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Short Communication

Evaluation of APEX modifications to simulate forage production for grazing management decision-support in the Western US Great Plains

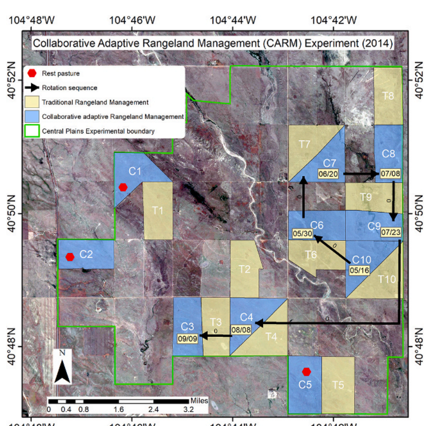
G. Cheng[a,b], R.D. Harmel[c,*], L. Ma[d], J.D. Derner[e], D.J. Augustine[d], P.N.S. Bartling[d], Q. X. Fang[f], J.R. Williams[g], C.J. Zilverberg[h], R.B. Boone[i], D. Hoover[d], Q. Yu[a,b,**]

[a] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Northwest A&F University, Yangling 712100, China
[b] College of Natural Resources and Environment, Northwest A&F University, Yangling 712100, China
[c] USDA-ARS, Center for Agricultural Resources Research, Fort Collins, CO 80526, USA
[d] USDA-ARS, Rangeland Resources and Systems Research Unit, Fort Collins, CO 80526, USA
[e] USDA-ARS, Rangeland Resources and Systems Research Unit, Cheyenne, WY 82009, USA
[f] Qingdao Agricultural University, Qingdao 266109, China
[g] Texas A&M University, Temple, TX 76502, USA
[h] Dakota Lakes Research Farm, Pierre, SD 57501, USA
[i] Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, CO 80523, USA

HIGHLIGHTS

- Rangeland models can serve as decision-support tools after calibrating against experimental data.
- CStudy evaluated APEX improvements related to grazing impacts on forage production impacts and a new rotational grazing modification.
- APEX was able to simulate the responses of forage production to grazing management and soil type.
- Current rotational sequences based on stakeholder criteria were optimal for grazing management in the semi-arid region.
- APEX can assess grazing decisions on forage production and improve grazing management in semi-arid environments.

GRAPHICAL ABSTRACT



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ABSTRACT

Context: Understanding how grazing management decisions influence the productivity and composition of rangeland plant communities is essential for the development of effective strategies to sustainably produce multiple ecosystem goods and services. Informed with experimental measurements, simulation models can advance our understanding and stewardship of rangeland ecosystems.

* Correspondence to: R. D. Harmel, USDA-ARS, Center for Agricultural Resources Research, 2150 Centre Avenue, Bldg. D, Fort Collins, CO 80526, USA.
** Correspondence to: Q. Yu, State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Northwest A&F University, Xinong Road No. 26, Yangling, Shaanxi 712100, China.
E-mail addresses: daren.harmel@usda.gov (R.D. Harmel), yuq@nwafu.edu.cn (Q. Yu).

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APEX
Forage functional groups
Semiarid environment
Shortgrass steppe

Objective: Our main objective was to evaluate the APEX (Agricultural Policy/Environmental eXtender) plant growth modules and grazing animal selectivity in simulating forage production using experimental data collected from both traditional season-long grazing and adaptive rotational grazing management on western rangelands. Specifically, we evaluated APEX's capability to simulate forage productivity and its response to soil types and climate conditions under grazing management options.
Methods: Capitalizing on a comparative field study with 20 large pastures (> 123 ha each), APEX modifications were evaluated by comparing simulated forage production with experimental data. The field study evaluated traditional grazing (season long grazing on a single pasture) and an alternative grazing system that utilized collaborative adaptive rangeland management with stakeholders engaged in decision making (such as when and where to rotate a single herd). APEX was modified to include rotational grazing based on a user-defined sequence and automatic rotational grazing based on user-defined forage grazing limits and minimum/maximum grazing durations.
Results and conclusions: The APEX model was able to simulate the relative differences in forage production between grazing treatments, across years, and among soil types; however, APEX underestimated forage production in 2015 and 2017 due to overestimating drought stress for the warm season perennial grass functional group. Simulation of grazing management scenarios showed that the collaborative adaptive management decision criteria resulted in grazing durations that produced more forage than consistent 7- or 14-day rotation intervals.
Significance: These modifications were needed to capture the complexity of semiarid environments and thus enhance APEX to better assess grazing management decisions on forage production in regions such as the Western US Great Plains.

