystem to sustain a population in a pre-industrial environment (the period before AD 1850) by using simple approach through a System Dynamic (SD) modelling procedure. The SD modelling procedure is a top-down analysis where variables are sorted to understanding cause and effect and outlined in a Causal Loop Diagram (CLD) (Roberts *et al.*, 1983). By understanding processes on an aggregated level, it is possible to gain an overview of the basic system properties (Richardson and Pugh III, 1981; Ford, 1999; Maani and Cavana, 2000).

The Icelandic environment is treated as a single system that exists on multiple hierarchal levels, i.e. the ecosystem productions and the abiotic environmental factors. The observation takes the 'eagle' perspective and focuses on feedbacks that are responsible for sustaining CC. The main approach is simplicity over details and the purpose is to obtain an approximate overview. The study aims to:

- To use earlier model effort to develop a new model that includes livestock population, human population and erosion
- Estimate the potential biological production available for livestock
- Evaluate the potential human population in the pre-industrial Icelandic environments
- Investigate the impact of land degradation on a) the total potential biological production, and on b) the potential human population size

The key questions the study seeks to answer are:

- How large pre-industrial population could the Icelandic ecosystem sustain during and after the settlement period (AD 900)?
- What is the impact of land degradation on maximum sustainable population after the declination of the forests and vegetation cover?

3 Carrying capacity

The concept of CC, in it most generic form, determines the maximum livestock or wildlife population that a habitat or ecosystem can support on a sustainable basis (Kessler, 1994). Kessler (1994) and Monte-Luna *et al.* (2004) define CC as the maximum population size that is sustained on multiple hierarchal levels of biological integration and environmental processes on a given area, with finite resources, that is confined both spatially and temporally. Regarding land-use, the human CC is depended on maximum exploitation of resources in a given area (spatially and temporally) that are used sustainable and cause no irreversible land degradation. Monte-Luna *et al.* (Monte-Luna *et al.*, 2004) points out that the CC is dynamic and can vary according to the interplay between different biotic and abiotic feedback processes. In sub-arctic and arctic environments, this interplay is very sensitive toward climatic fluctuations. Climatic changes may sprout a new development to the ecosystems, in which the ecosystems have to adapt towards the changes (Woodward, 1987; 1992). However, numerous definitions on the CC exist and the concept has been largely debated and criticized. Dijkman (1999) gives a detailed review of the different definitions and discusses if the concept still is a useful management tool. He concludes the concept to be an important issue in the present natural resource management. Hence, along with the increasing recognition on sustainable development, CC may advocate management of land use within sustainable limits.

Haraldsson and Olafsdsottir (2003) generated a model for simulating long term potential vegetation and forest cover in Iceland during the Holocene. Their model give a rise to examine the ecosystems CC. Hence, how large human population could the vegetation and forest cover sustain during the pre-industrial period? The pre-industrial period in Iceland is regarded as the time from the recorded Viking settlement in AD 874 until mid 19th century. Further, is the human settlement the triggering factor of the ecosystems decline?

4 Theoretical background

4.1 Previous modelling effort

In the Haraldsson and Ólafsdóttir (2003) study, a CLD was developed to map out the important factors and feedback loops responsible for vegetation development and land degradation during the Holocene (Fig. 3).

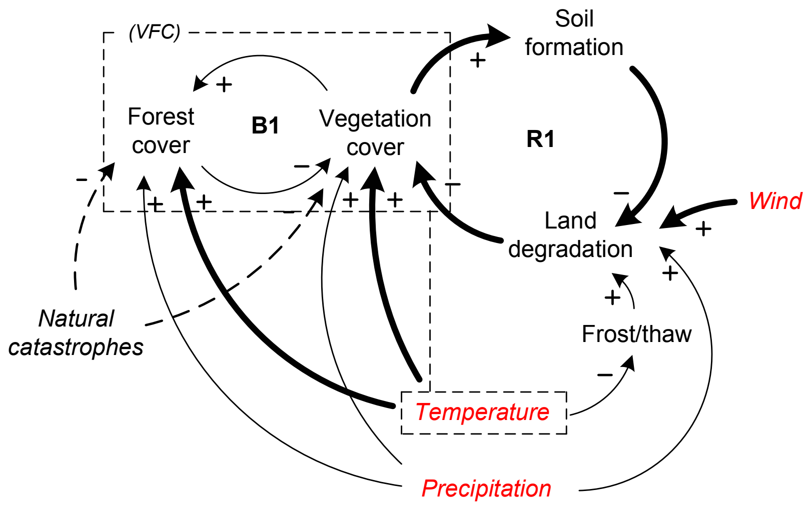

Fig. 3: *A CLD representing an overview of the processes of vegetation and land degradation in Iceland during Holocene (excluding human interference). The dotted line represents the first stage (Stage I) of the model (VFC) as published by Haraldsson and Ólafsdóttir (2003).*

Of influencing variables, temperature drives both of the loops (B1 and R1) and is through vegetation cover responsible for increased soil formation. Land degradation is influenced by wind, precipitation and frost/thaw processes. These variables constantly drive land degradation and the only way to suppress it is through increased vegetation cover that increases the soil formation (or reclaims the degraded land). In that sense, there exists a tug of war between the processes that serve to increase the vegetation/forest cover and the degrading forces that are constantly at work. The first modelling effort (stage I) focussed on developing vegetation and forest cover model (VFC) dependant on temperature (Fig. 3) (Haraldsson and Ólafsdóttir, 2003).

4.2 Present model development

Before the Viking settlement no herbivorous mammals are known to have existed in the Icelandic ecosystems. Hence, it has been suggested that the loss of forest cover due to grazing pressures in combination with a colder climate, resulted in an accelerated land degradation and consequently lower CC of the environment to sustain its population (Þórarinsson, 1961; Arnalds *et al.*, 1997). If anthropogenic factors are added to the above CLD analysis (Fig. 4), it is clear that increased population and livestock reduces the forest and vegetation cover and may result in accelerated land degradation (Loop R1). Still, the climatic fluctuations, through temperature, either increase the forest and vegetation cover sufficiently to counter the utilisation of the livestock and population or enhance the destruction of the cover.

