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Research article

Economically optimized forage utilization choices in drylands for adapting to economic, ecological, and climate stress

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ABSTRACT

Improving the economic performance of range forage in drylands internationally faces challenges from economic, ecological, and climate stress. Stakeholders in these drylands wish to protect range forage ecosystems while assuring economic viability of ranching. Despite several recent research achievements, little work to date has integrated relationships among precipitation, grazing pressure, animal performance, and forage production to protect ranching incomes faced with economic, ecological, and climate stress in dryland areas. This work addresses that gap by developing an empirical mathematical programming model for optimizing economic performance of livestock grazing on range forage ecosystems that adapt to several stressors. Its unique contribution is to formulate and apply a ranch income optimization model calibrated using positive mathematical programming. The model replicates observed economic, forage, and climate conditions while accounting for interacting relations among stocking rates, forage conditions, grazing pressure, animal performance, and ranch economic productivity. Results show ranch incomes ranging from about $5 to $88 per acre and marginal values of forage ranging from $0.01 to $0.12 per pound of forage, depending on economic, ecological, and climate conditions. Results reveal how all these stressors affect economically optimized choices of grazing levels, ranch income, and economic values of forage for a range of six biomes seen in the US west. Results help livestock ranchers to adjust stocking and forage choices as well as farm policymakers who seek flexible government programs to adapt to changes in economic, ecological, and climate conditions. The work's importance comes from applicability to forage management problems in dry regions internationally.

1. Background

1.1. Problem

Climate change is a central challenge facing forage users in arid and semi-arid regions internationally. These regions make up about 40 % of the earth's land area, for which an important use is forage for livestock grazing [1–6]. Drylands are primarily covered by shrubs and grasses consumed by grazing ruminants. Various ecosystems are associated with these dry places: steppes, prairies, desert

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shrub woodlands, savannas, and tundra. Many communities rely on the management of range forage both ecologically and economically. Communities in these regions facing climate change often seek policies that protect rangeland ecosystems, but these policies can increase short term costs for livestock ranching [7–10]. More generally, drylands range managers internationally in 2024 face several significant challenges. These include:

Climate Change and Variability: Climate change has increased the frequency and severity of droughts, leading to reduced water availability, altered precipitation patterns, and increased temperatures [11–14]. These changes threaten the productivity and sustainability of rangelands, making it harder to maintain vegetation cover and support livestock.

Land Degradation and Desertification: Overgrazing, deforestation, and sometimes unsustainable land management practices contribute to soil erosion, loss of soil fertility, and desertification [14–17]. This degradation reduces the land's capacity to support vegetation and wildlife, leading to a decline in biodiversity and ecosystem services.

Economic Pressures: Increasing human populations and requirements for land use change, e.g., agriculture and urbanization put additional pressure on rangelands [18–21]. Conflicts over land and water resources, as well as the need for sustainable livelihoods for local communities, add complexity to range management efforts. Addressing these economic challenges requires balancing conservation with the needs of regional populations.

Overall, it is a challenge to manage forage in drylands while producing economically viable ranching operations because of climate stress and changing precipitation patterns. There are also high amounts of uncertainty concerning the timing and amounts of rainfall in these areas [22–25]. Reduced precipitation reduces forage productivity, reduces the number of animals economically stocked, and increases costs in many cases. Associated forage productivity reductions can also decrease selling weight [26–29].

A variety of approaches can be used to support forage productivity, while permitting grazing the number of cattle for an economically viable livestock operation. Ranchers make choices that protect their rangeland ecosystems and economically benefit their ranch. In general, it is important to investigate a range of measures to mitigate risks, optimize animal performance, and help ranchers discover income optimized stocking patterns. Discovery of economically and ecologically viable policies for adapting to climate change and drought is an important activity for healthy rangeland forage ecosystems, high animal performance, and viable ranch income.

1.2. Previous work

Considerable previous research has investigated measures to optimize rangeland ecosystems in addition to benefiting ranchers by optimizing income through improved cattle performance. There is some literature that statistically analyzes a variety of forage productivity levels and its connection to animal performance, although this research is not always motivated by the need for policy analysis [30,31].

A 2010 analysis [32] investigated flexible and conservative stocking strategies and found that flexible stocking strategies bring more gross revenue but may raise production costs. Some work [33] has developed income maximization as a framework to guide improved stocking rates at various levels of risk. Another investigation found that ranchers compare alternative stocking rates by assessing impacts on grazing pressure, for which results showed that average daily weight gain (ADG) decreases with an increasing grazing pressure (GP) index. Some findings have suggested the use of a grazing pressure index to standardize stocking rates adapting to several rangeland ecosystems [34,35].

Some previous works have investigated a range of measures that promote environmental protection and rancher income when facing drought and climate stress. Examples of these policies include measures to connect grazing fees to grazing intensity, subsidies, additional feed, and improving technology [36]. These studies typically compare two or more policies in each geographical location, or they conduct a case study targeted to one location.

Drought and climate change are major challenges for ranchers in addition to economic stress caused by reduced cattle prices, elevated feed costs, some environmental policies, and urban growth [37]. One study found that during a 1999–2004 drought period, 75 % of respondents said they were not prepared and resorted to federal programs, whereas only 25 % of surveyed respondents stated the drought had neutral or positive effects in cases where ranchers had more access to water and hay. Many ranchers adapted by developing conservation plans, reducing stocking rates, diversifying income, and enrolling in insurance programs [38]. Other literature suggested drought preparedness such as early drought warning systems as well as grass banking presented adaptation options [39]. Another work indicated that moderate grazing was the best strategy to sustain rangelands, contribute to improved forage diversity, and increase the rangeland's flexibility to drought and climate stress compared to other strategies like high-intensity grazing or eliminating grazing [40]. There are also other noteworthy studies using optimization frameworks such as stochastic dynamic programming models and a dynamic bioeconomic model which handle economic and climate stressors [41].

One strategy for ranchers to adapt to drought include adjusting the species grazed [42]. Other strategies include drought evading strategies as well as drought enduring strategies. Pastoralists, common in developing countries, often favor drought evading strategies which include lighter stocking rate which allows the pasture and ecosystem to recover from reduced forage or from poorly timed precipitation. Pastoralists typically live a nomadic lifestyle and move their livestock to different pasture areas periodically. Drought enduring strategies, more common in United States and in more developed countries, include securing purchased feed during drought periods [43], especially if it is anticipated to be over soon. In addressing these issues, the journal *Heliyon* has published some works [44–46] dealing with interactions among forage, livestock, and climate. Other peer reviewed journals have also addressed some of these challenges [47–51].

1.3. Gaps

Despite several important achievements described above, no existing work we found has developed and applied a framework to handle multiple economic, ecological, and climate stresses. Additionally, no other work has developed and applied a calibrated model that simultaneously optimizes livestock management choices while adapting to a range of climate, forage, and price conditions. Finally, few analytical frameworks published to date have sufficiently incorporated many moving parts needed to handle the complex interactions among livestock ranching, forage ecosystem protection, and information to make more efficient and flexible rangeland policy decisions.

1.4. Unique contribution

The original contribution of this work is to develop an empirical mathematical programming model using a new application of positive mathematical programming [52–54] that optimizes the economic performance of livestock forage ecosystems under a range of economic conditions, vegetation biomes, and climate stresses. While our model is applied to six biomes in the US west, its approach has potential for application to various conditions. This work's objective is implemented by conceptualizing and applying a ranch income optimization model that can guide ranchers and policymakers to economically optimize choices applied to several livestock ranching regions in the western US. The flexibility of this optimization framework lights a path to ranch managers and policymakers who seek guidance on plans that optimize ranch income in the face of multiple economic and/or climate stressors.

