Evaluation of long-term economic and ecological consequences of continuous and multi-paddock grazing

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Abstract

This paper constructs a dynamic model to study the economic and ecological consequences of continuous and multi-paddock (MP) grazing. Simulations are carried out in the context of a commercial stocker operation in the Southern Great Plains of North America. Results show that compared to continuous grazing, MP grazing 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. While more paddocks and shorter grazing length generate better animal performance and higher economic profit when the grass is abundant, animal numbers always need to be adjusted to ensure sufficient forage is available. The advantage of MP grazing is more pronounced under xeric conditions, longer grass dormancy period, and initial prevalence of less palatable grasses and weeds. The advantages of MP grazing are not evident after a single year but after as short a period as 5 years the advantages become apparent and increase with time.

Keywords: continuous grazing; multi-paddock grazing; grass composition; rangeland health; economic returns.

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 1960's (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 (Holecheck, Pieper and Herbel, 1989) 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 the intensive-early-stocking can outperform season-long-stocking strategy in a variety of circumstances; Huffaker and Cooper (1995) studied the 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 optimal stocking rates that maximize rangeland condition, maintain rangeland condition, or achieve the maximum profit under different initial rangeland conditions;

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 to a large extent, inappropriate grazing management strategies can still cause a gradual change in grass composition towards the less desired species, because livestock in large paddocks tend to consume preferred plants and patches repeatedly, leaving the most desirable plants intensively grazed and the less desired species seldom utilized (Fuls, 1992; O'Connor, 1992; Bailey et al., 1998; Teague et al. 2004). Thus aside from stocking rates, decisions on grazing management strategy are also consequential in terms of long-term economic return and ecological conditions. Despite the intensive scrutiny on the economic significance of stocking rates, previous economic literature has rarely analyzed the importance of grazing management strategies as a means of achieving economic and ecological goals. To fill this void, our paper studies the long term economic and ecological consequences for two different grazing management strategies, namely continuous and multi-paddock (MP) grazing, under a range of stocking rates. In doing so, we take account of the palatability differences of different grass species and the spatially heterogeneous impact of animals grazing in large landscapes.

MP grazing management has been recommended since the mid-20th century as an important tool to adaptively manage rangelands ecosystems for the purpose of sustained productivity and improved animal management (Gerrish, 2004). Since then abundant experimental ecological studies have emerged to compare MP grazing with the continuous grazing strategy in terms of the species composition, forage production and animal weight gain. Divergent conclusions have been reached by existing ecological literature. Experimental studies indicate increased levels of stocking are possible for MP grazing with increasing plant growth and vigor, improving soil health and providing more constantly nutritious diets for the cattle (Chestnut et al., 1992; Davis et al., 1995; Morrow et al., 1991; Gerrish, 2004; Biondini and Manske, 1996; Henning et al., 2001; White and Wolf, 1996; Teague et al., 2011). However, a review of some selected rangelands grazing studies suggests that MP grazing improves neither vegetation nor animal production relative to continuous grazing (Briske et al. 2008).

To overcome some of the short-comings inherent in most field experiment-based grazing management research (Teague et al., 2013), this paper uses a simulation approach with a dynamic mathematical model that includes three components: 1) an ecological component that describes the essential features of plant responses under livestock grazing; 2) a livestock grazing component that characterizes the livestock grass consumption as a function of livestock weight, forage availability and stocking rates; and 3) an economic component that expresses economic profit as a function of purchase and selling prices and weights, as well as the total cost incurred on the farm. To better convert grass intake into animal weight gain and then to economic returns, we carried out our study in the context of a rangeland forage based stocker operation, which serves as a bridge between the cow-calf and feedlot operations by providing grazing for weaned calves before they enter the feedlot for finishing (Galyean, Ponce and Schutz, 2011).

Simulations are carried out using parameters that emulate pasture growth and response to cattle herbivory in tallgrass prairie of the Southern Great Plains of North America. We evaluate long-term economic profitability for continuous vs. various MP grazing management strategies under assumptions of various grass growth rates, initial ecological conditions and feeder market prices. Optimal stocking density and ecological conditions including grass biomass and composition condition are determined for each grazing strategy.

Model

In this section first we introduce three components of our model, which are ecological component, livestock grazing component, and economic component. Parameters for the baseline scenario are specified based on literature values. In addition, we list several alternative scenarios under which the two grazing practices will be further compared.

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. In the Southern Great Plains, examples of the perennial palatable grasses include big bluestem and Indian grass; while examples of perennial less palatable grasses include silver bluestem and meadow dropseed. Unless the rangeland is poorly managed, annual grass in the Southern Great Plains is inconsequential; therefore it is not considered in our paper. To simplify, we will refer to the perennial palatable grass as palatable grass, and the perennial less palatable grass as less palatable grass.

Following Noy-Meir (1981), we describe the grass growth-competition functions in the form of the Lotka-Volterra equation:

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

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

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), we assume $g^1 > g^2$. While V_m is the maximum plant biomass per unit of land, or potential carrying capacity, V^1 and V^2 denote biomass densities of the palatable and less palatable grass respectively.

In addition to the single grass growth functions, we also include the variable $\rho \in [0,1]$ to capture the competition between these two grass functional groups, represented by $\rho \in [0,1]$. If $\rho = 0$, there is no competition between the two and the growth function is the same as the single grass growth function described in Noy-Meir (1976). If $\rho \neq 0$, then the growth rate of each grass species is negatively related to the biomass density of the other. This means an abundance of the less palatable grass will inhibit the growth of the palatable grass and vice versa. A lower value of ρ means lower competition, or the growth rate of one grass is less affected by the abundance of the other grass.

For easy comparison, we assume initial grass compositions are the same for all grazing management practices. Given that the initial biomass density is V_0, with s_p percent of palatable grass and s_u percent of less palatable grass, $s_p + s_u = 1$. Given that the initial biomass density is V_0, then the initial biomass density is $V_0^1 = V_0 s_p$ for palatable grass and $V_0^2 = V_0 s_u$ for less palatable grass. While the paddock is under grazing, the defoliation rate for palatable grass is assumed as d_p and that for the less palatable grass is d_u. As livestock tend to defoliate a higher percentage of the palatable grass in both management practices, we have $d_p \geq d_u$.

MP grazing generates more uniform grass utilization than continuous grazing owing to the short periods of much higher animal density in each paddock when being grazed. Thus we assume the defoliation rates for both grass species under MP grazing are higher than those under continuous grazing. The overall percentage of grass that is defoliated can be calculated as $d = s_p d_p + s_u d_u$. The patch selective grazing by animals has largely been ignored by existing literature (e.g. Noy-Meir, 1976; Huffaker and Cooper, 1995). This is a significant departure from the research demonstrating non-uniform grazing over time in landscapes because livestock grazing large paddocks exhibit spatial patterns of repetitive use (O'Connor, 1992; Bailey et al., 1998).

