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Evaluating long-term economic and ecological consequences of continuous and multi-paddock grazing - a modeling approach

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ABSTRACT

Aside from overstocking, inappropriate grazing management strategies may cause rangeland degradation in commercial scale ranches. In this paper we construct a dynamic model to study the economic and ecological consequences of continuous and multi-paddock (MP) grazing. Simulations on long-term economic profitability and ecological indices were carried out for continuous vs. MP grazing management strategies under different grass growth rates, grass dormant periods, initial ecological conditions and various installation costs for MP grazing. Results show that compared to continuous grazing, MP grazing on large commercial ranches greatly increases the optimal 30-year net present value (NPV) by sustaining much higher stocking rates. At realistic stocking rates, MP grazing both increases long-term economic profit and improves ecological conditions. The advantage of MP grazing is more pronounced under xeric conditions, longer grass dormancy period, and initial prevalence of less palatable grasses and weeds. However, ranch managers for smaller ranches and/or ranches under short-term leases are less likely to adopt MP grazing due to its diminished economic advantages on those ranches.

1. Introduction

Arid and semi-arid rangeland make up about one third of the earth's land use area (Sayre et al., 2012) and the primary use of these ecosystems is livestock grazing. Global livestock production has been increasing steadily since the 1960s (FAO, 2010) in response to increasing demand for animal protein and other products by a growing world population (Rosegrant et al., 2009). Unless resources are managed sustainably, the pressure on these ecosystems will cause degradation that will adversely impact the continued delivery of ecosystem goods and services upon which human well-being depends (Teague et al., 2013). With at least one billion people relying on rangelands for their livelihoods (Ragab and Prudhomme, 2002), it is vital for land managers to maintain resilient rangeland ecosystems while optimizing long-term economic returns.

In this regard, stocking rate decisions have been widely considered as the most important in terms of vegetation, livestock, wildlife and economic returns (Holechek et al., 1989; Briske et al., 2008) and thus have received intensive examination under various circumstances. Among these, Huffaker and Wilen (1991) investigated optimal stocking rate under conditions of declining forage and pointed out that intensive-early-stocking can outperform the season-long-stocking strategy in a variety of circumstances; Huffaker and Cooper (1995) studied optimal annual stocking decisions and the long-term impacts of the composition of rangeland vegetation; Kobayashi et al. (2007) examined the stocking decision for herders with restricted access to capital and found that increased capital cost will lower optimal stocking rates; Ritten et al. (2010) studied the impact of stochastic precipitation on optimal stocking density and suggests optimal stocking rates and profitability decrease in the face of increased precipitation variability; Teague et al. (2009) demonstrated that stocking for maximum long-term profit decreased ecological condition while managing stocking rates to improve ecological condition over the long term resulted in reduced profit; while Torell et al. (1991) compared the stocking decisions under short- and long-terms and found that stocking rate to maximize profit in the long term was well below that which caused severe deterioration of the rangeland.

While proper stocking rate ensures forage production and individual livestock performance in the short-term, inappropriate grazing management strategies can still cause rangeland degradation in commercial scale operations (Quaas et al., 2007; Wang et al., 2016). Despite the intensive scrutiny on the economic significance of stocking rates,

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previous economic literature has rarely analyzed the importance of grazing management strategies as a means of achieving economic and ecological goals. An exception is Jakoby et al. (2014), who found that MP grazing using a high number of paddocks per herd resulted in higher net returns, lower income variability when grazing using short periods of grazing with long periods of recovery. In this paper we study the long-term economic profitability for continuous vs. various multi-paddock (MP) grazing management strategies under different grass growth rates, initial ecological conditions and feeder market prices. Ecological conditions, including grass biomass and composition dynamics, are also determined for each grazing strategy.

Native grasslands comprise a mixture of many plant species and provide greater and more stable primary production as a consequence of this high diversity. Most modeling studies, however, have assumed the presence of only one species of grass, when comparing different grazing strategies (e.g., Noy-Meir, 1976; Woodward et al., 1993, 1995; Martin et al., 2014; Jakoby et al., 2014, 2015). By incorporating spatial heterogeneity, multispecies and grass selectivity, as well as intra-annual processes into the model, Wang et al. (2016) overcame short-comings inherent in most small-scaled experimental research as well as some limitations of modeling studies due to the monoculture assumption. However, it includes no economic component to reflect the significant short- and long-term costs from installing the infrastructures necessary for MP grazing. Therefore, for producers who mainly focus on monetary incentives, either in the short or long-term, Wang et al. (2016) provides little guidance.

In this paper we will extend the modeling framework of Wang et al. (2016), in which a dynamic mathematical model was developed that includes two interacting components: 1) an ecological component that describes the essential features of plant responses under livestock grazing and 2) a livestock grazing component that characterizes livestock grass consumption as a function of livestock body mass, forage availability and stocking rates. In this paper, an economic component has been added to the Wang et al. (2016) model to assess livestock production and economic implications of using MP grazing relative to continuous grazing management. To simplify the modeling and interpretation of results, our study only considers a stocker operation simulating the growth of feeder animals on native rangeland from weaning to sale off the ranch for finishing in a feedlot or on forages.

