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Original Research

Evaluation of the APEX cattle weight gain component for grazing decision-support in the Western Great Plains

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A B S T R A C T

Rotational grazing studies have produced mixed results related to animal performance (weight gain), which has contributed to producer uncertainty regarding grazing management decisions. To enhance decision-support for producers, we improved algorithms in the Agricultural Policy/Environmental eXtender (APEX) model to better represent cattle weight gain in real-world rangeland conditions under two grazing management strategies. Simulated weight gain and related forage effects were evaluated with experimental data from 2014 to 2018 under two grazing strategies. The traditional rangeland management strategy used continuous season-long grazing stocked at a moderate level. The collaborative adaptive rangeland management strategy employed grazing with one large herd rotated using a sequence developed by a stakeholder group with movement between pastures driven by predetermined decision triggers. For each grazing strategy, yearling steers grazed from mid-May to October on ten 130-ha pastures. With the APEX modifications, daily weight gain was adequately simulated for both continuous (traditional rangeland management) grazing and management intensive rotational (collaborative adaptive rangeland management) grazing. Dry matter intake, total digestible nutrients, and temporal distribution of dry matter intake were the primary influencers of cattle performance (weight gain). Once shown to be accurate, we used APEX to evaluate several management alternatives (i.e., stocking rate, rotation interval, and rotation decision criteria) to showcase its decision support capabilities. These important enhancements increase the utility of APEX in semiarid environments, such as the western Great Plains, in providing science-based rangeland decision support to ranchers, agency land managers, and policy makers.

Introduction

Rangelands are the most extensive land cover type on earth and provide numerous ecosystem services, such as biodiversity, water, carbon sequestration, food, fiber, fuel, and cultural values (Briske, 2017). Rangeland degradation exacerbated by improper grazing management has been widely identified in the world's arid and semiarid rangelands (Moreno García et al. 2014). Simply reducing stocking rate often does not prevent undesirable plant invasion and mitigate further degradation (Teague et al. 2013). Thus, grazing managers and scientists regularly evaluate various alternative grazing management systems. Alternative grazing management strategies exist (e.g., rotational grazing), but results for cattle weight gains are inconsistent, often because of confounding effects of stocking rate and grazing strategy, as well as system complexity

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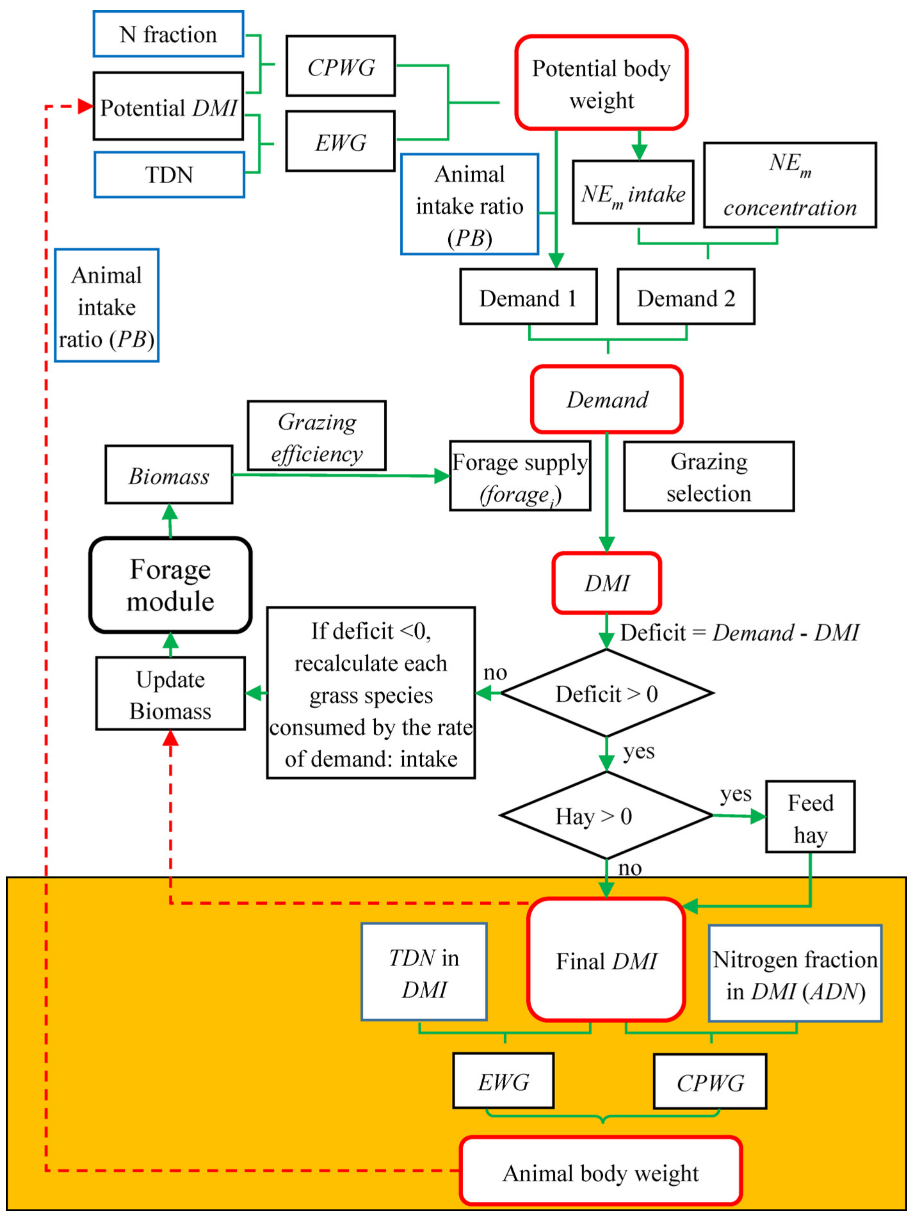

Figure 1. Simplified diagram of the beef cattle weight gain process in APEX.

(Briske et al. 2008, 2011; Hawkins 2017; Harmel et al. 2021). For example, Teague et al. (2013) concluded that several factors influence the potential benefits of rotational grazing, including 1) providing for adequate plant recovery, 2) modifying livestock distribution and grazing intensity, and 3) regulating livestock nutrition and feeding behavior. Also, the application of experimental findings to commercial ranches often does not occur because they lack flexibility and feedback mechanisms relative to the temporal and spatial scales of actual operations (Roche et al. 2015; Derner and Augustine 2016).

To address limitations of prior studies and better understand production impacts, the collaborative adaptive rangeland management (CARM) experiment was implemented in 2014. The study was conducted at a real-world ranch scale (2 600 ha), and annual stocking rate was kept the same between the CARM and traditional rangeland management (TRM) treatments. In contrast to previous studies, which intentionally excluded the human dimensions (Briske et al. 2011), this study incorporated participatory decision making for adaptive management by an 11-member stakeholder group composed of ranchers, nongovernment conservation organizations, and state/federal land managers (Wilmer et al. 2018). Grazing strategy did not influence vegetation responses, but the CARM strategy consistently reduced cattle weight gains (11%–16%) during the first 5 yr of the comparison (Augustine et al. 2020).