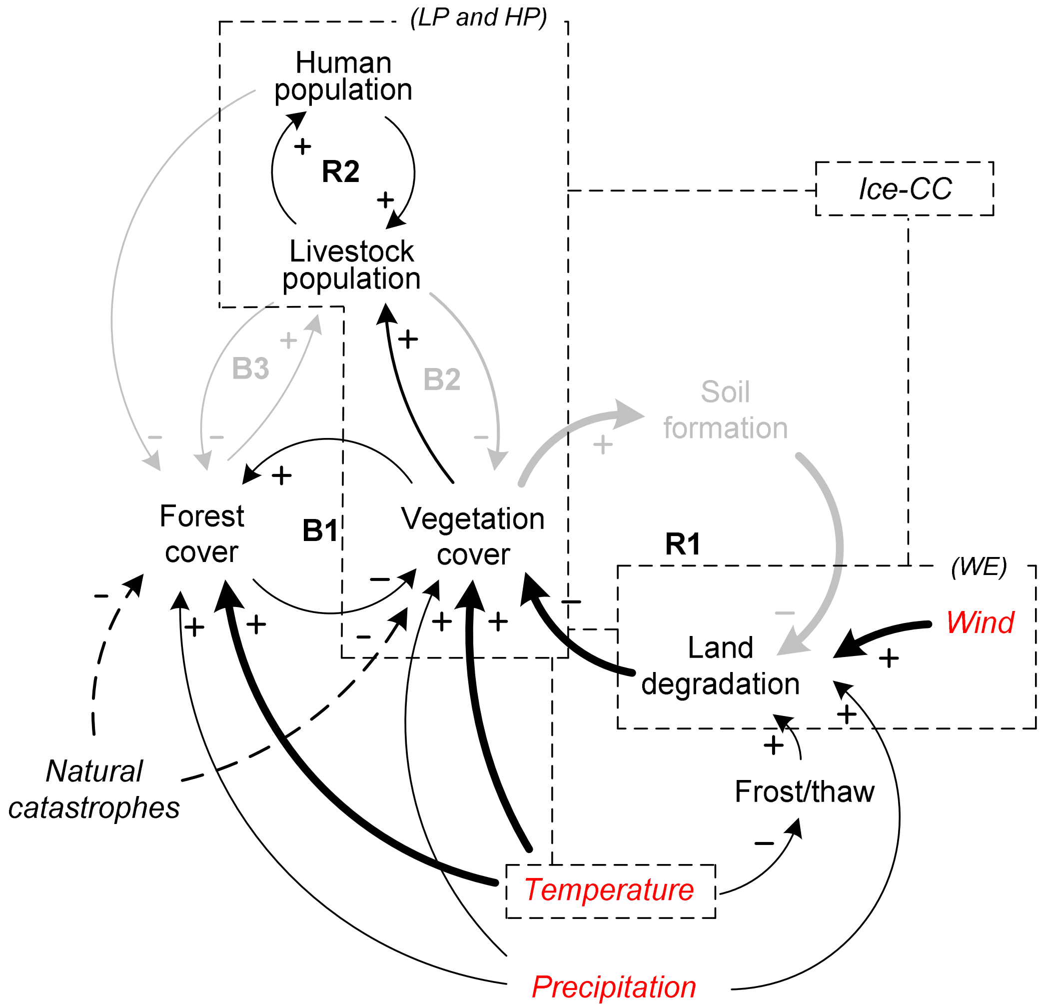

Fig. 4*: An overview of the integrated natural and anthropogenic factors influencing potential biological production in Iceland. The dotted line shows the stage I model simplified with sub-models; livestock and Population model (LP and HP) and wind erosion model (WE), added in stage II for building the combined Ice-CC model used for simulating the natural carrying capacity for human population in Iceland. The shaded links and loops show feedbacks that are not used in the Ice-CC model setup.*

The stage II model development builds upon the VFC modelling effort which has been modified to simulate vegetation cover (VC) only. As in the VFC model, temperature drives the VC model. The VC model divides the vegetation cover up to six different modules that represent vegetation cover at different elevation levels (*c.f.* Fig, 10). The VC model is used to simulate biological production (*c.f.* parameterisation in chapter 6) which sets the limits for the maximum number of livestock (LP) and the LP in turn sets the limits for maximum human population (HP). In the model setup, the LP and the HP model have no feedback to the VC model (*c.f.* CLD shaded links in Fig. 4). As a result the VC model simulates biological production as a natural sustainable production and the LP and HP use that as basis. A wind erosion model (WE) is attached to the VC model to recreate erosion history. The WE model is independent from VC model (i.e. there is no feedback, *c.f.* Fig. 4). The WE model, only intents to recreate the erosion history and starts right after the settlement. The combination of the VC, WE, LP and HP make up the Ice-CC model that is used tosimulate the CC for the human population in Iceland.

5 The principles of the VC, LP, HP and WE models

5.1 The VC, LP and HP models

The basic approach in the models structure is simplicity. The purpose is to give an overview of approximate numbers in the simulations and at the same highlighting the assumptions and the limitations. The basic function in the VC model calculates the area of vegetation as follow *(dA/dt)*:

$$\frac{dA}{dt} = k_g \cdot A \cdot \left(\frac{A_p - A}{A_p} \right) - \left(A \cdot k_d \right) \tag{1}$$

Where k_g is coefficient of growth establishment rate and k_d is the coefficient of decay rate, A is the actual area cover in km^2 according to the function $k_g \cdot A$ and the favorable area A_p is depended on the calculated number of Degree-Days (Haraldsson and Ólafsdóttir, 2003). The A_p is the maximum vegetation cover that can be sustained according to the conditions given by the Degree-Days. The basic principles are shown as a CLD and a System Dynamic Tool Diagram (SDTD), (Fig 5). The basic structure of the VC was used as a template for simulating the LP and the HP model.