2. Methods of analysis

2.1. Scenarios

2.1.1. Modeling scenarios

Several scenarios were developed in this model, including a range of vegetation biomes, forage supplies as influenced by rainfall, livestock buying price, livestock selling price, and drought/climate scenarios. The optimization model is calibrated to replicate rancher behavior for observed (baseline) conditions. After the base model is calibrated it is re-run to discover effects on optimally adjusted ranch income under different forage levels, climate scenarios, livestock buying prices, and livestock selling prices. Six geographical regions for selected locations in the US west are presented to represent six vegetation biomes. The judicious use of scenarios for this work shows the model's flexibility and capability to optimize income through economically efficient adjustments of stocking levels that adapt to a range of circumstances.

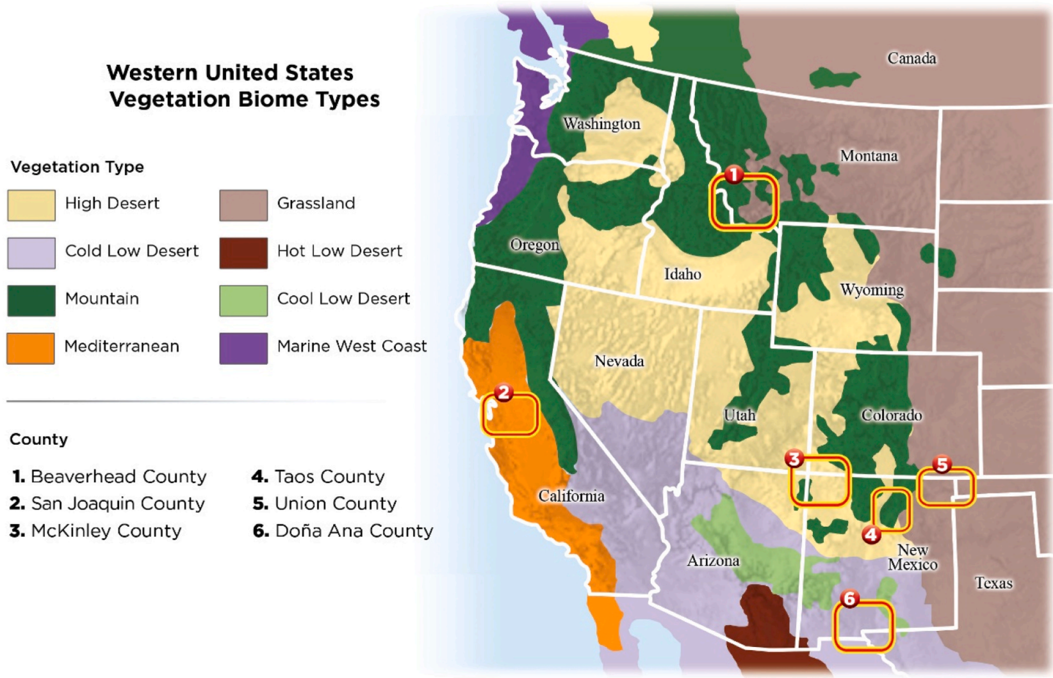

Fig. 1. Western United States vegetation biome types.

2.1.2. Vegetation biomes

The vegetation biomes in this study are common for rangelands across the world (Fig. 1). While this case study investigates six vegetation climate types from the western US, they contain similar vegetation, climate, and precipitation patterns as seen internationally, so strategies and polices can be adapted to different geographical areas. For instance, the Chihuahuan desert ecology and climate has some similarities in vegetation and climate to other desert regions internationally at similar elevations. Grassland plains areas also have similar vegetation and climate patterns in arid and semiarid regions internationally, as well as in the North American Southwest. These biomes are represented by a county with a dominant vegetation biome. Many biome classifications consider vegetation, soil, climate, and wildlife. This work focuses mostly on vegetation and climate. While we recognize that the science of vegetation biome analysis is considerably more complicated than simplifications made for this research, these assumptions streamline our work for tractability while losing only minimal essential detail.

Several vegetation biomes in the US state of New Mexico were used as a foundation for this work because that region has a large scale of livestock ranching activity as well as wide variation of climate and vegetation biomes, ranging from low desert to high mountain. Four New Mexico vegetation biome categories were selected for this study. These vegetation biome classifications are derived mostly from the U.S. Geologic Survey (USGS) classifications with data derived from the New Mexico State University climate and weather classifications [55,56].

The New Mexico mountainous region is located in the Mogollon Plateau in the northern central part of the state and represents the mountain vegetation biome used for this work. Mountain vegetation regions in New Mexico typically range from 8000 to 13,000 feet (2400 to 4000 m), for which vegetation changes with elevation. That vegetation biome is an alpine climate with mountain-based vegetation including pine, fir, and aspen. The model uses Taos County as that region, which has the highest mean elevation of any US county outside of Colorado.

The warmer high plains vegetation example in this study is located in northeastern New Mexico and is similar to semi-arid shortgrass prairie in the eastern part of Colorado. The New Mexico eastern prairies contain vegetation such as Blue grama (*Bouteloua gracilis*) and other short grasses. The climate in the warmer high plains regions is dry, but not as dry as the more desert regions of the state. This warmer high prairie region experiences early cool season rains. The classification for warm high plains vegetation is selected to be Union County, New Mexico.

The high desert vegetation biome is located in northwestern New Mexico in the Colorado Plateau geographically near southwestern Colorado. The high desert vegetation biome has a climate with cold winters and the vegetation includes greasewood (*Sarcobatus vermiculatus*), sagebrush (*Artemisia tridentata*), shadescale (*Atriplex canescens*), and other plant life that grows in salty soils. The high desert vegetation biome in this study is represented by McKinley County, New Mexico.

The cooler low desert vegetation biome is found in the cooler part of Chihuahuan desert in New Mexico as opposed to the hot low desert positioned towards the middle of the Chihuahuan desert in New Mexico. In cool low desert vegetation regions, warm season rains tend to be common and appear later in the grazing season into the summer or early part of autumn. Common vegetation in this vegetation region includes Shrubby creosote *(Larrea tridentata*). The cool low desert vegetation biome is represented by Dona Ana County, New Mexico.

The cold high plains vegetation biome used for this work occurs in southwestern Montana. This region has a higher latitude than our New Mexico regions. The cold high plains vegetation biome has more extreme changes in temperature throughout the seasons than the warm high plains vegetation biome of northeast New Mexico. This Montana region is dominated by grassland, but there is also a small amount of mountainous alpine vegetation there. The region has a continental climate with a semi-arid, but strong seasonal variation. Beaverhead, County Montana represents that vegetation biome.

The Mediterranean vegetation biome occurs in the California Central Valley, one of the most productive agricultural areas internationally. Mediterranean biomes experience hot, dry summers that transition to milder rainier winters during which a large percentage of forage grows in the spring and winter. This model uses San Joaquin County, California to represent that region.

2.1.3. Forage supply and other scenarios

Forage supply scenarios are based on forage production per acre, which is driven largely by the level and the timing of rainfall. The forage supply scenario is important because the main form of available water for forage productivity on a ranch is rainfall. Pastures are generally not irrigated because of high costs. This rainfall produces forage, a resource of essential importance to ranchers' economic viability.

This study assumes that all the season's forage production is consumed by cattle and converted to weight gain. For that reason, this model carries a one-year time frame. This research only considers the stocking rate for that period, so no forage carries over, partly because of well-known difficulties ranchers face when forecasting future forage production levels at the end of the current season [47,57,58]. The years 2017–2019 were selected because they reflect a drought period in New Mexico when compared to the long-term climate record. An upgraded model linking current and future forage and grazing is a top priority for future work.

Climate stress is defined simplistically in our work as a condition for which forage is reduced compared to the observed baseline level. The climate stress parameter is defined based on two levels: the historically observed level and a climate stressed level, for which the latter is set to 75 % of the historical observed level. Many other possible forage climate stress reductions could be selected [59]. For the economic parameters, use was made of both historically observed cattle price per pound as well as a lower price for both the buy prices (costs of production) and sell prices (affecting revenues).