While producers and field studies are working to better understand the impacts of sophisticated grazing management alternatives, simulation models lack the capacity to accurately predict cattle response. Grazing models such as SPUR (Stout et al. 1990), GPFARM-Range (Andales et al. 2005; Andales and Ahuja 2006; Fang et al. 2015), and GRAZPLAN (Moore and Ghahramani 2013) have shown varying degrees of success in predicting cattle weight gain under basic management scenarios and various environmental conditions. To enhance prediction capabilities on grassland grazing systems, Zilverberg et al. (2017, 2018) made important enhancements to the Agricultural Policy/Environmental eXtender (APEX) model (Williams and Izaurralde 2006). Specifically, Zilverberg et al. (2017) modified the APEX plant growth module to better represent forage yield and environmental impacts. Zilverberg et al.

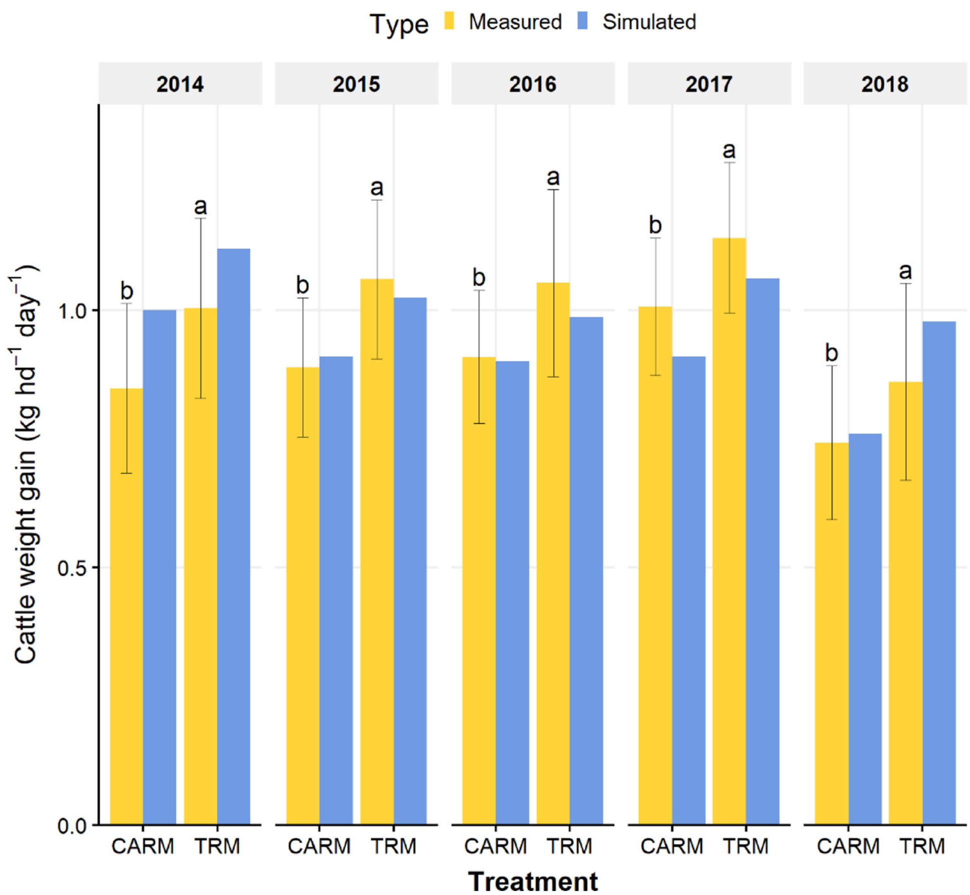

Figure 2. Average daily weight gains (kg hd^{-1} d^{-1}) for steers grazing under collaborative adaptive rangeland management and traditional rangeland management at the US Department of Agriculture–Agricultural Research Services Central Plains Experimental Range, Nunn, Colorado. Different lowercase letters in each year indicate a significant difference due to the treatment effect (as tested by least significant difference at $P < 0.05$).

(2018) modified grazing selectivity in APEX by incorporating forage quality based on four factors: 1) forage nitrogen concentration, 2) forage total digestible nutrients, 3) forage antiquality factors, and 4) grazers' tolerance of antiquality factors. Building on these improvements, Cheng et al. (2021) further enhanced APEX through parameterization of subshrub plants, use of actual forage intake for weight gain under forage deficits, and ability to use flexible rotations among pastures.

For APEX to meet its potential in grazing management support, it must adequately simulate cattle weight gains under sophisticated grazing management strategies, especially those with complex decision making as used under CARM (Derner et al. 2008). Thus, our main objective was to evaluate the capability of APEX for simulating daily cattle weight gains under alternative grazing management strategies. It was also important to use APEX to evaluate factors affecting daily weight gains under CARM and TRM and to explore the effects of multiple alternative grazing management scenarios on daily weight gains.

Materials and methods

Experimental data

Model enhancement and evaluation used experimental data from the CARM study conducted on semiarid short-grass steppe at the US Department of Agriculture–Agricultural Research Services Central Plains Experimental Range (40°49′N, 107°47′W) near Nunn, Colorado (Wilmer et al. 2018; Augustine et al. 2020). This USDA-ARS Long-Term Agroecosystem Research (LTAR) network site has a mean annual temperature of 8.6°C and a mean annual precipitation of 340 mm mostly as rain from May to September (Lauenroth et al. 2008).

In 2014 at the initiation of the CARM study, twenty 130-ha pastures were divided into 10 pairs with each pasture pair having similar soils and plant communities, mean topographical wetness index, and prior management history at a moderate stocking rate (Augustine et al. 2020; Derner et al. 2021). In each pasture pair, one pasture was randomly assigned the CARM grazing strategy and the other to the TRM grazing strategy (Augustine et al. 2020). Under the CARM treatment, an 11-member stakeholder group determined annual stocking rate, pasture grazing sequence, and pastures for planned rest (2/yr) (Wilmer et al. 2018). Stakeholders met quarterly and received weekly email updates during the grazing season.

British-bred (angus and angus-cross, *Bos taurus*) yearling steers grazed the pastures from mid-May to early October each year with 214, 224, 234, 244, and 280 steers in 2014, 2015, 2016, 2017, and 2018, respectively. For TRM, steers grazed season long in each of the ten 130-ha pastures (1 herd of 21–28 steers per pasture), resulting in a stock density range of 0.15–0.22 steers ha^{-1} during the study. For CARM, one herd of steers (214–280) was rotated among the 8 grazed pastures with a 10-fold higher stock density per pasture but the same system-level stocking rate as TRM (Wilmer et al. 2018). Steers were individually weighed at the beginning and end

