Rangeland Ecology & Management xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Rangeland Ecology & Management

journal homepage: http://www.elsevier.com/locate/rama

Evaluation of Continuous and Multipaddock Grazing on Vegetation and Livestock Performance—a Modeling Approach☆

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ARTICLE INFO

Article history:
Received 8 February 2016
Received in revised form 11 May 2016
Accepted 1 July 2016
Available online xxxx

Key Words:
continuous grazing
grass composition
livestock consumption
multipaddock grazing
rangeland health

ABSTRACT

Although the impact of optimal stocking rate on rangeland health and ranch profitability has been extensively studied, grazing management practice has received far less attention in mathematical modeling analyses. This paper uses a mathematical model to examine the impacts of continuous grazing and multipaddock (MP) grazing on vegetation and livestock forage consumption. Simulations are carried out using parameters applicable to the southern tallgrass prairie of North America. On small areas of land with no difference between defoliation rates across different grazing methods, the performance of MP grazing is no better than continuous grazing. At the scale of commercial ranches, MP grazing with improved defoliation management improves grass composition and productivity, as well as livestock consumption relative to continuous grazing, especially with heavier stocking rates and unfavorable initial biomass composition. The advantages of MP grazing, however, are reduced with favorable rainfall conditions, light stocking, low levels of undesirable plants, and inadequate recovery periods.

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Introduction

As rangeland provides important ecosystem services beyond forage for livestock, including maintenance of stable and productive soils, the delivery of clean water, the sustenance of plants, animals, other organisms, and natural resources, maintaining ecosystem function in extensive rangeland systems is critical for human well-being (Teague et al., 2013). However, rangeland degradation is common in most of the world's semiarid rangelands due to continuous grazing (Vetter et al., 2006; Moreno García et al., 2014) and supplementary feeding (Müller et al., 2015). This is manifested by degradation of vegetation and soils (Milchunas and Lauenroth, 1993; Teague et al., 2011), declines in productivity and biodiversity, and a reduction in ecosystem resilience (Knopf, 1994; Frank et al., 1998; Peterson et al., 1998).

One of the main threats to rangeland health is the invasion of undesirable plants, often caused by grazing, and sometimes by extrinsic factors (Watkinson and Ormerod, 2001; Simberloff, 2011; Vilà et al., 2011). Examples include indigenous undesirable plant species in Southern Great Plains, such as *Aristida* spp., *Bothriochloa laguroides, Erioneuron pilosum Sporobolus compositus, Ambrosia psilostachya, Gutierrezia texana,* and *Aster ericoides*. Compared with palatable and productive native grasses, in most cases these invasive plants are of poor grazing value. Moreover, they displace more desirable plant species and reduce forage quality and quantity. In many cases, the undesirable plants also have relatively small surface foliage and deep taproot systems, which negatively affect soil quality as they contribute less organic matter near the soil surface, increase surface water runoff, and reduce water infiltration rates (Olson, 1999; DiTomaso, 2000).

Stocking rate has a great impact on animal and vegetation production and, consequently, has been extensively investigated as a key management factor needed to maximize ranchers' long-term profits while maintaining rangeland functionality (Huffaker and Wilen, 1991; Torell et al., 1991; Huffaker and Cooper, 1995; Kobayashi et al., 2007; Teague et al., 2009; Ritten et al., 2010). Proper stocking rate alone, however, will not suffice in preventing the invasion of undesirable plants and avoiding rangeland degradation (Teague et al., 2013). As animals exhibit spatial patterns of repetitive use in large paddocks, consuming preferred plants and patches repeatedly, the most desirable plants are intensively grazed while the less desired species are seldom used (Fuls, 1992; O'Connor, 1992; Bailey et al., 1998; Teague et al., 2004). Due to this uneven grazing impact, even a low stocking rate can cause a change in composition toward the unfavorable species.

Timing and spatial distribution of livestock grazing are, therefore, important components in grazing management. While continuous overgrazing exacerbates degradation of plant communities and results in invasion of low-grazing-quality plant species (Dyksterhuis, 1946,

☆ This work was supported by the Dixon Water Foundation [project H8179]. http://dx.doi.org/10.1016/j.rama.2016.07.003.

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http://dx.doi.org/10.1016/j.rama.2016.07.003
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Please cite this article as: Wang, T., et al., Evaluation of Continuous and Multipaddock Grazing on Vegetation and Livestock Performance—a Modeling Approach, Rangeland Ecology & Management (2016), http://dx.doi.org/10.1016/j.rama.2016.07.003

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1948; Crawley, 1983; Mack, 1989, and Bullock et al., 1994), multipaddock (MP) grazing can improve species composition and ecosystem function under appropriate management (DeRamus et al., 2003; Gerrish, 2004; Teague et al., 2013). In the rangeland profession, however, the topic of whether MP grazing improves forage composition, forage production, and animal production has been a hotly debated topic over the past several decades. Briske et al. (2008) concluded that rotational grazing was no better than continuous grazing in both plant production and animal production. To explain the contradictory stories between commercial ranch managers and scientific experiments, Briske et al. (2011) suggested that adaptive management, omitted by most experiments, might be the key that led to the success of rotational grazing on working ranches. Teague et al. (2013) indicate that MP grazing research[1] had arrived at the opposite conclusions when it was 1) conducted at the scale of ranching operations; 2) conducted over more meaningful time frames; 3) adaptively managed as conditions changed to achieve desired ecosystem and production goals; and 4) included measurement of parameters indicating change in ecosystem function.