2.2. Data and assumptions

2.2.1. Forage production

Forage production sees considerable variability across vegetation biomes. Elements such as temperature, climate, and rainfall all affect it. In addition, there is no pasture irrigation modelled, so rainfall is the dominant hydrologic factor affecting forage productivity. Forage stress and climate stress will be used interchangeably throughout this paper. Forage supply, in this model, exhibits variability across our six biomes investigated. Forage is converted to weight gain. Our model is one season (spring to fall) for a single year, for which half of the total forage produced in that season is consumed by livestock for that season based on the principle of "take half leave half," [60], for which the ungrazed part is left as a risk management strategy in case too little precipitation materializes in the following year. Base forage data only measures forage consumed by the cattle and not forage to sustain the rangeland. Trampling is not addressed in the forage level data. This model seeks to optimize forage grazed for weight gain during a grazing season, ranging from 4 months to 7 months, varying by vegetation biome. Forage production data for New Mexico, Montana, and California [61–63] were compared to long term average forage production by season and county for the years 1984–2019. Table 1 shows the forage production data used. It shows forage production per acre, while Table 2 shows total forage consumed by county [61–63].

2.2.2. Other data

Other types of data included in this study are grazing season length, animal survival rate, buy weight per head, sell weight per head, daily forage requirements per animal, observed ADG, number of animals observed on the pasture, livestock sell price, livestock buy price, and ranch production costs. Additional information on data used appear in Appendix A, which contains a more detailed explanation as well as the actual GAMS© code used. Most of the economic and productivity data are taken from representative ranch budgets from the land grant universities in the regions described [64,65]. An Idaho ranch budget was used as a proxy for the Montana Beaverhead County region because of better accessibility [66]. The annual model includes both fixed and variables costs. A large part of the variable input costs consist of purchased stocker animals in the spring, for which two scenarios were used, reflecting two sets of buy prices: observed and low.

The price per unit weight of cattle sold is slightly less than the price per unit weight of cattle purchased, and is based on a unique survival rate published in the budgets. In this study, a high price was used based on historical prices from 2017 to 2019 and a low price was used, which is a modification of the historical high prices. This study acknowledges that cattle prices are much more variable and dynamic than in this study, but this work simplifies the dynamic prices for which the optimization model accounts for a change of prices from high to low instead of the entire price range.

Data on cattle numbers for New Mexico were sourced from the State Department of Taxation and Revenue with cooperation from the New Mexico Office of the State Engineer [67]. The California and Montana livestock numbers were categorized as beef cows inventory from the United States Department of Agriculture (USDA) Quickstats database [68,69]. The survival rate is equal to one minus the death rate, sourced from the published ranch budgets. The survival rate is 97 % for New Mexico [64], 99 % for Montana [66], and 98 % for California [65].

The buy weight is the weight of the animal during the spring when the animal is bought before grazing and weight gain occurs. The New Mexico buy weight is set to 400 pounds for this work [70]. Montana's buy weight is 600 pounds and California's buy weight is 530 pounds, both from that region's respective ranch budgets [65,66].

The cattle sell weight is the animal weight at the end of the grazing season after all seasonal weight gain occurs. These cattle are sold to the next step in the production process. The New Mexico sell weight is 750 pounds for all counties [64]. Montana's sell weight is 875 pounds and California's sell weight is 800 pounds based on the respective ranch budgets [65,66].

Sell prices, for this work, are sourced from feedlot prices. The sell price is $1.65 per pound, while the buy price is $1.67 per pound

Table 1
Observed forage per acre for livestock grazing by region (lbs/acre/year).

Region	Average Elevation (feet above sea level)	Latitude	Longitude	Year	Forage Production (lbs/acre/year)
01_Mtn_US_SW	6972	36.41° N	105.57° W	1_2017	265
01_Mtn_US_SW				2_2018	189
01_Mtn_US_SW				3_2019	261
02_HP_US_SW	5167	36.37° N	103.36° W	1_2017	576
02_HP_US_SW				2_2018	444
02_HP_US_SW				3_2019	437
03_HD_US_SW	6670	35.72° N	108.24° W	1_2017	178
03_HD_US_SW				2_2018	129
03_HD_US_SW				3_2019	199
04_LD_US_SW	4298	36.37° N	106.72° W	1_2017	265
04_LD_US_SW				2_2018	187
04_LD_US_SW				3_2019	159
05_Med_US_CA	49	37.92° N	121.17° W	1_2017	1647
05_Med_US_CA				2_2018	1279
05_Med_US_CA				3_2019	1833
06_NP_US_MT	6240	45.21° N	113.11° W	1_2017	718
06_NP_US_MT				2_2018	872
06_NP_US_MT				3_2019	763

Table 2
Total observed forage for livestock grazing by region, climate stress level, and year (lbs/year).

Region	Climate stress	1_2017	2_2018	3_2019
01_Mtn_US_SW	01_historical	19,680,128	19,059,962	19,059,962
01_Mtn_US_SW	02_stressed	14,760,096	14,294,971	14,294,971
02_HP_US_SW	01_historical	768,465,171	1,006,367,973	933,022,371
02_HP_US_SW	02_stressed	576,348,878	754,775,979	699,766,778
03_HD_US_SW	01_historical	30,826,927	28,865,698	20,717,760
03_HD_US_SW	02_stressed	23,120,195	21,649,273	15,538,320
04_LD_US_SW	01_historical	46,091,417	36,349,263	39,971,935
04_LD_US_SW	02_stressed	34,568,563	27,261,947	29,978,951
05_Med_US_CA	01_historical	93,993,964	80,634,416	75,863,148
05_Med_US_CA	02_stressed	70,495,473	60,475,812	56,897,361
06_NP_US_MT	01_historical	328,725,540	295,852,986	287,634,848
06_NP_US_MT	02_stressed	246,544,155	221,889,740	215,726,136

for the year 2019, with adjustments for other years [64]. The buy price is greater than the sell price due to supply and demand conditions associated with the cattle pricing. The daily forage parameter, the mean daily forage consumption per animal, averaged just under 25 pounds of forage/day/animal [71] with some variation by region. The data for observed average daily gain was calculated as sell weight minus buy weight with the difference by the number of days in the grazing season.

2.3. Model description and equations

The model is designed to discover how optimized ranch net income behaves in different conditions, termed scenarios, to guide ranchers and policy makers in making difficult economically motivated and ecologically constrained choices, influenced by vegetation, climate, and economic factors. A calibration method generates parameters targeted to equations to support the optimization model. The calibration exercise enables the model optimization to replicate observed historical data when those historical conditions occur, as shown in detail in several equations below. The mathematical programming model begins with the base scenario and expands to the full range of scenarios such as sell and buy price, climate scenarios, and vegetation biomes. Fig. 2 presents a visual flowchart of the model.