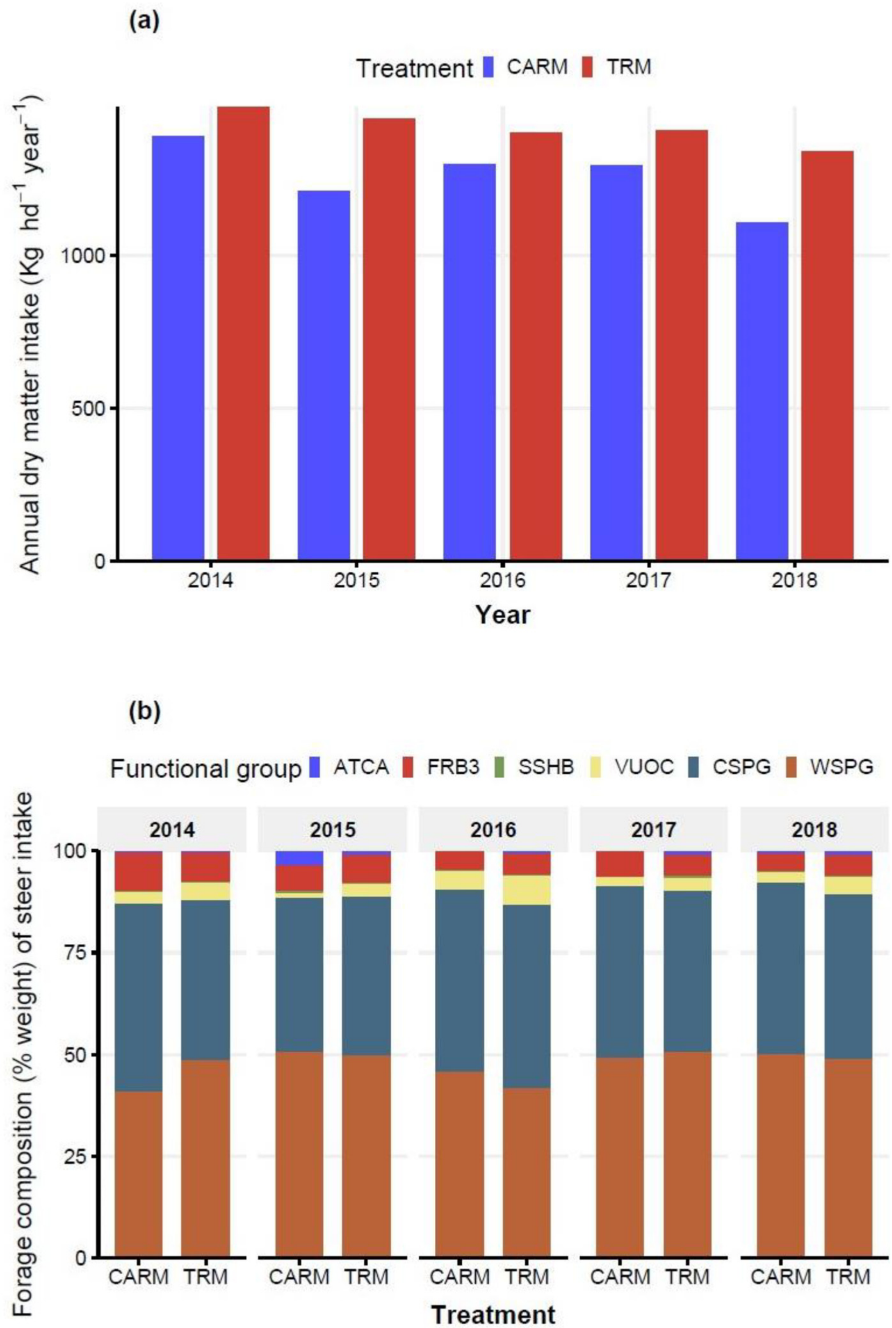

Figure 3. Simulated (**a**) annual dry matter intake (kg hd^{-1} yr^{-1}) of steers grazed under collaborative adaptive rangeland management (CARM) and traditional rangeland management (TRM); and (**b**) forage composition (% weight) of annual intake by steers for six different plant functional groups (ATCA, shrub; SSHB, subshrubs; VUOC, cool-season annual grass; FRB3, forbs; CSPG, cool season perennial grass; WSPG, warm season perennial grass) and two grazing treatments (CARM and TRM) at the USDA-ARS Central Plains Experimental Range, Nunn, Colorado.

of each grazing season. Detailed information on the experiment is available in Augustine et al. (2020) and Derner et al. (2021).

Description of the APEX Plant and Animal Modules

APEX is a process-based model with a simple rotational grazing option (Williams and Izaurralde 2006) to assess the agronomic and environmental impacts of grazing management (Osei et al. 2000; Gassman et al. 2006; Park et al. 2017). In APEX (v1605), plant growth modules simulate forage growth variables such as dry matter accumulation and forage distribution. The grazing modules simulate forage selectivity, animal dry matter intake (DMI), and steer daily weight gain (DWG). Zilverberg et al. (2017) improved the APEX plant growth module for simulating multispecies vegetation on rangelands. Subsequently, Zilverberg et al. (2018) improved the selective grazing module to better represent animal weight gains to account for forage digestibility by simulating total digestible nutrients (TDN). Recent enhancements by Cheng et al. (2021) demonstrated that APEX adequately simulated forage production under both traditional and sophisticated grazing management strategies. **Figure 1** is a simplified diagram of the enhanced APEX cattle weight gain module (details are described later).

In APEX, TDN is calculated daily on the basis of plant growth stage. Indigestible nutrients (1-TDN/100) are excreted as feces, and

