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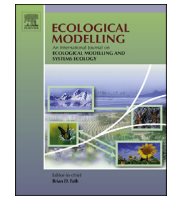

Modelling rangeland productivity in response to degradation in a semi-arid climate

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ABSTRACT

Modelling rangeland is essential for capturing changes at the large temporal and spatial scales at which these systems respond to climate and institutional changes and increasing population pressure, but rangeland models applicable to data sparse regions are rarely available. We developed and evaluated a novel rangeland model aimed at simulating rangeland at different stages of degradation using limited parameterisation and measurements.

The developed model Linrange is a biophysical simulation model of the aboveground part of a mixed grass sward, combined with sub-models for evapotranspiration, soil water dynamics, and root development. Main processes of the biomass model are growth through a source/sink limited mechanism, reserve storage and remobilisation, basal area dynamics, winter dormancy. The grass sward is simulated based on average species characteristics of the dominating grass community.

We show that a model based on simplified biophysical processes and a single set of parameters for a mixed sward can satisfactorily simulate mixed-species rangeland vegetation. The model also could reproduce year-to-year phytomass dynamics, including for exceptionally wet and dry years. Without calibrating specifically for it, the model was able to reproduce observed water-use efficiency values, indicating a good representation of the relationship between the main limiting factor, water, and productivity. By recalibrating the model using only five parameters associated with degradation, the accuracy of simulated degraded rangeland states was close to that of undegraded rangeland. We therefore consider the Linrange model a good tool for research on rangeland dynamics and degradation resulting from management and climate. We also point to directions of further model improvement, particularly regarding the modelling of parameter changes with degradation states.

1. Introduction

Arid and semi-arid rangelands are adapted to high climatic variability, and have been shaped by drought, grazing and fire (Ruppert et al., 2015), and more recently, but more dramatically, by human impact (Milton and Siegfried, 1994; Vetter, 2013). The more permanent effects of these factors and their interactions only become apparent on long time scales, and over large spatial extents. With predicted increasing effects of climate change (IPCC, 2013), and increasing population pressure (Millennium Ecosystem Assessment, 2005), both the importance of rangelands for people's livelihoods (Kassahun et al., 2008), and the pressure on these rangelands increase (Vetter, 2013), and land degradation becomes a major risk (Meze-Hausken, 2000). In semi-arid, grass-dominated rangeland systems in central South Africa, grasslands are grazed by cattle, sheep, and goats, mainly for meat, wool, and fibre production. Through combined effects of institutional change, and large-scale ownership and management changes (Vetter, 2013), these systems presently undergo unprecedented alterations (Holm et al., 2003). Therefore there is a need for assessing the sustainability of existing communal and commercial rangeland (Smet and Ward, 2005; Vetter, 2009), the degradation risks (Snyman, 1998), and the recovery potential of already weak communal lands (Harrison and Shackleton, 1999).

Extensive research has been done on rangeland development and degradation under varying management regimes (O'Connor and Bredenkamp, 2004), grazing intensities (Liang et al., 2009) and drought intensities (Ruppert et al., 2015) in many regions in the world (e.g. Hein, 2006; McKeon et al., 1990; Palmer et al., 2010; Swemmer et al., 2007). Experimental research, however, has only limited applicability at the large spatial and temporal scales at which rangelands function, and climate change alters rangelands

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in ways that can hardly be captured experimentally, and are not covered by previous experience (Tietjen and Jeltsch, 2007). It is for this reason that these authors identify modelling as an important tool for rangeland research. Compared to crop and grassland research, modelling in rangeland research is not yet widely used (Wiegand et al., 2004). Likely, this is due to the extensive management of rangelands (with low stocking densities, and hence low revenues per hectare), combined with modelling challenges such as mixed perennial swards as opposed to annual monocultures (i.e. crops), large scale heterogeneity instead of homogeneous fields, and presence of disturbances such as drought, grazing and fire.

For simulating the herbaceous layer, a rangeland model has to account for a grass-dominated sward consisting of up to 50 species of graminoids and forbs. In order to characterise how rangeland models deal with mixed swards three general approaches can be distinguished, based on how species are grouped before parameterisation. In the species-based approach, each species in the sward is modelled using its own set of plant parameters. In the group-based approach, plant species are grouped based on certain common properties or functional characteristics, and each group is parameterised separately. In the community-based approach (also referred to as sward or ecosystem models elsewhere), the whole sward, or plant community, is represented by one set of plant parameters, i.e. all species are grouped together. As droughts and overuse are the main factors causing (semi-arid) rangeland degradation, a representation of degradation and recovery is an important feature of a model that simulates future impacts on rangelands.

