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Evaluating the APEX model for alternative cow-calf grazing management strategies in Central Texas

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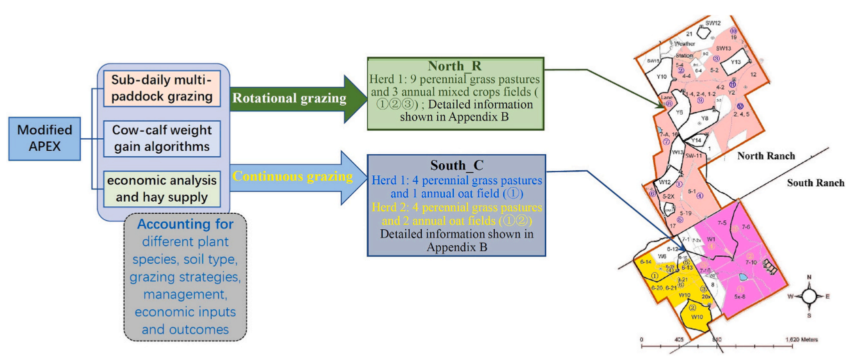
HIGHLIGHTS

- Better assessing grazing strategies needs accounting for spatial variability of vegetation and management at ranch scale.
- APEX was modified to simulate alternative multi-paddock grazing systems.
- Energy-based weight gain method showed larger effect of grazing on plant growth than TDN-based method.
- TDN-based weight gain method had a more pronounced response to forage supply than energy-based method.
- The APEX model enhancements extended its ability to assess alternative grazing strategies at the ranch scale.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Simulation tools are increasingly used to inform grazing management decisions by assessing livestock performance, as well as environmental and economic impacts. Ability to represent the grazing of multiple pastures (i.e., paddocks) that differ in soil, hydrology, vegetation, and management is critical for reliable grazing management decision support.

OBJECTIVE: The main objectives of this study were to: 1) modify APEX (Agricultural Policy/Environmental eXtender) for sub-daily grazing, cow-calf weight gain, and supplemental hay, and 2) evaluate the APEX modifications in terms of simulating biomass, calf weight gain, economic impacts of alternative cow-calf grazing management strategies.

METHODS: APEX was modified to enhance its ability to simulate alternative grazing management strategies by including sub-daily grazing among multiple paddocks, supplemental hay estimation, and optional simulation of cow-calf weight gain based either on energy or total digestible nutrients (TDN). Simulation results were

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evaluated against a 5-year experimental data set from Central Texas comparing multi-paddock rotational grazing and conventional continuous grazing.

RESULTS AND CONCLUSION: The modified APEX model adequately simulated the responses of vegetation biomass (coefficient of determination, $R^2 = 0.60–0.70$), hay consumption ($R^2 = 0.94–0.95$), calf weaning weight ($R^2 = 0.52–0.65$), costs ($R^2 = 0.98$), and profits ($R^2 = 0.89$) to the two grazing treatments across years. Simulations with the energy-based weight gain algorithm showed more pronounced effects on above-ground biomass, whereas the TDN-based algorithm had a more pronounced weight gain response to forage intake and hay quality. No significant differences ($p > 0.05$) in biomass and calf weaning weight were observed between treatments across the years for measured data and for energy-based APEX simulation; however, the TDN-based algorithm simulated lower calf weaning weight in multi-paddock rotational grazing than in continuous grazing. Measured and simulated data also showed similar profits between the two grazing treatments, but total cost and gross return per ha were greater for continuous grazing.

SIGNIFICANCE: The model enhancements for sub-daily grazing, cow-calf weight gain, and supplemental hay improved the potential utility of APEX for assessing environmental and economic impacts of alternative grazing strategies at ranch scale.

1. Introduction

The economic and ecological sustainability of livestock systems has received increasing attention in recent years (Gillespie et al., 2008; White and Capper, 2013; White et al., 2014; Rouquette, 2017). Managing grazing sequence and stocking rate to match animal demand with forage production under various weather conditions can increase both forage species and animal performance, while reducing the risk of soil degradation due to over-grazing, which is essential to sustainable grazing systems (Rouquette and Aiken, 2020; Wang et al., 2020). Although, continuous and rotational grazing strategies have been studied extensively under different soil and climate conditions for decades (Briske et al., 2008; di Virgilio et al., 2019), differing conclusions on plant growth, cattle weight, and economic return (Teague et al., 2011, 2013; Crawford et al., 2019; Venter et al., 2019; Augustine et al., 2020; Harmel et al., 2021) have been reported. These varying results likely resulted from confounding factors, such as grassland type and vegetation management (Holechek et al., 1999), stocking rate (Whitson et al., 1982; Briske et al., 2008, 2011), and hydroclimatic conditions (Heitschmidt et al., 1990; Harmel et al., 2021). For example, di Virgilio et al. (2019) identified grazing intensity, livestock type, grazing season duration, precipitation pattern as key factors to reduce negative impacts such as land degradation and improve sustainability. Additionally, forage type, fertilizer input, and hay supply affect biological and economic responses to these factors (Silveira et al., 2014; Rouquette, 2017). Therefore, synthesizing these multiple factors is needed to identify appropriate grazing management (e.g., stocking rate, grazing sequence) for different soil and climate conditions (Grice and Hodgkinson, 2002; Rouquette, 2015, 2017).

By synthesizing multiple factors into simulations, grazing system models can be useful decision support tools in terms of predicting economic and environmental outcomes (Snow et al., 2014; Ma et al., 2019; Wang et al., 2016, 2018; Mosnier et al., 2009; White et al., 2014). As simulation capacity and scientific understanding advances, improved simulation is needed for vegetation response to competition, nutrients, and environment factors (Wang et al., 2016, 2018; White et al., 2014) and for impacts of forage supply (quantity and quality), grazing duration within paddocks, and forage management (planting, tillage, and fertilizer) (Teague et al., 2015; Wang et al., 2016). Several models have been shown to adequately simulate animal production (e.g., LINCFARM, Cacho et al., 1995; IFSM, Rotz et al., 2005; SPUR, Teague and Foy, 2002) or have detailed soil water and nutrient dynamics and forage growth processes (e.g., APSIM, Holzworth et al., 2014; ALMANAC, Kiniry et al., 2007; GPFARM, Andales et al., 2005); however, these models do not account for spatial variability in soil characteristics and management alternatives among various paddocks and cannot estimate impacts on vegetation, livestock performance, hydrology, and water quality at watershed scale. Thus, improved simulation capacity is needed for grazing system assessment and decision-support for land managers (Teague et al., 2013; Snow et al., 2014).

The Agricultural Policy/Environmental eXtender (APEX) model, which was developed from EPIC (Environmental Policy Integrated Climate, Williams and Izaurralde, 2006), has been applied to numerous agricultural system and environmental analyses at the watershed scale (Gassman et al., 2010). APEX was originally designed for annual crop simulation (Williams and Izaurralde, 2006), but its plant growth module was recently enhanced for simulating rangeland vegetation growth (Zilverberg et al., 2017). The APEX grazing module was also improved for selective grazing of plant species and dietary-specific excretion of urine and feces under different stocking rates (Zilverberg et al., 2018). The model was also recently evaluated for simulating rotational grazing effects (grazing one pasture for a certain period and then grazing another one) on forage production between continuous and rotational grazing (Cheng et al., 2021). These APEX enhancements, however, did not consider multiple paddock grazing management and spatial differences in forage management (Wang et al., 2016).

Additionally, the traditional APEX assumption that based daily calf weight gain on cow weight is overly simplistic. In contrast, weight gain is estimated in other models based on energy (e.g., ISFM, Rotz et al., 2005; LINCFARM, Cacho et al., 1995) or total digestible nutrients (e.g., SPUR, Teague and Foy, 2002; GPFARM, Andales et al., 2005). Both energy-based and total digestible nutrients (TDN)-based algorithms adequately simulate weight gain under various soil and climate conditions (Wang et al., 2016; Mosnier et al., 2009; White et al., 2014; Fang et al., 2014), but the energy-based method has been more widely applied due to better description of feedstuff composition in animal dry matter intake (NAS, 2016).

This study evaluated APEX enhancements for multiple paddock grazing accounting for spatial variability and management impacts at the ranch scale. Specifically, the main objectives were to: 1) present APEX modifications for sub-daily grazing, cow-calf weight gain, and supplemental hay, and 2) evaluate the APEX modifications in terms of simulating biomass, calf weight gain, and economic impacts of alternative cow-calf grazing management strategies.