2.3.1. Model approach

The following description of the model calibration [72] is based on a one-year ranch income optimization. It is understood that

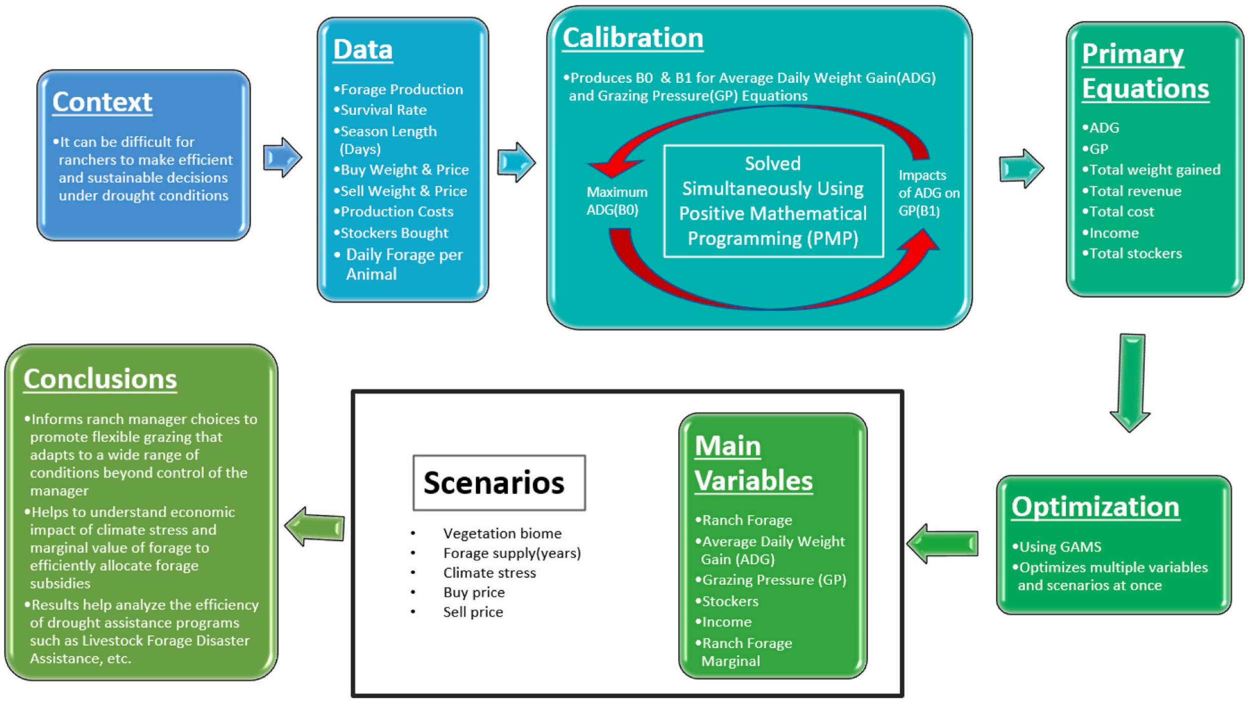

Fig. 2. Model flowchart.

there are other important goals to the rancher such as risk minimization, pasture sustainability, and capacity to quickly adapt to changing conditions, but the model does not account for them in its current implementation. Risk management is an important area for future research.

The foundation of this model is developed from microeconomic theory relevant to livestock economics as well as mathematical optimization analysis [54]. The analysis uses an innovative simultaneous equation system to disentangle complex rancher behavior that leads to stocking choices that optimize income. Ranch income and its generating process is described with the following equations (1)–(4). This set of equations represent the information and relationships among them guiding ranch income maximization. The equations were derived from back-calculating production function parameters that result in income optimizing behavior consistent with observed data for which we assume ranchers seek income optimization, a calibration process known as positive mathematical programming or PMP [54]. The four principal equations of this model are similar to an earlier work [73]:

$$\alpha = P_{Out} * Q(STK) - P_{in} * STK - C_{\text{fix}} \tag{1}$$

where

$$Q(STK) = GSL * SR * STK * ADG + SR * STK * W_{buy} \tag{2}$$

$$ADG = C_1 + C_2 * GP \tag{3}$$

$$GP = GSL^* \left[\frac{SR * STK}{F}\right] \tag{4}$$

where.

α = income (profit) produced by livestock purchasing, stocking, and selling.

$Q(STK)$ = production function, total livestock weight gain for the grazing season.

ADG = average daily weight gain.

GP = grazing pressure.

STK = total animals bought for stocking.

SR = survival rate (1 – death loss)

W_{buy} = buy weight.

P_{Out} = livestock sell price per pound (output price)

P_{in} = variable cost per animal stocked (input price)

F = total forage production for the grazing season.

C_{fix} = fixed cost for ranching region with a known land area, independent of stocking rate.

GSL = length of grazing season (days)

C_1 = maximum average daily gain for the first animal stocked.

C_2 = marginal loss in ADG for each added unit of grazing pressure (GP)

The income-optimized stocking decision as identified by taking the mathematical derivative of ranch income with respect to the total stocking rate (*STK*) the rancher chose. This assumes that the observed number of animals stocked (*STK*) has its foundation in annual ranch income maximization behavior of the rancher. The mathematical language of differential calculus is used here to characterize economically optimized rancher behavior as:

$$\frac{d\alpha}{dSTK} = P_{out}\,\frac{dQ}{dSTK} - P_{in} = 0, \tag{5}$$

which has an important economic interpretation: the marginal income from additional stocking equals the value of the marginal product from additional stocking minus the input price per animal stocked.

In equation (5), the term $dQ/dSTK$ can be expressed from substitution of the sort taught in most mathematics classes in calculus by using equations (1)–(4), which results in:

$$\frac{dQ}{dSTK} = GSL^* SR^* \left\{ STK^* \left[C_2^* \frac{d(GP)}{dSTK} \right] + C_1 + C_2^*(GP) + W_{buy} \right\} \tag{6}$$

$$\frac{dQ}{dSTK} = GSL^* SR^* \left\{ STK^* \left[C_2^* \frac{GSL}{F} \right] + C_1 + C_2^*(GP) + W_{buy} \right\} \tag{7}$$

By combining equations (5) and (7), the result is:

$$\frac{d\alpha}{dSTK} = P_{out}^* \left[GSL^* SR^* \left[STK^* C_2^* \left(\frac{GSL}{F} \right) + C_1 + C_2(GP) + W_{buy} \right] \right] - P_{in} \tag{8}$$

$$\frac{d\alpha}{dSTK} = P_{out}^* \left[GSL^* SR^* \left[STK^* C_2^* \left(\frac{GSL}{F} \right) + C_1 + C_2 \left(GSL^* \left(\frac{STK}{F} \right) \right) + W_{buy} \right] \right] - P_{in} = 0 \tag{9}$$

$$\left[\frac{2 * C_2 * STK * SR^2 * GSL}{F}\right] = \left[\frac{P_{in} - P_{out} * W_{buy}}{P_{out} * GSL} - C_1\right] \tag{10}$$

At this point, solving equations (8)–(10) is necessary to find the unknown values of the C_1 and C_2 parameters that generated the observed stocking rate (STK). The solutions for C_1 and C_2 are:

$$C_1 = \frac{\left[\frac{F * \left(P_{in} - P_{out} * SR * W_{buy}\right)}{\left(2 * P_{out} * (GSL * SR)^2 * STK\right.}\right] - \left[\frac{ADG}{GP}\right]}{\left[\frac{F}{2 * GSL * SR * STK}\right] - \left[\frac{1}{GP}\right]} \tag{11a}$$

$$C_2 = \left[\frac{(ADG - C_1)}{GP}\right] \tag{11b}$$

The right-hand side of (11a) contains only observed data and the right side of (11b) can be calculated after C_1 is calculated in (11a). Both parameters C_1 and C_2 are therefore calculated from observed data. These terms C_1 and C_2 come from a calibration exercise to reflect observed average daily weight gain (ADG) in equation (3), for which grazing pressure (GP) appears an independent variable and ADG is the dependent variable. Average daily gain is calculated as sell weight minus buy weight, for which the difference is divided by days. Calculated values of C_1 and C_2 amount to finding two calibration coefficents to permit the optimization model to replicate observed data on cattle numbers and forage consumed under observed conditions.

The term C_1 reflects the maximum average daily gain for a particular ecological region and set of economic conditions. There is considerable variation of C_1 among the ecological biomes. These values will change if the forage levels change and are determined in part by the data in Tables 1and2 and the other observed data described in the equations above. The parameter C_2 reflects the marginal effect of one extra unit of grazing pressure on average daily gain.