1. Introduction

Rangeland models can be used to evaluate risks and decision impacts of alternative management strategies under different circumstances (Derner et al., 2012; Ma et al., 2019). Previous studies showed that process-based rangeland models (e.g., SPUR, Stout et al., 1990; GPFARM-Range, Andales et al., 2005; Andales et al., 2006; Qi et al., 2012; Fang et al., 2014; GRAZPLAN, Moore and Ghahramani, 2013) can simulate elementary grazing impacts such as seasonal responses of plant growth (total biomass) and animal weight gain under varying stocking rates in a single pasture or rangeland type for a given season or year under continuous grazing. Recently, the Agricultural Policy/Environmental eXtender (APEX, v1605, Williams and Izaurralde, 2006) was enhanced with modifications to the plant growth module to simulate forage production (Zilverberg et al., 2017) and for selectivity by grazing animals for beef production in mixed grass prairie (Zilverberg et al., 2018).

Potential plant growth in APEX is driven by daily heat units and photosynthesis. Daily photosynthesis rate is based on radiation use efficiency and then modified for CO_2 concentration and vapor pressure deficit effects. Leaf area index (LAI), plant height, biomass partitioning to roots, and root growth are functions of heat units. Actual plant growth is modified by environmental factors, such as water, nitrogen, soil aeration, and temperature stresses. Actual daily root growth is also affected by soil bulk density (Williams, 1995; Williams and Izaurralde, 2006). Plant species compete for sunlight based on LAI and for water and nutrients based on plant demands and root distribution of each species (Kiniry et al., 1992; Williams and Izaurralde, 2006). Improvements to APEX by Zilverberg et al. (2017, 2018), however, did not address predicting forage production under rotational grazing management, which is an urgent need for rangeland management decision support tools (Derner et al., 2012; Fust and Schlecht, 2018).

Our main objective was to evaluate the APEX plant growth modules and grazing animal selectivity in simulating forage production using experimental data collected from both traditional season-long grazing and adaptive rotational grazing management on western rangelands (Augustine et al., 2020). Specifically, we evaluated APEX's ability to simulate total forage production and production for plant functional groups and their response to different soil types and climate conditions under grazing management options.

2. Materials and methods

2.1. Experimental data

Model evaluation utilized experimental data from the collaborative adaptive rangeland management (CARM) study conducted at the USDA-ARS Central Plains Experimental Range (40°49' N, 107°47' W), a Long-Term Agroecosystem Research (LTAR) network site (https://ltar.ars.usda.gov). Soils, rainfall, and vegetation at the site are representative of the extensive shortgrass steppe region in the western Great Plains (Burke and Lauenroth, 1993). Mean annual precipitation is 321 mm, with more than 80% of precipitation occurring from May to September (Lauenroth et al., 2008). Mean annual temperature is 8.6 °C, and the mean monthly temperature ranges from −5 to 22 °C (Nichols et al., 2018). Soils range from fine sandy loams on upland plains to alkaline salt flats bordering a large drainage running north-south in the eastern portion of the site (Augustine et al., 2020). The dominant soil in each pasture was classified roughly as a loam, sandy clay loam, or sandy loam based on the soil texture of the top 30 cm, which contains a majority of the forage species roots (Lane et al., 1998). Soil bulk density (Mg m^{-3}), field capacity (kg kg^{-1}), and wilting point (kg kg^{-1}) were taken from the USDA Natural Resource Conservation Service (http://websoilsurvey.sc.egov.usda.gov/). For the soil input parameters see Supplementary Material Table 1A. Meteorological data used for APEX were recorded at the experimental site, including daily solar radiation, maximum daily temperature, minimum daily temperature, precipitation, relative humidity, and wind speed.

Plant communities are dominated by warm-season (C_4 photosynthetic pathway), grazing-tolerant shortgrasses such as blue gramma (*Bouteloua gracilis*) and buffalograss (*B. dactyloides*), which contribute >70% of aboveground net primary productivity (Augustine et al., 2017). Other common species are cool-season (C_3 photosynthetic pathway) grasses such as needleleaf sedge (*Carex duriuscula)* and western wheatgrass (*Pascopyrum smithii)*, and the perennial forb scarlet globemallow (*Sphaeralcea coccinea)*. Forage production on loamy soils averages 750 kg ha^{-1} (Augustine et al., 2014; Milchunas et al., 1994).