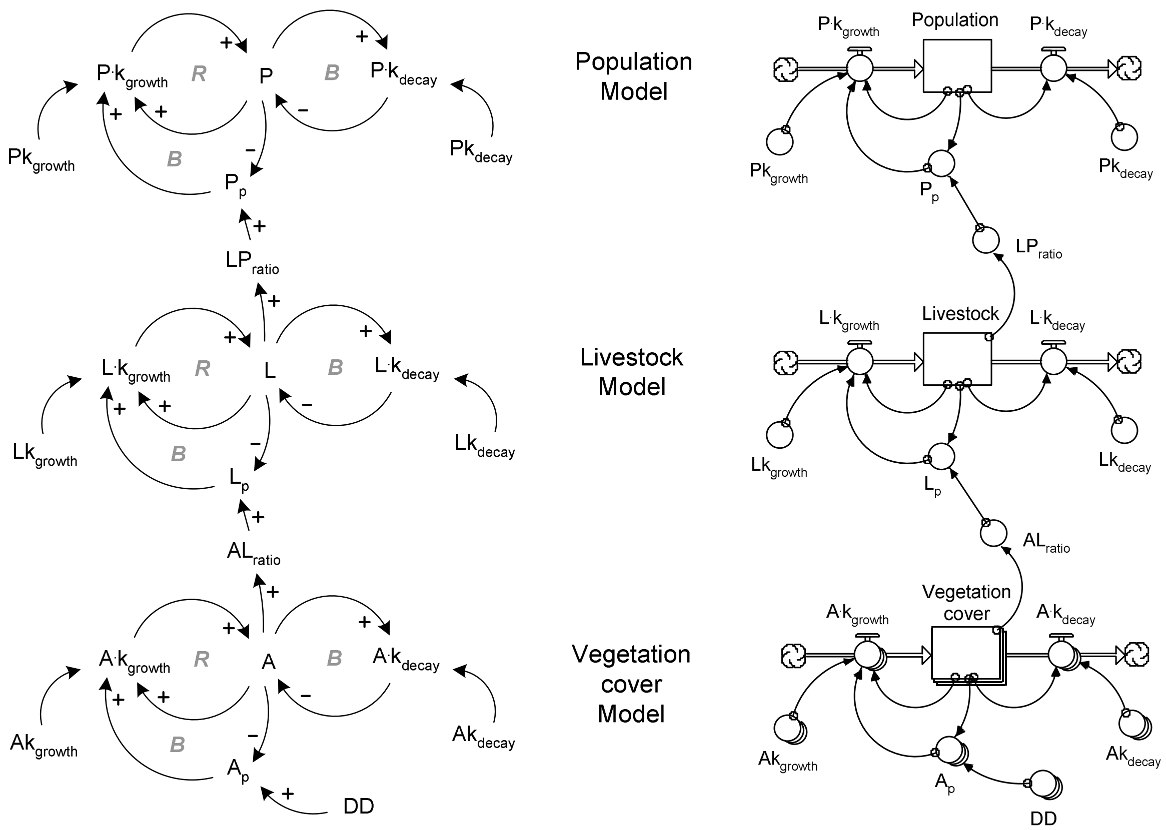

Fig. 5: *The VC, LP and HP models. The CLD was translated into a SDTD which is used for the numerical simulation. The VC model is arrayed to represent the effect of elevation. The model is the basis for the LP and the HP model.*

The L_p and P_p variables are limiting factors for the size of LP and HP populations. The models, VC, LP and HP are combined through ratios that have the dependence functions AL_{ratio} and LP_{ratio}. The size of the vegetation cover A is translated, using the ratio AL_{ratio}, into the potential biological production for sustaining a livestock population. The number of livestock

L is translated, using the LP_{ratio}, into the maximum sustained human population. For the purposes of this paper the variables A_p, L_p and P_p are defined as the carrying capacity for each module. The L_p is the sum of the biological production available for livestock, the P_p is the sum of livestock available for human population. The simulated sustainable population is ultimately dependent on the variable A_p and the temperature fluctuations.

5.2 The WE model

Wind erosion is considered to be the largest erosion mechanism in the Icelandic environments (e.g. Arnalds *et al*. (1997)). The effect of wind erosion on vegetation cover in Iceland has been categorised into six stages (Aradóttir *et al.*, 1992). The first stage represents fully vegetated area and the sixth stage represents total lack of vegetation (Fig. 6). The third and fourth stages show the critical thresholds triggering changes in stable stages. The loss of vegetation over time is conceptually perceived through non-linear behaviour.

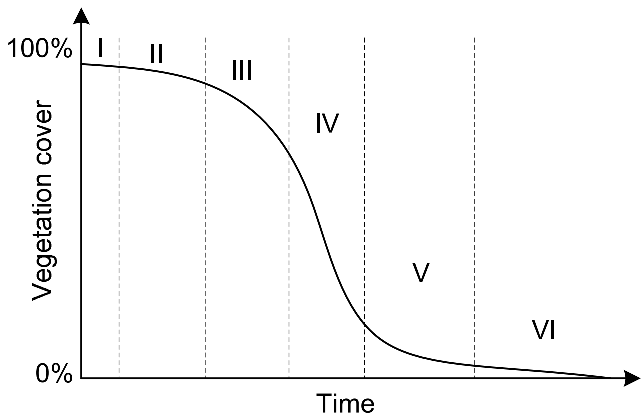

Fig 6: *A conceptual model of the effect of erosion on vegetation cover (Aradóttir et al., 1992).*

A CLD describing the principles of erosion is presented in Fig. 7. Vegetated area (highland and lowland) is reduced by erosion, which in turn is determined by the erosion rate. The CLD for the erosion is translated into a SDTD for running numerical simulation of WE model forvegetation cover. The WE model was divided into five sections according to the five given erosion grades, and attached to each elevation interval (Fig. 7).