Based on the finding that livestock tend to graze in preferred areas from previous years (Bailey et al. 1998), we assume that the livestock frequent the defoliated spots all the time, and avoid the non-defoliated areas. We denote the biomass density of the defoliated and non-defoliated palatable grass as V_d^1 and V_{nd}^1 with $V_d^1 d_p + V_{nd}^1(1-d_p) = V^1$ and the biomass density of the defoliated and non-defoliated less palatable grass as V_d^2 and V_{nd}^2 with $V_d^2 d_u + V_{nd}^2(1-d_u) = V^2$. We assume the initial biomass density for the defoliated and non-defoliated portions are the same, so $V_d^1 = V_{nd}^1$ and $V_d^2 = V_{nd}^2$. Initially we have $V_d^1 = V_{nd}^1 = V_0 s_p$ for palatable grass and $V_d^2 = V_{nd}^2 = V_0 s_u$ for less palatable grass. Consequently, the defoliated palatable grass will change over time as:

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

Note that $C^1(w, V_d^1)$ stands for the consumption of defoliated palatable grass per steer at a weight of w, which 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. Note that the growth rate of the defoliated palatable grass is a function of the biomass of the defoliated palatable grass and the average biomass of the less palatable grass. This is because we are not sure if the defoliated palatable grass is competing with the defoliated less palatable grass or the non-defoliated less palatable grass, so we choose the average biomass of less palatable grass.

In a similar way the defoliated portion of less palatable grass will change over time according to:

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

The consumption of defoliated less palatable grass is denoted as $C^2(w, V_d^1, V_d^2)$, with more discussion on it provided in the grazing component section. Given that no consumption occurs on the non-defoliated grass, overall the palatable grass will change over time based on:

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

Similarly the less palatable grass will change over time according to:

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

Note that for the paddocks currently under recovery, the consumption rates of both palatable grass and less palatable grass are specified as zero. 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, $BI = \left(V^1 + V^2\right) / V_m$, while the grass composition index (CI) is defined as the palatable grass biomass divided by the total biomass, $CI = V^1 / \left(V^1 + V^2\right)$.

Livestock grazing component

Following Noy-Meir (1976), we describe our MP grazing scheme as determined by two parameters, the number of paddocks, n, and the length of the MP cycle, t_r. For simplicity, we consider only the strict cyclic MP grazing scheme as defined by Woodward and Wake (1995), where the animals are introduced to successive paddocks in strict MP sequence and spend the same number of days grazing on each paddock. This means for the first t_r / n days out of a typical MP cycle, the first paddock is being grazed, while the other $n-1$ is on recovery; the second t_r / n days the second paddock is being grazed and so on. A continuous grazing scheme can be treated as a special case where $n=1$, with one paddock that is continuously grazed as long as the stocker steers are retained on the farm.

Suppose the average stocking density on the entire pasture is H, then the stocking density for the paddock under grazing is nH if the grass is 100% defoliated (Noy-Meir, 1976). In our paper the overall grass defoliation rate is d, therefore the stocking density on the defoliated grass is $\overline{H} = nH / d$, while that on non-defoliated grass is 0. For the recovery $t_r(n-1)/n$ days, the first paddock is in recovery, the stocking density is 0 and consumption is 0.

As mentioned in the ecological component, the livestock consumption function for the two grass species is $C^1(w, V_d^1)$ for defoliated palatable grass and $C^2(w, V_d^1, V_d^2)$ for defoliated less palatable grass. Here we assume that C^1 increases with the defoliated palatable grass biomass density V_d^1 and reaches a satiation point at high density of V_d^1.

If the biomass density of both species is greater than the residual biomass density, that is $V_d^1 > V_r^1$, $V_d^2 > V_r^2$, then we assume that the consumption function takes the form of the Michaelis function of vegetation biomass above ungrazeable residuals, as assumed by Noy-Meir (1976). Therefore:

$$(7)\qquad C^1(w,V_d^1)=c_m^1\frac{V_d^1-V_r^1}{(V_d^1-V_r^1)+(V_k^1-V_r^1)}\overline{H}\,;$$

$$(8)\qquad C^2(w,V_d^1,V_d^2)=c_m^2\frac{V_d^2-V_r^2}{(V_d^2-V_r^2)+(V_k^2-V_r^2)}\overline{H}\,.$$

The overall satiated amount of consumption for a grazing stocker steer at weight w is $c_m(w)=\kappa\cdot w$, where κ is denoted as the satiated forage consumption rate. The satiation consumption increases as the steer weight w increases. Following Huffaker and Cooper (1995), we assume the satiated consumption rate of the palatable grass is $c_m^1=c_m(w)$, while that of the less palatable grass is $c_m^2=c_m(w)-C^1(V_d^1)$. Note that the specification C^1 is not at all affected by biomass density of the defoliated less palatable grass, V_d^2, while C^2 is negatively affected by biomass density of the palatable grass, V_d^1, reflecting the fact that the livestock will eat little or none of the less palatable grass if they get a sufficient supply of the palatable grass. Variable $V_k^i(i=1,2)$ denotes the Michaelis constant, at which the animal consumption is half of the satiated consumption rate. A lower Michaelis constant is associated with higher quality grass, or that the livestock can achieve desired performance with less quantity of forage. Therefore we assume $V_k^1\le V_k^2$.

Suppose 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 less palatable grass only. That is, if $V_d^1\le V_r^1$ and $V_d^2>V_r^2$ then we have:

(9) $$C^1(w, V_d^1) = 0;$$

(10) $$C^2(w, V_d^1, V_d^2) = c_m^2 \frac{V_d^2 - V_r^2}{(V_d^2 - V_r^2) + (V_k^2 - V_r^2)} \overline{H}.$$

Finally if $V_d^1 \le V_r^1$ and $V_d^2 \le V_r^2$, then the consumption of both grass species is zero, i.e.:

(11) $$C^1(w, V_d^1) = 0 \text{ and } C^2(w, V_d^1, V_d^2) = 0.$$

Clearly this case is non-sustainable. The stocker steer weight, starting from the purchase weight of w_p, will change over time according to:

(12) $$\frac{\delta w}{\delta t} = \theta \cdot \left[C^1(w, V_d^1) + \ell \cdot C^2(w, V_d^1, V_d^2) \right]$$

The consumption to weight gain conversion ratio is denoted as θ, which means 1 kilogram of daily grass consumption will generate θ kilogram of daily weight gain. We use parameter ℓ to stand for the relative conversion rate of less palatable grass to that of the palatable grass. In other words, 1 kilogram of less palatable grass is equivalent to ℓ kilogram of palatable grass for weight gain purpose. Given that less palatable grass could sometimes be of higher nutritious value than palatable grass, therefore parameter ℓ is not necessarily less than 1.

Economic Component

On a per steer basis, economic profit for cohort b can be defined as:

(13) $$\pi(b) = w_s(b)P_s(b) - w_p(b)P_p(b) - TC(b)$$

The purchase price and purchase weight of the weaning steer for cohort b are denoted as $P_p(b)$ and $w_p(b)$, while the selling price and selling weight of the steer are $P_s(b)$ and $w_s(b)$. The total cost incurred on the farm on a per steer basis is denoted as $TC(b)$.