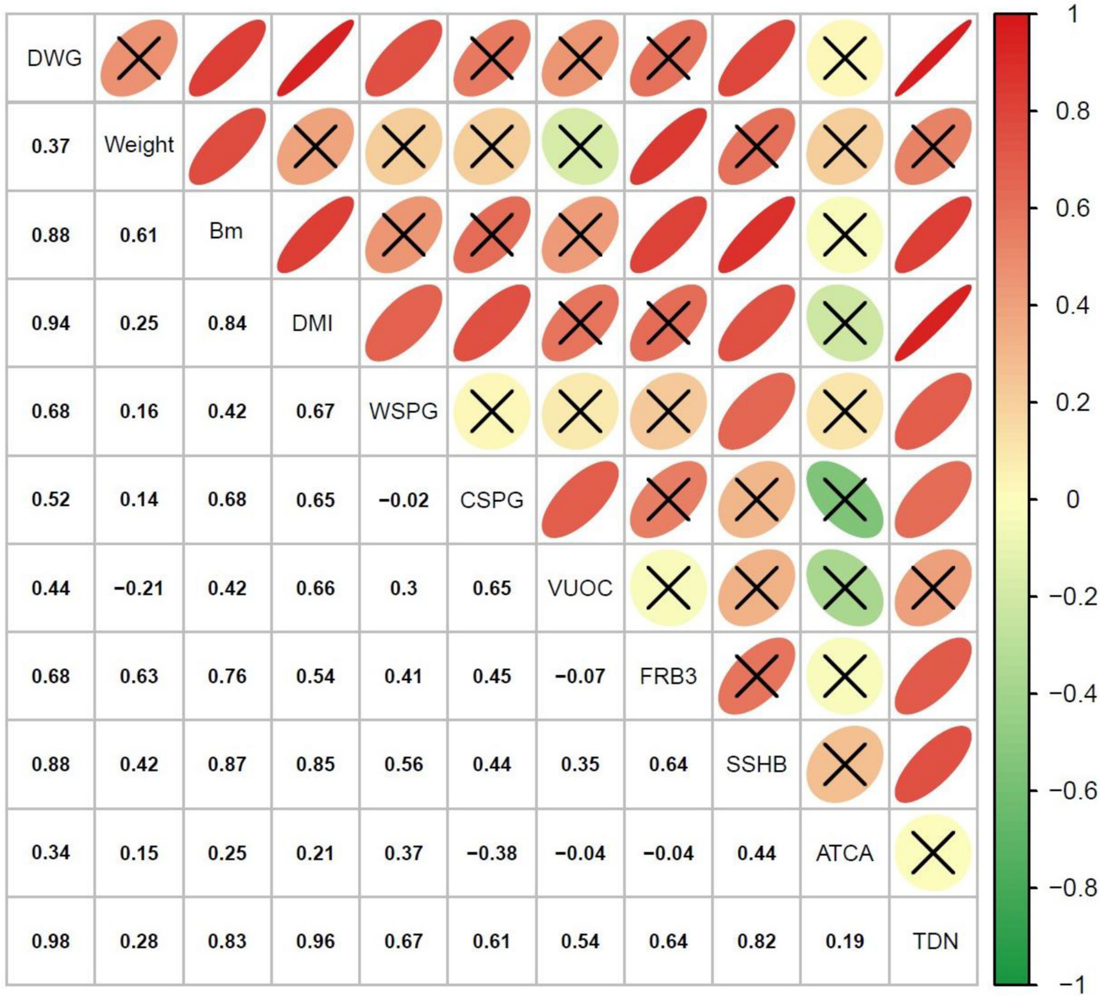

Figure 4. Correlation among daily weight gain (DWG), dry matter intake (DMI), total biomass (Bm), total digestible nutrient (TDN) intake and intake by plant functional group (WSPG, warm season perennial grass; CSPG, cool season perennial grass; VUOC, cool season annual grass; FRB3, forbs; SSHB, subshrubs; ATCA, shrub) at the US Department of Agriculture−Agricultural Research Services Central Plains Experimental Range, Nunn, Colorado (2014−2018). The numbers below the 1:1 diagonal squares are the correlation coefficients. An "X" in the colored ellipses indicates that the correlation between the two variables was statistically nonsignificant ($P > 0.05$). Also, the narrower the ellipse, the stronger the correlation.

31% of water consumed is released as urine based on hard-coded values (Zilverberg et al. 2018). Nutrients (i.e., nitrogen [N] and phosphorus [P]) consumed but not converted to tissue are also excreted. Forage species are classified as preferred, desirable, and undesirable. Desirable forage species (as noted in Zilverberg et al. 2018) can also be referred to as "acceptable" to grazing animals to provide three distinct categories in the common vernacular of ranchers. Forage quality is based on its N concentration, TDN, antiquality factor (0−1), and grazer's tolerance (0−1) on a daily basis (Zilverberg et al. 2018). An antiquality factor of 0 indicates no restrictions on intake of a given plant species, and grazer tolerance is used in combination with antiquality factor in the forage intake. Forage antiqualities are plant parameters that vary by species, and initial values were set based on previous studies (Zilverberg et al. 2017, 2018). For example, the antiquality factor for all grasses was 0, whereas the antiquality factor for ragweed *(Ambrosia psylostachia)* was set to 0.7 at emergence and 0.9 at maturity.

In APEX, the potential DMI of yearling beef cattle ($DMI_{potential}$) is calculated as a fraction of shrunk body weight:

$$DMI_{potential} = PB \times SBW \tag{1}$$

where *SBW* is the shrunk body weight of each steer in the herd at the beginning of the day (kg hd^{-1}) and *PB* is the fraction of body weight defined by the user to calculate intake demand based on body weight (set to 0.026 in the present study).

On the basis of the National Nutrient Requirements of Cattle Beef (National Academies of Sciences, Engineering, and Medicine 2016), APEX calculates cattle potential DWG using energy and crude protein. The weight gain based on energy (EWG) is calculated as:

$$RE = max\left(0.001, \left(1000 \times DMI_{potential} \times SR - EMNR/EMN\right) \times EGN\right) \tag{2}$$

$$EWG = 13.91 \times RE^{0.9116} \times EQSBW^{-0.6837} \tag{3}$$

where *RE* is retained energy (Mcal/kg), *EMNR* is net energy requirement for maintenance from feed; *EMN* is net energy for maintenance content (Mcal/kg); *EGN* is net energy for weight gain content (Mcal/kg); and *EQSBW* is equivalent shrunk body weight (kg).

Weight gain based on crude protein *(CPWG)* is calculated using:

$$3.8 \times SBW^{0.75} + 544.7 \times CPWG - 3.8 \times EQEBW^{0.75} \times (0.956 \times CPWG)^{1.097} = 6250 \times ADN \times 1000 \times DMI_{potential} \times SR \tag{4}$$