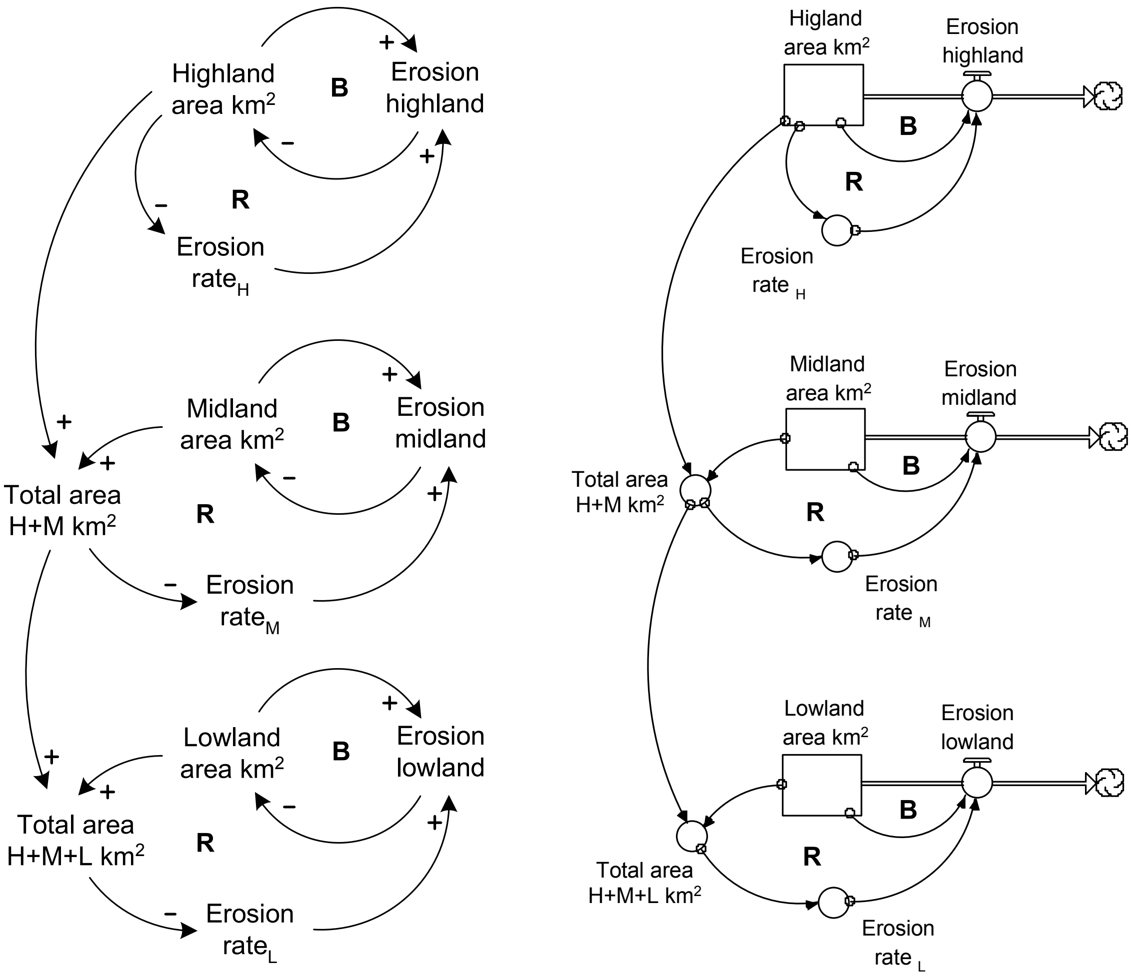

Fig. 7: *Basic layout of erosion setup used in the erosion model (WE), represented in CLD and SDTD.*

Erosion rate for each interval is given the start value (*c.f.* Fig. 10), where grade one is given to the lowest elevation interval (0-100m) and the grade five is given to the highest elevation interval (400-600m). The erosion rate of the lower elevations is affected twofold, by the area km^2 under its elevation interval and the sum of area of the vegetation cover above its interval range, i.e. sum area between 200-300m plus the sum of all area above 300m. The assumption is made that erosion on lower elevations is affected by the erosion on higher grounds through wind borne materials that is transported to onto the lowlands. At higher elevation larger erosion rate is assumed since the vegetation cover is more vulnerable towards the climatic changes than the vegetation cover in lowlands.

5.3 The Ice-CC model

The Ice-CC model is an integration of the VC, WE, LP and HP models. Ice-CC evaluates the CC. Figure 8 illustrates the simplified CLD and how it is translated into a SDTD.

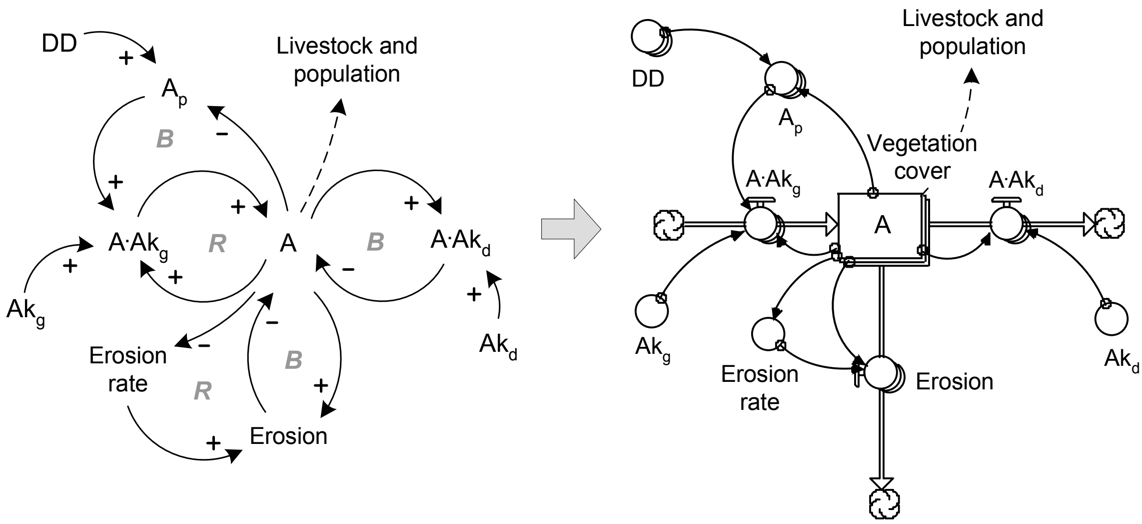

Fig. 8: The Ice-CC is an integrated model from the VC, LP, HP and the erosion model (WE).

