State and Transition Models in Space and Time – Using STMs to Understand Broad Patterns of Ecosystem Change in Iceland

I. C. Barrio
Agricultural University of Iceland, Iceland

D. S. Hik
Simon Fraser University, Canada

T. A. Mulloy
Simon Fraser University, Canada

J. Thorsson
Soil Conservation Service of Iceland, Iceland

K. Svavarsdóttir
Soil Conservation Service of Iceland, Iceland

See next page for additional authors

The XXIV International Grassland Congress / XI International Rangeland Congress (Sustainable Use of Grassland and Rangeland Resources for Improved Livelihoods) takes place virtually from October 25 through October 29, 2021.

Proceedings edited by the National Organizing Committee of 2021 IGC/IRC Congress

Published by the Kenya Agricultural and Livestock Research Organization

Presenter Information
I. C. Barrio, D. S. Hik, T. A. Mulloy, J. Thorsson, K. Svavarsdóttir, B. Marteinsdóttir, and I. S. Jónsdóttir

State and Transition Models in space and time – using STMs to understand broad patterns of ecosystem change in Iceland

Barrio, I.C.[1]; Hik, D.S.[2]; Mulloy, T.A.[2]; Thorsson, J.[3]; Svavarsdóttir, K.[3]; Marteinsdóttir, B.[3]; Jónsdóttir, I.S.[4]
[1]Agricultural University of Iceland, Árleyni 22, 112 Reykjavík, Iceland; [2]Simon Fraser University, 8888 University Drive, Burnaby, British Columbia, Canada, V5A 1S6; [3]Soil Conservation Service of Iceland, Gunnarsholt, 851 Hella, Iceland; [4]University of Iceland, Sturlugata 7, 102 Reykjavík, Iceland

Key words: adaptive management; conceptual models; land degradation; land management; sheep grazing

Abstract
Managing ecological systems sustainably requires a deep understanding of ecosystem structure and the processes driving their dynamics. Conceptual models can lead to improved management, by providing a framework for organizing knowledge about a system and identifying the causal agents of change. We developed state-and-transition models (STMs) to describe landscape changes in Iceland over three historical periods with different human influence, from pre-settlement to present days. Our models identified the set of possible states, transitions and thresholds in these ecosystems and their changes over time. To illustrate the use of these models for predicting and improving management interventions, we applied our present-day STM to a case study in the central highlands of Iceland and monitored ecosystem changes within an ongoing field experiment with two management interventions (grazing exclusion and fertilization) in areas experiencing contrasting stages of degradation. The results of the experiment broadly align with the predictions of the model and underscore the importance of conceptual frameworks for adaptive management, where the best available knowledge is used to continuously refine and update the models.

Introduction
Extensive land degradation and soil erosion in Iceland have been linked to natural processes associated with a harsh climate and frequent volcanic activity, and to human activities since settlement, including woodcutting and livestock grazing. Humans settled in Iceland in the 9th century, and the paleoenvironmental record suggests that widespread shifts in environmental processes occurred after that time (McGovern et al. 2007). Because of the relatively short history of human land use and the detailed documentation of this period, Iceland provides a unique opportunity to study the patterns and processes associated with land degradation.

In this context, conceptual models can help in organizing our knowledge about a system and offer a framework for research into the processes driving the system. Here, we use state-and-transition (STMs) models as a framework to describe patterns of ecosystem change in Iceland. STMs were developed in the context of rangeland management (Westoby et al. 1989) to deal with discontinuities and irreversible transitions in vegetation dynamics in grazing systems. STMs have been successfully applied to ecosystems worldwide but less extensively for high-latitude rangelands. We use STMs at a country-wide scale for three time periods with different historical human influence, from pre-settlement to present days (Barrio et al. 2018). We also apply our general STM to a rangeland in the central highlands of Iceland to illustrate the potential application of these models at spatial scales that are relevant to land management.

Our models recognized the occurrence of an ecological threshold (Aradóttir et al. 1992), beyond which only direct, extensive and often costly management interventions are needed to revegetate degraded rangelands. Based on our current understanding of the system (Barrio et al. 2018; Mulloy et al. 2019), we predicted that management interventions like grazing exclusion could effectively reduce rangeland degradation if implemented early, before the ecosystem has crossed the functional threshold. Once the threshold has been crossed, grazing exclusion alone would be too slow or ineffective for re-establishing vegetation cover, and only more active interventions, including fertilization combined with grazing exclusion, could allow the recovery of vegetation.