Assuming that only one cohort is produced annually, the net present value (NPV) on a per steer basis over a span of B years is calculated as:

$$NPV(B) = \sum_{b=1}^{B} \beta^b \pi(b) \tag{13}$$

where $\beta \le 1$ denotes the discount factor, meaning that the \$1 economic return earned in year b is equivalent to \$ β^b earned in the current period. Given that the average stocking rate is H, NPV on a per hectare basis can be defined as $NPV(B) \cdot H$.

Simulation experiments

No simple analytic solution is readily obtainable for the MP grazing even in the one grass case (Noy-Meir 1976). Therefore, we conduct simulation experiments using a set of parameters to compare long-term economic and ecological consequences under the different grazing scenarios. The model parameters are chosen to capture the characteristics of a stocker operation in Texas tallgrass prairie. Table 1 provides a summary of parameter values used in our baseline model.

While Noy-Meir (1976) assumed a maximum plant biomass per unit of land (V_m) as 5000 kg DM ha^{-1}, we chose a V_m value of 4000 kg DM ha^{-1}, or 400 g/m^2. This is based on field data from Teague et al. (2011) in North Texas which estimated the peak biomass from heavy continuous (HC), light continuous (LC), multi-paddock (MP) and ungrazed areas (EX) as 2696, 3960, 4680 and 5149 kg DM/ha respectively. The average is 4121 kg DM ha^{-1}, which is close to the estimates of 4000 kg DM ha^{-1}by Wright and Baars (1976). As a baseline we assume each paddock is comprised of $s_p = 50\%$ palatable grass and $s_u = 50\%$ less palatable grass, with initial palatable and less palatable biomass densities of 100 g/m^2 for each.

The Michaelis constant, or V_k, is assumed to be 20% of the peak biomass V_m (Noy-Meir 1976; Huffaker and Wilen, 1991). As a lower Michaelis constant generally stands for higher grass quality, in our simulation we assumed $V_k^1 = 15\% \cdot V_m$ and $V_k^2 = 25\% \cdot V_m$. Similar to Noy-Meir (1976), the ungrazeable residual plant biomass V_r is assumed as 200 kg DM ha^{-1}, or 20 g/m^2.

For simplicity, Noy-Meir (1976) used a relative maximum grass growth rate of 0.1 per day all year long, which represents grassland of high productivity. In Texas tallgrass prairie, the grass grows more slowly in the less mesic rangeland so we assume the maximum grass growth rate for palatable grass averaged 0.03 per day during the grass growth season. In Southern Great Plains area, we assume both grass functional groups considered in our paper will be dormant in winter and for 120 days, from mid-November to mid-March, for which the growth rate of the grass is assumed as zero.

We assume the average growth rates of the two grass functional groups are correlated in the way that $g^2 = \rho \cdot g^1$. This means that more rainfall will stimulate faster growth of both groups though the less palatable grass always grows at a slower rate than the palatable grass. Following Noy-Meir (1981), we assume the interaction between these two grass groups is $\rho = 0.8$. Under this assumption, maximum growth rate of the palatable grass will be low when the biomass density of the less palatable grass is high, and vice versa. Meanwhile, we assume the average daily death rate of the grass as 0.01 per day when not consumed. Even in the dormant period we assume the same grass death rate, because although the microbial breakdown of the grass is slower, the wind breakdown rate is higher.

For MP grazing, we assume the number of paddocks is $n = 30$, and the length of the MP grazing cycle is T_r = 90. This means the cows spend 3 days on each paddock per cycle, to provide a recovery of 87 days before the next grazing. Jacobo et al. (2006) assumed a grazing period of 3 to 15 days and a recovery period between 25 to 90 days in a sub-humid condition. Modeling a more xeric condition, we set our rotation parameters on the lower end of grazing period length and the upper end of the recovery period length as specified by Jacobo et al. (2006). Regarding recovery period, our assumption is close to that for the semi-arid rangeland outlined in Teague et al. (2013), citing from published work that recovery periods after moderate defoliation need to be between 30 days in mesic and 90-120 days in semi-arid to arid ecosystems.

According to Teague et al. (2013), little or no grazing of the less palatable grass occurs under light continuous grazing, while utilization of the less palatable grass is much higher under MP grazing due to increased stock density in the smaller paddocks while they are grazed. For less palatable grass we assume a low defoliation rate of 10% under continuous grazing (d_u^c), and a defoliation rate of 50% under MP grazing (d_u^r). For palatable grass, we assume $d_p^c = 80\%$ under continuous grazing and $d_p^r = 100\%$ under MP grazing. Based on our assumptions, each paddock is comprised of 50% palatable grass (s_p) and 50% less palatable grass (s_u), with an overall defoliation rate of d^c = 45% for continuous grazing and d^u = 75% for MP grazing. For simplicity we did not vary the defoliation rates when stocking rates change. In reality, the defoliation rate of palatable grass may not be 100%, especially under the light stocking rate, as livestock prefer areas close to water and shade (Fuhlendorf and Engle, 2001). Also light stocking may cause greater variation in the grazing pressure over the grazed paddock, so the difference between defoliation rates on palatable grass and less palatable grass is even greater than that in heavy grazing (Earl and Jones, 1996).

The maximum or satiated forage consumption rate is assumed as 2.5% of body weight per day while they are grazing. Following Huffaker and Wilen (1991), we adopt the forage conversion coefficient as 0.096. In the baseline case the relative conversion rate of less palatable grass to that of the palatable grass is assumed as $l = 0.75$, the same as that used in Huffaker and Cooper (1995). As the less palatable grass may sometimes be more nutritious than palatable grass, later on we will also consider another scenario where it has a higher forage conversion coefficient than palatable grass.

On a representative stocker ranch in Southern Great Plains, weaned calves are stocked each year on November 15 with an average weight of 216 kg (475 lbs). In our model, we assume they are sold at the end of the growing season, which is mid-August of the following year [i]. For modeling purposes, we assume the steers spend a total of 270 days on the farm. For the first 120 days on the farm, the grass is in dormant period, as discussed previously. We assume the steers graze on the standing grass during this period, which is the initial plant biomass, assumed as 3200 kg ha^{-1}, i.e., 80% of the maximum plant biomass.

The prices of feeders at 204 kg (450 lbs), 295 kg (650 lbs) and 341 kg (750 lbs) are \$4.07 kg^{-1}, \$3.46 kg^{-1} and \$3.24 kg^{-1} respectively, based on the most recent 5-year average data (Cattle Fax). The purchase and selling prices of feeder are thus calculated on a sliding basis based on these three benchmark prices. For steers weighing 182-227 kg (400-500 pound), the unit price decreases by \$0.00176 for each of the kilograms gained (or \$0.0008 for each of the pound gained). If the ending weight is between 272-318 kg (600-700 pound), then the unit selling price decreases by \$0.00132 for each of the kilograms gained (or \$0.0006 for each of the pound gained); if the ending weight is above 318 kg (700 pound), then unit selling price decreases by \$0.0011 for each of the kilograms gained (or \$0.0005 for each of the pound gained). In our case, the purchase price can be calculated as \$4.05 kg^{-1}. The selling price is contingent on the cattle ending weight, which differs for the various scenarios we consider.