2. Materials and methods

2.1. APEX model enhancements

In this study, APEX was modified to include sub-daily grazing, cow-calf weight gain, and hay supplementation (Fig. 1). The traditional APEX daily simulation allowed grazing of only one subarea each day (https://epicapex.tamu.edu/apex/), whereas the modification facilitates multiple paddock grazing and rotation of herds in one day. For the sub-daily simulation (Fig. 1), a certain grazing time for each grazed paddock was determined based on paddock area (e.g., longer grazing times for bigger paddocks). The fraction of grazing time in each paddock to total daily grazing time (assuming 12 h a day) was used to determine animal demand in the paddock (e.g., longer grazing time means higher daily animal demand; Fig. 1). The actual forage intake in each paddock is based on animal demand and forage supply in the paddock. The total daily forage intake is the sum of actual forage intake in each grazed paddock. Daily weight gain is based on total forage intake from all grazed paddocks in one day, and vegetation biomass in each paddock is based on forage intake from that paddock (Fig. 1). Thus, APEX can now simulate rotational grazing within multiple paddocks each day and in theory better capture the spatial variation in soils, vegetation, and management (Table B2) among paddocks.

As shown in Fig. 1, two cow-calf weight gain algorithms were also added to APEX: an energy-based algorithm "APEX_NRBC" (NAS, 2016) and a TDN-based algorithm "APEX_GPFARM" (Andales et al., 2005). Both algorithms have the same forage growth module and selective grazing method (Zilverberg et al., 2017, 2018), but they have different calculations of animal demand, maintenance requirement and calf weight gain (Eqs. (1)–(17), Appendix A).

APEX uses a crop budget and accounting subsystem (https://epicapex.tamu.edu/manuals-and-publications) with a Micro Budget Management System budget generator program (McGrann et al., 1986). APEX previously allowed hay supplementation, but the economic component did not consider duration of hay feeding, hay availability, or hay cost. Therefore, the grazing submodule was modified to estimate daily hay supplementation (based on the difference between animal demand and forage supply), which can be constrained by user-defined duration of hay feeding and by the available hay supply and can account for the hay cost (Fig. 1).

2.2. Model input and evaluation data

The case study of Harmel et al. (2021) from 2012 to 2016 in Central Texas provided a near-ideal data set with which to evaluate the APEX enhancements for cow-calf operations. That study compared planned rest-rotation grazing to conventional continuous grazing at the USDA-ARS Riesel Watersheds (Fig. 2). The planned rest-rotation grazing system (North_R) had a single-herd with three cultivated grazed fields planted with both warm- and cool-season multi-species forage mixes and nine perennial pasture paddocks, some of which were over-seeded multi-species forage mixes. The conventional continuous grazing system (South_C) used two herds on three cultivated grazed fields and eight perennial pasture paddocks (Fig. 2). During grazing season, the herds grazed several pastures in one day where gates between pastures prevent free movement of cattle between paddocks. In general, the oat fields are used to supply early spring forage to cows for part of the day. Cows are most likely to obtain a majority of their intake from oat fields. In the summer when grass production increases, cows increasingly grazed the grassland paddocks. In the winter, hay is supplied to maintain cow wellbeing. Detailed information on grazing events appears in Appendix B (Table B1). In North_R, organic fertilizer (poultry litter) was applied periodically to the three cultivated grazed fields. In South_C, chemical fertilizer was applied to pasture paddocks in most years and the cultivated grazed fields annually. Multiple tillage operations were used on South_C, while less tillage was used on the North_R (Table B2). Hay was generally fed from December to April in both systems, with higher annual amounts (100–130 Mg) supplied to the South_C than the North_R (40–65 Mg). Detailed management information is shown in Appendix B (Table B2). The daily average stocking density across seasons was higher in North_R (3.09 ± 2.82 cow-calf/ha) than in South_C (0.64 ± 0.12 cow-calf/ha) because the herd was confined to individual paddocks (Fig. 3). The high stocking density in North_R generally occurred before winter (September–November) and spring (March–May). The average annual stocking rates are lower in North_R (0.30 cow-calf/ha) than in South_C (0.43 cow-calf/ha). The costs associated with each management activity and the revenue from calf sales were used to evaluate APEX economical simulation results.

From 2012 to 2016, vegetation productivity was evaluated by

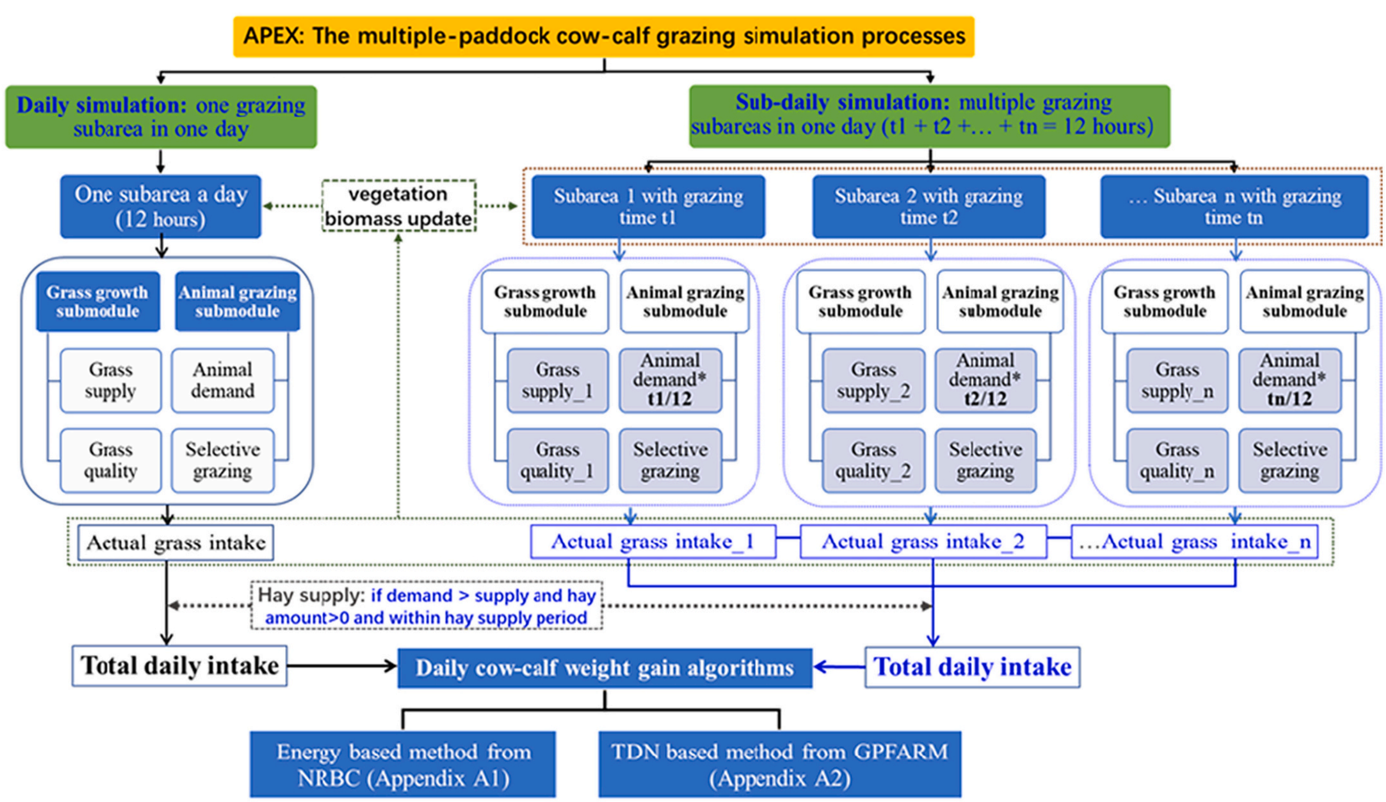

Fig. 1. APEX modifications for sub-daily grazing, cow-calf weight gain, and hay supplementation to improve simulation of alternative grazing management strategies.