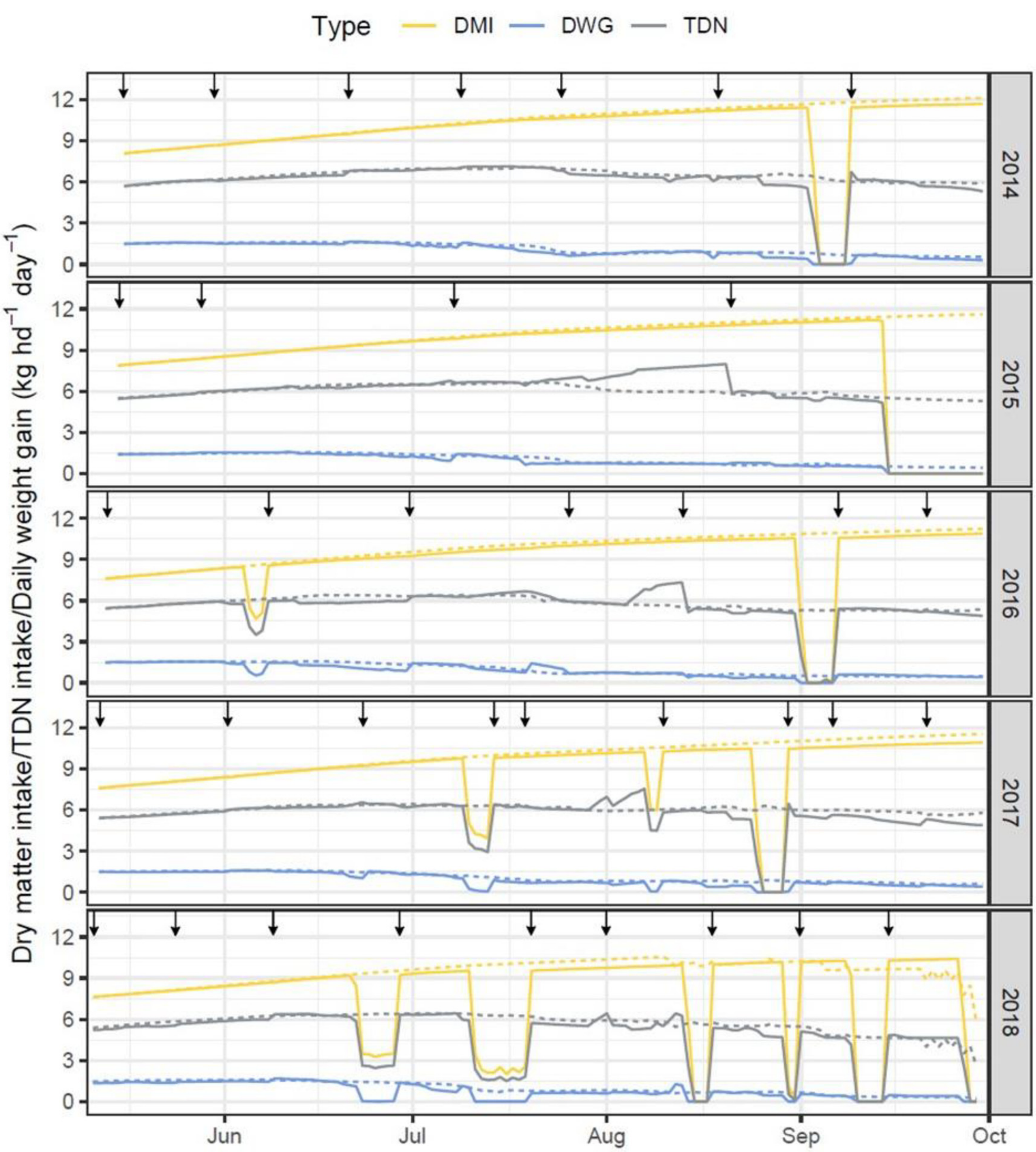

Figure 5. Simulated average dry matter intake *(yellow lines)*, total digestible nutrient intake *(gray lines)*, and daily weight gain *(blue lines)* for steers grazed under collaborative adaptive rangeland management (CARM, *solid lines*) and traditional rangeland management (TRM, *broken lines*) at the US Department of Agriculture–Agricultural Research Services Central Plains Experimental Range, Nunn, Colorado (2014–2018). Herd movement to a new pasture indicated by *black arrows.*

where *ADN* is the nitrogen fraction of *DMI*. The *CPWG* was initially set as 1 to solve the nonlinear equation [4] using the Newton method.

And APEX calculates potential *DWG* using the minimum of *EWG* and *CPWG* as:

$$Potential\ DWG = \min(EWG, CPWG)/0.96 \tag{5}$$

where 0.96 is the coefficient to convert shrunk body weight gain to *DWG*. Cattle weight loss cannot occur in APEX because EWG and PCWG are positive values.

The potential DMI demand of yearling beef cattle *(Demand)* is calculated from a maximum of 1) as a fraction of potential body weight and 2) dividing the NEm (net energy required for maintenance, calculated from body weight) by NEm concentration.

Actual DMI (DMI_{actual}) is calculated on the basis of cattle demand and forage supply for each forage species:

$$forage_i = Biomass_i \times Grazing\ efficiency \tag{6}$$

$$DMI_{actual} = \sum_{i=1}^{n}\left(min\left(forage_i,\ Preference_j \times Demand \times \frac{forage_{ij}}{forage_{iT}}\right)\right) \tag{7}$$

where $forage_i$ is the forage supply for species *i; Biomass*$_i$ is biomass for forage species *i; Grazing efficiency* is the fraction of DMI_{actual} divided by the total amount that disappears; $Preference_j$ refers to the fraction of diet that is preference class *j;* $forage_{ij}$ refers to forage supply for species *i* in preference class *j;* and $forage_{iT}$ refers to the total forage supply in preference class *j*; *n* is the number of forage species.

Since APEX v1605 does not update the actual DWG after calculating the actual DMI, we use DMI_{actual} instead of $DMI_{potential}$ to recalculate equations [2]–[5] to obtain the actual DWG in this study (see area shaded in orange, **Fig. 1**). To simulate automatic rota-

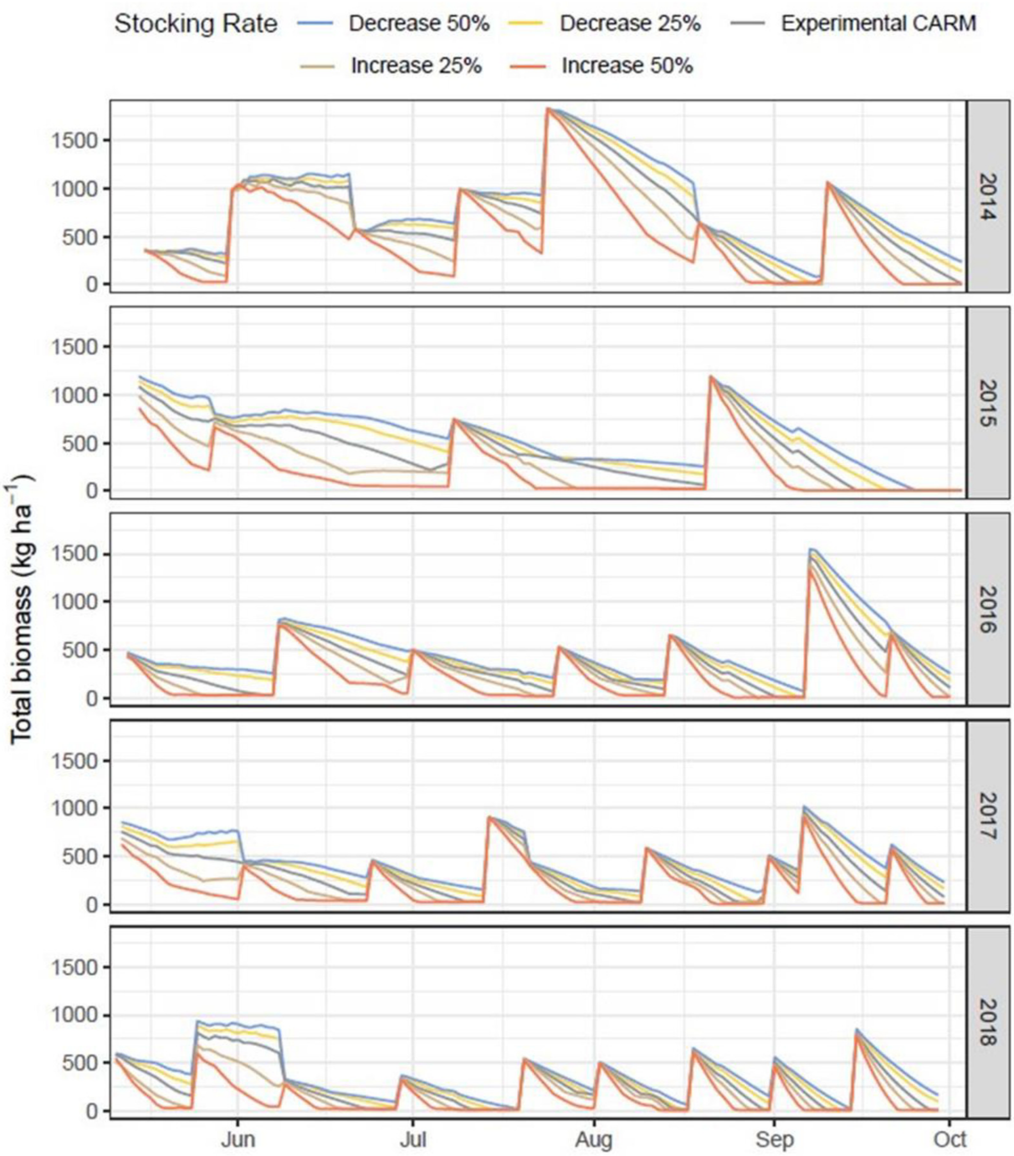

Figure 6. Simulated forage biomass for different stocking rates under collaborative adaptive rangeland management at the US Department of Agriculture–Agricultural Research Services Central Plains Experimental Range, Nunn, Colorado (2014–2018).

