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

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1. Background

Land degradation in Iceland

- 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 widespread shifts in environmental processes after that time
- The relatively short history of human land use combined with the detailed documentation of this period allows Iceland to provide a unique opportunity to study the patterns and processes associated with land degradation.

Using conceptual models in management

- 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.

State and Transition Models (STMs)

- Developed in the context of rangeland management to deal with discontinuities and irreversible transitions in vegetation dynamics in grazing systems.
- Applied to ecosystems worldwide but less extensively to high-latitude rangelands.

Can STMs be used as a framework to describe large-scale patterns of ecosystem change in Iceland?

2. Methods

a

Landscape changes in Iceland over time?

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 recent times

b

Application of conceptual models to management?

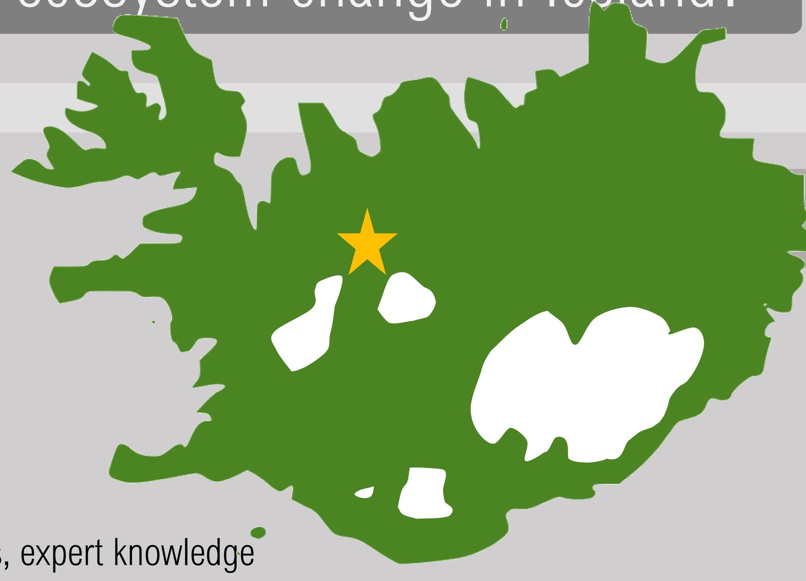
We applied our present-day STM to a case study in the central highlands of Iceland, using an ongoing **field experiment** with two management interventions (grazing exclusion and fertilization) in areas experiencing contrasting stages of degradation

2a. Development of STMs for Iceland

Country-wide STM model: broad habitat types, coarse resolution
3 historical periods with different human influence
(Barrio et al. 2018):

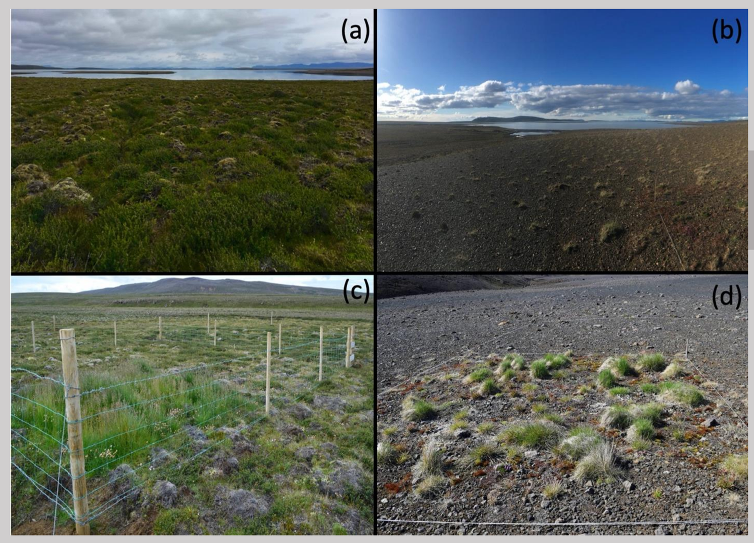
- before human settlement in the late 9th century (pre-landnám)
- until 1900s (pre-industrial period): early human impacts
- after 1900s: increased efforts in restoration

Data sources: literature, paleoecological evidence, historical records, expert knowledge



2b. Testing the general STM model in the field

- Field experiment established in 2016 in Auðkúluheiði, a site traditionally used for summer grazing by domestic sheep
- 2 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/m² of each element; Mulloy et al. 2019).
- Percent cover of **bare ground**, a proxy for the level of degradation, was visually estimated in permanent 1x1 m subplots in summer 2019.
- Linear Models including experimental treatment and habitat, and their interaction, as predictor variables.