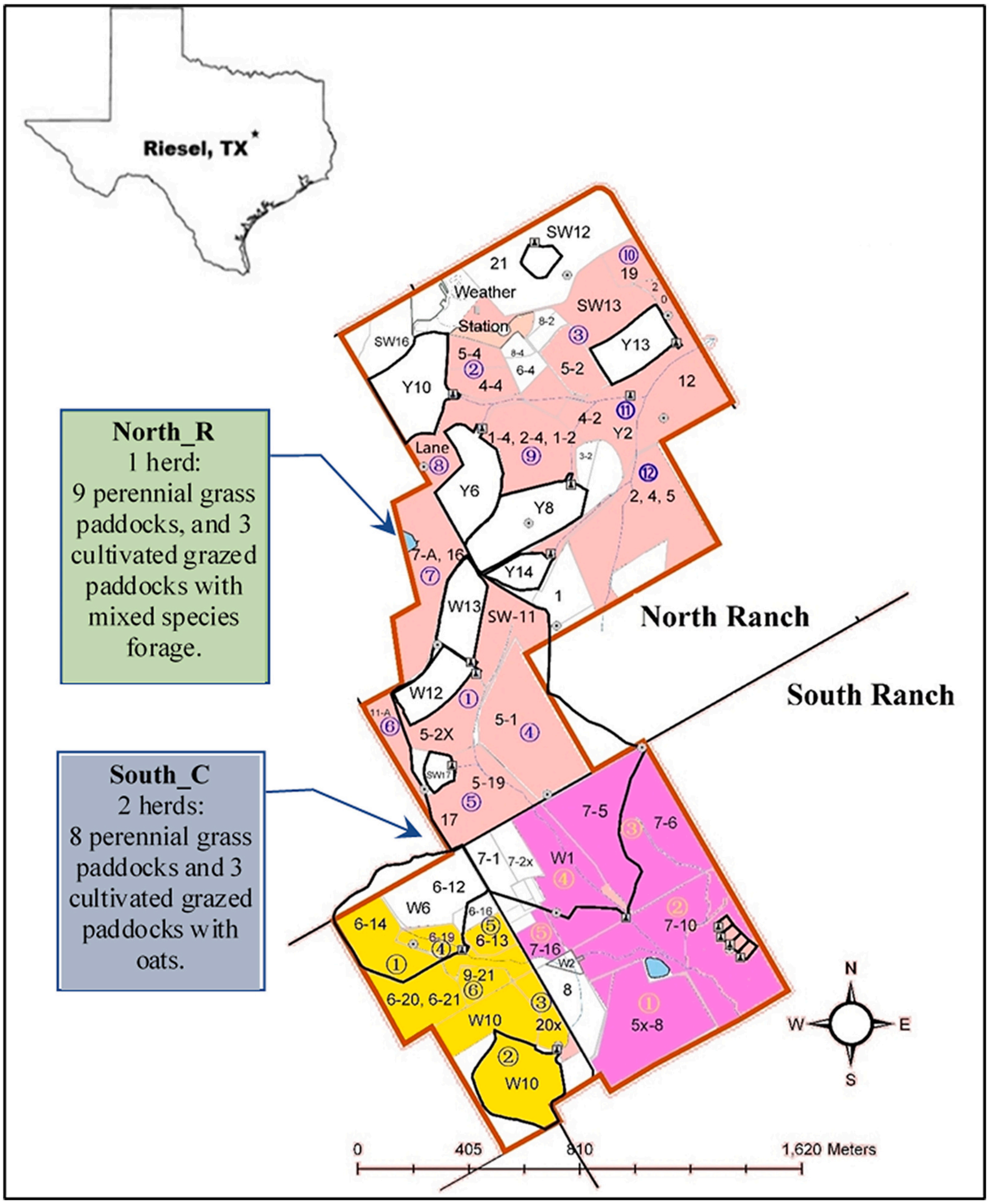

Fig. 2. The USDA-ARS Riesel Watersheds experimental site. On the North Ranch, planned rest-rotation grazing was conducted on 12 paddocks (North_R). On the South Ranch, conventional continuous grazing was conducted on 11 paddocks (South_C). Detailed management information for each treatment is presented in Appendix B.

establishing grazing exclosures in selected paddocks for each grazing system (Fig. 2). Plots were clipped in the summer and late fall each year. The vegetation biomass from grazed and un-grazed plots was used to evaluate grazing effects on forage growth as simulated by APEX. Grasslands onsite are predominately native rangeland or improved pasture with bermuda grass (*Cynodon dactylon*). In terms of total production at the site, bermuda grass accounts for more than 60%, and bluestem (*Schizachyrium scoparium*) accounts for 10–30%. Other warm-season grasses are buffalo grass (*Bouteloua dactyloides*), johnson grass (*Sorghum halepense*), and white tridens (*Tridens albescens*). The cool-season species, such as brome (*Bromus japonicus*) and winter grass, are much less productive (less than 5%) than warm-season species. To supply cool-season forage, the cultivated paddocks in North_R were planted to summer and winter multiple-species cover crops, while the cultivated paddocks in South_C were sewn to monoculture oats (Table B2). Cow weight was not measured in the field study, thus APEX simulations assumed cow weights to be average maturity weight as was done by Wang et al. (2016). Calf weaning weight was recorded for each calf, and these data were used to evaluate cow-calf weight gain algorithms.

Daily weather data, including maximum and minimum air temperature, solar radiation, and rainfall from the legacy database for the Riesel Watersheds (www.ars.usda.gov/spa/hydro-data; Harmel et al., 2014), were used as APEX inputs. The Riesel Watersheds receive 884 mm of average annual precipitation, with highest amounts occurring in May and October (Harmel et al., 2003). For the study years, annual precipitation was 825, 1064, 788, 1511 and 1166 mm and varied considerably (Fig. 4).

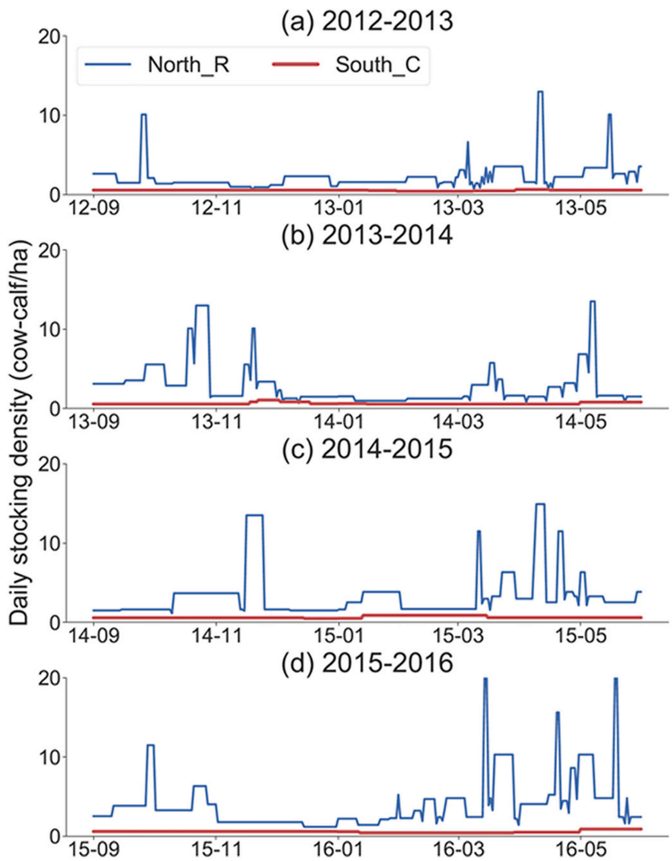

Fig. 3. Daily stocking density (cow-calf/ha) for the two cow-calf grazing systems (North_R and South_C).

2.3. APEX calibration and validation

APEX has been shown to accurately simulate soil water content, runoff, and water quality in response to tillage and fertilizer management at the Riesel Watersheds (e.g., Wang et al., 2006; Green et al., 2007; Doro et al., 2017). The watershed characteristics and soil parameters from those studies were used in this study without modification. Each paddock was simulated as a subunit with homogeneous land use and a dominant soil (Houston Black clay; Fig. 2). The soil physical and chemical properties for Houston Black clay were obtained from USDA-NRCS Soil Survey Geographic Database (https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/survey/).

Vegetation and management (Table B2) data were input and results simulated at the paddock-level. For simplicity, the dominant grass species of bermuda and bluestem were chosen. Other grasses, which represent a small portion of the biomass, were simulated as warm-season gramma grass (*Bouteloua gracilis*) as was done by Zilverberg et al. (2017) and cool-season brome grass (*Bromus texensis*). The default crop parameters for annual warm- and cool-season forage crops were used without calibration because default values produced accurate crop yield predictions in previous APEX/EPIC simulations at the site (Wang et al., 2006).

The APEX parameters for bermudagrass, bluestem, gramma, and brome grass were calibrated by trial-and-error starting with default parameter values from ALMANAC (Kiniry et al., 2007; Kiniry, 2014) (Table 1). Simulated vegetation biomass was compared with measured above-ground biomass from grazing exclosures (ungrazed) for calibration, while above-ground biomass data from grazed plots were used for model validation. The data used for calibration and validation is not independent, but this calibration procedure helped identify the grazing effects on simulated biomass and calf weight gain with the different weigh gain algorithms. Because biomass data for individual species were not available, we set parameter values close to default values used for simulating grassland in Texas (Kiniry et al., 2007; Kiniry, 2014). Due to high vegetation biomass at the site, the WA (Biomass-Energy ratio) and DMLA (maximum potential leaf area index) parameters (Table 1) were increased for the two dominant grass species of bermuda and bluestem to match measured biomass data using parameter ranges reported by Kiniry et al. (2007); Kiniry (2014). The plant parameters for gramma and brome received less attention in calibration since their production accounted only for a small portion of the total. Other parameters, such as the N fraction in plant and the maximum/minimum total digestible nutrients (TDN) related to energy intake and calf weigh gain (Table 1), were obtained based on previous studies conducted in Texas (Ball et al., 2007; Hill, 2017). The two cow-calf weight gain algorithms were primarily compared for their effects on forage demand, supply, intake and calf weight gain for the two grazing treatments.

