Use of integrated crop-livestock systems to reduce economic risk to rangeland grazing systems

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Abstract
The economic sustainability of rangeland livestock operations requires that the land resource be properly managed while also optimizing the supply of forage produced and grazed. Keeping this balance of range health and adequate grazing supply, and therefore animal production, is dependent on a producer's ability to adapt to stochastic shocks, such as drought or delayed growing seasons; one such adaptive mechanism is to use alternative forages, such as cover crops, as a supplementary grazing source.

Using a simulation modelling approach on 20-years of rangeland production data from the Sandhills ecoregion of Nebraska, USA, a mixed-grass prairie in the central plains of North America, we analysed the variation in annual production risk to a grazing operation associated with having a set, non-flexible grazing plan. We then analysed how that production risk changes when a spring-grazed cover crop of cereal rye is added as an early-season grazing alternative. Within the model, forage resources of rangeland, cover crop, and hay were available to be used, with hay only being utilized once the other forages were no longer available. The model determined when to graze the cover crop and rangeland in order to maximize the total grazing days, based on the forages' within-season growth rates.

Our results indicate that there are compounding benefits to rangeland forage production by delaying grazing even by a short time, with a one day of grazing delay resulting in multiple days of additional forage later in the season. However, we also find that a spring-grazed cover crop is not an appropriate alternative forage to consistently reduce production risk in the Sandhills. This highlights the importance of having a diverse portfolio of forage types available to reduce different drivers of risk. Production risk to Sandhills graziers should be re-evaluated using a late season cover crop.

Introduction
The integration of livestock grazing into cropland is not a new concept; it was, however, historically more popular in the United States' Midwest than it is today, with major decreases noted in the 1925-1945 period (Smart *et al.*, 2021). More recently, as a response to multiple factors, including cover crop use on winter croplands and as potential mitigation to climate variation affecting livestock forage supply, integrating livestock into cropping systems has seen a resurgence in popularity (Bowman *et al.*, 2024). This increase in popularity has been

complemented by an increase in studies focusing on integrated crop-livestock systems, including studies on soil health, animal production, and agronomic benefits, but a systems-level evaluation investigating how grazing cover crops may affect other aspects of a year-round grazing system was lacking. Several studies based in annual grassland systems of Australia (Thomas *et al.*, 2015; Thomas *et al.*, 2012; Dove, 2018) did evaluate the system-level impacts of grazing a dual-use crop, or a cash crop that is resistant to grazing during a portion of its growth, and found production benefits as well as the risk management benefits associated with diversified systems.

Economically, modelling livestock production within cropping systems is relatively straight-forward. The agronomic modelling of a monocrop can be algebraically determined, and livestock weights are easily tracked; Coufal (2019) modelled the farm-level benefits of grazing a cereal rye cover crop in Nebraska using this methodology. Production-level economic studies for rangeland systems are more challenging and uncommon in the literature, one reason for this is the challenges with modelling production for heterogeneous landscapes without distinct spatial boundaries. Rangeland production is, instead, typically tracked using early- and late- season biomass measurements and then correlated with climatic and grazing variables (Smart *et al.*, 2007; Stephenson *et al*., 2019) and economic studies are largely derived from animal weight data (Windh *et al.*, 2020).

In this study, we modelled production of a cereal rye cover crop using an algebraic set of equations, and we modelled a mixed-grass rangeland pasture using a sigmoid growth function for the individual cool- and warm-season grass components. We then evaluated the production-level impacts of delaying grazing to the rangeland system in the Sandhills of Nebraska, USA, by grazing the spring cover crop.

Methods

Modelling the growth of cereal rye model followed the mathematical system of equations laid out in Coufal (2019) and can be seen in detail in Windh (2023). The model was adapted to our study area at the University of Nebraska-Lincoln Barta Brothers Research Ranch near Rose, Nebraska, USA using climatic data from an on-site weather station. The model was most limited by the availability of soil moisture data. The equations follow the growth of rye on a daily time step from germination through maturity, with temperature and water stress limiting growth by an adjustment factor. The daily time-step model was important for our ability to model re-growth while grazing was occurring in our final simulation model.

Rangeland grass biomass data from the Barta Brothers Ranch was used to inform the rangeland production model. Current year herbaceous biomass was clipped from within grazing exclosures twice annually, once in mid-June to correspond with peak cool-season production and once in mid-August to correspond with peak warm-season production. Data was collected annually from 2000 to 2020, separated by functional group, and the exclosures were moved annually after the final biomass collection.

