Strategies for Assessing Grassland Degradation with Biogeochemical Models

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Abstract
Marginal grasslands provide the basis for livestock rearing and rural livelihoods globally, but are subject to permanent degradation from mismanagement and climate change. Global biogeochemical models are so far not able to represent degradation tipping points in marginal grasslands because plant growth is dependent only on bio-climatic conditions and nutrient availability. Due to their central role for sustaining livelihoods, this lack of representation in such models needs to be addressed. We present an idea on processes and interactions to be considered and on the actual implementation of necessary changes. The model for which we exemplarily develop implementation strategies, LPJmL, accounts already for grassland dynamics globally in a fully coupled framework including soil dynamics and the hydrological cycle. Recent developments include the implementation of grassland harvesting schemes, the nitrogen cycle, fire management practices and representation of a variety of grass and legume species. Existing knowledge on the role of annual and perennial grass species for drought resistance will have to be utilized in order to advance model development. Different strategies for forming below-ground plant organs (roots and storage) have to be better understood from experimental studies before this can be implemented in models. Here, assumptions on functional relationships can be implemented and the resulting grass productivity can be analysed in comparison to field observations. Additionally, the formation of closed swards or tussocks plays a big role for the vulnerability to degradation by avoiding bare soil patches. This spatial phenomenon is usually neglected in models and can only be included by assumptions or in the form of aggregated effects. The long-term development of seed banks of key species determine the capability of regrowth after major drought periods so that seed bank formation and persistence is another component of necessary model development. All these components together with current developments of species competition and niche separation would build a framework that allows scenario assessments on tipping points depending on climatic conditions and management.

Introduction
Marginal grasslands play an important role for sustaining livelihoods in regions where crop cultivation is not feasible because of the prevailing climatic conditions and soils (Blair et al. 2014, O'Mara 2012). A major share of marginal grasslands is located in arid or semi-arid regions such as steppes in cooler climates or as part of savannahs in warmer climates (Suttie et al. 2005). Under these conditions, a range of ruminant livestock systems exist, which provide nutrition and income to the local population (Mishaud 2004). However, the productivity and the provision of livelihoods from marginal grasslands is threatened by degradation from mismanagement, overgrazing and climate change (Kirtman et al. 2013, Collins et al. 2013, Kemp et al. 2013). Extensive mismanagement and overgrazing can have almost irreversible effects when tipping points are reached (Fernândez-Giménêz et al. 2017, Scheffer et al. 2001), while climate change may generally increase the stress on the vegetation (Wu et al. 2011, Beier et al. 2012), pushing currently non-degraded and well managed systems towards degradation. Changes in frequency, duration and intensity of droughts will require new or adjusted management practices to maintain livestock-dependent livelihoods. Global biogeochemical models (dynamic global vegetation models, DGVM) are so far not able to represent such tipping points that refer to drastic and often non-reversible shift between different states of ecosystems (Reyer et al., 2015). In DGVMs, plant growth is dependent on bio-climatic conditions and nutrient availability, but several important mechanisms are missing: First, the co-existence of different species with different ecological strategies to deal with drought including trait plasticity, tolerance and avoidance. Second, a feedback between damage to vegetation cover from grazing or trampling to soil erosion (Knoll and Hopkins 1959). Third, the formation of seed banks allowing vegetation in marginal areas to re-establish after long periods of unfavourable climatic conditions. We refer to the LPJmL dynamic global vegetation model (Schaphoff et al. 2018) as an example to lay out a path towards the integration of the mechanisms described above. The LPJmL model already accounts for global grassland dynamics in a consistent framework with coupled carbon and nitrogen dynamics in soils and plants, as well as hydrological processes (von Bloh, et al. 2018). Here, we develop ideas about the processes and interactions that should be considered in such models as LPJmL in order to better represent important grassland dynamics and tipping points and discuss the implications of the necessary

implementations. With this, we aim at providing not only a conceptual framework but also a more tangible blueprint for other grassland modelling groups.

Methods

LPJmL is a DGVM that explicitly represents managed grasslands. It simulates carbon, nitrogen, water cycles within the soil plant atmosphere continuum. In the model, vegetation consists of plant functional types (PFT) that are represented by one average individual per PFT. Their growth is simulated on a daily basis including the following processes: (a) reproduction of present PFTs and establishment of new PFTs, (b) turnover of plant material and litter and soil organic matter, (c) change of biomass as a result of gross primary production (GPP) and respiration, with (d) limitations according to environmental conditions and competition for resources. Direct biotic interactions are not implemented. We will briefly describe those processes for which we discuss the need for improvement to represent degradation tipping points and refer to Schaphoff et al. (2018) and von Bloh et al. (2018) for a detailed model description.