2.3.2. Significance of calibration

There have been several examples of model calibration used to analyze agricultural systems [74,75], but among the few other comprehensive rangeland models that integrate ecological, agronomic, and economic elements, none of which we noticed conceptualized, described, implemented, and illustrated the use of positive mathematical programming (PMP) to calibrate model results to observed ranch incomes and associated ranch manager choices. The set of equations showing the complexity of the different elements of rancher performance is displayed in equations (11a) and (11b). These equations permit calculation of (not directly observed) maximum animal performance (C_1) and the incremental effects of grazing pressure on animal performance (C_2). They permit those two unobserved parameters to be calculated by solving simultaneous equations using observed data. These two equations characterize the goal for which ranchers maximize economic returns shown in equations (1)–(4), all of which are based on observed data. The earliest use of PMP, before implemented in the present work, was initially presented in 1997 [54], and has seen applications outside the sphere of livestock forage economics since that time [52,53].

2.4. Mathematical programming model

Our work is a nonlinear (quadratic) mathematical programming model [76], calibrated to find the income-optimizing stocking level under a range of forage supply, vegetation biome, and economic scenarios that reflect the variety of possibilities ranchers do face or could face. The mathematical programming model was coded in GAMS®. This software was selected because it allows a combination of interdependent variables to optimize simultaneously, which is important when considering a rangeland enterprise that contains interacting ecological, biological, and economic dimensions. Other optimization packages have received some attention in the literature, including Pythyon®, MATLAB®, Maple®, and Mathematica®. The GAMS® code shown in Appendix A consists of equations that compute the two canonical parameters described above. An additional appendix, B, is presented as a spreadsheet for format model results in easily readable tables. The structure of this model allows for various levels of upscaling: it can be expanded to include extra time periods, drought and climate stress levels, vegetation biomes or other study areas, policy options, price or costs, and additional parameter options if needed for future work.

3. Results

3.1. Forage production rates

Table 1 presents observed forage production per acre, organized by region, elevation, latitude, longitude, and year. This model input information shows that vegetation biome has a considerable effect on forage production. Desert regions such as the high desert (03_HD_US_SW) and low desert (04_LD_US_SW) have the lowest forage productivity rates, influenced by their low precipitation levels and high temperatures. Similarly, the Mediterranean region (05_Med_US_CA) has the highest forage productivity rates, as influenced by their high precipitation levels and comparatively moderate temperatures.

Forage production is one of the most important resources influencing a ranch's potential profitability. Forage production indicates the carrying capacity of animals that a pasture can absorb. Forage production can be used as a starting point for biologically characterizing ranching operations located in different climates internationally. Access to this information along with information on prevailing economic conditions can inform stocking rate choices to optimize ranch income from forage utilization.

3.2. Total forage use

Table 2 shows total forage supply used for grazing by multiplying the forage production rate of Table 1 by the absolute scale of acreage suitable for livestock grazing by county. This calculation allows the model to approximate the amount of forage used by cattle, for which that total forage use varies by county, forage production rate, and number of animals stocked. The model has considerable flexibility as multiple scenarios can be calculated for each vegetation biome based on varying potential or actual conditions. In future work, there are plans for an expanded and improved model that will deal with conditions for which forage utilization is lower and where the rancher holds in storage additional forage not currently grazed as a risk management measure to handle potential drought in case it appears. Vegetation biomes with more precipitation also carry the flexibility to deviate in the opposite direction by increasing forage utilization in years with high levels of precipitation.

Each of the counties shown in the results represents a unique vegetation biome. There is large variation in forage among the different vegetation biomes when looking at the county (macro) level. For example, Table 2 shows the High Plains Union County New Mexico (02_HP_US_SW) has 39 times the forage compared to the mountain Taos County New Mexico (01_ Mtn_US_SW) for the year 2017. There is uneven, rocky terrain in the mountain region compared with the plains vegetation biome which is mostly flat with much forage and few trees. The Mediterranean climate (05_Med_US_CA) has a large difference in ranking with the other regions between forage production per acre in Table 1 versus total forage use shown in Table 2. This shows there is a much lower percentage of ranching acreage in that Mediterranean climate, albeit highly productive acreage.

Table 3
Average Weight Gain per Animal by Region, Year, Observed Value, climate Stress, and Livestock Buying and Selling Price (Pounds/Animal/Day).

Region	Year	Observed Value	Observed Animals Stocked	climate scenario	Buy Price			
					01_hi_buy	01_hi_buy	02_lo_buy	02_lo_buy
					Sell Price			
					01_hi_sell	02_lo_sell	01_hi_sell	02_lo_sell
01_Mtn_US_SW	1_2017	2.50	6451	01_historical	2.50	2.71	2.42	2.62
01_Mtn_US_SW	1_2017			02_stressed				
01_Mtn_US_SW	2_2018	2.68	6248	01_historical	2.68	2.68	2.89	2.60
01_Mtn_US_SW	2_2018			02_stressed				
01_Mtn_US_SW	3_2019	2.70	6248	01_historical	2.70	2.70	2.92	2.62
01_Mtn_US_SW	3_2019			02_stressed				
02_HP_US_SW	1_2017	2.12	195,934	01_historical	2.12	2.12	2.30	2.05
02_HP_US_SW	1_2017			02_stressed				
02_HP_US_SW	2_2018	2.28	256,591	01_historical	2.28	2.28	2.45	2.20
02_HP_US_SW	2_2018			02_stressed				
02_HP_US_SW	3_2019	2.29	237,890	01_historical	2.29	2.29	2.48	2.22
02_HP_US_SW	3_2019			02_stressed				
03_HD_US_SW	1_2017	2.46	10,438	01_historical	2.46	2.46	2.67	2.38
03_HD_US_SW	1_2017			02_stressed				
03_HD_US_SW	2_2018	2.64	9774	01_historical	2.64	2.64	2.85	2.56
03_HD_US_SW	2_2018			02_stressed				
03_HD_US_SW	3_2019	2.67	7015	01_historical	2.67	2.67	2.88	2.58
03_HD_US_SW	3_2019			02_stressed				
04_LD_US_SW	1_2017	1.89	11,434	01_historical	1.89	1.89	2.05	1.83
04_LD_US_SW	1_2017			02_stressed				
04_LD_US_SW	2_2018	2.03	9017	01_historical	2.03	2.03	2.19	1.97
04_LD_US_SW	2_2018			02_stressed				
04_LD_US_SW	3_2019	2.05	9916	01_historical	2.05	2.05	2.21	1.98
04_LD_US_SW	3_2019			02_stressed				
05_Med_US_CA	1_2017	1.50	18,715	01_historical	1.50	1.50	1.69	1.42
05_Med_US_CA	1_2017			02_stressed				
05_Med_US_CA	2_2018	1.63	16,055	01_historical	1.63	1.63	1.82	1.55
05_Med_US_CA	2_2018			02_stressed				
05_Med_US_CA	3_2019	1.63	15,105	01_historical	1.63	1.63	1.83	1.55
05_Med_US_CA	3_2019			02_stressed				
06_NP_US_MT	1_2017	1.41	76,000	01_historical	2.08	1.41	1.60	1.32
06_NP_US_MT	1_2017			02_stressed				
06_NP_US_MT	2_2018	1.54	68,400	01_historical	1.54	1.54	1.73	1.45
06_NP_US_MT	2_2018			02_stressed				
06_NP_US_MT	3_2019	1.54	66,500	01_historical	2.26	1.54	1.74	1.45
06_NP_US_MT	3_2019			02_stressed				

3.3. Average weight gain

Successful ranchers watch performance per animal carefully. Average daily gain (ADG) presented with model-optimized results in Table 3, with its calculation presented in equation (3), shows the weight gain per animal per day, averaged over the grazing season, shown both as observed values and matching values from the optimization model under base conditions using the calibration procedure described earlier. The model translates forage consumption to average daily gain, an important influence on a year's ranch profitability. Table 3 presents a number of notable patterns, for which the most obvious is its wide variability by year, region, buy price, and sell price.