Similar to most experimental studies, earlier modeling studies on MP grazing also concluded that the advantages of MP grazing were either nonexistent, existed only in rare cases, or were very limited (Noy-Meir, 1976; Woodward et al., 1993, 1995). In these studies, several essential features of the grazing systems such as spatial heterogeneity and grass selectivity were not taken into account. Of the few recent studies that took spatial heterogeneity grazing behavior into account, however, the advantage of MP grazing was found to be evident and robust under changing climate conditions (Jakoby et al., 2014; Martin et al., 2014; Jakoby et al., 2015).

To our best knowledge, no modeling study on MP grazing management has considered the effect of palatability differences caused by different species. When considering only one grass species, the grass selectivity issue is ignored and therefore the change in grass composition that may contribute greatly to the benefits of MP grazing cannot be addressed. In this regard, Huffaker and Cooper (1995) and Kaine and Tozer (2005) included two grasses of different palatability in their mathematical modeling under continuous grazing management. Neither study, however, has compared continuous with MP grazing in terms of grass composition and animal consumption consequences.

To address these omissions, we extend the model of Noy-Meir (1976) by adding the following features. First, our model incorporates selective grazing implications by including two types of grasses, namely palatable and less-palatable grasses. This allows us to study the dynamics of grasses under different grazing practices. Second, we consider the issue of area selective or spot grazing over the landscape by including a defoliation percentage, which is dependent on grass species and grazing practices in our simulation. Simulations were conducted using parameters that emulate pasture growth and response to cattle herbivory in tallgrass prairie of the Southern Great Plains of North America. The advantage of the simulation analysis is that we can easily adjust the baseline parameter values and test the robustness of our results through sensitivity analysis. Our general mathematical model also has direct relevance to other semiarid C4 grasslands throughout the world including those in South America, Australia, Africa, and Asia.

With these more realistic assumptions, we aim to make a more complete comparison between the two grazing practices in a wide range of scenarios, which include differences in 1) grass defoliation levels; 2) stocking rates; 3) initial proportions of palatable grass; 4) levels of initial biomass; 5) length of recovery period; and 6) competition and growth rates between grass species.

[1] Under MP grazing, or management intensive grazing (MIG), livestock are generally being rotated every 1 − 3 days on many paddocks, usually more than 16; under traditional rotational grazing, however, livestock are rotated every few weeks or months, usually using fewer than 8 paddocks.

Methods

Model

The growth-competition functions of the two grass species are defined in the form of the Lotka-Volterra equation, as described in Noy-Meir (1981):

$$G^1\left(V^1, V^2\right) = g^1 V^1\left(1 - \frac{V^1 + \rho V^2}{V_m}\right) \tag{1}$$

$$G^2\left(V^1, V^2\right) = g^2 V^2\left(1 - \frac{\rho V^1 + V^2}{V_m}\right) \tag{2}$$

Here $G^1(\cdot)$ and $G^2(\cdot)$ represent the growth rate functions of the palatable and unpalatable grass, respectively, while g^1 and g^2 are the maximum relative growth rate of the palatable grass and the unpalatable one. Note that if $g^1 \neq g^2$, then Equations (1) and (2) imply asymmetric competition on the species level (Freckleton and Watkinson, 2001).

The biomass densities of the palatable and unpalatable grass are represented by

V^1, V^2, respectively, while V_m is the maximum plant biomass per unit of land that determines potential carrying capacity. The competition parameter between these two grass species is represented by $\rho \in [0,1]$. A lower value of ρ means that the growth rate of one grass is less affected by the abundance of the other grass. If $\rho = 0$, then the growth function in this case is reduced to the single grass growth function as described in Noy-Meir (1976). When $\rho \neq 0$, we can see from Equations (1) and (2) that the growth rate of each grass species is negatively related to the biomass density of the other grass.

If the biomass density of both species is greater than the residual biomass density[2], which is the ungrazeable part of the plant, that is $V^1 > V_r^1$, $V^2 > V_r^2$, then we assume that the consumption function takes the same function form as assumed by Noy-Meir (1976):

$$C^1\left(V^1\right) = c_m^1 \frac{V^1 - V_r^1}{(V^1 - V_r^1) + (V_k^1 - V_r^1)} H \tag{3}$$

$$C^2\left(V^1, V^2\right) = c_m^2 \frac{V^2 - V_r^2}{(V^2 - V_r^2) + (V_k^2 - V_r^2)} H \tag{4}$$

Equation (3) describes the livestock consumption function for palatable grass while Equation (4) describes that for unpalatable grass. Following Huffaker and Cooper (1995), we assume that the consumption of palatable grass, $C^1(\cdot)$, is not at all affected by biomass density of the unpalatable grass, V^2, as the livestock will pick the palatable grass first. However, the consumption of unpalatable grass, $C^2(\cdot)$, is negatively affected by biomass density of the palatable grass, V^1, as the livestock will eat little or none of the unpalatable grass if they get a sufficient supply of the palatable grass.

The animal stocking density is represented by H. The overall satiated consumption rate of a cow is assumed as c_m, and the satiated consumption rate of the palatable grass is $c_m^1 = c_m$, while that of the unpalatable grass is $c_m^2 = c_m - C^1(V^1)$ based on Huffaker and Cooper (1995). $V_k^i (i = 1,2)$ is the constant, referred to as the *Michaelis constant*, that characterizes the grass quantity at which the animal consumption is half of the satiated consumption rate. A lower Michaelis constant can be interpreted as a pasture with higher-quality grass, as an animal can achieve desired performance with less quantity of forage. Therefore, it is reasonable to assume that $V_k^1 \leq V_k^2$.

[2] We assume that when the consumption of the palatable grass reaches the point such that the existing palatable grass biomass is less than the residual biomass, then the animal will consume the unpalatable grass only.

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