2.4. Statistical analysis

For both measured and simulated data, a one-way analysis of variance with fixed effect linear model was used to test the treatment effects (North_R and South_C) across the four seasons because there was no treatment replicate in the system-level case study (Sima et al., 2020). The average values across seasons were compared between treatments using the least significant differences (LSD) at the 5% confidence level. For model evaluation, mean deviation (MD), root mean squared error (RMSE), relative RMSE (RRMSE), coefficient of determination (R^2), and Willmott's D Index of Agreement (IA) were used to assess the predictive accuracy of model simulations (Moriasi et al., 2015).

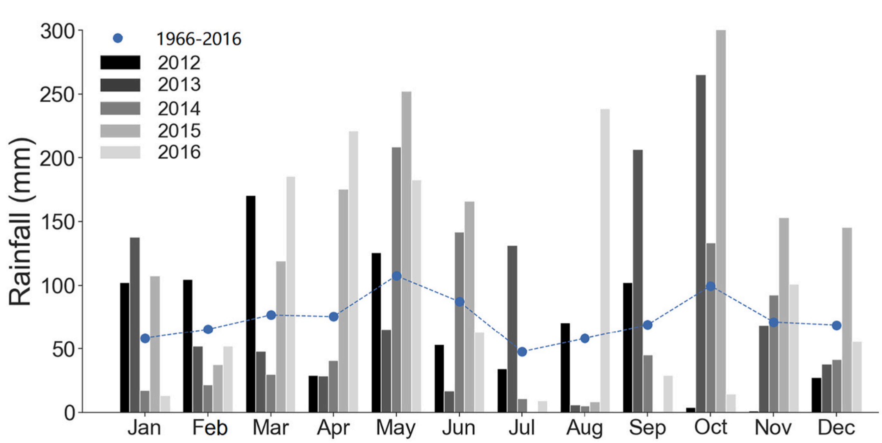

Fig. 4. The monthly rainfall distribution from 2012 to 2016 and long-term mean monthly rainfall from 1966 to 2016 at the Riesel Watersheds.

Table 1
Calibrated (and default) values for selected plant parameters in APEX.

Parameter	Definition	Bermuda	Bluestem	Grama	Brome
WA	Biomass-Energy Ratio (CO_2 = 330 ppm), kg/ha/MJ	41 (35)	29.2 (25)	24.2 (20)	34.8 (33)
TOP	Optimal temperature for plant growth, °C	27.5 (27.5)	25 (25)	25 (25)	18 (18)
TBS	Minimum temperature for plant growth, °C	15 (12)	12.3 (12)	11.29 (12)	1 (0)
DMLA	Maximum potential leaf area index, dimensionless	4.67 (4)	2.95 (2)	2 (2)	2 (2)
DLAI	Fraction of growing season when leaf area declines	0.99 (0.99)	0.35 (0.35)	0.33 (0.35)	0.84 (0.85)
DLAP1	First point on optimal leaf area development curve	15.15 (15.05)	5.15 (5.1)	5.01 (5.05)	15.41 (15.01)
DLAP2	Second point on optimal leaf area development curve	50.85 (50.95)	25.55 (25.70)	30.55 (30.70)	50.85 (50.95)
RLAD	Leaf area index decline rate parameter	1 (1)	0.5 (0.5)	0.1 (0.1)	1 (2)
HMX	Maximum crop height, m	1 (1)	1 (1)	0.3 (0.3)	0.8 (0.8)
RDMX	Maximum root depth, m	2 (2)	2 (2)	1.2 (1.4)	1 (2)
WAVP	Parameter relating vapor pressure deficit to WA	7 (7)	8 (8)	8 (8)	8 (8)
VPTH	Threshold of vapor pressure deficit to leaf conductance, kPa	0.5 (0.5)	0.5 (0.5)	0.5 (0.5)	0.5 (0.5)
VPD2	vapor pressure deficit affecting leaf conductance, kPa	4.75 (4.75)	4.75 (4.75)	4.75 (4.75)	4.75 (4.75)
RWPC1	Fraction of root weight at emergence	0.8 (0.9)	0.79 (0.8)	0.82 (0.8)	0.8 (0.7)
RWPC2	Fraction of root weight at maturity	0.4 (0.3)	0.3 (0.2)	0.41 (0.4)	0.4 (0.4)
PPLP1	Plant Population for Crops Grass-1st Point on curve	22.3 (20.2)	20.3 (22.5)	22.3 (22.5)	10.1 (10.2)
PPLP2	Plant Population for Crops/ Grass -2nd Point on curve	40.85 (50.9)	50.98 (50.95)	40.9 (40.71)	50.98 (50.9)
BN1	N fraction in plant at emergence	0.03 (0.022)	0.03 (0.03)	0.03 (0.03)	0.027 (0.026)
BN2	N fraction in plant at mid-season	0.015 (0.015)	0.011 (0.0106)	0.013 (0.013)	0.014 (0.014)
BN3	N fraction in plant at maturity	0.008 (0.011)	0.008 (0.0078)	0.009 (0.0086)	0.011 (0.0107)
TDNX	Maximum total digestible nutrients when immature, %	75 (75)	75 (75)	75 (75)	75 (75)
TDNN	Minimum total digestible nutrients when mature, %	50 (50)	53 (50)	50 (50)	55 (50)

3. Result and discussion

3.1. Above-ground biomass

Overall, APEX was able to simulate measured annual above-ground biomass reasonably well in grassland paddocks *in ungrazed conditions* (Fig. 5, Table 2). RMSE values ranged from 2521 to 2677 kg/ha, which in relative terms were 0.33–0.38 based on the RRMSE, R^2 from 0.67–0.70, and IA from 0.90–0.92 (note that the weight gain algorithm does not impact ungrazed biomass simulation; therefore, biomass predictions are the same for APEX_NRBC and APEX-GPFARM). In grazing exclosures on grassland paddocks, measured and simulated annual above-ground vegetation biomass (mean ± standard deviation) averaged 7647 ± 3977 kg/ha and 6939 ± 3363 kg/ha, respectively, for North_R and 7020 ± 4391 kg/ha and 7632 ± 3988 kg/ha, respectively,

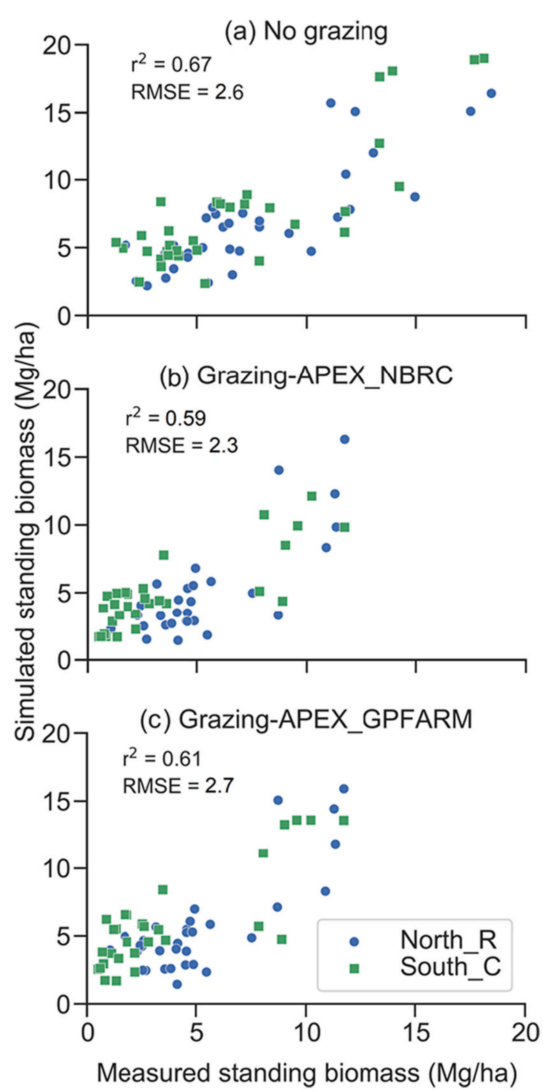

Fig. 5. Measured and simulated above-ground biomass from grassland paddocks: (a) without grazing, and (b-c) with grazing.

Table 2
Measured and simulated above-ground biomass (kg/ha), hay consumption (kg/yr), and calf weaning weight (kg). Simulated results are presented for the energy-based APEX_NRBC algorithm and the TDN-based APEX_GPFARM algorithm.