For each PFT, LPJmL simulates one average individual that is characterized by a given set of traits and consists of leaf and root biomass, i.e. ignoring differences between individuals of the same species. The development of the average individual is scaled up to the grid cell area, which covers an area of 0.5 by 0.5 degrees in the standard application but can be applied at any spatial scale. Photosynthesis is described by a simplified Farquhar model (Haxeltine & Prentice 1996) together with a big leaf approach. It derives numerically the optimum photosynthetic activity as a trade-off between light and RuBisCo availability. A key determinant of the calculated photosynthesis is the vegetation cover of each PFT, which is a function of the PFT's specific leaf area index (LAI) and light extinction coefficient. Due to the non-linearity of this function and because total foliage projected cover (FPC) must not exceed 100%, the realised FPC of each PFT is weighted by all PFTs present in the plot. Limitations due to water and nitrogen stress are accounted for by comparing resource demand and supply. Plant available soil water for each PFT depends on its maximum water transport capacity, vertical root distribution, and FPC. If the demand cannot be fulfilled, a reduced stomatal conductance is calculated from the water supply to adjust the PFT specific photosynthesis. Establishment of new PFTs and expansion of already established PFTs into non-vegetated areas is computed daily. Each PFT can establish independent of the current occurrence of the PFT if bioclimatic limites of the PFT and unvegetated areas allow for establishment.

Results and Discussion

We identified three areas in which additional model development is needed in order to represent tipping points of degradation. First, the representation of the plants' physiology, especially below-ground plant organs. Second, the patchiness of the vegetation and the differentiation between closed swards and tussocks. Third, the seed formation and the maintenance of seed banks.

Plant physiology

In order to simulate adequate responses of the community to changing environmental conditions omanagement, a more detailed representation of the plant itself is necessary (Herrero et al. 2000). Considering different plant architecture within available models, we focus here on the widespread differentiation of plants in DGVMs as several pools of carbon and nitrogen but are aware of more sophisticated allometric descriptions such as in individual-based models (e.g. GRASSMIND, Taubert et al. 2012). In addition to the plant compartments leaves and roots, models should account for above- and below-ground storage organs which allow for survival under unfavourable conditions and improve the recovery of the plant community after a drought. Leaves should further be distinguished into photosynthetically active and senescent leaves that are still attached to the plant, as this will improve the representation of the litter cover. The coverage of the soil by dead or live biological material alters the properties of the soil surface which influences its vulnerability to degradation. Another aspect is the consideration of root traits and their role for the acquisition of resources. So far, roots are underrepresented in DGVMs because of scarce knowledge. However, initiatives such as GRooT (Guerrero-Ramirez et al. 2021) recently improved data availability. These data may be used to connect water and nutrient uptake to functional traits allowing to simulate additional trade-offs within plant strategies. Especially in arid and semi-arid regions, growth strategies for leaves and roots are strongly linked to resilience and degradation of grasslands (Puigdefábregas 1998). Therefore, an improved representation of roots is essential to better understand causes and consequences of degradation and to develop management strategies that avoid grassland degradation.

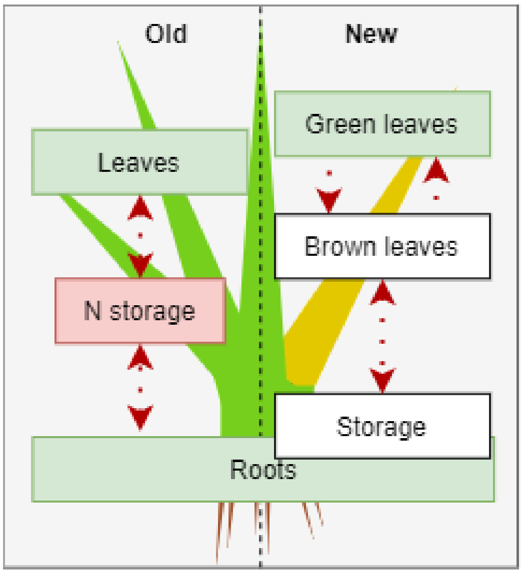

Figure 1 Schematic representation of grass plants by leaves and roots only (old, left) and additional plant compartments of brown leaves and a storage (new, right).

Patchiness

The degree of patchiness of a grassland, ranging from a closed sward without bare soil towards patchy vegetation cover dominated by a number of tussocks, is important for its resistance against soil degradation (Puigdefábregas & Sanchez 1996, Lal 2012). Here, the performance of large-scale models such as DGVMs is strongly limited, because the coarse spatial resolution precludes an explicit simulation of the spatial configuration of covered and bare patches. To overcome this, small scale individual-based models could be used to systematically asses the vulnerability and reaction of the vegetation regarding different levels and patterns of patchiness (or amounts of bare soil) to derive scaling relationships for simulations of DGVMs at larger scales. Even though there are approaches using statistical models to upscale patchiness effects (Wang et al. 2018), a dynamic understanding would enhance the ability to represent the process at larger scales.

Seed banks

While grass plants mainly reproduce vegetatively, their survival in marginal environments may still depend on generative reproduction via seeds. While large investments into seed formation are unnecessary in productive environments, in marginal environments that are prone to unfavourable conditions, a well maintained seed bank is necessary to re-establish after periods of stress. However, the current implementation does not distinguish these strategies, and assume constant availability of seeds for re-establishment. Overcoming this will allow for better assessments of grassland resilience and long-term dynamics.

Conclusions

With the example of LPJmL, we showed that current generation DGVMs need substantial development in order to simulate degradation of marginal grasslands. We identify current limitations in LPJmL and how these could be overcome. As large areas are marginal grasslands globally, large-scale modeling tools, such as DGVMs, are necessary to assess their dynamics and vulnerability to climate change and changes in management, such as livestock densities and grazing frequencies. A better understanding of degradation tipping points is necessary to assess climate change impacts on grassland ecosystems as well as on herders and transhumance livelihoods.

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