Modelling Grazing and Burning in Communal Rangelands to Help Understand Trade-offs between Production, Carbon, and Water

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Abstract

Rangelands cover more than 80% of South Africa's land area, providing critical ecosystem services, livelihoods and cultural values related to livestock. Communally owned rangelands are often overgrazed and subject to runaway fires but lack of data limits our understanding of how these threats impact production. In this transdisciplinary project, we use models to test hypotheses and predict future scenarios as a planning tool for resource-poor communal farmers. We think that moderate grazing and fire regimes will increase overall production and carbon sequestration with uncertain trade-offs for water and nutrient cycling. To test this, we trained two process-based biogeochemical models (DAYCENT and SPACSYS) with individual merits to simulate known fire returns and grazing pressures on a 40-year old long-term ecological research grassland site, and validated models with data from Mvenyane, a nearby communal livestock grazing area. DAYCENT and SPACSYS simulated observed soil organic carbon well, while accuracy for aboveground herbaceous biomass differed between models. DAYCENT projected that soil organic carbon could increase by ca. 1000 g C m^{-2} over ten years or 1 t C ha^{-1} yr^{-1} with moderate increases in biomass and no change in water fluxes when changing from continuous high pressure to moderate pressure grazing in a two-camp rotation, with or without fire. These and other scenarios, including future climate projections, will be used to evaluate biophysical and social trade-offs so that sustainable land use plans can be created in Mvenyane and the wider rangeland community.

Introduction

Rangelands cover more than 80% of South Africa's land area, providing critical ecosystem services, livelihoods and cultural values related to livestock. Rangelands evolved with both herbivory and fire and are essential to create landscape heterogeneity and cycle nutrients. Communally owned rangelands are often overgrazed and subject to runaway fires but lack of data limits our understanding of how these threats impact production. Poor management is associated with loss of both traditional practices and reduced agricultural services during and post the Apartheid era (1948-1994). The uMzimvubu Catchment Partnership endeavours to support resource-poor communal livestock farmers to restore rangelands and livelihoods linked to livestock via Conservation Agreements (CA), which include the re-introduction of *maboella*, a traditional two-camp rotation where areas are alternatively 'rested' or grazed during the austral summer growing season. To date, various combinations of grazing and fire have not been introduced to CAs due to lack of data on how this will change production, soil carbon, water fluxes, and thus risk to farmers. For this reason, we used two ecosystem-level models to test hypotheses and predict future scenarios. We expected that moderate grazing and fire regimes within a two-camp rotation would increase overall production and ecosystem functions, including carbon sequestration via pyrogenic organic carbon, with uncertain trade-offs for water fluxes, while continued unplanned, continuous heavy grazing pressures would reduce ecosystem services and livelihoods, exacerbated by climate change. We intend model outputs to act as scenarios that will aid decision-making and co-development of land use plans with community members.

Methods and Study Sites

The 40-year-old Brotherton Long Term Ecological Research (LTER, uKhahlamba-Drakensberg Park) site is ca. 180 km north of the area of interest, Mvenyane, a communally owned rangeland area in the Grassland Biome of South Africa. The sites have similar climate, soil, and vegetation characteristics but different management and herbivore types (Table 1). Model uncertainty was evaluated by training and testing model predictions with the Brotherton and Mvenyane data sets, respectively (Table 1). Two ecosystem-level models were used, DAYCENT ('savanna' module, v.1, 2018) developed by Parton et al. (1998) and Del Grosso et al. (2009), and SPACSYS (Wu et al. 2007; 2019). The SPACSYS model simulates plant growth and development, soil C, N and P cycling, water fluxes and energy transformation, animal growth rates, milk yield, energy requirement for maintenance, production, growth and activity, excretion and gaseous emissions based on livestock breed, climate, soil and feed quality and quantity. The DAYCENT model simulates similar processes except animal production. Training model inputs were derived from the nearby Mike's Pass weather station, field collections (soil pH, bulk density, texture, field capacity, root and foliar organic carbon, soil organic carbon (SOC) fractions; herbaceous biomass), remote sensing (NDVI, normalized difference vegetation index via Copernicus Sentinel data [2019] for Sentinel data on the Google Earth Engine platform), literature (wildlife counts) and the SPAW model (wilting point, hydraulic conductivity) using field soil texture (Saxton, 1986). Climate data for the test data set was derived from the nearby Kokstad weather station for periods relevant to validation data (2009-2019), and from modelled climate data for dates prior to 2009 (Copernicus Climate Change Service [2017] via the Google Earth Engine platform). Other test data were derived from field collections (herbaceous biomass, SOC, livestock counts) and beta SoilGrids (SoilGrids 2019). We assessed model accuracy and fit using the coefficient of determination / adjusted R^2. The pre-condition for the 2019 validation year and future scenarios was an overgrazed mixed C3/C4 grassland with a three-year fire return. Scenarios from 2020-2030 were created using the observed weather for 2009-2019 and various management options.