			Measured	APEX_NRBC					APEX_GPFARM				
	Treatment		Mean	Mean	RMSE	RRMSE	R^2	IA	Mean	RMSE	RRMSE	R^2	IA
Above-ground biomass (kg/ha)	North_R	Ungrazed	7647a*	6939a	2521	0.33	0.67	0.90	6939a	2521	0.33	0.67	0.90
	South_C	Ungrazed	7020a	7632a	2677	0.38	0.70	0.92	7632a	2677	0.38	0.70	0.92
	North_R	Grazed	5107a	5023a	2248	0.44	0.60	0.87	5574a	2191	0.43	0.66	0.89
	South_C	Grazed	3600a	5184a	2474	0.69	0.69	0.88	5949a	3182	0.88	0.69	0.84
Hay intake (kg/yr)**	North_R	Grazed	49237b	51774b	5411	0.10	0.94	1.00	51445b	5233	0.10	0.95	0.99
	South_C	Grazed	114985a	115655a	7748	0.06			104605a	8561	0.07		
Calf weaning weight (kg)**	North_R	Grazed	296a	299a	18	0.06	0.65	0.85	289b	19	0.07	0.52	0.83
	South_C	Grazed	305a	321a	22	0.07			321a	24	0.08		

* Means within treatments (North_R and South_C) followed by the different letter in each column are significantly different at $p < 0.05$ (LSD-test).
** The R^2 and IA values were calculated for pooled (ungrazed and grazed condition) data.

on South_C. Although, APEX simulated annual above-ground biomass quite well in ungrazed grassland paddocks, it tended on average to underpredict biomass for North_R (−708 kg/ha) but to overpredict biomass for South_C (+612 kg/ha), which affects grazing system comparison. The most notable difference in measured and simulation values occurred in 2015 due to high water stresses in response to low rainfall from July to September when biomass was under predicted for North_R (−18%) and South_C (−16%), suggesting an over sensitivity of APEX to plant water stress. Thus, the plant growth submodule, adapted from the cultivated crop growth module in APEX (Zilverberg et al., 2017), may need to be improved by increasing grass resilience to water stress (e.g., Fariaszewska et al., 2020). No significant difference ($p > 0.05$) between treatments was found in measured or simulated above-ground biomass across these years (Table 2), indicating similar above-ground biomass between the two treatments without grazing.

APEX simulation of above-ground biomass in grassland paddocks *under grazed conditions*, more appropriately termed standing biomass, was not as accurate (Fig. 5, Table 2) with RMSE ranging from 2191 to 3182 kg/ha, RRMSE from 0.43–0.88, R^2 from 0.60–0.70, and IA from 0.87–0.89 at the time measured data were collected. Measured standing biomass averaged 5107 ± 2753 kg/ha on North_R with grazing, and simulated values were 5023 ± 3085 kg/ha for APEX_NRBC and 5574 ± 3230 for APEX_GPFARM (Table 2), which is an average overprediction of 191 kg/ha. Measured standing biomass on South_C with grazing was 3600 ± 3232 kg/ha, and simulated values were 5184 ± 2472 kg/ha for APEX_NRBC and 5949 ± 3165 kg/ha for APEX_GPFARM, which is an overprediction of 1967 kg/ha. This overprediction for South_C was largely due to very low amounts of standing biomass (~500 kg/ha) measured after grazing in the fall of 2015. One factor for the larger prediction error in South_C was the difficulty in estimating grazing time in each paddock for continuous grazing when cattle come and go from paddock to paddock. The same influence likely contributed to large simulation errors for spatially distributed grassland productivity in the UK (Qi et al., 2017; Topp and Doyle, 2004). In contrast, grazing time in each paddock in the planned rest-rotation grazing system was carefully controlled and recorded making this an easy and accurate model input. APEX accounts for the physical trampling of vegetation by grazing animals (Zilverberg et al., 2018), where APEX assumes a certain percentage (harvest index) of forage is trampled and not available to animals. In spite of the simulated high mean values, simulated standing biomass values were within the range of measured data on both treatments (467–4757 kg/ha for North_R; 259–5593 kg/ha for South_C). The relatively high R^2 values (0.60–0.70) and IA values (0.87–0.89) also provided confidence in the simulated biomass response to grazing (Table 2), although improvement is needed in simulating the interactions between grazing and vegetation regrowth (Zilverberg et al., 2017, 2018).

The measured forage utilization averaged 36 ± 21% for North_R with simulated values of 28 ± 10% for APEX_NRBC and 21 ± 9% for APEX_GPFARM. For South_C, the measured forage utilization was 53 ± 23%, and simulated values were 36 ± 13% for APEX_NRBC and 27 ± 14% for APEX_GPFARM. The underprediction of forage utilization for both grazing systems can be attributed to an underestimation of animal demand especially for APEX_GPFARM (see section 3.2) and an overestimation of forage quality as related to forage utilization (section 3.3). Both measured and simulated results indicate lower grazing pressure and the potential for higher stocking rates for North_R. Potential increases in forage production from multi-paddock rotation grazing versus continuous grazing have been reported in some studies (e.g., Teague et al., 2011, 2013; Harmel et al., 2021) but not in others (e.g., Briske et al., 2008; Venter et al., 2019); thus further investigation is needed on the drivers in ecosystem services (e.g., vegetation, economic, and wildlife) between different grazing strategies (Augustine et al., 2020; Harmel et al., 2021).

3.2. Cow-calf forage demand

The simulated animal forage demand by both weight gain algorithms generally increased from about 10 kg/day at calf birth in September–October to 20 kg/day in January–February (Fig. 6). From March until weaning in May–June, APEX_GPFARM predicted lower forage demand mainly due to differences in estimated cow and calf nutrition requirements between the two algorithms (Eqs. (1), (4), (5) vs. Eqs. (12)–(14); Appendix A). Both grazing treatments showed similar trends in forage demand, although North_R was more variable due to rotation among paddocks with differing forage quality (data not shown) and forage quantity (Fig. 7).

3.3. Forage intake

Similar to predicted animal forage demand (Fig. 6), APEX_NRBC tended to predict higher forage intake than APEX_GPFARM after January–February (Fig. 8), which was consistent with the simulated forage utilization between the two algorithms. The simulated TDN intake showed similar trends to the simulated forage intake across these treatments and seasons (data not shown) due to similar TDN contents between the two dominant grasses of bermuda and bluestem at the site (Table 1). The selective grazing method in APEX classifies forage species as preferred, desirable, or undesirable based on their forage quality (TDN content) but does not consider differences between plant tissues (e.g., leaves, stems and twigs; Zilverberg et al., 2017).

Hay was the main source of cow-calf intake during the winter months until the cool-season forage crops on cultivated paddocks were sufficient for grazing. The actual average annual hay consumption of 49,237 kg for North_R and 114,985 kg for South_C were simulated very well with APEX_NRBC and APEX_GPFARM with $R^2 > 0.94$ and IA > 0.99 (Table 2), although APEX_NRBC simulated slightly higher hay consumption than APEX_GPFARM (South_C). The reduced hay consumption for North_R relative to South_C ($p < 0.05$; Table 2) occurred due to management differences. Specifically, less hay was made available on North_R to encourage cattle to utilize standing dry matter on pasture

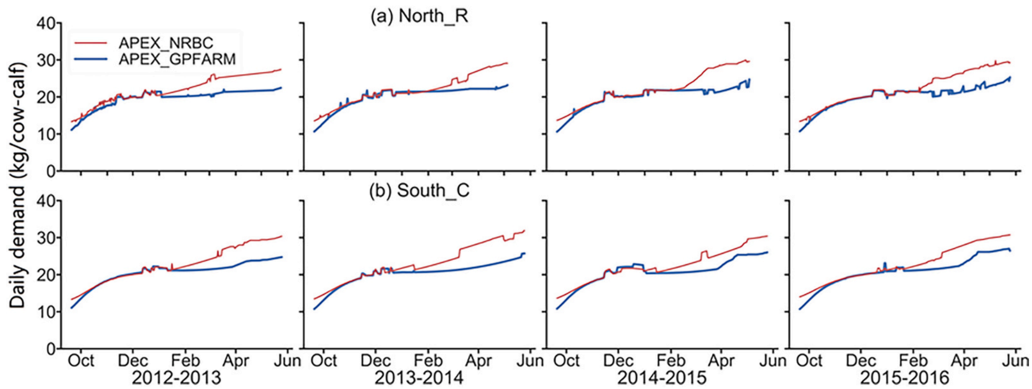

Fig. 6. Simulated cow-calf daily demand based on APEX_NRBC and APEX_GPFARM for North_R and South_C.

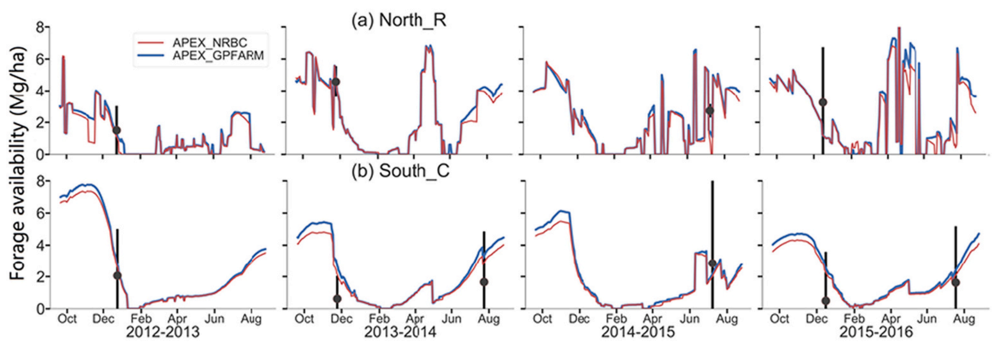

Fig. 7. APEX simulated daily forage availability (not including hay) as represented by standing biomass from the pastures with grazing for North_R and South_C. Measured data shown by points and error bars (standard deviation).