Dwarf shrub heath (a) and gravelly desert (b), and fence/fertilizer applications (c, d)

3a. Using STMs to describe ecosystem change in Iceland over time

Our models identify the set of possible states, transitions and thresholds in ecosystems in Iceland and their changes over time, and suggest increasing complexity in recent times, with a clear influence of human activities in creating new ecosystem states and accelerating some transitions (Figure 1).

Before human settlement in Iceland in the 9th century, landscape changes were driven mostly by climate and natural disasters. Birch woodlands were more extensive before settlement, although their extent fluctuated with variations in climate.

The settlers brought with them livestock, and the use of natural resources (clearcutting, haymaking) increased, especially in the lowlands. The extent of rangeland degradation and soil erosion rapidly escalated in some parts of Iceland.

Human population steadily increased since the late 1890s. Numbers of domestic animals also increased, particularly sheep, which reached a peak in the late 1970s, but declined shortly after. Restoration and reforestation efforts increased since the early 1900s.

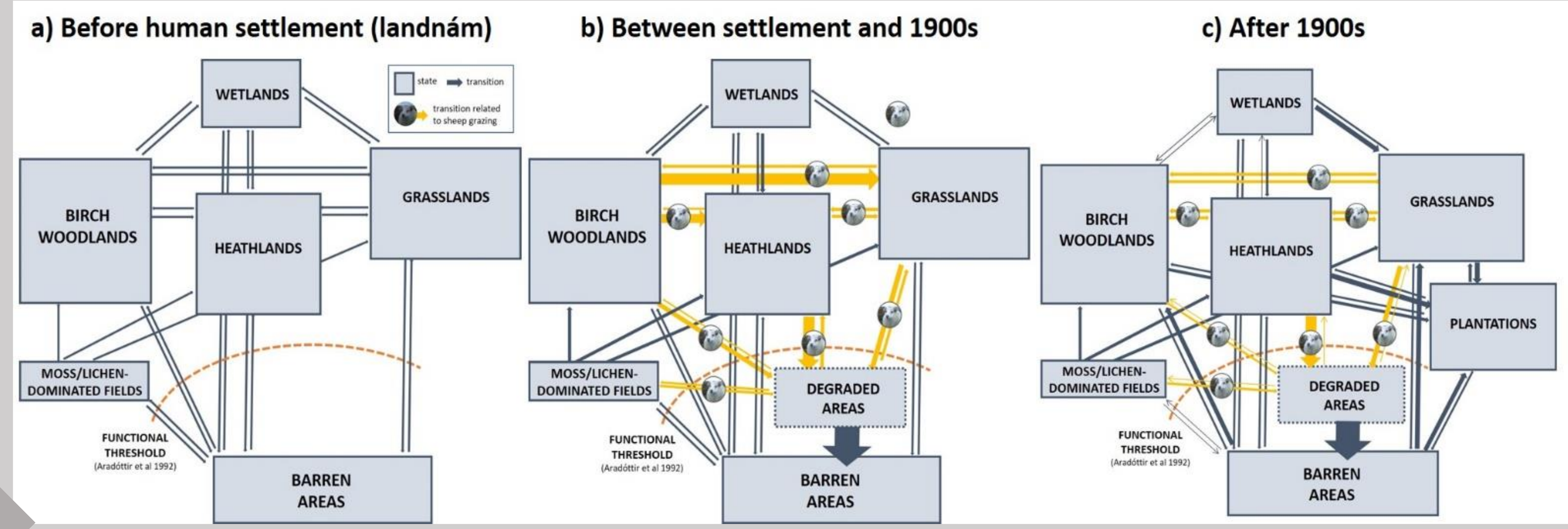


Figure 1. Simplified state-and-transition models (STMs) for three time periods in Iceland with contrasting human influence: a) before human settlement (landnám) in the 9th century transitions between ecosystem states were mostly driven by climate (Little Ice Age) and catastrophic events (volcanic eruptions). 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).

3b. Application of STM in the field

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 a 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 vegetation recovery.

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). 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; $t=0.10$, $df=8$, $p=0.92$).