tional grazing, APEX v1605 was modified in the present study to rotate among pastures based on user-defined forage grazing limits or maximum grazing days. In previous APEX versions, pasture rotation sequence was typically based on the remaining pasture with the highest biomass. However, this may not be appropriate in rangeland conditions where the pasture with greatest biomass is not adjacent to the currently grazed pasture or where other operational logistics constrain management options. For instance, forage quality of the pasture with the highest biomass may not result in the best cattle performance because of the presence of low-quality forage such as subshrubs and shrubs. Using the forage biomass and antiquality factor for each grass species, we created a new total biomass *(Bm)* variable that considers forage antiquality instead of using only total biomass to determine the best pasture for cattle to rotate onto. *Bm* is calculated as:

$$Q_i = 1 - ANTQ_i \tag{8}$$

$$Bm = \sum_{i=1}^{n} \left(Bm_i \times \frac{Q_i}{Q_{max}} \right) \tag{9}$$

where Q_i is the quality index for forage species *i* (1 refers to preferred forage and 0 refers to undesirable forage); $ANTQ_i$ is antiquality for forage species *i* in the original model; Q_{max} is the maximum quality index among all kinds of forage; and Bm_i is the biomass for forage species *i*.

Statistical analysis

After calibrating the newly enhanced APEX forage component (Cheng et al. 2021), the animal component was calibrated manually by trial and error against measured cattle weight gains for each grazing season by optimizing DWG parameters under both grazing strategies. As recommended by Harmel et al. (2018), multiple performance measures, including the index of agreement (D), percentage bias (PBIAS), root mean squared deviation (RMSD), and relative RMSD (RRMSD), were used to make a comprehensive evaluation of simulated APEX weight gains versus measured values. Model performance was defined as “acceptable” when $D > 0.8$, $-15\% < PBIAS < 15\%$, and the $RRMSD$ was < 0.3 (Chen and Qi 2016). Considering

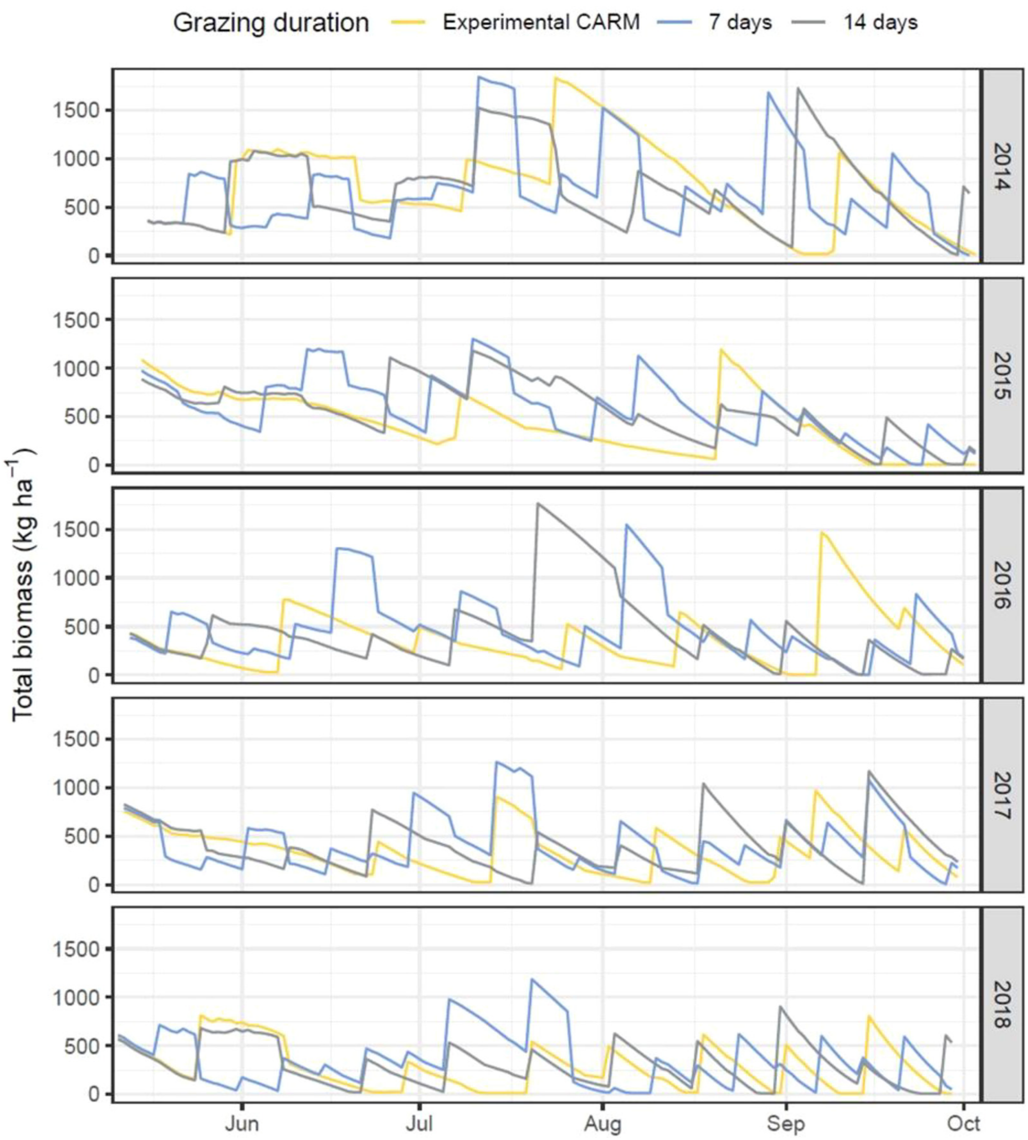

Figure 7. Simulated forage biomass for different rotation intervals (grazing durations) under collaborative adaptive rangeland management at the US Department of Agriculture–Agricultural Research Services Central Plains Experimental Range, Nunn, Colorado (2014–2018).

measurement uncertainties, the modified F-test was used to evaluate model performance as well (Sima et al. 2018).

We used Spearman's rank correlation to compare simulated DWG with the total biomass and with initial steer weight at the beginning of the grazing season, DMI, and intake of warm season perennial grass (WSPG), cool season perennial grass (CSPG), cool season annual grass (VUOC), forbs (FRB3), subshrubs (SSHB), and shrubs (ACTA). Mean separation for significant factors was conducted using the least significant difference test ($P < 0.05$). These comparisons were made using the "lsd.test" function provided in the "agricolae package" (v1.3-2) in R (v4.0.0).