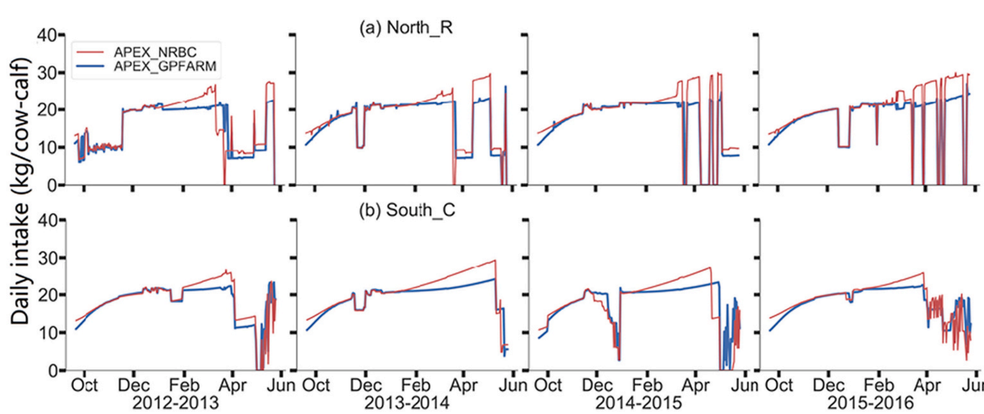

Fig. 8. Simulated daily intake (including forage and hay) based on APEX_NRBC and APEX_GPFARM for North_R and South_C.

paddocks. Both APEX_NRBC and APEX_GPFARM were able to capture the inverse relationship between forage availability in the paddocks and hay consumption (Figs. 7, 8).

Consistent with simulated forage demand (Fig. 6), simulated daily forage intake during winter (including hay) was similar between the grazing treatments, and started to diverge in April–May (Fig. 8). The low simulated forage intake per cow-calf unit from November to December in 2012 for North_R (Fig. 8a) was due to poor establishment and growth of cool-season forage and to low forage quality of dry biomass (> 80% classified as undesirable). The lower simulated daily forage intake (< 10 kg/day) in April–May for North_R (e.g., 2013 and 2014; Fig. 8a) was due to low productivity of cool season forage (Mullenix and Rouquette, 2018) as shown in Fig. 7a and the intentional reduction of available hay. This limited forage availability on North_R until warm-season pasture biomass exceeded that of the South_C.

3.4. Calf weight gain

APEX_GPFARM simulated lower calf weight gains than APEX_NRBC in September–November (Fig. 9) when forage demand and intake were low. Based on Eqs. (16)–(17) (Appendix A), APEX_GPFARM predicted higher calf maintenance requirement (75% of intake) and lower TDN available for calf weight gain (25% of total intake) than did APEX_NRBC. APEX_NRBC predicted lower calf maintenance requirement since calves were younger and weighed less (Eq. (11) Appendix A). The opposite occurred when forage demand and intake were high (February–April) as higher calf weight resulted in higher calf maintenance requirement in APEX_NRBC predictions. Based on the simulated forage demand (Fig. 6)

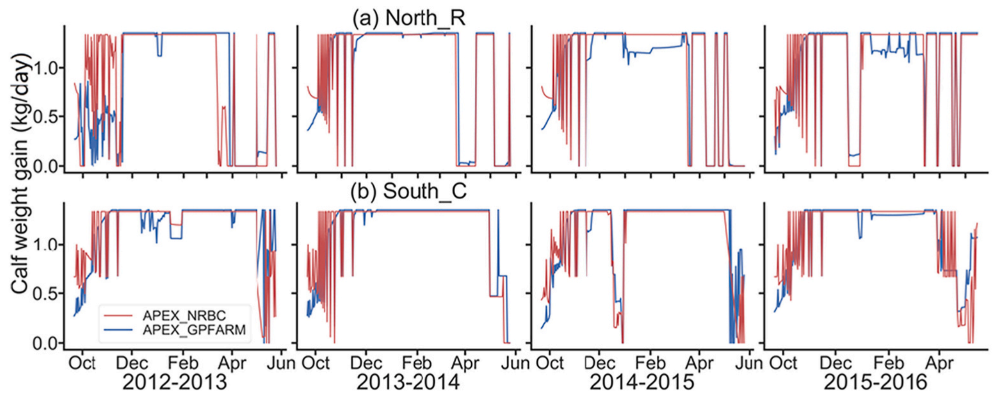

Fig. 9. Simulated daily calf weigh gain based on APEX_NRBC and APEX_GPFARM for North_R and South_C.

and intake (Fig. 8), APEX_GPFARM predicted daily weigh gain (Fig. 9) was more responsive to forage intake (e.g., winter forage with hay) and hay quality.

The simulated calf weight gain (Fig. 9) was low and fluctuated during September–October, especially for South_C because pasture biomass has reduced quality and quantity and calves were young and thus weighed less. Calf weight gains then typically increased to the maximum level (Appendix A) during early November and remained high, especially for South_C. In contrast, calf weight gain on North_R fluctuated more because of limited cool season forage production, limited hay feeding, and forced grazing of less desirable standing hay (with low TDN). APEX assumes no negative weight gain even with limited forage intake (e.g., April–May in 2013 and 2014 for North_R; Figs. 8 and 9), as is assumed in other cattle weight gain models (Rotz et al., 2005; Teague et al., 2015). However, we recommend that this be adjusted (as occurs in SPUR, Teague and Foy, 2002) because negative calf weight gain does occur when energy intake is insufficient to meet maintenance requirement.

3.5. Calf weaning weight

Both APEX_GPFARM and APEX_NRBC were able to accurately predict weaning weights with RMSE <24 kg, $R^2 > 0.52$, and IA > 0.83 (Table 2). This result is consistent with previous studies that also showed accurate simulation of calf weaning weights for the energy-based algorithm (Romera et al., 2004) and the TDN-based method (Andales et al., 2005). Simulation accuracy was good despite likely overestimation of forage quality since APEX does not consider the decline in forage quality (e.g., TDN content) that occurs when forage utilization increases with stocking density and grazing duration (e.g., Smart et al., 2010; Fang et al., 2014). This likely overestimation was evidently offset by underestimation of forage utilization because simulated hay consumption matched well with measured data (Table 2).

There was no statistically significant difference in measured average annual calf weaning weights between the grazing systems (296 ± 7 kg for North_R; 305 ± 22 kg for South_C), and simulations based on APEX_NRBC and APEX_GPFARM showed similar results with slightly lower weights for North_R (Table 2). On a year-by-year basis, simulated calf weaning weights were generally within ±1SD of measured values; however, APEX_GPFARM underpredicted weights in 2013 for North_R and overpredicted weights in 2015 for South_C (Fig. 10). With increased stocking rate from 2015 to 2016 (33 to 45 cows), both measured and simulated calf weaning weights for North_R were similar between the two years (Fig. 10a) and higher than South_C (51 and 49 cows), suggesting a higher potential to increase stocking rate in North_R than in South_C. This result for North_R was mainly associated with higher forage availability during spring (Fig. 6a) with multiple grazing paddocks and longer rest time for grass recovery (Holechek et al., 1999).

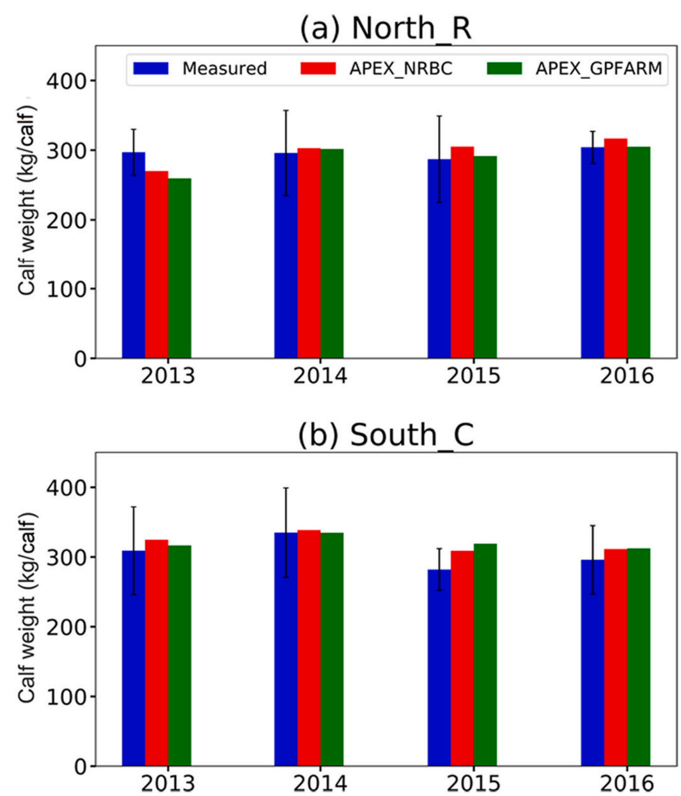

Fig. 10. Measured and simulated calf weaning weight based on APEX_NRBC and APEX_GPFARM for North_R and South_C.