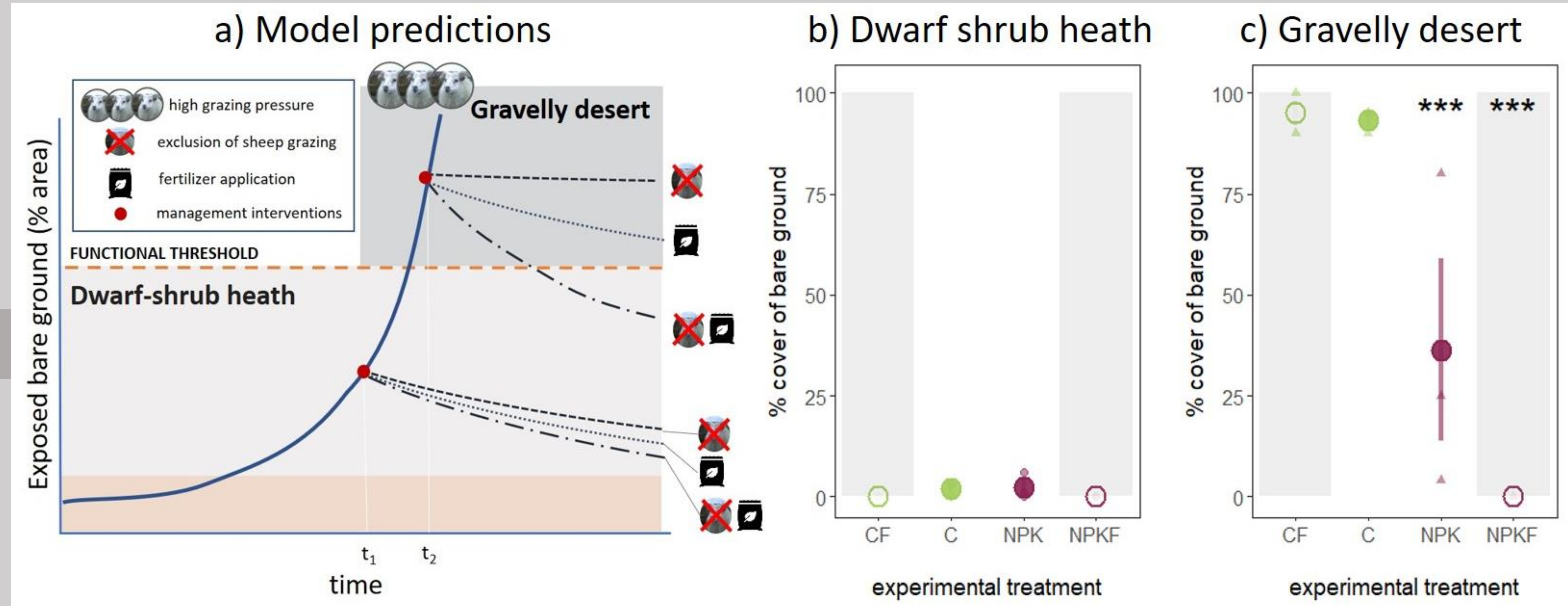
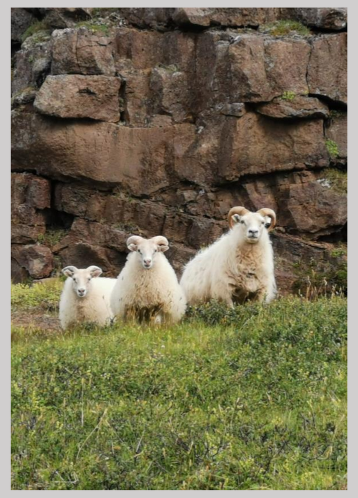


Figure 2. a) The present-day STM was applied to a case study in the central highlands of Iceland and predicted that management interventions (red dots) like grazing exclusion could effectively reduce rangeland degradation if implemented early, before the ecosystem has crossed the functional threshold (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).

4. Implications



- 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.
- STMs 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, and can help prioritize inputs and management efforts. STMs can provide a solid base for nationwide monitoring systems like GróLind (www.grolind.is).
- 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. 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.
- 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.

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Take home-messages

- Conceptual frameworks are central to adaptive management, where the best available knowledge is used to continuously update the models
- STMs can be applied to explain broad ecosystem change over time and provide a valuable tool to organize our understanding of a system and to identify drivers of change
- STMs can be refined using field data to understand how disturbed ecosystems respond to different management interventions and help develop effective management strategies

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