It is important to note that ADG does not vary by climate stress level. The reason is not obvious at first inspection. The table shows that an elevated climate stress, which reduces forage to 75 % of observed level, sets in motion economic incentives that motivate the income-maximizing rancher to reduce cattle numbers along with an associated reduction in grazing pressure (not shown). This reduction of cattle numbers continues as ADG returns to its base observed level. The table shows that ADG reaches a new equilibrium with the rancher stocking fewer cattle on the land as ADG returns to its base observed level. After income maximizing ranchers observe reduced forage productivity for the climate stressed situation, the rancher reduces livestock numbers the observed level of ADG is restored with fewer cattle.

It should be noted that the model is based on access to accurate information by the rancher, assuming the rancher knows in advance the amount by which forage productivity will be reduced if the rains fail to materialize, enabling an optimized choice on how many fewer cattle to stock. In reality, producers in most places rarely know how much forage they will have when they decide how many cattle to buy and stock in the spring, since future rainfall patterns forthcoming for the grazing season are unknown in advance. Of course, weak data on future information presents a problem for any enterprise. A corporation builds a hotel, restaurant, or factory of a given size not knowing how many customers will appear or what its production costs will be for any future day, month, or year. If the number of animals the rancher stocks ends up being too many, they might try to sell some early, but may face barriers from forward

Table 4
Economic performance: Optimized ranch income per unit land by region, year, climate stress, and livestock buying and selling price ($US/acre/year).

Region	Year	Climate Stress	buy price			
			01_hi_buy	01_hi_buy	02_lo_buy	02_lo_buy
			sell price			
			01_hi_sell	02_lo_sell	01_hi_sell	02_lo_sell
01_Mtn_US_SW	1_2017	01_historical	19.85	11.34	23.28	14.09
01_Mtn_US_SW	1_2017	02_stressed	14.89	8.50	17.46	10.57
01_Mtn_US_SW	2_2018	01_historical	19.34	12.32	22.03	14.58
01_Mtn_US_SW	2_2018	02_stressed	14.51	9.24	16.52	10.94
01_Mtn_US_SW	3_2019	01_historical	24.08	14.78	27.72	17.80
01_Mtn_US_SW	3_2019	02_stressed	18.06	11.09	20.79	13.35
02_HP_US_SW	1_2017	01_historical	33.58	19.18	39.38	23.84
02_HP_US_SW	1_2017	02_stressed	25.19	14.39	29.53	17.88
02_HP_US_SW	2_2018	01_historical	35.30	22.48	40.20	26.61
02_HP_US_SW	2_2018	02_stressed	26.47	16.86	30.15	19.96
02_HP_US_SW	3_2019	01_historical	31.30	19.21	36.03	23.14
02_HP_US_SW	3_2019	02_stressed	23.47	14.41	27.02	17.35
03_HD_US_SW	1_2017	01_historical	13.79	7.88	16.17	9.79
03_HD_US_SW	1_2017	02_stressed	10.34	5.91	12.13	7.34
03_HD_US_SW	2_2018	01_historical	13.57	8.64	15.45	10.23
03_HD_US_SW	2_2018	02_stressed	10.18	6.48	11.59	7.67
03_HD_US_SW	3_2019	01_historical	18.96	11.64	21.83	14.02
03_HD_US_SW	3_2019	02_stressed	14.22	8.73	16.37	10.52
04_LD_US_SW	1_2017	01_historical	15.03	8.59	17.63	10.67
04_LD_US_SW	1_2017	02_stressed	11.28	6.44	13.22	8.00
04_LD_US_SW	2_2018	01_historical	14.46	9.21	16.47	10.91
04_LD_US_SW	2_2018	02_stressed	10.85	6.91	12.35	8.18
04_LD_US_SW	3_2019	01_historical	11.11	6.82	12.78	8.21
04_LD_US_SW	3_2019	02_stressed	8.33	5.11	9.59	6.16
05_Med_US_CA	1_2017	01_historical	46.34	15.23	64.27	26.71
05_Med_US_CA	1_2017	02_stressed	34.76	11.42	48.20	20.03
05_Med_US_CA	2_2018	01_historical	54.01	24.95	69.05	36.00
05_Med_US_CA	2_2018	02_stressed	40.51	18.71	51.79	27.00
05_Med_US_CA	3_2019	01_historical	66.85	27.48	88.15	42.40
05_Med_US_CA	3_2019	02_stressed	50.14	20.61	66.11	31.80
06_NP_US_MT	1_2017	01_historical	26.55	9.04	36.82	15.72
06_NP_US_MT	1_2017	02_stressed	19.91	6.78	27.61	11.79
06_NP_US_MT	2_2018	01_historical	47.46	22.02	60.96	31.96
06_NP_US_MT	2_2018	02_stressed	35.60	16.52	45.72	23.97
06_NP_US_MT	3_2019	01_historical	36.00	14.94	47.67	23.15
06_NP_US_MT	3_2019	02_stressed	27.00	11.20	35.75	17.36

contracting or lack of market demand at that time. In this case, they would end up with lower ADG than they had expected. This model does not account for that kind of uncertainty in climate conditions when stocking decisions must be made. Handling this uncertainty with acceptable rigor is an important area for future research.

Relative to a base buy price (01_hi_buy), the lower buy price (02_lo_buy) reduces variable costs of production, which, as predicted by neoclassical economic theory makes it more economically attractive to increase animals stocked, reducing the ADG. A good example is shown by comparing the optimal 2.50 average daily gain seen for the Mountain Southwest Region (01_MTN_US_SW) in the year 2017 under base buy (01_hi_buy) and base (01_hi_sell) prices to the lower optimal 2.42 average daily gain for the same place and time for a low buy price (02_lo_buy) and the unchanged sell price (01_high sell). This pattern is maintained for all the entries (all years and regions) shown in Table 3.

3.4. Economic performance: income per unit land

Table 4 shows total ranch income per unit land by biome region, year, climate stress level, and livestock buying and selling price, measured in $US per acre. It shows a wide variability in income per unit land ranging from a low of just over $5 to a high of about $88. This lowest income occurs for the case of a high livestock buying price and low selling price in 2019 facing climate stressed forage conditions for the southwestern low desert (04_LD_US_SW). The more than 17 times higher $88 per acre occurs for the case of a low livestock buying price (low input cost) and high selling price (high revenue) for the year 2019 in the Mediterranean region of California under historical climate conditions.

Climate stress conditions that reduce forage productivity to 75 % of base levels reduce average income per acre to 75 % of base levels for all cases. This shows that an X percent forage productivity reduction reduces income per acre by the same X percent. Base forage levels consider sustainability and the data only measures forage that will be consumed by the livestock as well as for sustaining the rangeland (take half leave half). Trampling impacts are an important area for future research. This finding is not surprising because of the considerable influence of forage productivity per acre in producing ranch income. It is reaffirmed by the fact that the production function used for this work shows constant returns to scale in forage, by which increases in forage productivity by a given proportion (e.g., double) increases optimized ranch income by the same proportion (double). This table vividly illustrates that the forage on a piece of ground as well as the beef sector's economic conditions carry huge implications for ranching income earning opportunities. One hundred acres in the best conditions produces more income than 1700 acres in the worst conditions.

Table 4's findings showing optimized ranch income per acre carry importance for several reasons. The first is the table's capacity to inform and support economic analysis: livestock ranching is a significant sector under various ecological, climate, and economic conditions of the rural economy internationally [77], so access to information on income produced by this sector sheds important light on the overall economic health and well-being of rural regions. Additionally, the information in the table carries important information to guide policy design. Information on ranching income per unit land can be used to inform policy decisions related to agriculture, such as grazing fees charged to ranchers. This information can also inform planning and management: livestock income information can be used by ranchers to better plan, assess, and manage their operations in the face of newer or better information.