During each production period, we assume both continuous grazing and MP grazing incur a common production cost of \$162 $steer^{-1}$, which includes labor cost, herbicide cost, veterinarian costs, supplemental feed cost, interest cost, repair cost and property tax (Bevers, pers. comm.)[ii]. However, as the focus is on the relative performance of the two grazing strategies, this common production cost incurred by both grazing strategies is immaterial for our comparison. An important factor to consider is the additional cost incurred by MP grazing, which we discuss below.

For MP grazing, some initial investment on infrastructure is necessary, which includes new fencing and water systems. A detailed description of the extra cost incurred for MP grazing is presented in the Appendix. Overall, the initial investment amounts to \$15,341 on a 2072-hectare (5120-acre) ranch. As most ranchers complete installation in increments with existing ranch labor, which has already been covered above, no separate labor cost is accounted. Similarly, there is no extra annual labor cost for MP grazing, as although there is more labor involved in moving the cattle, it saves labor to check a concentrated herd rather than a scattered herd. To evaluate the long-term grazing management impact on economic return and ecological condition, we chose a study period of 30 years. For the initial MP grazing investment, except for the fence cost (\$320), which requires replacement every 5 years, and the float valves (2 @ \$30 each), which lasts around 10 years, everything else will last for 30 years with minor maintenance.

Analysis of key elements

To evaluate the economic and ecological consequences of different grazing strategies under various stocking rates, several other scenarios are analyzed besides the baseline scenario. For each studied scenario, we varied the stocking rates and examined the impact of grazing strategies on NPV at both per cow and per hectare basis. We also checked the ending steer weight, average daily grass biomass index, and average daily composition index for year 30, the last year of the studied period [iii]. These possible scenarios are:

1) Grass dormant period. We considered an alternative situation where grass dormant period is 90 days vs. the baseline of 120 days.
2) Grass growth rate. We checked how the key variables change under a relatively high grass growth rate. Specifically, we chose $g^1 = 0.04$ (fast growth rate period) and $g^2 = 0.8g^1=0.032$.
3) Short-term vs. long-term decision. We compared the profit maximizing stocking rate decision made on the 30-year NPV basis with that made on single year economic profit basis.
4) Additional cost incurred by MP grazing strategy. We compared NPV under different grazing strategies when the extra cost of MP grazing is twice the extra cost incurred in the baseline scenario.
5) Initial grass composition index. Under a lower initial grass composition index $CI = 0.3$ vs. baseline of $CI = 0.5$ we investigate how the key variables are affected.

6) The forage conversion rate for less palatable grass. We considered the case where less palatable grass has a higher forage conversion coefficient, which is $l = 1.25$, against the baseline case where $l = 0.75$.
7) Initial biomass index. We compared the lower initial biomass index scenario $BI = 0.6$ with the baseline scenario $BI = 0.8$.
8) Length of grazing periods. We examined the impact of using different MP grazing scenarios, namely 18 paddocks with 5-day grazing period on each paddock, 30 paddocks with 3-day grazing period on each paddock, and 45 paddocks with 2-day grazing period on each paddock. As larger paddocks are associated with longer grazing periods, it is reasonable to assume the same defoliation rates under all three MP scenarios specified in table 1.

Results and discussion

In this section the long term economic and ecological consequences of different grazing practices are discussed. To check the robustness of the baseline results, we also present the results from the alternative scenarios.

Baseline model result

Table 2 demonstrates the 30-year steer selling weight, NPV, biomass index and composition index under continuous and MP grazing. Different stocking rates are considered for both grazing strategies. Regarding steer selling weight, given the grazing strategy fixed, it is not surprising that a higher stocking rate always results in lower selling weight. Intuitively, grazing becomes more competitive with higher stocking rate, resulting in lower consumption per steer. At the same stocking rate, MP grazing has a consistent advantage over continuous grazing for all stocking densities. However, when the stocking rate increases beyond 0.05, the final steer weight from MP grazing decreases more rapidly than with continuous grazing. This demonstrates that MP grazing can sustain a much higher stocking rate than continuous grazing. However, both grazing strategies have an optimal stocking rate limit, beyond which animal performance will be greatly compromised.

The 30-year NPV, which is related to ending weight [iv], also indicates that MP has an apparent advantage over continuous grazing for each stocking rate. On a per steer basis, NPV inevitably decreases for both grazing strategies as the stocking rate increases. On a per hectare basis, however, NPV first increases then decreases after stocking rate reaches certain thresholds, which differ for the two grazing methods as table 2 demonstrates. For example, when the stocking rate increases from 0.03 to 0.04, the NPV per hectare starts to decrease sharply for continuous grazing, while it still increases considerably for MP grazing. Therefore it can be inferred that by sustaining a much higher stocking density compared to continuous grazing, MP grazing greatly increases maximum NPV. Similar conclusions have been reached in field experiments, as Heitschmidt et al. (1982) and Teague et al. (2011) showed that MP can satisfactorily support livestock at stocking rates appreciably greater than normally expected for continuous grazing.

Both grass composition and biomass indices are high for very low stocking rate, and low under extremely high stocking rate. The biomass index declines gradually and the difference between the two grazing strategies remains constant, indicating that for MP grazing there is more grass available for cattle to consume under each stocking scenario. Compared to biomass index, composition index under continuous grazing decreases more precipitously, lagging far behind its MP counterpart under moderate stocking rates. It shows that due to severe patch grazing under continuous grazing, the favorable grass species are rapidly consumed and the invasion of less palatable grasses and weeds becomes an increasing problem even under moderate stocking. Under extremely high stocking rate, though, weed invasion is inevitable for both grazing methods.

Considering only continuous grazing strategy, Teague et al. (2011) demonstrated that the higher stocking rates will inevitably result in poorer range condition. However, this is no longer the case when different strategies are considered. For example, as we can see in table 2, when comparing continuous grazing at stocking rate of 0.03 with MP grazing at stocking rate of 0.04, the latter is noticeably superior in each of the categories. Therefore, compared to continuous grazing, the alternative MP grazing strategy could achieve the goal of increasing stocking rates and economic returns without deteriorating ecological conditions.

Grass dormant period

In table 3, a shorter grass dormant period is considered - 90 days versus the baseline scenario of 120 days in table 2. We can see that a shorter dormant period increased the animal performance, economic profit and biomass index considerably under continuous grazing. The corresponding indicators increased for MP grazing too, but to a lesser extent. Therefore the advantage of MP grazing diminished under the shorter grass dormant period, especially under the low stocking rate. For example, at the stocking rate of 0.02, compared to continuous grazing the MP grazing strategy increased the 30-year NPV by 81% for the 120-day dormant period scenario and by only 9% for 90-day dormant period scenario. This implies that when the grass is dormant for a longer period, continuous grazing has more detrimental effect to the grass biomass and thus animal performance will be greatly affected due to lack of grass. Supplement hay needs to be purchased to meet the animal nutrition requirement. MP grazing, however, requires less supplement feed, since the negative influence of a longer dormant period is partly counteracted by utilization of a greater proportion of the whole grazing unit and the more even grazing of the available grass. The results of table 2 and table 3 reveal that the benefit of MP grazing is more explicit under high stocking rate and longer grass dormant period.