6 Model parameterisation

6.1 Parameterisation for human population and livestock population

Historical records are used to estimate the human population size in the early settlement period and to create the ratio of livestock per person and furthermore the potential biological production per hectare land. The beginning of the human settlement in Iceland is set to AD 874 and the following 100 years are assumed to be the settlement period. According to historical records (Júlíusson, 1990) the human population size is believed to have fluctuated around 50,000 inhabitants until the 18^{th} century where it progressively increased to the present level of 290,000 (Statistic Iceland 2004). The following assumption and limitation strategy is used in the Ice-CC model:

- The forest cover is assumed to be part of the vegetation cover. The model, therefore, only simulates vegetation cover.
- Only livestock is affected by vegetation cover and not vice versa
- Erosion only recreates historical behaviour and is not affected by vegetation cover.
- The model uses livestock (sheep, cattle and horses) to influence human population.
- The human population renewal and decline is an arbitrary number of 2%.
- Studies have shown that biomass availability for livestock in moderate grazing conditions range between 35-45% (Holechek *et al.*, 1999). This study uses 35%.
- Lowland is considered all the area below 300 meters a.s.l., and highland all the area above 300 meters a.s.l.
- Biological production from lowlands and highlands is converted into 'winter feed' units for livestock.
- Estimates of farmable land area in Iceland range between 10-15,000 km^2 (Jóhannesson, 1960). Currently the land utilised for farming is c.a. 1,200 km^2. Before AD 1900 the farming land was approximate 170 km^2 (Þorsteinsson, 1972). Kristinsson (1998) uses 6,000 km^2 as easily farmable area after subtracting wetlands areas, that number is used in this simulation.
- The biological production in lowlands is a triangular function. The highest productions are at sea level and close to zero at the transitional zone at the upper limits of the vegetation cover. The biological production is a function of annual temperature (9.5×10^{-3} * (Degree Days)-2.04) which is derived and modified from Þorsteinsson (1972).

- Individual minimum requirements of livestock *(LP_{ratio})* for human population was estimated from Júlíusson (1998) and (Ólafsdóttir and Júlíusson, 2000) as: 1 cow, 5.5 sheep, 0.5 per individual for horses.
- The annual renewal of livestock *(Lk)* in favourable conditions is based on individuals requirements for livestock (i.e. 1 cow/person, 0.5 horse/person and 5.5 sheep/person). The decline is a function of biological production availability per livestock. Ten percent of the livestock is removed if requirements are not met.
- Annual produced biomass per hectare is converted into units for winter feed *(AL_{ratio})*. Biomass requirements per animal are based on daily dry matter intake (DMI) of their live weight (LW). Table 1 shows required winter feed per livestock according to LW.

Table 1. Annual winter feed requirements for livestock.

Livestock	LW kg	Daily requirement % DMI of LW	Annual winter feed DMI in Tonnes
Horse	350	2[a]	1.5
Cattle	400	3[b]	4.02
Sheep	70	2.5[c]	0.37

[a](Planck, 2001), [b](OMAF, 2004), [c](NRS, 1985)

- 20% is subtracted from the total biological production due to loss of nutrition in the storing process of the winter feed.
- Fishery activities are excluded as a part of diet for the population
- Catastrophic events (such as volcanic activity) and plagues are excluded from the model

6.2 Erosion model parameterisation

To model an annual loss of vegetation cover in Icelandic ecosystems this study uses the erosion calculations by (Arnalds *et al.*, 1997). They use five erosion grades to describe the condition of the vegetation cover from fully vegetated to barren landscape, where the most degraded land is graded 5. This information is used to plot the rate of erosion according to proportion of vegetation cover in all the erosion grades (Fig 9). The different erosion grades used by Arnalds *et al*. (1997) are consistent with the conceptual diagram developed by Aradóttir *et al*. (1992). Hence, it is assumed that the rate of erosion for each grade in Fig. 9 could be combined with the different stages in Fig. 6. This information is used for calculating the erosion rate in the WE.

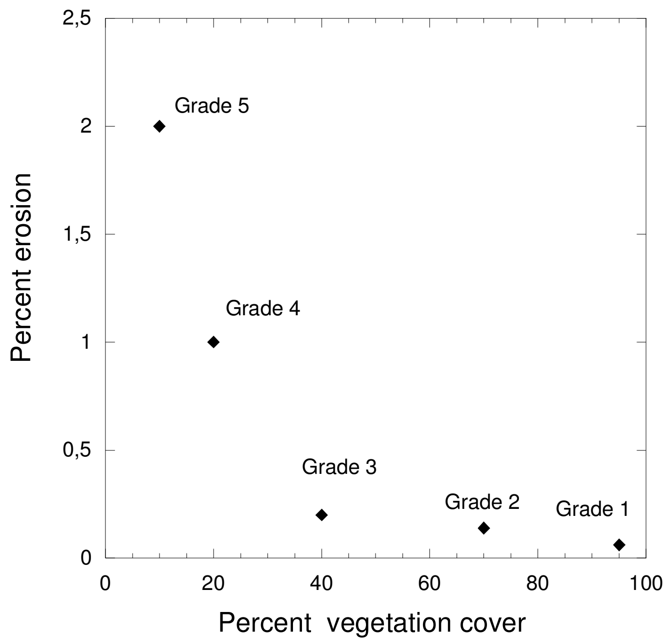

Fig. 9: *The rate of erosion in relation to proportion of vegetation cover (modified from (Arnalds et al., 1997).*

7 Integrated model utilisation

The input parameters for the Ice-CC model are the same as for the *stage I* VFC model with additional coefficients for the human and the livestock population as well as coefficients for erosion. The whole model utilisation process for the modelling procedure is shown in Fig. 10.