3.5. Value of additional forage

Fig. 3 shows the economic value of additional forage (shadow price) for grazing by location, year, climate stress level, and livestock buying and selling price. It reflects the incremental (marginal) ranch income produced by additional forage. It is a different metric from that shown in the average income per unit forage in Table 4. Sometimes termed "shadow prices," these marginal values of forage

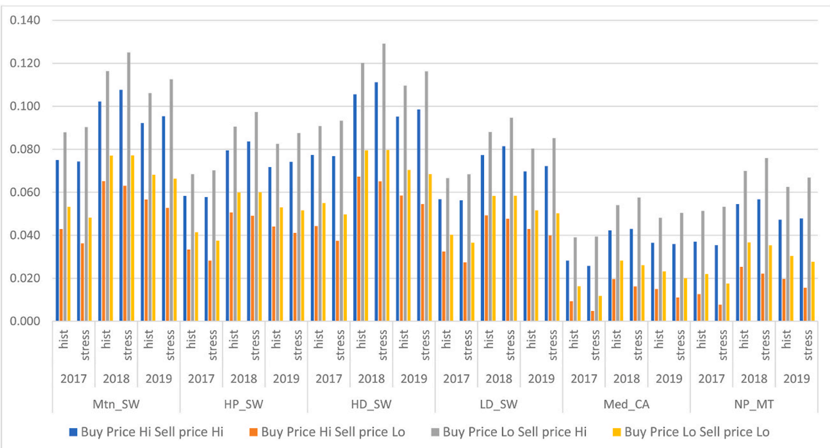

Fig. 3. Economic value of additional forage for livestock grazing by location, year, climate stress, and livestock buying and selling price ($US/Pound forage).

present important information for ranchers as well as for policymakers charged with promoting viable use of rangelands. The figure shows this incremental economic value of additional forage, if made available through additional rainfall, irrigation, substitute feeds, or reduced stocking intensity.

A shadow price for a scarce resource like forage presents an important principle for guiding the allocation of that scarce resource. It represents the implicit value of that resource in the context of a constrained optimization problem such as developed for this paper. It is the amount by which the objective function (net ranch income) would improve if an additional unit of the scarce resource were available. Here are a few key points about shadow prices:

Marginal Value: The shadow price measures the marginal value of the scarce resource. It measures the change in the ranch net income per unit increase in the resource.

Constrained Optimization: Shadow prices appear in problems where there are constraints on resources, such as livestock forage. These constraints limit the feasible solutions, which for this paper's problem, makes forage more valuable when it is more scarce, when livestock prices are higher, or when their costs of production are lower.

Economic Interpretation: The shadow price for this work indicates how much the ranch would be willing to pay for an additional unit of the scarce resource. It is a valued piece of information that can guide on-the-ground choices made by the rancher.

Mathematical Programming: For mathematical programming exercises, such as the one described for this work, the shadow price corresponds to the dual variable associated with the constraint representing the resource limit. The GAMS® software used produces these shadow prices for valuing forage for the full range of economic and biological conditions assessed for this work.

Marginal values are forward looking, while average values present information looking backward. For the case of livestock forage, the shadow price measures the economic value of the forage to the livestock producer if more forage could be secured, taking into account factors like nutritional value of the forage, the availability of alternative forage sources, and cost and returns from buying and stocking additional animals. Shadow prices are informative for economic analysis, as they underpin the optimized allocation of stocker animals.

In the constrained optimization model developed for this work, the shadow prices shown in the table reflect the economic gain per unit relaxation of the forage constraint in the optimized value of the ranch net income objective function. Since the objective function described earlier is annual ranch net income, the shadow price is the marginal income produced by one more unit of forage if it could be secured. For this work's ranch business application, the forage shadow price is the maximum price that the rancher can pay for an extra unit of the forage. For the mathematically minded scientist, the forage shadow price is the value of the Lagrange multiplier [78, 79] at the economically optimized solution. In the Newtonian sense, it is the small change in the optimized economic objective divided by the small change in the forage constraint.

Marginal values of forage are constant over a range of forage productivity changes. Although this is not directly shown in Fig. 3 to economize on space, that constancy occurs because the income production function appearing in equations (1)–(4) above exhibits constant returns to scale in the face of an upscaling of forage productivity per unit land. This constant marginal value from decreased or increased forage occurs as the income optimizing livestock rancher reduces herd size to offset the reduction in forage due to climate stressed conditions. However, marginal values are not constant from changes in ecological or economic conditions as shown in Fig. 3. Marginal values of forage are greatest for the High Desert US Southwest zone and Mountain US Southwest zones. The smallest marginal values occur in the California Mediterranean zone.

As economic insights predict, the marginal value of forage is reduced with a lower livestock selling price and is increased with a lower buying price. This result occurs because a lower buying price reflects lower input costs, giving rise to a greater income capacity for the existing forage available. When livestock selling prices are lower or input costs are higher, this provides a signal to the livestock rancher or public lands range manager that it is a less attractive economic decision to develop more forage.

The importance of these shadow prices has been well-recognized for a number of years in various kinds of literature addressing forests, fisheries, water, land, and minerals [80–86]. Still, the findings here are one of the few among published works noted presenting marginal values of livestock forage under a wide range of ecological, climate, and economic conditions.

It may seem counter-intuitive that for any year, biome, and location, the table's shadow prices are constant over both climate stress conditions. For example, in the Mountain Southwest region (01_Mtn_US_SW) for the year 2017 under conditions of a high livestock buying price and low selling price per pound, the marginal value of forage is $0.075 per pound under both historical and climate stressed conditions. This finding reflects the fact that the income-maximizing rancher adjusts stocking rate when forage productivity changes to maintain the base level of forage marginal values. There are several ways that a range ecosystem manager or livestock manager can use the information provided by the shadow prices shown in Fig. 3:

Allocation of Resources: These shadow prices can guide in determining the most economically efficient allocation of scarce forage. Their numerical values indicate the economic value of the scarce forage for the conditions in which they were measured. This economic data can be used to guide choices on how to allocate forage.

Benefit-Cost Analysis (BCA): Shadow prices can be used to guide implementation of BCA. The use of BCA permits comparison of benefits and costs of different forage protection or enhancement plans. When used for this purpose, BCA can provide insight to determine the economically highest valued use of resources, and in assessing the most economically efficient methods to achieve economic goals.

Forage Pricing: The shadow prices shown in Fig. 3 can be used to inform, guide, or support forage pricing decisions. An example is assessing the price at which forage would be sold or rented if a market appeared for that forage. This would provide valuable information for a rancher who is considering renting forage belonging to another rancher, rather than developing their own.

Lack of Market Price Information: The shadow prices shown in Fig. 3 can be used when market prices of forage are not available or do not reflect the real economic value of the forage when used, or the opportunity cost of using the forage for something else when not used for livestock grazing. For example, shadow prices may be used in assessing the value of forage in places where forage markets are poorly developed or where existing prices are distorted by a number of external factors. Table 5 shows sources of selected information used to parameterize and inform our optimization model.

4. Discussion

4.1. Relevance

Optimized values of ranch income per unit land presented in this work (Table 4) can inform climate adaptation plans by providing valuable information about the potential economic impacts of changes in forage availability and quality due to drought and climate stress [87]. This information can be used to target regions of economic vulnerability, guide ranch investment decisions, and formulate or assess strategies for mitigating effects of climate change and its stress on forage production [88–93]. For example, if forage production is expected to decline at a particular time or place due to observed or forecast changes in precipitation patterns, information on forage economic values can be used to guide decisions on substitutes for precipitation supported forage, such as investing in increased irrigation, purchasing feed, planting drought-tolerant crops, or investing in water conservation measures.