Methods and Study Site
First, we developed STMs to describe landscape changes in Iceland over three historical periods with different human influence: before human settlement in the late 9th century (pre-landnám), until 1900s (pre-industrial period) and after 1900s (Barrio et al. 2018). To build these models we recognized different states for rangelands in Iceland based on broad, structurally distinct habitat types (Ottósson et al. 2016) and we used a compilation

of the ecological impacts of sheep grazing in Iceland (Marteinsdóttir et al. 2017), paleoecological evidence, historical records and expert knowledge. Our models identify the set of possible states, transitions and thresholds in these ecosystems and their changes over time.

Secondly, we applied the present-day STM to a case study in the central highlands of Iceland, to test predictions for alternative ecosystem trajectories within a management context using an ongoing field experiment. The experiment was established in 2016 in Auðkúluheiði (65°13'N, 19°42'W; 459 m a.s.l.), in a region that has been traditionally used for summer grazing by domestic sheep. The experiment targeted two adjacent habitats in contrasting stages of degradation: a moderately degraded dwarf-shrub heath (>90% vegetation cover), and a severely degraded gravelly desert (<10% vegetation cover). Twelve 5x5 m plots were established in each habitat, and were fenced and/or fertilized (NPK 10 g/m^2 of each element; see more details in Mulloy et al. 2019). In each plot, as a proxy for the level of degradation, the percent cover of bare ground was visually estimated in a permanently marked 1x1 m subplot in summer 2019. Bare ground estimates give indication of the degradation of an ecosystem. To assess the effects of the experimental treatments on the percent cover of bare ground we built Linear Models (LM), where the experimental treatment and habitat, and their interaction, were included as predictor variables.

Results

Development of STMs

Our models describing landscape changes in Iceland suggest increasing complexity in recent times, in the models with stronger human influence (**Figure 1**). Following human settlement and the introduction of livestock grazing in the 9th century the extent of rangeland degradation and soil erosion rapidly escalated in some parts of Iceland. Human population in Iceland has steadily increased since the late 1890s (Haraldsson and Ólafsdóttir 2006). Despite the increased restoration and reforestation efforts since the early 1900s and a considerable reduction in the number of sheep since the historical maximum in the late 1970s, many Icelandic rangelands remain in poor condition.