Grass growth rate

Table 4 illustrates the response of key variables under higher average yearlong grass growth rate. More favorable rainfall conditions result in a considerable increase in economic returns and biomass index for both grazing strategies. This is because mesic rangeland condition promotes higher grass growth rate, which can sustain more grazing steers without overgrazing. A comparison between tables 2 and 4 clearly demonstrates the importance of rainfall in determining the productivity and optimal stocking rate.

Though the absolute amount of palatable grass increases under more mesic conditions, the composition index does not increase under a lower stocking rate, as seen with $H = 0.04$. This is due largely to the livestock's more selective consumption of abundant palatable grass. When the stocking rate increases, the selective grazing behavior decreases and the composition index under more mesic conditions also surpasses that under xeric conditions, as more mesic conditions allow the palatable grass to recover from defoliation more rapidly.

While MP grazing still excels for each of the indicators studied, this relative advantage diminished for all stocking rates compared to the xeric scenario as depicted in table 2. Take the stocking rate of 0.03 for example, compared to continuous grazing the MP grazing strategy increased the 30-year NPV by 226% in xeric conditions and by 53% in mesic conditions. This indicates the importance of using an effective grazing strategy to minimize the impact of drought years.

Short-term vs. long-term decision

Tables 5 and 6 show the effect of grazing practice on economic profit and ecological index after the first year after implementation of MP grazing. Compared to the long term corresponding results in tables 2 and 3, we can see one year was insufficient time for the advantages of MP to manifest themselves, especially with lower stocking rates and a shorter dormant period. For example, when the grass dormant period is only 90 days, continuous grazing financially outperforms MP when the stocking rate is no greater than 0.03 (table 6). Even though MP still has a minor advantage in animal performance, the extra fixed cost in infrastructure negates such additional revenue.

In contrast, after 5 years the advantages of implementing MP grazing are already apparent even if the cost of this is calculated at double the rate (table 7). In the long run, without implementing MP grazing higher stocking rates will severely deteriorate ecological conditions as reflected in the declining trend of the biomass and composition indices (table 2). However, in one or two years, neither the improvement nor the damage to ecological conditions is very evident, giving ranchers more incentive to stock at higher levels if only short term returns are considered.

Additional cost of MP grazing

To be more conservative, we also considered the scenario where the additional cost of MP grazing is twice the estimated cost. This scenario might apply to those producers who have no experience in MP grazing. Thus some additional cost such as consulting fees will be incurred, which greatly increases the cost. For the baseline scenario, even when the additional cost of MP grazing is doubled, we can see that MP grazing is highly advantageous in the long term. It is acknowledged that a shorter grass dormancy period and favorable rainfall conditions can both diminish the advantage of MP grazing, especially under the relatively low stocking rate. Even so, Table 7 indicates that the advantage of MP is still robust under the scenarios of 90-day grass dormancy period and the 33% increase in grass growth rate.

From a short run perspective, the advantage of MP grazing over continuous grazing is greatly reduced. For example, when the grass dormancy period is 90 days, continuous grazing generates more economic profit than MP grazing when the stocking rate is no higher than 0.05. Even if the grass dormancy period is 120 days, continuous grazing generates considerably higher profit than MP grazing at a low stocking rate of 0.02.

Overall, we can conclude the advantage of MP grazing strategy remains robust in as short a time as 5 years and increases over the long term, especially under long grass dormancy periods and drought conditions.

Initial grass biomass index

Table 8 shows the impact of a lower initial biomass index of 0.6 (compared to the baseline of 0.8), with other conditions remaining the same. Compared to table 2, we see that at the end of the 30-year period the animal performance and ecological condition resemble that of the baseline case, with no impact from the initial biomass index change observable. There is a noticeable decrease in NPV for each stocking rate, though it is generally no greater than 10% for either grazing strategy. This is due to the reduced final weight in the first couple of years, as a result of the initially low grass biomass. Therefore, we can see a one-time shock to overall biomass amount will not alter the ecological condition in the long term, and therefore its impact on long term economic returns is also very small.

Initial grass composition index

In table 9, we consider a lower initial composition index of 0.3 (from the baseline 0.5) with all the other conditions the same as the baseline case in table 2. Compared to a lower initial biomass index, we can see a lower initial composition index has a more serious negative influence. For MP grazing, the composition index at the end of 30-year period declines to a certain degree, especially when the stocking rates are high. However, the composition index for continuous grazing is much more severely affected, even at the low stocking rate. Compared to the composition index, the biomass index is affected to a much lesser degree. For MP grazing, biomass indices display no change at all when the stocking rate is no higher than 0.03. But for higher stocking rate under MP grazing and all the stocking rates under continuous grazing, the biomass indices decrease slightly. This is mainly caused by the prevalence of less palatable grass and weeds, which generally have a lower growth rate compared to the palatable grass.

When the palatable grass ratio is initially low, results suggest MP grazing strategy generates more robust economic returns than continuous grazing strategy. For example, a comparison between table 2 and table 9 reveals that, at the stocking rate of 0.03, the 30-year per hectare NPV decreases from \$136 to \$-81 for continuous grazing, a 160% decrease; while it decreases from \$442 to \$388 for MP grazing, a 12% decrease. This is due to the less selective grazing behavior and periods of adequate recovery with MP grazing, which under moderate stocking rate results in much higher grass composition index than continuous grazing and therefore compensates the initial low ratio of palatable grass. In addition, a more uniform grazing behavior for MP grazing increases overall grass availability; therefore the animal performance is affected to a much lesser degree by the initially low palatable grass ratio.

Higher forage conversion rate for less palatable grass

In the previous scenario, it is found that if palatable grass is less abundant, then the animal performance could be seriously affected, especially under continuous grazing. To check the robustness of this conclusion, we consider another case, where less palatable grass has a higher forage conversion coefficient, which is l = 1.25 (table 10). Compared to table 9, higher forage conversion rate for less palatable grass in table 10 increases animal performance and economic profit for both grazing strategies, especially for those scenarios where the composition indices are low. In those cases, the animal has to consume mainly less palatable grass and the increased forage conversion rate will promote the animal weight gain to a greater degree. The ecological indices for both grazing strategies are barely influenced though, since there is no change in grass growth and competition behavior. The minimal changes in ecological indices are caused solely by the increase in animal daily consumption, due to slightly increased steer weights over time.

As MP grazing results in a lower ratio of less palatable grass, the advantage of MP grazing diminishes by a small degree under the higher forage conversion rate for less palatable grass. For example, at the stocking rate of 0.02, compared to continuous grazing, MP increases the steer ending weight and 30-year NPV by 8.3% and 254% respectively when l = 0.75 (table 9), versus the corresponding 7.6% and 177% increase when l = 1.25 (table 10). The advantage of MP grazing remains robust for each of the stocking rates.