Voisin (1954) modelled the “kinetics” of grass growth and showed how marginal growth rates can be used to determine the optimal length of rest, post-grazing, before a pasture can be grazed again. Later, Cacho (1993) readdressed this topic and showed that a sigmoid curve has a better fit than other mathematical models to sets of both grazed and non-grazed grass biomass data. Following from these, we fit our data to a Gompertz growth curve; the Gompertz curve (Equation 1) is an asymmetrical, four-parameter, sigmoid equation:

$$x = Ae^{(-b)e^{-kt}}$$

The output, *x*, is grass biomass in lbs/acre. *A* is the maximum potential growth during the growing season; this defines the asymptote of the curve and is set based on measured end-of-year biomass data. *b* is the displacement of the curve on the x-axis. The displacement is necessary because grass growth does not begin when *t*, which in this case is cumulative growing degree days (GDD) with a base temperature of 40˚F, equals zero. An accumulation of several days with GDD greater than zero are required to stimulate grass to begin growing. In this equation *t* is growing degree days, rather than time, in order to compare multiple years of growth directly. Finally, the *k* parameter is the growth rate of the grass. We fit the data to the curves using known data to inform *A*, *b*, and *t*, and used the *easynls* package in R to determine the best fit for *k*, resulting in 21 annual growth curves. The derivatives of the curves gave us the daily growth rates for the simulation model.

Using the cereal rye and rangeland production values, we created a simulation model to show how the cereal rye could complement the rangeland grazing. We wanted to model how to best use our available forage portfolios on a daily time-step to 1) maximize rye use, 2) minimize hay needs, and 3) maintain rangeland health (i.e., prevent overgrazing). We modelled the simulation under three scenarios, 1) terminating rye on May 20 to plant a cash crop, 2) allowing rye grazing until it fully matures and it's quality as forage is low, and 3) a no-rye scenario to evaluate the other two rye contributions.

We developed a simulation model that follows the behavior of a cost minimization model; however, the output of interest is how each forage is selected for daily use, rather than the "minimized cost".

$$min\, C_t = \sum_{t=0}^{T} p_F x_F$$

where *F* is the three available forages: rye, rangeland, and hay, *t* is the daily timestep parameter, *x* is the daily (*t*) use of the selected forage (*F*), and *p* is the "price" set on each forage for the purpose of creating the desired behavior. p_{rye} is set as the lowest value to induce the model to use up the entire supply of rye biomass available. p_{hay} is set as the highest value to ensure the model only selects it as a last resort. $p_{rangeland}$ is set to some intermediate value, such that it is used after the rye but before the hay. Three constraints are used to emulate the properties that make the model realistic to an operation in the Sandhills of Nebraska: 1) the forage growth constraint, which used the cereal rye and rangeland production models to simulate regrowth post daily grazing events; 2) the daily use constraint, which constrains daily use of any combination of feed to 1 animal unit day worth of forage; and 3) the rangeland health constraint, which prevents the rangeland from being grazed below 650 lbs per acre. Further mathematical configuration of the model can be referenced in Windh (2023).

Results

Production models

The first surprising result was that cereal rye yields were very low in the location of our study; annual yields were 450 to 600 lbs/acre, whereas yields if 1700 lbs/acre are more common elsewhere in Nebraska. Yields of this magnitude are unlikely to provide any benefit to livestock producers as a grazing cover crop, unless there is sufficient land area to allow for stocking rates of 3 or more acres per animal unit (AU). Due to this unexpected result, we set the stocking rate of our simulation to 3 acres per AU.

The rangeland production curves, on the other hand, yielded quite varied results based on the year modelled (Figure 1). The Gompertz curve was successful in fitting curves to total annual production as well as annual warm-season production, however it was unsuccessful in fitting a curve for cool-season production due to the first data point

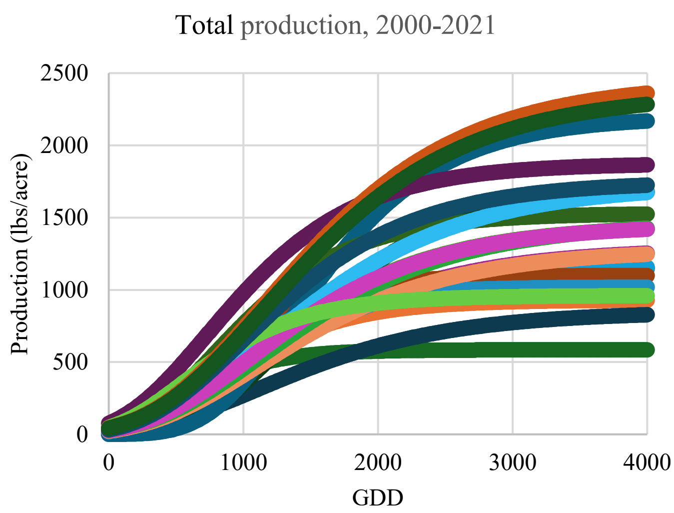

Figure 1. Total production curves derived through estimation with the Gompertz curve. Each line represents total production within one year between 2000 and 2021.