3.6. Costs and revenue

Based on the APEX economic analysis, total cost predictions were close to measured values on a per ha basis with RMSE < \$9/ha, $R^2 = 0.98$, and IA =1.0 (Table 3), and both experimental data and simulation results indicated higher total cost for South_C (Table 3). The accuracy of cost simulation was largely expected because management costs (except for hay consumption) were model inputs and thus were not subject to prediction error. The low RMSE of \$8/ha and high R^2 (0.95) and IA (1.0) values for hay consumption indicate that the enhanced supplemental hay routines appropriately represented experimental conditions. Simulated revenue from calf sales, which was based largely on calf weaning weight (at the time of sale in this study), was also close to measured data with RMSE = \$21/ha, $R^2 = 0.97$, and IA = 1.0. Both measured and simulated data indicated higher revenue for South_C (Table 3).

Since profit was determined as the difference between revenue and

Table 3
Measured and simulated average annual cost, revenue, and profits ($/ha).

	Measured		Simulated*		RMSE	R^2	IA
	North_R	South_C	North_R	South_C	All treatments		
Hay cost	44 ± 6b**	103 ± 25a	46 ± 2b	99 ± 22a	8	0.95	1.00
Fertilizer cost	30 ± 36a	102 ± 57a	30 ± 36a	104 ± 60a	2	1.00	1.00
Other management cost	81 ± 8a	57 ± 15b	79 ± 6a	55 ± 14b	5	0.90	1.00
Other costs (i.e., labor, chemicals, fuel, capital investment)***	83	103	83	103	–	–	–
Total cost	237 ± 29b	365 ± 76a	238 ± 34b	361 ± 76a	9	0.98	1.00
Gross revenue	276 ± 64b	406 ± 26a	275 ± 74b	427 ± 18a	21	0.97	1.00
Profits	38 ± 70a	41 ± 94a	37 ± 86a	66 ± 80a	28	0.89	0.97

* Average of predicted values from APEX_NRBC and APEX_GPFARM are presented.
** Means within treatments (North_R and South_C) followed by the different letter in each row are significantly different at $p < 0.05$ (LSD-test).
*** The other costs (i.e., labor, chemicals, fuel, capital investment) were obtained from Harmel et al. (2021).

cost, simulated profits were also quite good overall; however, profit on South_C was overpredicted largely due to the overprediction of calf weaning weight (16 kg) and thus revenue (Table 2; Fig. 10). Since APEX overpredicted profits on South_C (continuous grazing) but slightly underpredicted profits on North_R, further analysis of the sensitivity of revenue predictions may be warranted, especially as models are increasingly used to evaluate the long-term sustainability of alternative grazing management systems and to evaluate economic risks considering long-term weather variation and its interactions with management options on vegetation production (Teague et al., 2015).

4. Conclusions

The APEX modifications enhanced its ability to simulate vegetation biomass, calf weaning weight, and total cost and returns. Between the two calf weight gain algorithms, APEX_NRBC showed much larger grazing effects (forage intake) on above-ground standing biomass (especially in South_C), which is attributed to its higher simulated animal demand and forage intake. On the other hand, the APEX_GPFARM algorithm showed a greater response in weight gain to forage TDN content and forage supply. APEX_NRBC performed slightly better than APEX_GPFARM in predicting above-ground biomass and calf weaning weights. However, both cow-calf weight gain algorithms do not consider negative weight gain and other constraints (e.g., nutrient, fiber, and ruminal fill limitations), which would require additional detail but might further improve daily weight gain estimates. The accurate prediction of hay consumption indicates that the APEX supplemental hay routine improved the model's ability to represent this critical nutritional component. These enhancements for sub-daily grazing, calf weight gain, and hay supplementation no doubt increase the utility of APEX for agro-economic assessment of alternative and conventional grazing strategies. The capability to rotate grazing herds among pastures in a single day enhance simulation of the impacts of spatial variability (e.g., differences in soil type, hydrology, vegetation, and management) at ranch scale. However, since APEX overpredicted profits for the continuous grazing system, further analysis and improvements of revenue calculation in APEX may be warranted.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. USDA is an equal opportunity employer and provider.

Acknowledgements

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Appendix A

The cow-calf submodule in APEX estimates cow-calf demand, forage intake, and calf weight gain from calving to calf weaning. It assumes a birthing period (1–2 months from the middle of September to the end October in the current study) where both pregnant cow and cow-calf pairs are simulated together; after that, all cows and calves were simulated individually. Calf birth weight is assumed as a fixed percent (7.4%) of cow weight, and the cow weight is assumed stable from calving to weaning. Traditionally, daily calf weight gain was assumed as fixed percent of cow weight (0.16%)

To improve APEX simulation, two cow-calf weight gain algorithms were added. The APEX_NRBC weight gain algorithm is based on energy available in forage intake (National Academies of Sciences, Engineering, and Medicine (NAS), 2016). The APEX_GPFARM algorithm is based on TDN in forage intake (Andales et al., 2005).

A.1. Energy-based cow-calf weight gain algorithm (APEX_NRBC)

The cow-calf forage demand (DMI, kg/day) is estimated based on cow dry matter requirement (including cow milk production, YMLK) (DMI_{cow}, kg/day), calf dry matter requirement (DMI_{calf}, kg/day) and calf nursing requirement (DMIN, kg/day) as following:

$$DMI_{cow} = \frac{(GZWT*0.96)^{0.75}*(0.04997*NEM^2+0.04631)}{NEM} + 0.2*YMLK \quad (1)$$

$$\mathrm{YMLK} = (\mathrm{DSP}/7.0+0.3571)\Big/\left(\left(\frac{1}{0.3197*PMLK}*e^{-0.0168*\mathrm{DSP}}\right)+0.042\right) \quad (2)$$

$$NEM = 1.34ME - 0.138ME^2 + 0.0105ME^3 - 1.12 \quad (3)$$

$$\text{DMI}_{calf} = \frac{(CAWT*0.96)^{0.75}*\left(0.2435*EMN_{Calf}NEM - 0.0466*EMN_{Calf}NEM^2 - 0.1128\right)}{NEM} \quad (4)$$

$$DMIN = 0.0033 + 0.000109*DSP*CAWT \quad (5)$$

$$DMI = DMI_{cow} + DMI_{calf} + DMIN \quad (6)$$

where GZWT is cow weight (kg); NEM is net energy value of diet for maintenance (Mcal/kg); ME is metabolizable energy concentration (Mcal/kg; estimated based on TDN); PMLK is peak milk production (9.0 kg/per day); DSP is days after calving; CAWT is calf weight (kg).

Actual forage intake (GZSM, kg/day) is estimated using a selective grazing method based on animal demand (DMI) and forage supply (including hay) for each day (Zilverberg et al., 2017). Calf weight gain (CWG, kg/day; always ≥0) is estimated based on available energy (RE, Mcal/day) from forage intake (GZSM) minus cow and calf maintenance requirement (EMNR_{cow} and $\text{EMNR}_{\text{calf}}$, Mcal/day) as following:

$$EMNR_{cow} = 0.077*(0.96*GZWT)^{0.75} \quad (7)$$

$$EMNR_{calf} = 0.077*(0.96*CAWT)^{0.75} \quad (8)$$

$$RE = \left(GZSM - \frac{EMNR_{cow}}{NEM}\right)*\text{NEG} - EMNR_{calf} \quad (9)$$

$$NEG = 1.42ME - 0.174ME^2 + 0.0122ME^3 - 1.65 \quad (10)$$

$$CWG(\geq 0) = Min\left(13.91*RE^{0.9116}*EQSBW^{-0.6837}, 0.0021*GZWT\right) \quad (11)$$

where NEG is net energy value of diet for cow growth (Mcal/kg); EQSBW (kg/calf) is equivalent empty body weight estimated from shrunk body weight; APEX_NRBC estimated calf weight gain (*CWG*) based on net energy available (RE), and the maximum calf weight gain is limited by a fraction (0.0021) of GZWT (Eq. (11)).