Length of grazing period

From the different scenarios discussed above we have established that, compared to continuous grazing, MP grazing is beneficial both ecologically and economically from the long term perspective, especially under longer grass dormancy periods, more xeric conditions and a lower initial palatable grass ratio. In this section we examine MP grazing only and determine the effects of number of paddocks per herd and length of grazing period on key performance variables.

Table 11 examines three MP grazing scenarios with different paddock numbers and length of grazing period, namely 18 paddocks with 5-day grazing period on each paddock, 30 paddocks with 3-day grazing period on each paddock, and 45 paddocks with 2-day grazing period on each paddock. At modest stocking rates, we can see that more paddocks and shorter grazing periods result in higher NPV. For example, it is clear that the 45-paddock, 2-day grazing scenario generates the highest NPV when the stocking rates are no greater than 0.05. As stocking rate increases further, however, the advantage of more paddocks, with shorter grazing periods disappears, as we can see that the 18-paddock, 5-day grazing scenario prevails under the stocking rates of 0.06 and 0.07. This is because at an extremely high stocking rates, the steers consume the palatable grass rapidly, rendering it unable to reach the point where maximum growth could occur, resulting in overgrazing and reduced consumption. Under a lower stocking rate, the overgrazing issue is less severe and can be offset by a longer recovery period, but it is no longer the case when the stocking rate continues to increase. As we can see 45-paddock results in lower composition index than the 18-paddock with the stocking density at stocking rates of 0.05, 0.06 and 0.07. In periods with less rainfall it remains imperative that stock numbers are reduced to ensure there is enough forage available to the animals as indicated in the simulation modeling results published by Teague et al. (2015) even with a high number of paddocks per herd. If this adjustment is made then the full advantage of a greater number of paddocks is maintained.

When the rainfall increases, the 45-paddock scenario performs the best under a wider array of stocking rates. This is not surprising, as the following two scenarios, 1) same rainfall level, lower stocking density and 2) same stocking density, higher rainfall level both result in higher availability of grass. This indicates that even with a 45-paddock scenario an adequate grass supply must be maintained by adjusting animal numbers. While more paddocks and shorter grazing period grazing days always generate financial gains under mesic conditions, the rancher must reduce the number of animals when drought occurs.

Conclusions

The motivation of this paper is twofold. One is to fill the void in economic literature regarding the impact of different grazing management strategies; the other is to address the discrepancies between the most commonly adopted experimental approach and the results of MP grazing strategy in achieving animal performance and ecological goals by using a modeling approach. In addition to main features of grass growth and animal consumption behavior, our model examines the differences between grazing management practices associated with the potential advantages of MP grazing: 1) to provide post-grazing recovery for palatable grass; and 2) to allow more uniform utilization of the grass, while under continuous grazing preferred patches are heavily grazed and less preferred patches lightly used.

Using parameters applicable to the stocker operations in Southern Great Plains of North America, our simulation results shows that compared to continuous grazing, MP grazing generates an increased long term economic profit and ecological conditions over time. This result is robust across all realistic stocking rates and the advantage of MP grazing is more pronounced with: 1) longer grass dormant period; 2) xeric conditions; and 3) low initial palatable grass composition. Among the two indices that are defined to describe the rangeland ecological condition, we find grass composition index drops more precipitously under continuous grazing when stocking rates increase. As MP grazing is better able to maintain forage productivity and combat invasion by less palatable grasses and weeds, it can sustain much higher stocking rates, which greatly increases the maximum long-term NPV compared to continuous grazing options. However, after implementation of MP grazing, the first year is unlikely to see a financial gain, because of the initial cost of infrastructure. But in as short a period as 5 years the advantages of MP grazing are evident, even if the cost of implementation is doubled.

Our results also suggest that the number of paddocks and grazing length should be chosen according to grass availability and rainfall conditions. While more paddocks and shorter grazing length always generate better animal performance and higher economic profit when the grass is abundant, animal numbers still need to be adjusted to make sure that there is constantly sufficient forage available to avoid poor animal performance and resource degradation.

The focus of our paper is mainly to compare the two grazing strategies under a variety of scenarios across different stocking rates. The emphasis is on selecting the right grazing strategy, rather than determining the optimal stocking rate and adjusting according to prevailing conditions. One limitation of our paper is that it has assumed constant weather conditions and cattle prices over the years. Potential future research could focus on (1) determining proactive adjustment of management practices under uncertain weather conditions; and (2) investigating the impact of stochastic market prices on different proactive adjustments to management practices and stock numbers.

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Table 1: Parameters of the Baseline Simulation Model

Symbol	Meaning	Units	Values
V_m	maximum plant biomass	g/m^2	400
V_0	initial plant biomass	g/m^2	320
V_r	ungrazeable residual plant biomass	g/m^2	20
s_p	percentage of palatable grass	%	50
s_u	percentage of less palatable grass	%	50
V_k^1	Michaelis constant for palatable grass	g/m^2	60
V_k^2	Michaelis constant for less palatable grass	g/m^2	100
ρ	interaction between two grasses	-	0.8
d_p^c	palatable grass defoliation rate- continuous grazing	%	80
d_u^c	less palatable grass defoliation rate- continuous	%	10
d_p^r	palatable grass defoliation rate- MP grazing	%	100
d_u^r	less palatable grass defoliation rate- MP grazing	%	50
g^1	maximum relative growth rate of palatable grass	day^{-1}	0.03
g^2	maximum relative growth rate of less palatable grass	day^{-1}	0.024
ϕ	average daily death rate	day^{-1}	0.01
n	number of paddocks		30
t_r	length of MP cycle	days	90
θ	Forage conversion coefficient	-	0.096
l	Relative conversion rate of less palatable grass	-	0.75
B	Length of study period	years	30
β	Discount factor	-	0.95
TC	Total cost incurred per steer	\$ steer^{-1}	162
P_p	Steer purchase price	\$ kg^{-1}	4.07
w_p	Steer purchase weight	kg	216
κ	Satiated forage consumption rate	-	2.5%

Table 2: Effect of grazing practice on 30-year steer selling weight, Net Present Value (NPV), biomass index and composition index (Growth rate $g^1 = 0.03$; $g^2 = 0.024$; initial biomass index is 0.8 and initial composition index is 0.5; grass dormant period is 120 days. Relative conversion rate of less palatable grass is 0.75. Under continuous grazing defoliation rate is 80% for palatable grass and 10% for less palatable grass; Under MP grazing there are 30 paddocks and the grazing period on each paddock is 3 days per MP cycle; defoliation rate is 100% for palatable grass and 50% for less palatable grass; the purchase price for a 216 kg (475 pound) steer is 4.05 per kg. Discount factor=0.95.