The stocker phase of the beef supply chain followed the cow-calf phase as featured by Wang et al. (2016), which assumed a fixed cow weight during the grazing period. Under the stocker phase, management aims at providing daily livestock weight gain. Therefore, for the livestock-grazing component, we incorporate an interaction between forage grazing and the livestock weight on a daily basis. The long-term economic profitability for continuous vs. MP grazing management strategies are simulated under different grass growth rates, grass dormant periods, initial ecological conditions and various levels of infrastructure costs required to implement MP grazing management. Through different simulation scenarios, comparisons of using MP grazing vs. continuous grazing will be made in terms of livestock, grass and economic performance.

2. Model

2.1. Ecological component

Here we consider two functional groups of grasses: perennial palatable grass and perennial less palatable grass. Each group may contain different grass species. To simplify, we will refer to the perennial palatable grass as palatable grass, and the perennial less palatable grass as less palatable grass. Following Wang et al. (2016), grass growth-competition functions can be described in the form of the Lotka-Volterra equation:

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

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

Similar to Noy-Meir (1976), g^1 stands for the maximum relative growth rate of the palatable grass, while g^2 denotes that of the less palatable grass. On a natural rangeland, as palatable grass of the same stature always grows faster than less palatable grass (Crawley, 1983; Oksanen, 1990; Teague and Dowhower, 2001). Consequently, we assume $g^1 > g^2$. Here V^1 and V^2 stand for biomass densities of the palatable and less palatable grass, respectively, and V_m is the maximum plant biomass on a per unit of land basis. Variable $\rho \in (0, 1]$ is used to capture the competition between these two grass functional groups. It indicates the growth rate of each grass species is negatively related to the biomass density of the other. An abundance of the less palatable grass will result in less growth of the palatable grass over the management unit and vice versa.

Given that the initial biomass density is V_0, with s_p percent of palatable grass and s_u percent of less palatable grass, where$s_p + s_u = 1$, the initial biomass density is thus ${V_0}^1 = V_0s_p$ for palatable grass and ${V_0}^2 = V_0s_u$ for less palatable grass. For the paddock currently under grazing, the defoliation rate for palatable grass is d_p and that for the less palatable grass is d_u. The overall percentage of grass that is defoliated is therefore $d = s_pd_p + s_ud_u$. As livestock tend to defoliate a higher percentage of the palatable grass in both management practices, we have $d_p \geq d_u$.

Similar to Wang et al. (2016), denote the biomass densities of the defoliated and non-defoliated palatable grass as ${V_d}^1$ and ${V_{nd}}^1$ and those of the defoliated and non-defoliated less palatable grass as ${V_d}^2$ and ${V_{nd}}^2$. Note that ${V_d}^1d_p + {V_{nd}}^1(1 - d_p) = V^1$ and ${V_d}^2d_u + {V_{nd}}^2(1 - d_u) = V^2$. Assume the initial biomass density for the defoliated and non-defoliated portions are the same and we have ${V_d}^1 = {V_{nd}}^1 = V_0s_p$ for palatable grass and ${V_d}^2 = {V_{nd}}^2 = V_0s_u$ for less palatable grass. The defoliated palatable grass will change over time as:

$$\frac{\delta V_d^1}{\delta t} = G^1(V_d^1, V^2) - C^1(w, V_d^1) - \phi \cdot V_d^1 \tag{3}$$

Note that different from Wang et al. (2016), the consumption of defoliated palatable grass, $C^1(w, {V_d}^1)$ is a function of steer weight, w, which is changing daily and will be explained further in the grazing component section. Here we assume the existing biomass will die at a rate of ϕ, which has the same value regardless of the grass species. In a similar way, the defoliated portion of less palatable grass will change over time according to:

$$\frac{\delta V_d^2}{\delta t} = G^2(V^1, V_d^2) - C^2(w, V_d^1, V_d^2) - \phi \cdot V_d^2 \tag{4}$$

The consumption of defoliated less palatable grass is denoted as $C^2(w, {V_d}^1, {V_d}^2)$, with more details provided in the grazing component section. Accordingly, the palatable grass and less palatable grass will change over time based on (5) and (6) respectively:

$$\frac{\delta V^1}{\delta t} = d_p\,[G^1(V_d^1, V^2) - C^1(w, V_d^1) - \phi \cdot V_d^1] + (1 - d_p)[G^1(V_{nd}^1, V^2) - \phi \cdot V_{nd}^1] \tag{5}$$

$$\frac{\delta V^2}{\delta t} = d_u\,[G^2(V^1, V_d^2) - C^2(w, V_d^1, V_d^2) - \phi \cdot V_d^2] + (1 - d_u)[G^2(V^1, V_{nd}^2) - \phi \cdot V_{nd}^2] \tag{6}$$

To provide a measurement of ecological condition on the rangeland, we define two ecological indices, namely the grass biomass index and the grass composition index. The grass biomass index (BI) is defined as the total available biomass divided by the maximum plant biomass, $BI = (V^1 + V^2)/V_m$, while the grass composition index (CI) is defined as