Table 1. Site characteristics of the Brotherton Long Term Ecological Research (LTER) site and the Mvenyane communal rangeland area. Abbreviations: MAT (mean annual temperature); MAP (mean annual precipitation); and LSU (livestock unit).

Site	Brotherton LTER (training data)	Mvenyane communal area, amaHlubi tribe (test data)
Established	1980	ca. 1800
Location	28.96°S; 29.26°E	30.57°S; 29.02°E
Altitude (m)	1890	1340
MAT (°C)	15	15
MAP (mm)	1075	874
Soil type[1]	Rhodic and Haplic Acrisols	Haplic Acrisols
Biome[2]	Grasslands	Grasslands
Vegetation type[2]	uKhahlamba Basalt Grassland (Gd7)	East Griqualand Grassland (Gs12)
Management	Burning trial in wildlife reserve; controlled 1-3 year fire returns	Communal livestock grazing area; unplanned grazing and 3 year fire return (average 2001-2019)
Predominant herbivores	*Alcelaphus buselaphus caama, Damaliscus pygargus phillipsi, Ourebia ourebi, Pelea capreolus, Redunca arundinum, Redunca fulvorufula, Tragelaphus oryx*[3]	*Bos taurus; Ovis aries, Capra aegagrus hircus*
Stocking rate ($LSU\ ha^{-1}$)[3,4]	*0.02 (appropriate wildlife stocking)*	*0.25-1.5 (tending to overstocking)*

[1]IUSS Working Group WRB, 2015; [2]Mucina and Rutherford, 2006; [3]Rowe-Rowe and Scotcher, 1986; [4]Conservation South Africa, pers comm.

Results

Both models accurately simulated herbaceous biomass of the LTER site, e.g. $R^2 = 0.5$ to 0.8 for various grazing and fire treatments in DAYCENT, while phenological patterns of grassland growth were also acceptably simulated (data not shown). Using the calibrated parameters from the LTER site with the climate and soil characteristics in Mvenyane, we found that measured and modelled biomass was similar for unrested areas (DAYCENT) or rested areas (SPACSYS). The DAYCENT simulation was accurate for both rested and unrested areas because the 'rested' area was, in reality, frequently trespassed by grazing livestock belonging to non-CA communities neighbouring Mvenyane, and biomass did not increase as expected (Fig. 1A). Supporting this, the 2019 NDVI time-series was near-identical for the unrested and 'rested' areas ($R^2 = 0.90$, data not shown). DAYCENT accurately simulated SOC and was similar for both rested and unrested areas, varying little between grazing treatments, while SPACSYS overestimated SOC especially in rested areas (Fig. 1B). Future scenarios using DAYCENT indicated that SOC could increase by ca. 1000 $g\ C\ m^{-2}$ (10 $t\ ha^{-1}$) over ten years or 1 $t\ ha^{-1}\ yr^{-1}$ with a change in management from continuous high pressure grazing to moderate pressure grazing in a two-camp rotation, with or without fire, while the SPACSYS model indicated a similar end-point SOC for low-moderate grazing pressures (Fig. 2).