4.2. Utility

Information on economic values of forage [94–98] shown in Fig. 3 can also help to assess the efficiency of U.S. Department of Agriculture (USDA) farm policy, such as the Livestock Forage Disaster Program (LFP), so ranchers can benefit without the government overspending on drought relief funds. A cost savings of this sort by way of a reduction in potential per-acre LFP payout would allow for more efficient use of resources for both taxpayers and ranchers. One would implement this improved information of marginal values of forage by comparing the per-acre LFP payout to our estimated change in optimized ranch income between the historical and climate stressed scenarios. Nevertheless, our estimates of income loss may be smaller than losses experienced by ranchers because our model assumes decisions under certainty, whereas ranchers necessarily make decisions under uncertainty.

Another risk management program that can be informed using this shadow price of forage shown in Fig. 3 is the Pasture, Rangeland, Forage Rainfall Index Crop Insurance Program (PRF). Knowing the shadow prices of forage allows the government to allocate coverage efficiently. Analyzing forage utilization rates in combination with shadow prices can also allow the government to more efficiently allocate insurance coverage to those who would secure an economic benefit from it. The USDA continues to seek feedback to improve and optimize these programs to make them more efficient and to help ranchers manage their risk. Additionally, understanding the economic value of forage can help ranchers and policymakers prioritize conservation efforts to protect or develop important forage resources [99].

4.3. Limitations

One important limitation of our model is that it assumes the rancher has perfect information about the timing and severity of climate stress and resulting forage reductions before making their stocking decision [100–102]. In reality, ranchers implement stocking decisions before they know how much forage will be available during the grazing season [41]. Estimated impacts of climate stress are therefore likely smaller than those experienced by ranchers who have to make their decisions with uncertain or unreliable information. There are emerging improvements in technology to forecast and monitor the amount of forage available for cattle use, such as Grass-Cast [103], the Rangeland analysis Platform [104], as well as others [105,106].

The model structure developed for this work is simplified to make its logic clear while also producing consistent and understandable results. It is limited to a one-year stocker model without a separate analysis performed for the considerably more complex case of a cow-calf operation. In fact, a considerable percentage of ranches in the western US are cow-calf operations [32,107–109]. In addition, improved pasture or small grain pastures [110] are often used for stocker operations.

Table 5
Data souces.

Data	Unit	Source
Forage Production	lbs. per acre	Klemm et al., 2020; Reeves and Baggett, 2014; Reeves et al., 2017; Reeves and Mitchell, 2011; Reeves et al., 2014
Survival Rate	%	Forero, 2017; Lillywhite, 2019; Eborn, 2020
Days in Season	# of days	Forero, 2017; Lillywhite, 2019; Eborn, 2020
Buy Weight	lbs. per animal	Eborn, 2020; Forero, 2017; Wooton and Wooton, 2024
Sell Weight	lbs. per animal	Forero, 2017; Lillywhite, 2019; Eborn, 2020
Production Costs	$US	Forero, 2017; Lillywhite, 2019; Eborn, 2020
Stockers Bought	# stockers by county	INTERA, 2020; United States Department of Agriculture, 2020a, b
Average Daily Gain	lbs. per animal per day	(Sell weight - buy weight)/days in season
Sell Price	$US	Lillywhite, 2019
Buy Price	$US	Lillywhite, 2019
Daily Forage per Animal	lbs.	Sawalhah, 2014

This model was developed for potential applicability to many rangeland conditions internationally with minimum changes in code needed to illustrate and promote its generalizability, though, of course, new data would be required characterizing those conditions. Changing livestock economic parameters or adding a number of international regions are possible enhancements.

4.4. Further research needs

Much work is needed to address the optimized level of carryover forage for future use, in light of unknown future rainfall and unknown future forage production. One of the commonly-held views on optimized forage use for one season is the widely-expressed rule of thumb "take half leave half" [111], for which the other half would be set aside for future seasons. Our model makes the assumption that half the current year's forage productivity is consumed by the livestock. In fact, our model has enough flexibility so that any fixed percentage of forage productivity could be used in the current year, which, of course, would cause our calibration coefficients to change, but would still show an optimized solution to match animals stocked, ranch income, and forage used.

For future work, we recommend development of the model to allow for optimized intertemporal stocking [112–114] that adapts to forage and rainfall forecasts, for which the revised objective would be the discounted expected net present value of a sequence of future ranch incomes. Other elements of a rangeland ecosystem optimization could include wildlife management, water supply, purchased feed or grain production. In its present state, the model is limited to rainfed driven forage supply.

5. Conclusions

Several challenges face livestock forage managers, including economic, ecological, and climate stress. Many policymakers and ranchers in the world's dry regions aim to protect rangeland ecological systems while keeping ranching as an economically viable base industry in these regions because many of these regions have ranching as a core industry, which makes this industry central to the local economies. This work integrates complex relationships, including precipitation, grazing pressure, animal performance, and forage production to sustain both ranching incomes and rangeland ecosystems. The unique contribution made by this work presents a calibrated ranch income optimization model supported by innovations in PMP that enable replication observed economic, forage, and climate conditions while incorporating various stocking rates, forage conditions, grazing pressure, animal performance, and ecological site productivity.

Results of this work suggest several actions that could be taken by livestock ranchers and policymakers to close the gap between actual (under uncertainty) versus optimal (under certainty) ranch profitability. These include better short-term forecasts of forage supplies throughout the grazing season so stocking plans can continually be updated. Better technology to monitor forage quantity and quality would be informative, especially for ranches with large land areas for which it is difficult to track forage productivity and livestock weight gain daily. Creative efforts to provide technical assistance and mentoring on operational drought management might be informative as might comprehensive user-friendly (through co-design) drought websites and extension information.

Results demonstrate how economic, ecological, and climate conditions affect the economically optimized choice and outcomes for a rancher can make under a wide variety of conditions. These optimized choices can provide guidance to policymakers and ranchers who wish to understand the implications of changes in climate and economic circumstances.

CRediT authorship contribution statement

Shanelle Trail: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis. **Frank A. Ward:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare no competing interests.

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Data used in this manuscript are available in this paper's citations as well as in the two attached appendices.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e35254.

Appendix Table 1
Average Livestock Buying Price by County, Year, and Buying Scenario ($US/lb)

Region	Year	Buying Scenario	
		01_hi_buy	02_lo_buy
01_Mtn_US_SW	1_2017	1.72	1.63
	2_2018	1.84	1.75
	3_2019	1.76	1.66
02_HP_US_SW	1_2017	1.72	1.63
	2_2018	1.84	1.75
	3_2019	1.76	1.66
03_HD_US_SW	1_2017	1.72	1.63
	2_2018	1.84	1.75
	3_2019	1.76	1.66
04_LD_US_SW	1_2017	1.72	1.63
	2_2018	1.84	1.75
	3_2019	1.76	1.66
05_Med_US_CA	1_2017	1.72	1.63
	2_2018	1.84	1.75
	3_2019	1.76	1.66
06_NP_US_MT	1_2017	1.72	1.63
	2_2018	1.84	1.75
	3_2019	1.76	1.66

Appendix Table 2
Average Livestock Selling Price by Region, Year, and Selling Scenario ($US/lb)

Region	Year	Selling Price Scenario	
		01_hi_sell	02_lo_sell
01_Mtn_US_SW	1_2017	1.62	1.48
	2_2018	1.74	1.59
	3_2019	1.65	1.51
02_HP_US_SW	1_2017	1.62	1.48
	2_2018	1.74	1.59
	3_2019	1.65	1.51
03_HD_US_SW	1_2017	1.62	1.48
	2_2018	1.74	1.59
	3_2019	1.65	1.51
04_LD_US_SW	1_2017	1.62	1.48
	2_2018	1.74	1.59
	3_2019	1.65	1.51
05_Med_US_CA	1_2017	1.62	1.48
	2_2018	1.74	1.59
	3_2019	1.65	1.51
06_NP_US_MT	1_2017	1.62	1.48
	2_2018	1.74	1.59
	3_2019	1.65	1.51

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