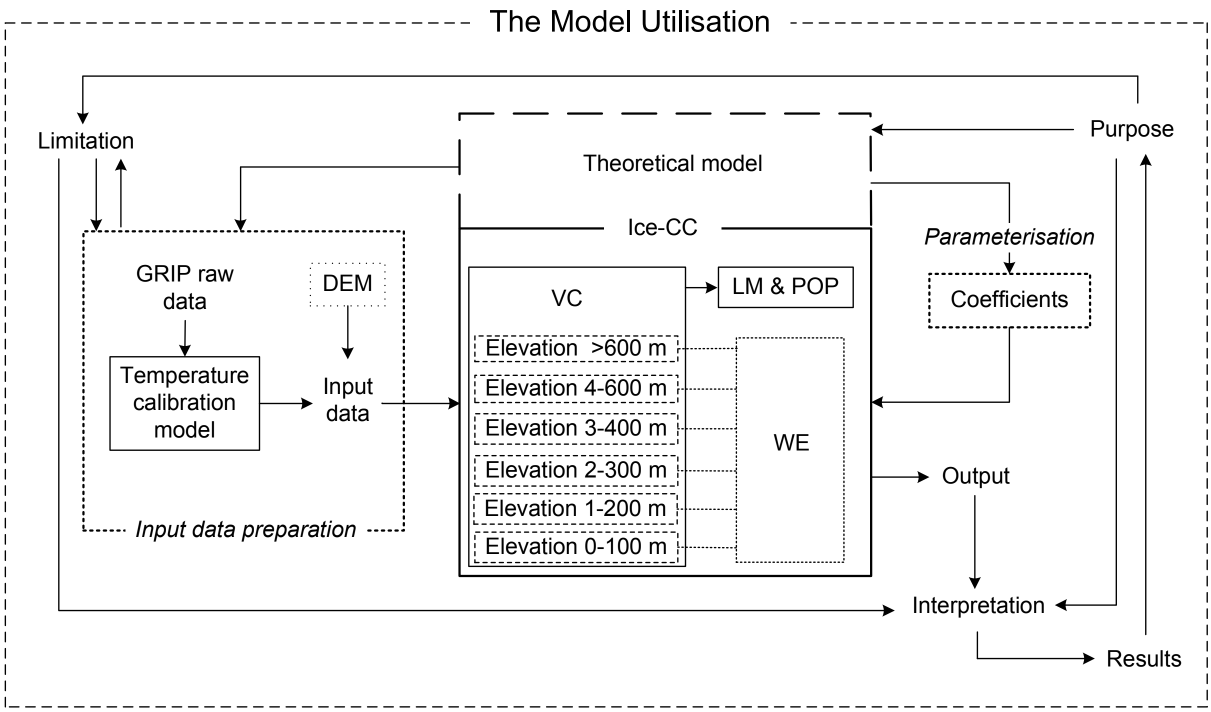

Fig. 10: *A Model Utilisation chart of the Ice-CC model and sub-models as well as its supporting modules for producing simulated outputs.*

The Model Utilisation includes the complete process form developing the core principles for the model theory to using different tools for input data preparation and parameterisation of the coefficient for the numerical model.

8 Results

8.1 Simulated Carrying Capacity

The simulated results are based on 30 year running mean with standard deviation (shaded area when shown) from 100 Montecarlo runs. Sensitivity was assessed by varying the input parameters by 10%. This was done for vegetation cover as well as for erosion. Simulated potential biological production for both lowlands and highlands is shown in Fig. 11. The simulation present sustainable production, i.e. the amount of biomass removed that does not affect the natural development of vegetation cover. Fluctuated trend in biomass over the whole period is observed, with apparent higher impacts for the vegetation in the highlands.

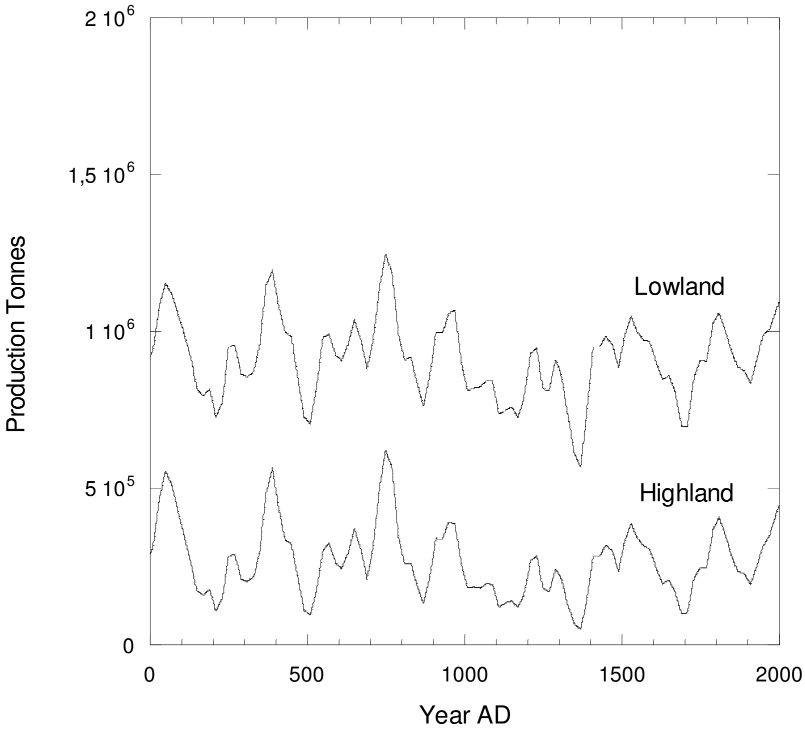

Fig. 11: *Simulated potential biological production in lowlands (<300m) and highlands (>300m) respectively.*

8.2 Pre-industrial carrying capacity

The simulations suggest that if all cultivatable land area is used sustainable as well as yieldable biological productions from the highlands, then the environment could support a human population between 40-80,000 during the pre-industrial period in Iceland (Fig. 12). The pre-industrial population in Iceland fluctuated from 50,000 to 60,000, which is within the simulated result of sustainable human population from the Ice-CC, assuming no erosion effects (Fig. 13).