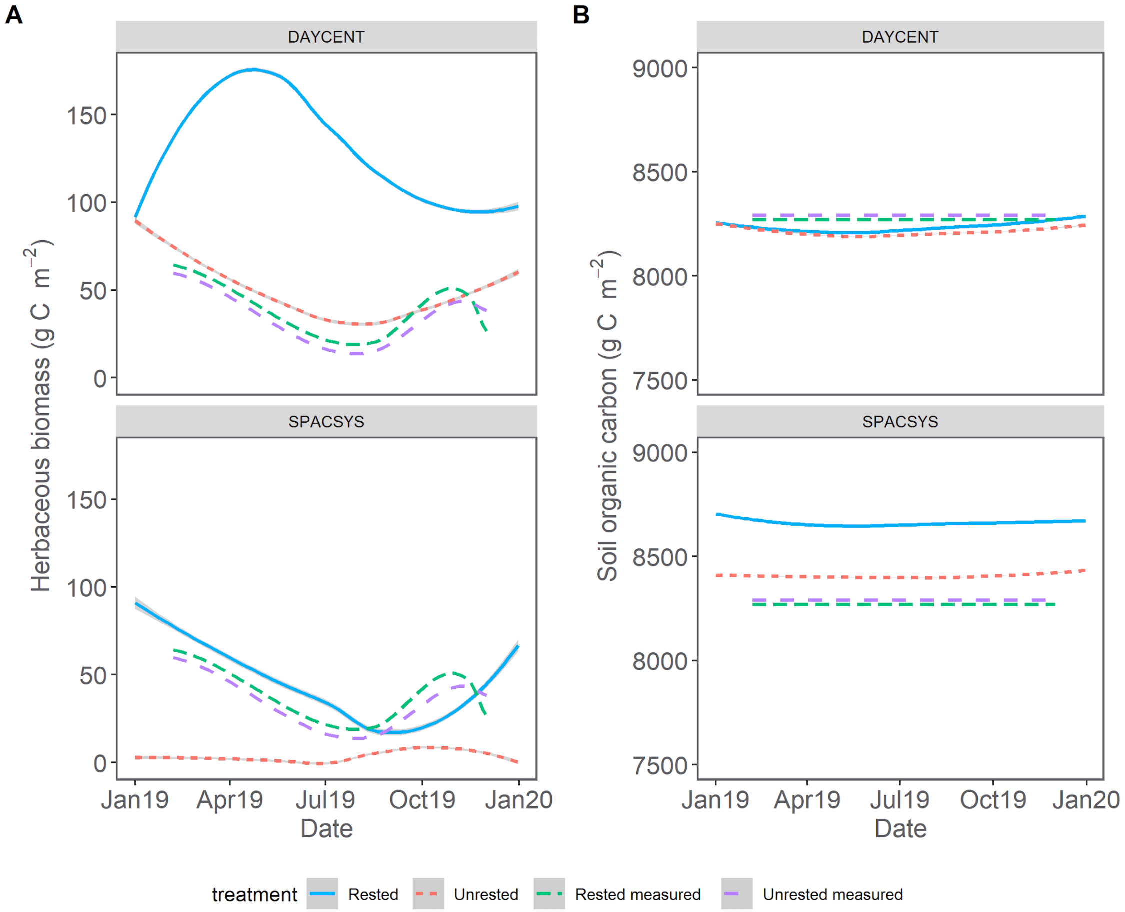

Fig. 1. Aboveground herbaceous biomass (A) and soil organic carbon (B) for modelled and measured data in the Mvenyane communal livestock area. The pre-condition for model simulations was the unrested state in both treatments.