The CARM experiment was initiated in 2014 (Wilmer et al., 2018). Twenty pastures (123–137 ha) were identified and grouped into 10 pairs with similar soil types (ecological sites), plant communities, pasture topographical wetness index, and prior management history (Augustine et al., 2020; Derner et al., 2021). From 2014 to 2018, both the traditional rangeland management (TRM) and CARM treatments were stocked with 214, 224, 234, 244, and 280 yearling steers, respectively (equivalent to 0.61,0.64, 0.67, 0.70, and 0.80 animal unit months ha^{-1};

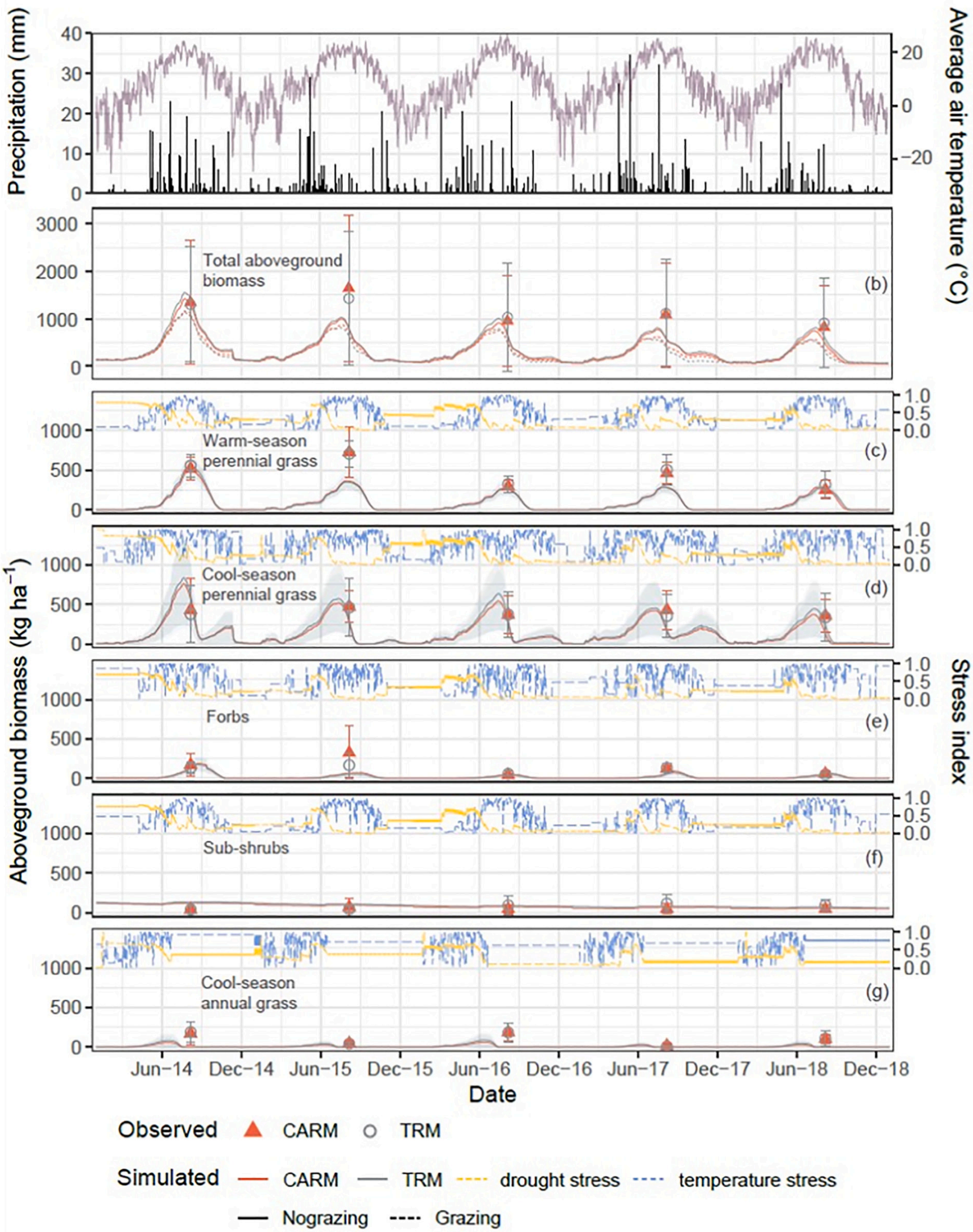

Fig. 1. For collaborative adaptive rangeland management (CARM) and traditional rangeland management (TRM): (a) precipitation and average temperature; (b) average simulated total aboveground biomass inside (ungrazed) and outside (grazed) exclusion cages; aboveground biomass measured in August inside exclusion cages; and (c-g) simulated and measured aboveground biomass and simulated growth stress index inside exclusion cages (shading around the solid lines represents standard deviation of simulations with $n = 10$ each for TRM and CARM, error bars - standard deviation of measurements with $n = 48$).

Augustine et al., 2020) for the 140 day grazing season (mid-May to the end of September). Cattle assigned to the TRM treatment were distributed in 10 separate herds, each of which grazed continuously in the assigned pasture during the grazing season. Cattle in the CARM treatment grazed as a single large herd and were rotated among 10 pastures. Each year, a suite of criteria based on forage residual biomass, cattle behavior, and a maximum limit on number of grazing days per pasture were used to determine the triggers for the CARM cattle to rotate to the next pasture in the grazing sequence (Supplementary Material Fig. 2A). Each year annual stocking rate, stock density, and rotation sequences among the pastures were determined by a stakeholder group using monitoring data (e.g., vegetation, cattle performance) and seasonal weather forecasts (Wilmer et al., 2018). The CARM herd rotation included 8 pastures to be grazed with 2 planned to be rested each year; however, this could be reduced to <8 pastures grazed in years with above-average forage productivity and increased to >8 in years with below-average forage productivity (Augustine et al., 2020).