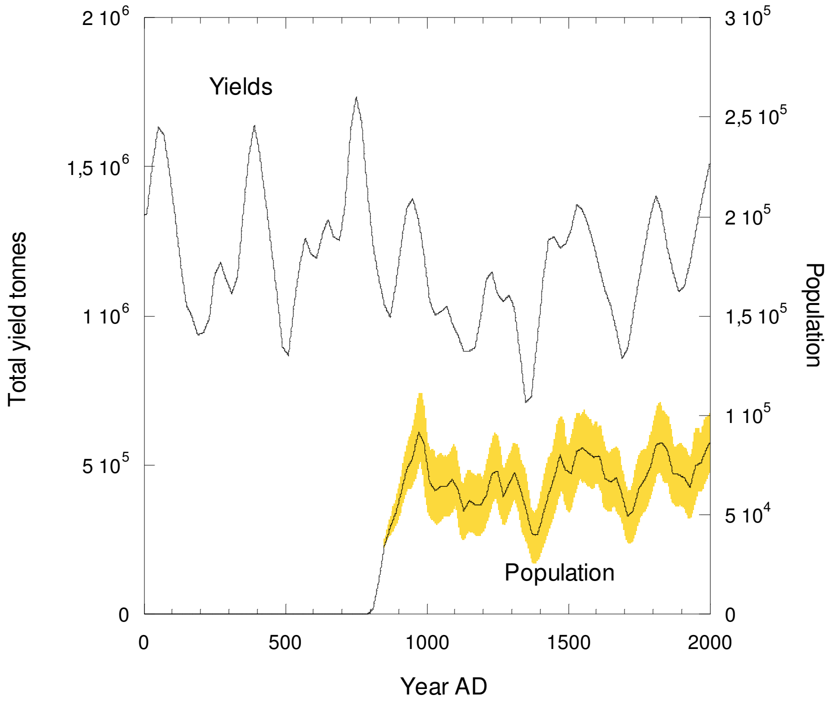

Fig 12: The Ice-CC results on pre-industrial carrying capacity. *(shaded area is standard deviation).*

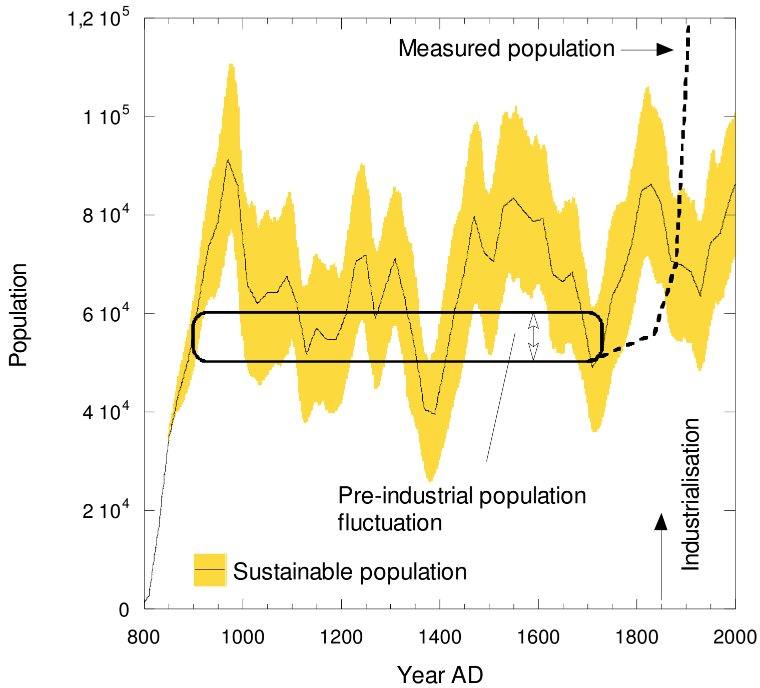

Fig. 13: *The simulated pre-industrial human population in Iceland.*

8.3 The relationship between land degradation and carrying capacity

The WE model attempts to recreate historical erosion behaviour. The impact of erosion on biological production is shown in Fig, 14. The impact of erosion on the human population carrying capacity is shown in Fig, 15.

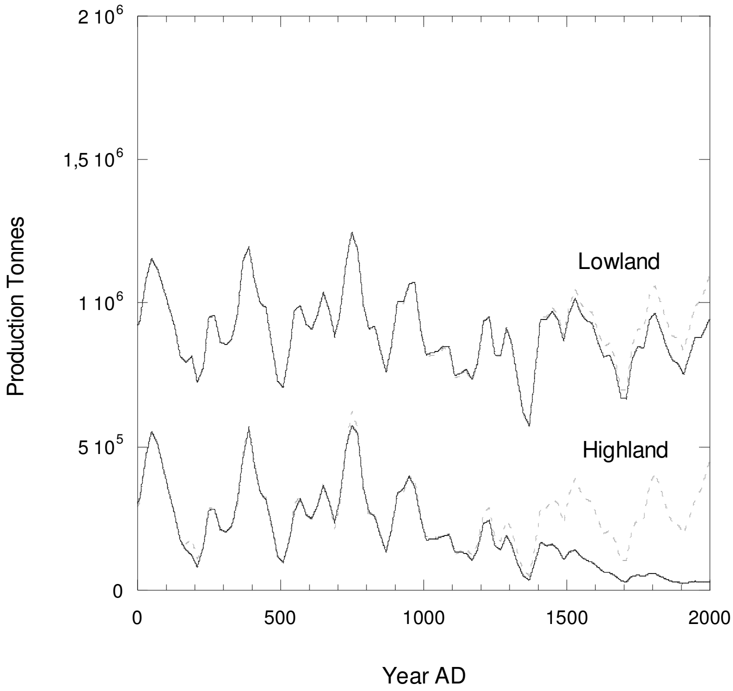

Fig. 14: *Biological production from cultivatable area from lowlands and usable area in the highlands with the impact of erosion.*