Stocking rate (*H*)	0.02	0.03	0.04	0.05	0.06	0.07
Ending Weight (kg steer^{-1})						
Continuous	337	323	300	285	275	267
MP	352	350	346	338	323	309
30-year NPV ($ steer^{-1})						
Continuous	875	452	22	-542	-961	-1279
MP	1583	1474	1283	948	382	-182
30-year NPV ($ ha^{-1})						
Continuous	175	136	9	-271	-577	-895
MP	317	442	513	474	229	-128
Biomass Index						
Continuous	0.42	0.40	0.39	0.38	0.37	0.37
MP	0.51	0.50	0.49	0.47	0.44	0.42
Composition Index						
Continuous	0.82	0.68	0.51	0.44	0.40	0.38
MP	0.86	0.80	0.71	0.59	0.44	0.35

Table 3. Effect of grazing practice on steer selling weight, Net Present Value (NPV), biomass index and composition index when the dormant period is 90 days, otherwise as for Table 2.

Stocking rate (*H*)	0.02	0.03	0.04	0.05	0.06	0.07
Ending Weight (kg steer^{-1})						
Continuous	354	347	326	304	291	281
MP	356	354	350	342	326	312
30-year NPV ($ steer^{-1})						
Continuous	1577	1305	593	260	-273	-689
MP	1720	1623	1444	1113	533	-482
30-year NPV ($ ha^{-1})						
Continuous	315	392	237	130	-164	-113
MP	344	487	578	556	320	-28
Biomass Index						
Continuous	0.51	0.49	0.46	0.45	0.44	0.44
MP	0.51	0.50	0.49	0.47	0.44	0.42
Composition Index						
Continuous	0.82	0.68	0.46	0.36	0.32	0.31
MP	0.86	0.79	0.71	0.58	0.43	0.35

Table 4. Effect of grazing practice on 30-year steer selling weight, Net Present Value (NPV), biomass index and composition index at growth rate $g^1 = 0.04$; $g^2 = 0.032$. Otherwise as for Table 2.

Stocking rate (*H*)	0.02	0.03	0.04	0.05	0.06	0.07
Ending Weight (kg steer^{-1})						
Continuous	354	347	336	321	309	301
MP	365	363	361	357	351	341
30-year NPV ($ steer^{-1})						
Continuous	1564	1320	914	386	404	85
MP	2101	2024	1910	1749	1513	1157
30-year NPV ($ ha^{-1})						
Continuous	313	396	366	193	242	60
MP	420	607	764	874	908	810
Biomass Index						
Continuous	0.56	0.55	0.53	0.52	0.51	0.50
MP	0.64	0.63	0.62	0.61	0.60	0.59
Composition Index						
Continuous	0.72	0.62	0.50	0.40	0.35	0.32
MP	0.73	0.68	0.64	0.58	0.50	0.41

Table 5: Effect of grazing practice on single-period steer selling weight, economic profit, biomass index and composition index when the dormant period is 120 days, otherwise the same as Table 2.

Stocking rate (*H*)	0.02	0.03	0.04	0.05	0.06	0.07
Ending Weight (kg steer^{-1})						
Continuous	338	331	323	315	307	300
MP	355	352	349	345	341	336
Annual Profit (\$ steer^{-1})						
Continuous	64	46	26	38	19	0.8
MP	72	76	73	67	58	46
Annual Profit (\$ ha^{-1})						
Continuous	13	14	11	19	11	0.6
MP	14	23	29	33	35	33
Biomass Index						
Continuous	0.47	0.46	0.44	0.43	0.42	0.41
MP	0.55	0.54	0.53	0.51	0.50	0.49
Composition Index						
Continuous	0.51	0.48	0.45	0.43	0.41	0.39
MP	0.54	0.52	0.50	0.49	0.46	0.44

Table 6: Effect of grazing practice on single-period steer selling weight, economic profit, biomass index and composition index when the dormant period is 90 days. Other parameters are the same as Table 2.

Stocking rate (*H*)	0.02	0.03	0.04	0.05	0.06	0.07
Ending Weight (kg steer^{-1})						
Continuous	355	350	344	337	329	321
MP	358	355	352	348	344	340
Annual Profit (\$ steer^{-1})						
Continuous	105	93	78	62	43	22
MP	80	85	83	77	68	57
Annual Profit (\$ ha^{-1})						
Continuous	21	28	31	31	26	16
MP	16	26	33	38	41	40
Biomass Index						
Continuous	0.54	0.53	0.51	0.50	0.48	0.47
MP	0.55	0.54	0.52	0.51	0.50	0.49
Composition Index						
Continuous	0.52	0.49	0.46	0.43	0.40	0.38
MP	0.54	0.52	0.50	0.48	0.46	0.44

Table 7. Effect of grazing practice on per hectare 30-year Net Present Value (NPV), or single year farm profit when the extra cost of MP grazing is twice of the estimated cost.

Stocking rate (*H*)	0.02	0.03	0.04	0.05	0.06	0.07
Baseline						
Continuous	175	136	9	-271	-577	-895
MP	309	434	505	466	221	-135
90-day dormant period						
Continuous	315	392	237	130	-164	-113
MP	336	479	570	549	312	-35
Growth rate $g^1 = 0.04$; $g^2 = 0.032$						
Continuous	313	396	366	193	242	60
MP	412	599	756	867	900	802
Single 1-year period, 120-day dormant period						
Continuous	13	14	11	19	11	0.6
MP	7	15	22	26	27	25
Single 1-year period, 90-day dormant period						
Continuous	21	28	31	31	26	16
MP	9	18	26	31	33	32
5-year period, 120-day dormant period						
Continuous	45	56	7	-49	-128	-213
MP	86	119	135	127	85	11
5-year period, 90-day dormant period						
Continuous	89	107	82	67	-9	-95
MP	87	124	146	143	105	34

Table 8. Effect of grazing practice on 30-year steer selling weight, Net Present Value (NPV), biomass index and composition index when initial biomass index is 0.6. Otherwise as Table 2.

Stocking rate (*H*)	0.02	0.03	0.04	0.05	0.06	0.07
Ending Weight (kg steer^{-1})						
Continuous	337	323	300	285	275	267
MP	352	350	346	338	323	309
30-year NPV ($ steer^{-1})						
Continuous	827	414	13	-581	-999	-1313
MP	1545	1435	1245	912	349	-217
30-year NPV ($ ha^{-1})						
Continuous	165	124	5	-291	-599	-919
MP	309	430	498	456	209	-152
Biomass Index						
Continuous	0.42	0.40	0.39	0.38	0.37	0.37
MP	0.51	0.50	0.49	0.47	0.44	0.42
Composition Index						
Continuous	0.87	0.68	0.51	0.44	0.40	0.38
MP	0.86	0.80	0.71	0.59	0.44	0.35

Table 9. Effect of grazing practice on 30-year steer selling weight, Net Present Value (NPV), biomass index and composition index when initial composition index is 0.3. Otherwise as for Table 2.