APEX decision support capabilities for rangeland grazing management

Using APEX with enhanced forage production and animal response routines calibrated for soil/plant/weather conditions at the study site, we evaluated the effects of several management alternatives to showcase APEX's decision support capabilities for working ranches. Specifically, we evaluated the influence of stocking rate (±25% and ±50%), rotation interval (7- and 14-d), and rotation decision criteria on daily weight gain (DWG) and dry matter intake (DMI). While the importance of on-the-ground decisions based on site knowledge cannot be overstated, science-based decision support tools can help ranchers and land management agencies explore the complex interactions and impacts of forecasted weather, market trends, and input costs to make better short- and long-term management decisions.

Results and discussion

Cattle weight gains

The enhanced APEX routines adequately simulated DWG on the basis of multiple model performance measures (for CARM: $D = 0.72$, $PBIAS = 1.90\%$, $RMSD = 0.08$, $RRMSD = 0.09$; for TRM: $D = 0.53$, $PBIAS = 1.04\%$, $RMSD = 0.09$, and $RRMSD = 0.09$). The F-test showed no significant differences between measured and simulated DWG when the experimental uncertainties were accounted for (CARM: $F = 0.30$, $P = 1$; TRM: $F = 0.28$, $P = 1$). In comparison, Augustine et al. (2020) reported that annual average measured DWG was 11.7%–16.2% lower for CARM than for TRM (differences were significant each year at $P < 0.05$, as tested by LSD), and simulated DWG was 8.7%–22.3% lower for CARM than TRM for the 5-yr study. In addition, simulated mean annual DWG ranged from 0.98 to 1.12 kg hd^{-1} d^{-1} for TRM and from 0.76 to 1.00 kg hd^{-1} d^{-1} for CARM (**Fig. 2**). These simulated values were similar to experimental data for TRM (0.86–1.14 kg hd^{-1} d^{-1}) and for CARM (0.74–1.00 kg hd^{-1} d^{-1}).

Dry matter intake

Simulated DMI was highest (**Fig. 3a**) with 1 392 kg hd^{-1} yr^{-1} for CARM and 1 487 kg hd^{-1} yr^{-1} for TRM in 2014 and was lowest in 2018 with 1 108 kg hd^{-1} yr^{-1} for CARM and 1 341 kg hd^{-1} yr^{-1} for TRM. Averaged across years, simulated DMI was 11.0% lower for CARM than for TRM and annual differences ranged from 6.4% to 17.4%. In 2015, DMI was 16.3% lower for CARM, and the largest difference (17.4%) occurred in the drought yr of 2018. The region's cool, semiarid climate and many cool season grasses rarely allows plant recovery/regrowth in the same grazing season and subsequent multiple grazing events. This contrasts with regions with wet summers and numerous warm season grasses where cattle rotation can more easily be synchronized with pasture rest/recovery (plant regrowth) cycles (Woodward et al. 1995).

The two most dominant plant functional groups comprised 48.3% and 41.2% of simulated DMI for warm and cool season perennial grasses, respectively. DMI differed each year under TRM (see Fig. 3a), but the composition of annual forage intake was relatively similar among years (see Fig. 3b), except in 2016 when the TRM forage composition might have been affected by a higher fraction of cool season annual grass in aboveground biomass (Cheng et al. 2021). Our findings are consistent with the previous APEX study of Zilverberg et al. (2018) who found that simulated species selectivity by cattle was unaffected by stocking rate under continuous grazing, likely due to moderate stocking rates. In contrast, Raynor et al. (2021) found grazing selectivity for both moderate and heavy grazing intensity. The annual DMI composition varied greatly under CARM, which we attribute to the annual variability in the number of pastures grazed (four in 2015, seven in 2014 and 2016, 9 in 2017 and 2018). Years with higher rainfall and more frequent rotations (i.e., more pastures grazed) exposed cattle to a greater range of plant communities; thus DMI was more consistent.

Correlations among cattle weight gains, dry matter intake, and forage biomass

The effects of DMI and forage intake on steer weight gains were assessed using Spearman's rank correlations. Strong positive correlation existed between steer DWG and forage biomass ($R = 0.88$), DMI ($R = 0.94$), TDN ($R = 0.98$), warm season perennial grass intake ($R = 0.68$), and subshrub intake ($R = 0.88$) (**Fig. 4**). Positive correlations existed between DMI and intake of warm season perennial grasses ($R = 0.67$), cool season perennial grasses ($R = 0.65$), and subshrubs ($R = 0.85$). These results demonstrated that DWG was strongly influenced by DMI because APEX simulates both energy and crude protein weight gain based on DMI (equations 2–5). These results are consistent with those of Davis et al. (2018), who reported a positive correlation between DMI and average daily weight gain.

Figure 5 shows the changes in simulated average DMI, TDN intake, and DWG during the grazing season. When forage biomass is sufficient, DMI increased from 7.6 kg hd^{-1} d^{-1} to 11.5 kg hd^{-1} d^{-1} under TRM and to 11.0 kg hd^{-1} d^{-1} under CARM. Consistent with Zilverberg et al. (2018), our simulation results showed that DMI under CARM decreased at the end of each grazing season, especially in 2018 when simulated actual DMI decreased multiple times during the season (see Fig. 5). APEX calculates TDN intake varied by diet composition due to selective grazing and growth stage. The TDN expenditure for maintenance increases over time due to the increase in body weight, reducing TDN available for weight gain. Average DWG under TRM increased slightly from the beginning of the grazing season to mid-June and then decreased until the end of the grazing season when it approached zero. The change of DWG dynamics was consistent with TDN intake, which shows TDN intake has a direct influence on DWG for both grazing strategies. Under CARM, DMI decreased due to the insufficient forage supply during the grazing season, which inhibited the TDN intake and decreased the DWG. At the beginning of the grazing season (May–June), cattle demand, DMI, TDN, and DWG were similar for both CARM and TRM, but DMI decreased when forage became limited until steers were rotated into new pastures.

Table 1
Simulated effects of stocking rate on daily weight gain (DWG, kg hd^{-1} d^{-1}) and dry matter intake (DMI, kg hd^{-1} yr^{-1}) under collaborative adaptive rangeland management (CARM) and traditional rangeland management for steers grazed at the US Department of Agriculture–Agricultural Research Services Central Plains Experimental Range, Nunn, Colorado (2014–2018).