A number of models of grazing lands, from savanna, to grassland, to pastures, have been developed. Their objectives, however, rarely allow for assessing the effects of both climate and management change on degradation and recovery. Also, most models are rather detailed representing species-based or group-based approaches which require large amounts of field data for model calibration and testing. This constraints application at larger scales and simpler approaches are needed.

Therefore, our goal is to simulate rangeland productivity with a dynamic mechanistic model that can account for the effects of climate variability and change, but that is simple enough to allow for reparameterisation for larger spatial and temporal scales without extensive experimental work. More specifically, we aim to develop a model that is able to simulate rangeland productivity for different stages of rangeland degradation in response to inter- and intra-annual variability in weather. The objectives are (i) to develop and (ii) parameterise the model using field observations, combined with literature data, (iii) to test the model with independent data for phytomass, basal area and water use efficiency.

Model calibration and validation are performed with data from a long-term experiment in a semi-arid climate, Bloemfontein, South Africa (Snyman, 2009).

2. Model development

2.1. Available modelling approaches

Several models are available to simulate grazed lands (savanna, grassland, pastures), but they differ in their approaches to account for species composition, management and climate change, and degradation and recovery.

Both the global savanna model G-Range (Boone et al., 2011), and the regional savanna model SAVANNA (Coughenour, 1993) are grid-based, with tree, bush and herbaceous vegetation classes. In G-Range, the herbaceous layer is simulated monthly using community parameters, and species change within this layer is not accounted for. Degradation is a result only of cover change of these three groups and bare ground. SAVANNA, on the other hand, also simulates basal area dynamics, resource competition and selective herbivory for any combination of species or functional groups within the vegetation classes, but only on a weekly basis.

The ARENA savanna model (Boer and Stafford Smith, 2003) is group-based, and uses two graminoid life forms (annual and perennial), and a tree/shrub class as functional groups. Degradation is represented by a shift from perennial to annual species dominance. This produces interesting results regarding the effects of grazing and fire on degradation. Climate change is not considered.

The rangeland model of Gross et al. (2006) simulates grassland as one community, although with hardly any biophysical detail. Its most interesting concept, however, is the representation of degradation through a reduction in herbaceous basal area, affected by both climate and grazing. Species composition change is not accounted for.

The SPUR2.4 rangeland model (Foy et al., 1999) simulates grassland through 4 plant functional type (PFT) groups, calling them species, but seems to be capable of greater detail if enough parameters were to be available. Relative abundances of the PFT groups can vary freely. An undesirable shift in PFT composition could be interpreted as degradation, although degradation is not explicitly focussed on.

The PUTU 11 rangeland model (Fouché et al., 1986, 1985) uses one PFT, grass, and only simulates rangeland in undegraded condition. Interesting is that it is based on functional equilibria between plant parts (Brouwers, 1963, cited in Lambers, 1983), and that a phenology, including dormancy and seed production, is implemented.

The annual Herb'sim model (Duru et al., 2009) of extensive, species-rich grazing pastures shows that it is possible to classify species into functionally similar groups based on only one characteristic, namely leaf dry matter content. It does not simulate changes in relative abundance of PFT groups: sward changes are represented through the biomass produced per group, not through the proportion of the sward they occupy.

The GrassGro model (Moore et al., 1997) of temperate grassland is group-based, and distinguishes annual and perennial grasses and forbs (i.e. 4 groups). In regions where a species shift from perennial to annual species is not the main degradation effect in terms of species composition, such a model lacks detail. Further explicit references to degradation are not made.

The Gemini model (Soussana et al., 2012) of extensive, species-rich grazing pastures is a species-based model. It is, due to its complexity, more suitable for ecosystem understanding (Maire et al., 2013), than for rangeland applications. Degradation is not explicitly mentioned, though grazing, cutting and fertilization all influence species composition.

The PaSim model (Riedo et al., 1998) for intensive grazing pastures uses highly detailed biophysical methods derived from the Hurley Pasture Model for a mixed sward using only community parameters. It is a single-year model only, however. Here we see a crossover, from single-species based to community.

As none of the above-mentioned models is able to model the effects of management and climate change on degradation and recovery on a daily time scale without collecting large amounts of field data, a different approach is needed. The Linrange model, as detailed in this paper, uses the community-based approach. This enables modelling of areas where enough individual plant characteristics to enable species- or group-based modelling is not feasible, and for which from literature only a limited number of parameters can be obtained [for example, although grazing response of individual grass species in a semi-arid climate has been researched in detail (e.g. Van der Westhuizen et al., 1999), this is limited to only certain biomes and rangeland types]. The Linrange model is developed to be applicable to different regions and