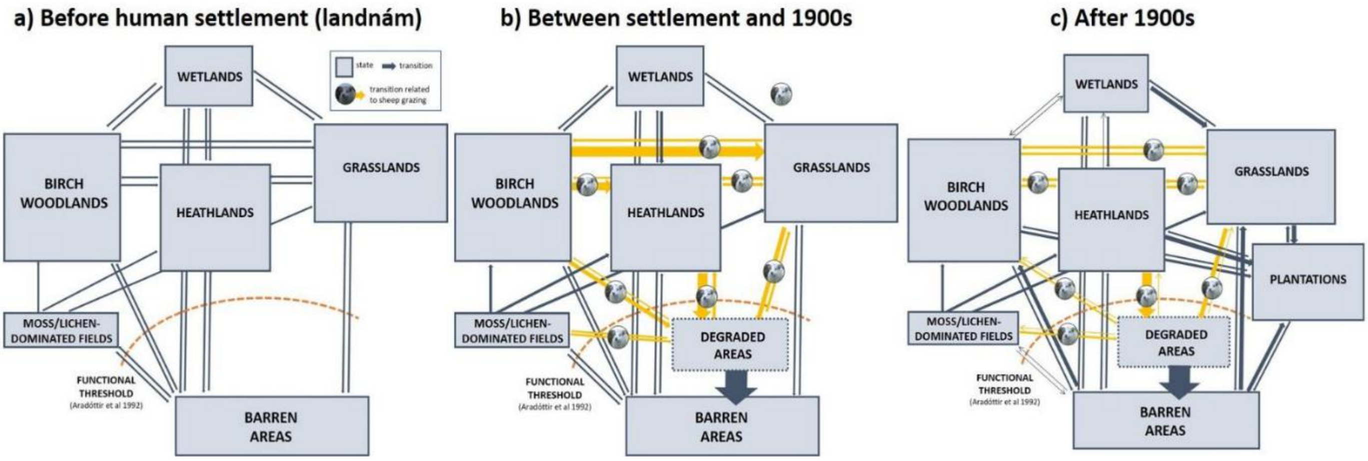

Figure 1. Simplified state-and-transition models (STMs) for three time periods in Iceland with contrasting human influence: a) before human settlement (landnám) in the 9th century transitions between ecosystem states were mostly driven by climate (Little Ice Age) and catastrophic events (volcanic eruptions). b) Between settlement and 1900s many changes occurred in Icelandic landscapes. Human settlers brought with them livestock; clearcutting, peat extraction, and haymaking were frequent in the lowlands. In the 19th century fertilizers and import of winter feed for sheep allowed rapid increase in sheep numbers. c) After 1900s sheep numbers were still on the rise until the late 1970s, but restoration and revegetation efforts became more common. Adapted from Barrio et al (2018).

Testing the model in the field

The field experiment was designed to assess the responses of two habitats in contrasting stages of degradation (a moderately degraded dwarf shrub heath, and a collapsed gravelly desert that had crossed the ecological threshold defined in our general model, coarsely estimated to be around 35% of bare ground; Barrio et al 2018) to different management practices: grazing exclusion and fertilization, or their combination (**Figure 2a**). The experimental treatments affected the amount of bare ground in gravelly desert ($F=16.35$, $p<0.001$) but not in the dwarf-shrub heath ($F=1.47$, $p=0.295$). In the gravelly desert, the amount of exposed bare ground was reduced in fertilized plots, whether fenced or not (**Figure 2**). The fenced plots receiving the full fertilizer treatment (NPKF) had the lowest percent of bare ground (mean= 0.03% compared to 93% for grazed controls).

Fenced plots tended to have lower percent cover of bare ground than the corresponding non-fenced plots when receiving fertilizer (NPKF:NPK; t=2.24, df=8, p=0.06), but not in the non-fertilized plots (CF:C; t=0.10, df=8, p=0.92; **Figure 2c**).

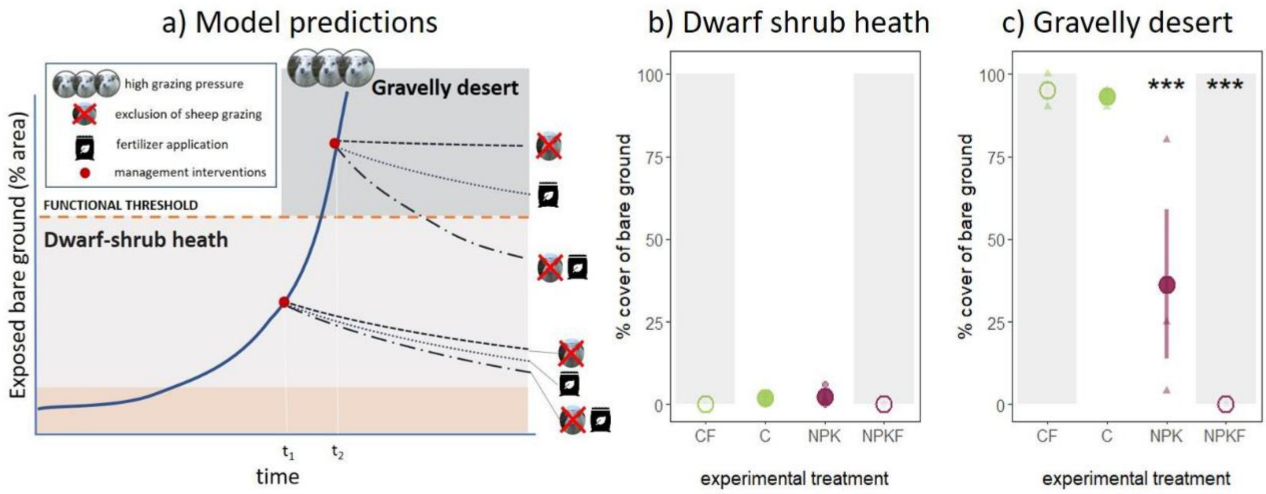

Figure 2. a) The present-day STM was applied to a case study in the central highlands of Iceland and predicted that management interventions (red dots) like grazing exclusion could effectively reduce rangeland degradation if implemented early, before the ecosystem has crossed the functional threshold (i.e., in the moderately degraded dwarf shrub heath). Once the threshold has been crossed, like in the gravelly desert, only more active interventions, including fertilization combined with grazing exclusion, would allow the recovery of vegetation. A field experiment was used to test these predictions, by measuring the percent cover of bare ground in plots exposed to different treatments mimicking these management interventions (control C-, fertilizer applications NPK and fences -F) four years after the start of the experiment, in: b) a dwarf shrub heath and c) a gravelly desert. Asterisks indicate significant differences relative to control plots (*** p<0.001).