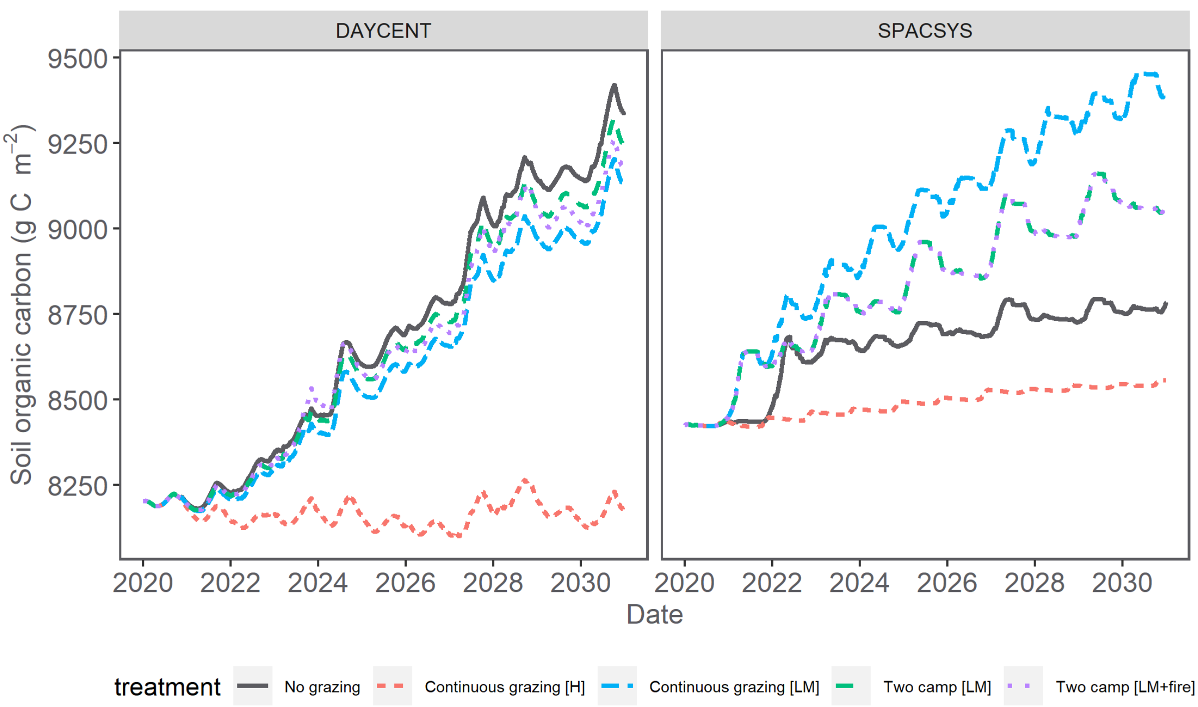

Fig. 2. Simulated soil organic carbon (200 mm depth) from DAYCENT and SPACSYS with various grazing and fire regimes in the Mvenyane communal livestock area over a ten-year period. Abbreviations: LM (low-moderate grazing pressure); H (high grazing pressure). The pre-condition was the unrested state or Continuous grazing [H].

Infrequent moderate fires did not change SOC (Fig. 2). Biomass increased but water fluxes did not change with changed management from high to moderate grazing pressure (data not shown).

Discussion

DAYCENT and SPACSYS have individual merits, e.g., SPACSYS can simulate exact stocking rates and DAYCENT can simulate fire (SPACSYS must apply a full harvest event to simulate fire, i.e., fire simulations are uncertain). Data revealed that so-called rested areas are being grazed, requiring better commitment to CAs and communication with non-CA communities neighbouring Mvenyane. As expected, predicted scenarios indicated that continuous, high pressure grazing reduced both primary production and SOC compared to lower pressure grazing, either with continuous grazing (SPACSYS) or a two-camp approach (DAYCENT). Two-camp or season-long rotation has the known advantage of maximally utilizing rangelands (increasing animal distribution) with little effort (Briske et al. 2011; Venter et al. 2019). Small increases in aboveground herbaceous biomass (ca. 100 kg ha^{-1} or 5 g C m^{-2}) have been found after clearing of alien vegetation in Mvenyane (Vundla et al. 2020) while our simulated change from high to low-moderate grazing pressure indicated a tripling at peak growing season within one year. This prediction seems reasonable given that the herbaceous biomass on protected areas and well-managed commercial private farms in the district is three times that of communally farmed areas (Nel et al. 2013). We also predicted that SOC could increase by ca. 1 t ha^{-1} yr^{-1} with a change in management from continuous high pressure grazing to two-camp and low-moderate grazing pressures. These and other scenarios, including future climate projections, will be used to evaluate biophysical and social trade-offs so that sustainable land use plans can be created in Mvenyane and the wider rangeland community.

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