A.2. TDN-based cow-calf weight gain algorithm (APEX_GPFARM)

The cow-calf forage demand (DMI, kg/ha) in APEX_GPFARM (Eqs. (15)–(18)) is based on cow TDN requirement (including cow milk production, YMLK in Eq. (2)) (DMI_{cow}, TDN/day), cow maintenance requirement (EMNR, TDN/day), and calf TDN requirement (DMI_{calf}; TDN/day) as described following:

$$DMI_{cow} = a*(GZWT)^{0.9}*TDN + 0.4*YMILK \quad (12)$$

$$EMNR_{cow} = 0.077*\frac{(GZWT + 0.4*YMILK)^{0.75}}{3.6*(0.486 + 0.243*TDN)} \quad (13)$$

$$DMI_{calf} = b*CAWT^{0.9}*TDN + 1.4*COND \quad (14)$$

$$DMI = Max\left(\frac{DMI_{cow}}{TDN}, \frac{EMNR_{cow}}{TDN}\right) + \frac{DMI_{calf}}{TDN} \quad (15)$$

where *a* and *b* are empirical constants (0.025–0.029; Andales et al., 2005); COND (0–1) is cow body condition based on current cow weight (GZWT, kg) and maturity weight (GZWM, kg) (COND = (GZWT+25)/GZWM).

The actual animal forage intake (GZSM, kg/day) is estimated using a selective grazing method in APEX (Zilverberg et al., 2017). Calf weight gain (CWG, kg/day; always ≥0) is estimated based on available TDN (RE, TDN/day) from forage intake minus cow maintenance (assuming 75% of total TDN in GZSM; Eq. (16)) as following:

$$\text{RE} = \text{GZSM*TDN*}(1 - 0.75) \quad (16)$$

$$CWG_{GPFARM}(\geq 0) = Min(1.4*COND, 0.6*RE) \quad (17)$$

where the conversion efficiency from available TDN (RE) to weight gain is assumed as 60% (Eq. (17)). The maximum calf weight gain is limited by cow body condition (COND) and a maximum weight gain value of 1.4 kg/day according to the targeted calf weaning weight and birth weight.

Table B1
Detailed Cow-calf grazing events for North_R and South_C (North_R: ①: 5-2×, SW-11; ②: 4–4, 5–4; ③: 5–2, SW13; ④: 5–1; ⑤: 5–19,17; ⑥: 11-A; ⑦: 7-A, 16; ⑧: LANE; ⑨: 1–4, 2–4, 1–2; ⑩: 19; ⑪: Y2 (4–2, 12); ⑫: 2–4-5; South_C-herd 1: ①: 5×-8; ②: 7–10; ③: 7–5-6; ④: W-1; ⑤: 7–16; South_C-herd 2: ①: 6–14, 6–20, 6–21; ②: W10; ③: 20×; ④: 6–19; ⑤: 6–13; ⑥: 9–21; Fig. 2).

Year	North_R (average 34 cow-calf)	South_C (average 49 cow-calf)	
	Herd 1	Herd 1	Herd 2
	Grazing paddocks		

(continued on next page)

Table B1 (*continued*)

Year	North_R (average 34 cow-calf)			South_C (average 49 cow-calf)					
	Herd 1			Herd 1			Herd 2		
	Grazing period	Grazing days	Grazing paddocks	Grazing period	Grazing days	Grazing paddocks	Grazing period	Grazing days	Grazing paddocks
	Grazing period	Grazing days		Grazing period	Grazing days	Grazing paddocks	Grazing period	Grazing days	Grazing paddocks
2012	1/1–3/4	64	2,8	1/1–3/27	87	1, 2, 3, 4, 5	1/1–5/24	145	1, 2, 3, 4, 5,6
	3/5–3/27	23	1,6,7	3/28–12/31	279	2, 3, 4, 5	5/25–12/31	221	2, 3, 4, 5,6
	3/28–5/21	23–26	4,9						
	5/22–5/31	10	5,6,7						
	6/1–7/18	5–20	one of 8, 9, 10, 11, 12						
	7/19–8/27	40	11						
	8/28–9/12	16	1						
	9/13–12/4	4–28	two of 4, 5, 7, 9, 11, 12						
	12/5–12/27	23	2,9						
	12/28–12/31	4	3,11						
2013	1/1–2/3	34	11						
	2/4–2/18	16	4	1/1–1/15	15	2, 3, 4, 5	1/1–1/15	15	2, 3, 4, 5, 6
	2/19–3/18	3–6	one of 2,3,4,5,7,11,12	1/16–3/29	73	1, 2, 3, 4, 5	1/16–3/8	52	1, 2, 3, 4, 5, 6
	3/19–5/14	3–16	1 and one of 4,5,9,10,11,12	3/30–11/17	233	2, 3, 4, 5	3/9–11/17	254	2, 3, 4, 5, 6
	5/15–6/30	3–10	one of 1,6,7,9,12	11/18–12/31	44	1, 2	11/18–11/21	4	1, 2, 3, 4, 5, 6
	7/1–7/30	30	4				11/22–12/2	11	2, 3, 4, 5, 6
	8/1–11/21	4–18	one of 1,2,3,6,7,8,9,10,11				12/3–12/31	29	1, 2, 3, 4, 5, 6
	11/22–12/1	11	1,5						
	12/2–12/4	3	2,9						
	12/5–12/12	9	2,11						
	12/13–12/31	20	1,5						
2014	1/1–1/8	8	1,5	1/1–1/14	14	1, 2	1/1–4/30	120	1, 2, 3, 4, 5, 6
	1/9–2/3	26	1,12	1/15–4/30	107	1, 3, 4, 5	5/1–12/31	245	2, 3, 4, 5,6
	2/4–3/3	28	1,4	5/1–7/21	82	3, 4, 5			
	3/4–3/7	4	1,5	7/22–12/14	145	2, 3, 4, 5			
	3/8–6/18	4–15	1 and one of 2,3,7,9,11,12	12/15–12/31	17	1, 2, 3, 4, 5			
	6/19–11/12	26–35	one of 1,4,9,11,12						
	11/13–11/15	3	11						
	11/15–11/24	10–24	one of 10,11,12						
2015	1/1–1/4	4	12	1/1–1/12	12	1, 2, 3, 4, 5	1/1–6/9	160	2, 3, 4, 5,6
	1/5–1/12	8	4	1/13–3/15	62	1, 4, 5	6/10–6/28	19	1
	1/13–1/31	19	5	3/16–6/9	86	2, 3, 4, 5	6/29–12/31	186	2, 3, 4, 5,6
	2/1–3/10	38	1,5	6/10–6/28	19	1			
	3/11–8/2	3–15	one of 1,3,4,5,6,7,8,10,12	6/29–12/31	186	2, 3, 4, 5			
	8/3–9/10	39	4						
	9/11–11/1	4–17	one of 5,6,7,8,9						
	11/2–12/14	43	11						
	12/15–12/31	17	3,11						
2016	1/1–1/10	10	12	1/1–1/11	11	2, 3, 4, 5	1/1–1/11	11	2, 3, 4, 5,6
	1/11–2/19	5–11	1+ one of 5,6,8,12	1/12–3/28	77	1, 2, 3, 4, 5	1/12–4/30	110	1, 2, 3, 4, 5, 6
	2/19–8/3	4–15	one of the12 pasture	3/29–11/21	238	2, 3, 4, 5	5/1–11/21	205	2, 3, 4, 5,6
	8/4–9/8	36	4	11/22–12/31	40	1, 2, 3, 4, 5	11/22–12/31	40	1, 2, 3, 4, 5, 6
	9/9–12/4	7–24	one of 2,5,6,7,9,11						
	12/5–12/8	4	2,11						
	12/8–12/31	24	1,12						

Table B2
Paddock management for the two grazing treatments from 2012 to 2016.

Managements options for paddocks		North_R	South_C
Paddocks	Number/area	12 paddocks totaling 113.8 ha	11 paddocks totaling 113.9 ha
Plant types	Annual crop/plant method	3 paddocks that are cultivated and planted to mixed-species forage each spring and fall Main crops: legumes; pea beans; oat	3 paddocks that are cultivated and planted to oats in September Main crop: oat
	Perennial mixed grasses	9 grassland paddocks with coastal bermuda; bluestem; buffalo grass; white tridens; brome; winter grass	8 grassland paddocks with coastal bermuda; bluestem; buffalo grass; white tridens; brome; winter grass
Fertilizer application	Type	litter	N-P-K: 30–10-0
	Amount	5000–6500 kg/ha	200–300 kg/ha
	Years applied	2013, 2015, 2016	2012–2016
	Pastures	Only 3 annual forage paddocks fields	Almost all pastures
Tillage	Type	Conservation tillage and no-till	Conservation tillage
	Time	2013, 2015, 2016	2012–2016
Supplemental hay	Period	December–April	December–April

(*continued on next page*)

Table B2 (*continued*)

Managements options for paddocks		North_R	South_C
Paddocks	Number/area	12 paddocks totaling 113.8 ha	11 paddocks totaling 113.9 ha
Grazing pattern	Amounts	40–65 Mg	100–130 Mg
	Quality	Lower quality with TDN contents of 50–55%	Higher quality with TDN contents of 55–60%
	Grazing method (see Table B1)	Short-term high-intensity grazing of 3–15 days for most paddocks	Uncontrolled "best pasture" grazing
	Stocking density	3.09 ± 2.82 cow-calf/ha	0.64 ± 0.12 cow-calf/ha
	Annual stocking rate	0.30 cow-calf/ha	0.43 cow-calf/ha

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