	Decrease 50%	Decrease 25%	CARM actual	Increase 25%	Increase 50%
	———DWG (kg hd^{-1} d^{-1})———				
2014	1.05	1.03	1.00	0.97	0.84
2015	0.96	0.94	0.91	0.77	0.58
2016	0.97	0.96	0.90	0.68	0.48
2017	1.01	0.98	0.91	0.78	0.58
2018	0.99	0.91	0.76	0.60	0.41
Average DWG	1.00	0.96	0.90	0.76	0.58
	———DWG per hectare (kg ha^{-1} d^{-1})———				
2014	0.84	1.24	1.61	1.95	2.03
2015	0.81	1.19	1.53	1.62	1.47
2016	0.85	1.27	1.58	1.50	1.27
2017	0.93	1.35	1.67	1.79	1.60
2018	1.04	1.44	1.60	1.58	1.29
Average DWG per ha	0.90	1.30	1.60	1.69	1.53
	———DMI (kg hd^{-1} yr^{-1})———				
2014	1 472	1 447	1 392	1 286	1 127
2015	1 331	1 275	1 213	1 003	774
2016	1 392	1 371	1 301	1 097	843
2017	1 400	1 376	1 297	1 128	876
2018	1 387	1 289	1 108	924	710
Average DMI	1 396	1 352	1 262	1 088	866

APEX decision-support capabilities for rangeland grazing management

Figure 6 and **Table 1** show the simulated effects of ±25% and ±50 changes in the actual/experimental CARM stocking rate in daily weight gain and dry matter intake. On average, decreasing the stocking rate by 50% and 25% increased DMI by 11% and 7%. Similarly, decreasing the stocking rate increased per head DWG by 11% and 8%, although the impact was especially evident in the dry yr of 2016 and 2018. Increasing the stocking rate by 25% and 50% decreased DMI by 14% and 31% and decreased DWG by 15% and 35%. These simulations revealed an important management consideration—variability in DWG increased as stocking rate increased. This finding is consistent with previous studies (Willms et al. 1986; Andales and Ahuja 2006; Reeves et al. 2013) and indicates that overstocking creates unpredictability in cattle performance, whereas lower stocking rates create more stable and predictable response. The simulations also allowed DWG to be examined on a per-area (ha) basis, in addition to a per-head basis. On a per-area (ha) basis, the optimal stocking rate varied from year to year (see Table 1) due to soil, rainfall, species, and animal energy requirement influences (Fales et al. 1995). The highest simulated DWG per ha was seen with a 50% stocking rate increase in 2014

Table 2
Simulated effects of rotation interval (grazing duration) and rotation decision criteria on daily weight gain (DWG, kg hd^{-1} d^{-1}) and dry matter intake (DMI, kg hd^{-1} yr^{-1}) for steers grazed at the US Department of Agriculture–Agricultural Research Service Central Plains Experimental Range, Nunn, Colorado (2014–2018).

	CARM actual	7-d rotation interval	14-d rotation interval	Autorotation to pasture with highest biomass
———————DWG (kg hd^{-1} d^{-1})———————				
2014	1.00	1.06	1.09	1.08
2015	0.91	0.98	0.98	0.97
2016	0.90	0.96	0.96	0.98
2017	0.91	1.03	1.00	1.05
2018	0.76	0.93	0.85	0.69
———————DMI (kg hd^{-1} yr^{-1})———————				
2014	1 392	1 444	1 471	1 452
2015	1 213	1 400	1 371	1 307
2016	1 301	1 356	1 306	1 194
2017	1 297	1 372	1 367	1 301
2018	1 108	1 323	1 270	1 026

CARM indicates collaborative adaptive rangeland management.

and with a 25% increase in 2015 and 2017, which indicates that the stocking rate might be able to be increased in "normal" precipitation years but not in dry yr (e.g., 2016 and 2018).

Table 2 and **Figure 7** illustrate the potential impacts of implementing rigid 7-d or 14-d rotation intervals instead of the flexible, management-intensive CARM rotation intervals. Using the flexible CARM rotation intervals, which ranged from approximately 16 to 35 d, simulated DWG ranged from 0.76 to 1.00 kg hd^{-1} d^{-1}. In contrast, the highest simulated DWG and DMI occurred for the 7-d rotation interval, followed by the 14-d rotation interval in most years due to increased total biomass in the beginning and middle of the grazing season (see Fig. 7). These results do support the general findings by Wang et al. (2016) that decreasing grazing durations increased total grass consumption in arid and semiarid conditions and by Teague et al. (2015) which found shorter grazing durations could improve both rangeland ecological condition and profitability. The data do not indicate that rigid rotation intervals are recommend for ranches in the northern Great Plains. Rather, these simulations indicate that the 16- to 35-d rotation intervals might need to be reexamined. Ideally, active producer involvement in adaptive management guided by model decision-support and alternative scenario analysis, which can simultaneously consider multiple drivers such as weather, soil, and vegetation variability, would produce optimal cattle performance.

The actual/experimental CARM rotation criteria were also compared with a model-driven, auto-rotation scenario. Under the predetermined CARM rotation criteria with cattle movement to the next pasture in a predetermined sequence, simulated DWG ranged from 0.76 to 1.00 kg hd^{-1} d^{-1} (see Table 2). In comparison, simulated DWG ranged from 0.69 to 1.08 kg hd^{-1} d^{-1} under the APEX autorotation scenario with a minimum simulated forage biomass threshold and movement to the pasture with the highest simulated biomass. Thus, this autorotation scenario increased simulated DWG by 0.06–0.14 kg hd^{-1} d^{-1} in 4 yr, likely by providing a more stable forage supply; however, autorotation reduced DWG by 0.07 kg hd^{-1} d^{-1} in 2018, a drought yr. Although the autorotation scenario often increased annual average DWG, it did not consistently increase DMI. In 2016, the DMI was substantially less because of greater forage supply before September. In 2018, both DWG and DMI were lower under autorotation than those under the actual/experimental CARM (13–21 d/pasture) because autorotation with longer grazing durations (16–35 d per pasture) led to forage quality decline without being grazed early in the season, especially since late-season rainfall was low (Cheng et al. 2021). These results suggest the collaborative decision making under CARM might be improved by integrating the rotation criterion (forage biomass threshold) and movement to the next pasture remaining in the sequence with the highest biomass.

Conclusion

In this study, we demonstrated that enhanced cattle performance routines in the APEX model were able to simulate relative differences in daily weight gains and dry matter intake under traditional grazing management and a novel adaptive management grazing system. Specifically, the enhanced routines improved APEX's ability to simulate cattle performance through more accurate simulation of daily weight gain and dry matter intake under both TRM and CARM grazing. Consistent with measured experimental data, simulated cattle weight gain was lower under CARM than under TRM, with RMSD values of 0.08–0.09 kg/d and PBIAS values of 1.04%–0.90%. The simulated lower daily weight gain for CARM was mainly due to the simulated lower DMI, while CARM showed higher variability in diet composition in DMI than TRM.

The capabilities of APEX to support ranch-level decision making were demonstrated by the analysis of several important management alternatives (i.e., stocking rate, rotation interval, and rotation decision criteria). Several important results emerged from these analyses:

1) Variability in daily weight gain increased as stocking rate increased. This suggests that overstocking creates unpredictability in cattle performance, whereas lower stocking rates create more stable and predictable response.
2) The power of active rancher involvement in adaptive management guided by model decision-support and alternative scenario analysis is more likely to obtain cattle performance goals, as it integrates local producer knowledge with scientific integration of factors, such as weather, soil, and vegetation that vary temporally and spatially.
3) Adaptive management under CARM might be improved by integrating simulation results, such as APEX autorotation criteria based on a minimum forage biomass threshold and movement to the pasture with the highest remaining biomass.

This improved capability along with additional enhancements recently presented in Cheng et al. (2021) are critical advances because APEX is increasingly used for grazing decision-support and adaptive rangeland management (Wang et al. 2011). Considering the high spatial and temporal variabilities of soil type, topography, plant populations, and weather conditions in US rangelands, further enhancements in APEX-specific soil and plant databases are needed to extend its applicability across the nation.

Declaration of Competing Interest

None.

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