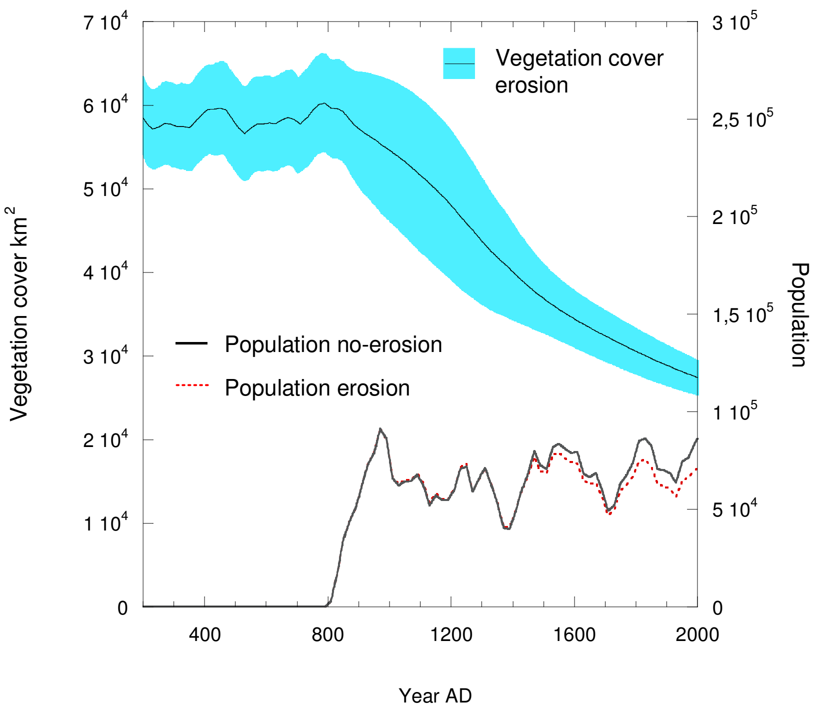

Fig. 15: *The impact of simulated erosion on sustainable human population is small compared to the declined vegetation cover. Human population in erosion scenario is imposed on population simulated with no erosion.*

9 Discussions and conclusions

9.1 Historical implications

The simulated biological production from cultivatable lands fluctuated considerably during the last 1000 years. The biological production from lowlands, obtained from the maximum possible land area suitable for winter feed, is 600,000 hectares, is probably not an underestimate since the area used today for winter feed production is 150,000 hectares. This suggests that the human population in the pre-industrial era maximised the total potential area for production. All winter feed needed during wintertime for livestock could only come from these sources unless winter grazing was practiced. This implies the sustainable threshold, i.e. the amount available for grazing without hampering vegetation development and triggering eventual degradation. The simulated results further suggest that the long-term effects of temperature fluctuations may have reduced the biological production up to 40% during the coldest periods of the LIA. This is somewhat more than estimated by Dýrmundsson and Jónmundsson (1987) which showed that fluctuations in the annual mean temperature could result in a 10-20% decrease in the biological production from the rangelands.

If the assumption is given that all of the easily accessible land (600,000 hectares) for biological production is utilized and the highlands are used for sustainable grazing, the maximum sustainable human population ranges between 40,000 and 80,000 according to the assumptions in section 6.1 (*c.f.* Fig. 12). This coincides with Júlíusson (1990) revealing the human population to fluctuate between 50,000 to 60,000 inhabitants in the pre-industrial era. That amount would have resulted in an occasional overstepping the natural carrying capacity. Sub-arctic environments are fragile and possibly less resilient toward grazing pressure than many other environments. In colder periods the vegetation cover is likely to have been under much stress, especially when livestock was winter grazed. The simulated sustainable population is frequently above the actual pre-industrial population (*c.f.* Fig. 13). Only in a few periods, the simulated sustainable population matched the actual population. Around AD 1400 there is a sharp decrease in the annual mean temperature which lasted few decades . It reflects a steep decline in the simulated population. Such a scenario would probably be devastating to the potential vegetation cover and perhaps be a trigger for the land degradation processes that characterised the LIA.

Land degradation shows a reduction in the total biological production (*c.f.* Fig, 14), resulting in reduced carrying capacity for the human population (*c.f.* Fig. 15). Livestock is dependant on the winter feed from the lowlands and since the most reduction in the vegetation cover takes place in the marginal areas in the highlands, there is not much reduction in the long-term CC of the human population. Thus, the potential vegetation cover may reduce in the highland and still show no significant changes on biological production from the lowlands and subsequently the CC of the human population (*c.f.* Fig. 15). That may explain why the land degradation continued without severe consequence for the population throughout the centuries into the mid 19^{th} century. The general notion (Hallsdóttir, 1987; 1995) is that loss of habitat for grazers kept the human population around the 50,000-60,000 limits . The simulated results in this study show much wider fluctuations and furthermore that loss of habitat was not the limiting factor but the biological production from the cultivatable areas in the lowlands.

Addressing the question initially stated in the paper, the following can be said; 1) The simulated human population (in the pre-industrial era) in Iceland fluctuated considerately the last 1100 years and thus the population CC was dynamic ranging between 40-80 thousands during the period. 2) The impact of land degradation on the population CC is marginal given the assumptions used in the model.

9.2 Model limitations and sensitivity
The limitation of the model is twofold; 1) the omission of feedback from livestock population to vegetation cover, and 2) the feedback from vegetation cover to erosion being omitted (see, CLD in Fig. 4). This is purposely done, since the model can actually answer the basic questions stated in the beginning without including these mechanisms. Therefore the performance of the model rests on the questions the model is designed around. If more detailed questions are required, e.g. how does livestock contribute to reduction of vegetation cover? Or how is the interplay between vegetation and land degradation?, the model will not be sufficient to answer that. A modification or a complete new model is required that is designed for addressing questions on these levels of details. For answering the basic questions in this study, the Ice-CC model performance ands its accuracy was adequate.

In order to address the initial question on land degradation with the sufficient performance, it was required to divide the vegetation cover into 6 segments. This was done in order to recreate the scenario as given by Aradóttir, *et al.* (1992) in Fig. 6.

The sensitivity setup in the model was identical to the one used in the Haraldsson and Ólafsdóttir (2003) study, i.e. 10% variation of the variables. Sensitivity analysis on erosion the rate, at the different erosion classes, showed not significant variation in loss of vegetation cover. Sensitivity on the biological production and livestock parameters were not performed but observed during the model construction. From these observation the Þorsteinsson (1972) function on biological production was a key sensitivity variable. It is a linear function for biological production and since that is such a key variable for the model, exchanging that one for, e.g. a non-linear one will produce different results.

Although the results are estimates with some complex assumptions, there are obvious advantages of using this simplistic approach. It serves to test initial ideas and give approximation on the historical population fluctuation after the colonisation period in Iceland.

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