Discussion

Our use of STMs at a broad spatial and temporal scale provides a novel approach for better understanding of the forces driving the landscape change in Iceland. Our models indicate increasing complexity over time, with a clear influence of human activities in creating new ecosystem states and accelerating some transitions. In the earlier period, before human settlement in Iceland, landscape changes were driven mostly by climate and natural disasters. The settlers brought with them livestock, and the use of natural resources (clearcutting, haymaking) increased, especially in the lowlands (Dugmore et al. 2005). Towards the end of the second period, around 1900s human populations began to increase steadily, and so did the number of domestic animals, particularly sheep, which reached a peak in the late 1970s. Despite the increased restoration and reforestation efforts in the 20th century and a considerable reduction in the number of sheep, many Icelandic rangelands remain in poor condition (Marteinsdóttir et al. 2020).

The application of our STM to a grazing common in the central highlands of Iceland illustrates how the general model can be adapted to a local case study and the usefulness of this approach to guide management efforts. The model hypothesized the occurrence of an ecological threshold, beyond which irreversible degradation would occur (Barrio et al. 2018). The existence of these thresholds and catastrophic shifts into collapsed ecosystem states has been previously described for Iceland (Aradóttir et al. 1992; Archer and Stokes 2000) and other ecosystems worldwide (Jefferies et al. 2006). Our model suggested that in order to achieve the desired restoration outcomes, appropriate management actions will depend on the stage of degradation. Once these ecological thresholds have been crossed, management interventions that only exclude sheep grazing would not revert the ecosystem to its vegetated state and more costly interventions, like fertilization, would be required to restore vegetation cover. Our field experiment showed that four seasons of grazing exclusion alone did not affect the amount of exposed bare ground in either the gravelly desert or in the dwarf shrub heath. However, fertilization, particularly when combined with grazing exclusion, reduced the amount of exposed bare ground in the gravelly desert to virtually zero.

In sum, our models show that STMs can provide a useful conceptual framework that facilitates a deeper understanding of the ecology of dynamic ecosystems in Iceland. Identifying what drives ecosystem change is essential to manage these systems, especially because some of these drivers, like grazing, are easier to manipulate than others, like climate or volcanic eruptions. Inputs and management efforts can therefore be prioritized. Further, a better understanding of how disturbed ecosystems respond to different management interventions is fundamental to develop effective management strategies. These responses might differ depending on the stage or severity of disturbance. For example, for systems where vegetation is still present but at risk of continuing degradation, applying management strategies before the area has crossed an ecological threshold may mitigate further and costly loss of ecosystem function. Future assessments should include other indicators of ecosystem degradation, such as changes in productivity or plant community composition. The development and use of conceptual models provides a framework for organizing our knowledge about a system, and targeted experiments can help refine these models (Bestelmeyer et al. 2009, 2017). In this context, STMs can provide a solid base for nationwide monitoring systems like GróLind (www.grolind.is). Our study provides a better understanding of the dynamics of grazed tundra ecosystems and offers insights for management plans targeting the restoration and conservation of specific habitats across the rangeland system (Briske et al. 2020).

Acknowledgements

Funding for this project was provided by Rannsóknasjóður (grant nr 152468-051), AXA Research Fund (15-AXA-PDOC-307) and Orkurannsóknasjóður Landsvirkjunnar (NÝR-09-2017, NÝR-14-2018, NÝR-12-2019) to ICB; Natural Sciences and Engineering Research Council of Canada (RGPIN-06691) to DSH; University of Iceland Research Fund (2015) to ISJ, and by the Soil Conservation Service of Iceland.

References

Aradóttir, Á.L., Arnalds, Ó. and Archer, S. 1992. Hnignun gróðurs og jarðvegs. In: Arnalds, A. (ed.) *Græðum Ísland.* Landgræðsla Ríkisins, Reykjavik, pp. 73–82.

Archer, S., and Stokes, C. 2000. Stress, disturbance and change in rangeland ecosystems. In: Arnalds, Ó. and Archer, S. (eds.) *Rangeland desertification.* Kluwer Academic Publishers, Dordrecht, pp. 17–38.