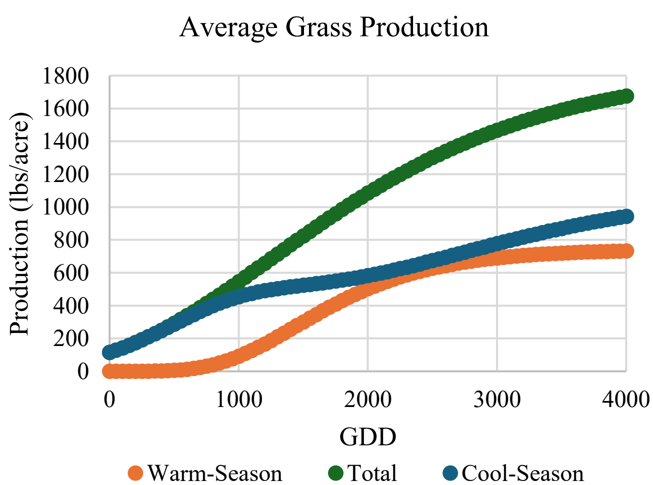

Figure 2. Average total, cool season, and warm season production curves across years 2000-2021

being from the peak cool-season production time. We were, however, able to take the difference in the total and warm-season curves to derive a cool-season curve with two-growth periods, which is consistent with the literature on cool-season grass production (Figure 2).

As mentioned, the soil moisture data was the limiting factor for modelling rye growth; due to this we ended up with 9 years for which we could simulate the full grazing system. Of those nine years, four of the years did not require any hay in addition to the cereal rye and the rangeland. The rye grazing was able to provide between 19 and 27 days of grazing in the cash crop model, and between 22 and 38 days in the no-crop model. We used the four years that did not require hay feeding to evaluate any benefits provided by the rye.

In the cash crop model, the rye is terminated on May 20 and rangeland grazing cannot occur before May 15; therefore, in this simulation the rye can only delay rangeland grazing by a maximum of 5 days. We wanted to evaluate the impact to the rangeland of delaying grazing, and while 5 days did not seem like much, it had substantial results. Between 77 and 205 lbs/acre of rangeland forage were available in excess of the 650 lb/acre threshold at the season's end; at a stocking rate of 6.66 acres/AUM that corresponds to between 19 and 52 additional grazing days as a result of a 5-day delay. More complete results can be found in Windh (2023, page 56).

Discussion

The Sandhills of Nebraska are one of the largest intact swathes of rangeland in the world, our cereal rye production results suggest that poor farming potential may have contributed to this preservation. Regardless, we can see small changes in production practices, such as delaying turnout, can yield large results. Dove (2018) found a 40% increase over the number of crop-grazing days delaying the livestock grazing. Our returns are substantially higher (400% to 1000% increase), but our stocking rates are quite conservative, especially with the 3 acres of rye per animal.

Within the production models, it would be interesting to know what caused the low cereal rye production values. The authors hypothesize that a late spring warm-up may be the cause, or possibly the soil water holding capacity of the regions' namesake sandy soils contributed to increased water stress. The cause would be interesting to investigate before producers, with more at stake, tried for a failed crop in a similarly unsuitable area. Within the rangeland production curves, further research is necessary to correlate the four parameters of the Gompertz equation with climatic drivers. Having some predictive context to the curves could clue producers into high production yields earlier in the season, or give forewarnings of climate-related forage shortages.

Despite our model not working as smoothly as one would hope, the benefits of integrating livestock into cropping systems have been shown in nearly every aspect of the system. Manure and urine add nutrients to the soil while hoof action contributes negligible soil compaction (Blanco-Canqui, 2020), cash crop yields are unaffected or increased (Bowman *et al.*, 2024), and the grazing creates another enterprise with which crop producers can diversify their operations. Further research is required to understand the full mechanics of these grazing systems, and how they work across ecoregions, but preliminary research shows it's a promising option.

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