Stocking rate (*H*)	0.02	0.03	0.04	0.05	0.06	0.07
Ending Weight (kg steer^{-1})						
Continuous	325	294	276	266	258	252
MP	352	349	342	327	310	299
30-year NPV ($ steer^{-1})						
Continuous	418	-271	-942	-1386	-1711	-1963
MP	1478	1293	959	368	-265	-713
30-year NPV ($ ha^{-1})						
Continuous	84	-81	-377	-693	-1026	-1374
MP	296	388	383	184	-159	-499
Biomass Index						
Continuous	0.41	0.38	0.37	0.37	0.36	0.36
MP	0.51	0.50	0.48	0.43	0.43	0.41
Composition Index						
Continuous	0.70	0.47	0.41	0.38	0.36	0.35
MP	0.84	0.76	0.64	0.47	0.35	0.31

Table 10. Effect of grazing practice on 30-year steer selling weight, Net Present Value (NPV), biomass index and composition index when the relative conversion rate of less palatable grass is 1.25. Otherwise as for Table 9.

Stocking rate (*H*)	0.02	0.03	0.04	0.05	0.06	0.07
Ending Weight (kg steer^{-1})						
Continuous	329	304	287	275	266	260
MP	354	354	352	343	332	322
30-year NPV ($ steer^{-1})						
Continuous	643	213	-465	-921	-1289	-1577
MP	1783	1733	1578	1208	757	366
30-year NPV ($ ha^{-1})						
Continuous	129	64	-186	-460	-773	-1104
MP	357	520	631	604	454	256
Biomass Index						
Continuous	0.41	0.38	0.37	0.37	0.36	0.36
MP	0.51	0.50	0.47	0.44	0.42	0.40
Composition Index						
Continuous	0.69	0.47	0.41	0.38	0.36	0.35
MP	0.84	0.76	0.63	0.44	0.33	0.30

Table 11: Effects of number of paddock and recovery period on 30-year steer selling weight, Net Present Value (NPV), biomass index and composition index (Three MP grazing scenarios are considered, namely 18 paddocks with 5-day grazing period on each paddock, 30 paddocks with 3-day grazing period on each paddock, and 45 paddocks with 2-day grazing period on each paddock; defoliation rate is 100% for palatable grass and 50% for less palatable grass for all MP scenarios; Otherwise as for Table 2).

Stocking rate (*H*)	0.02	0.03	0.04	0.05	0.06	0.07
Ending Weight (kg steer^{-1})						
MP (18,5)	352	350	346	338	324	310
MP (30,3)	352	350	346	338	323	309
MP (45, 2)	353	351	347	338	321	308
30-year NPV (\$ steer^{-1})						
MP (18,5)	1572	1456	1263	938	413	-141
MP (30,3)	1583	1474	1283	948	382	-182
MP (45, 2)	1599	1497	1312	962	332	-236
30-year NPV (\$ ha^{-1})						
MP (18,5)	314	437	505	469	248	-99
MP (30,3)	317	442	513	474	229	-128
MP (45, 2)	320	449	525	481	199	-165
Biomass Index						
MP (18,5)	0.51	0.50	0.49	0.47	0.45	0.43
MP (30,3)	0.51	0.50	0.49	0.47	0.44	0.42
MP (45, 2)	0.51	0.50	0.49	0.47	0.44	0.42
Composition Index						
MP (18,5)	0.86	0.80	0.72	0.60	0.46	0.37
MP (30,3)	0.86	0.80	0.71	0.59	0.44	0.35
MP (45, 2)	0.86	0.79	0.71	0.57	0.41	0.33

Table 12: Effects of number of paddock and recovery period on 30-year steer selling weight, Net Present Value (NPV), biomass index and composition index (at growth rate $g^1 = 0.04$; $g^2 = 0.032$; Otherwise as for Table 11).

Stocking rate (*H*)	0.02	0.03	0.04	0.05	0.06	0.07
Ending Weight (kg steer^{-1})						
MP (18,5)	365	363	360	356	350	342
MP (30,3)	365	363	361	357	351	341
MP (45, 2)	366	364	361	357	351	340
30-year NPV ($ steer^{-1})						
MP (18,5)	2092	2010	1892	1729	1501	1173
MP (30,3)	2101	2024	1910	1749	1513	1157
MP (45, 2)	2114	2043	1936	1778	1532	1125
30-year NPV ($ ha^{-1})						
MP (18,5)	314	603	757	865	900	821
MP (30,3)	420	607	764	874	908	810
MP (45, 2)	423	613	774	889	919	788
Biomass Index						
MP (18,5)	0.64	0.63	0.62	0.61	0.60	0.59
MP (30,3)	0.64	0.63	0.62	0.61	0.60	0.59
MP (45, 2)	0.64	0.63	0.62	0.61	0.60	0.58
Composition Index						
MP (18,5)	0.73	0.69	0.64	0.58	0.51	0.43
MP (30,3)	0.73	0.68	0.64	0.58	0.50	0.41
MP (45, 2)	0.73	0.68	0.63	0.57	0.49	0.38

Additional Initial Expense for Multi-paddock (MP) grazing

9 joule fence charger with remote	$320
6 – 6 foot ground rods with clamps	$100
3 lighting chokes @ $8.00	$24
3 throw switches @ $7.00	$21
poly tape for gates	$30
19.5 miles 12.5 high tensile wire	$2265
1287 .75 inch X 48 inch fiber glass sucker rod line posts @$4.00	$5148
48 6 inch top X 7 foot cedar posts @ $8.00	$384
48 .75 X 12 foot fiber glass risers @$12.00	$576
48 double U insulators @ $.78	$38
100 feet 12.5 insulated wire	$21
2 300 gal water troughs with float valves @ $250	$500
5280 feet 2 inch SDR11 HDPE pipe @ $1.12	$5914
	$15,341

Note: Installation to be done with ranch labor. The above figures are based on a 2072 ha (5120 ac) ranch. Data is provided by Walt Davis, Grazing Management Consultant, 262 SR 70E, Calera, OK 74730.

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[i] This assumption is similar to that made by Teague et al. (2015), which resembles the stocker phase of the grass-fed beef production. The stocker operation for feedlot beef production has a different time frame, which could be from November to April on wheat pasture or from March to September on rangeland.

[ii] Professor Stan Bevers, Extension Economist, Texas A&M AgriLife Extension, Vernon, Texas. According to Bevers, currently there are two methods to fatten the steers, either on owned grass, or on leased grass. It is generally assumed the costs incurred on owned grass are the same as those incurred on leased grass, when taking opportunity cost into account. So the cost on owned grass can be roughly estimated by using a calculation formula for the cost incurred on leased grass. Given that the steers gain 0.45 kg (1 pound) per day on average on the rangeland at a fattening cost of \$1.32 kg^{-1} (\$0.60 $pound^{-1}$), on leased grass it will cost about \$162 $steer^{-1}$ over the 270 day grazing period.

[iii] Note that each of these variables tend to reach the equilibria after around 20 years, therefore our reported values are also the equilibrium values.

[iv] Notice, though, that a decrease in weight does not necessarily lead to a reduction in NPV and vice versa due to the sliding price scale.