Barrio, I.C., Hik, D.S., Thórsson, J., Svavarsdóttir, K., Marteinsdóttir, B. and Jónsdóttir, I.S. 2018. The sheep in wolf's clothing? Recognizing threats for land degradation in Iceland using state-and-transition models. *L. Degrad. Dev.* 29: 1714–1725. doi:10.1002/ldr.2978.

Bestelmeyer, B.T., Ash, A., Brown, J.R., Densambuu, B., Fernández-Giménez, M., Johanson, J., Levi, M., Lopez, D., Peinetti, R., Rumpff, L. and Shaver, P. 2017. State and Transition Models: theory, applications, and challenges. In: Briske, D.D. (ed.) *Rangeland Systems.* Springer Series on Environmental Management. Springer, Cham, pp. 303– 345. doi:https://doi.org/10.1007/978-3-319-46709-2_9.

Bestelmeyer, B.T., Tugel, A.J., Peacock, G.L., Robinett, D.G., Shaver, P.L., Brown, J.R., Herrick, J.E., Sanchez, H. and Havstad, K.M. 2009. State-and-transition models for heterogeneous landscapes: a strategy for development and application. *Rangel. Ecol. Manag.* 62: 1–15. doi:10.2111/08-146.

Briske, D.D., Coppock, D.L., Illius, A.W. and Fuhlendorf, S.D. 2020. Strategies for global rangeland stewardship: Assessment through the lens of the equilibrium–non-equilibrium debate. *J. Appl. Ecol.* 57: 1056–1067.

Dugmore, A.J., Church, M.J., Buckland, P.C., Edwards, K.J., Lawson, I., McGovern, T.H., Panagiotakopulu, E., Simpson, I.A., Skidmore, P. and Sveinbjarnardóttir, G. 2005. The Norse landnám on the North Atlantic islands: an environmental impact assessment. *Polar Rec.* 41: 21–37. doi:10.1017/S0032247404003985.

Haraldsson, H. V. and Ólafsdóttir, R. 2006. A novel modelling approach for evaluating the preindustrial natural carrying capacity of human population in Iceland. *Sci. Total Environ.* 372: 109–119. doi:10.1016/j.scitotenv.2006.08.013.

Jefferies, R.L., Jano, A.P. and Abraham, K.F. 2006. A biotic agent promotes large-scale catastrophic change in the coastal marshes of Hudson Bay. *J. Ecol.* 94: 234–242. doi:10.1111/j.1365-2745.2005.01086.x.

Marteinsdóttir, B., Barrio, I.C. and Jónsdóttir, I.S. 2017. Assessing the ecological impacts of extensive sheep grazing in Iceland. *Icelandic Agric. Sci.* 30: 55–72. doi:10.16886/IAS.2017.07.

Marteinsdóttir, B., Þórarinsdóttir, E.F., Halldórsson, G., Stefánsson, J.H., Þórsson, J., Svavarsdóttir, K., Einarsson, M.Þ., Jónsdóttir, S. and Brink, S.H. 2020. *Stöðumat á ástandi gróður- og jarðvegsauðlinda Íslands.* Gunnarsholt.

McGovern, T.H., Vésteinsson, O., Friðriksson, A., Church, M., Lawson, I., Simpson, I.A., Einarsson, A., Dugmore, A., Cook, G., Perdikaris, S., Edwards, K.J., Thomson, A.M., Adderley, W.P., Newton, A., Lucas, G., Edvardsson, R., Aldred, O. and Dunbar, E. 2007. Landscapes of settlement in Northern Iceland: historical ecology of numan impact and climate fluctuation on the millennial scale. *Am. Anthropol.* 109: 27–51. doi:10.1525/aa.2007.109.1.27.

Mulloy, T.A., Barrio, I.C., Björnsdóttir, K., Jónsdóttir, I.S. and Hik, D.S. 2019. Fertilisers mediate the short-term effects of sheep grazing in the Icelandic highlands. *Icelandic Agric. Sci.* 32: 75–85. doi:10.16886/IAS.2019.07.

Ottósson, J.G., Sveisdóttir, A., and Harðadóttir, M. 2016. Vistgerðir á Íslandi. *Fjölrit Náttúrufræðistofnunar* 54: 1–299.

Westoby, M., Walker, B., and Noy-Meir, I. 1989. Opportunistic management for rangelands not at equilibrium. *J. Range Manag.* 42: 266–274. doi:10.2307/3899492.