To quantify functional species production under CARM and TRM, we established 16 (or 24 if the pasture contained salt flats) 1 × 1 m moveable grazing exclusion cages in each paired pasture randomly placed in April before the beginning of the grazing season (Augustine et al., 2020). Aboveground biomass was measured by harvesting all aboveground biomass in a 0.18 m^2 rectangular quadrat centered in each cage in early August. Harvested biomass was sorted into plant functional groups: 1) warm-season perennial grasses, 2) cool-season perennial grasses, 3) cool-season annual grasses, 4) forbs (both annual and perennial), and 5) sub-shrubs. Clipped samples were oven-dried at 55 °C to a constant weight. During the experiment, shrub aboveground biomass was not measured because of its low occurrence; however, we simulated shrubs given their importance to livestock production in western Great Plains ecosystems (e.g., Derner and Hart, 2007; Derner and Hart, 2005).

2.2. Model parameterization and calibration

The APEX v1605 version was improved by Zilverberg et al. (2017, 2018), including allocation of new biomass, response to drought stress, competition for soil water, regrowth of herbaceous perennials, and selectivity of grazing species. They found that these modifications simulated total biomass better than individual species under continuous grazing conditions; however, these modifications have not been evaluated for rotational grazing. To do so, we further added the capability to simulate rotational grazing based on either user-specified rotational sequences or user-defined criteria, such as forage grazing limits and minimum or maximum grazing days in each pasture.

In this study, APEX simulated forage production for the following plant functional groups: warm-season perennial grasses (dominated by *Bouteloua gracilis* and *B. dactyloides*), cool-season perennial grasses [consisting of needle-and-thread *(Hesperostipa comata)* and western wheatgrass *Pascopyrum smithii*], forbs, cool-season annual grasses (primarily six-weeks fescue *Vulpia octoflora*), sub-shrubs, and shrubs (typically four-wing saltbush, *Atriplex canescens*). Crop parameters were calibrated manually by trial and error against aboveground biomass measured for each functional species under both CARM and TRM in early August each year. Specifically, for each grass species, growing degree-days were determined following Frank and Hofmann (1989), and maximum plant height values were obtained from the National Plants Database (USDA, 2020). Initial values of radiation use efficiency, optimum growth temperature, base temperature, maximum LAI, maximum rooting depth, and ratios of belowground/aboveground biomass at emergence and at maturity were set according to previous studies (Zilverberg et al., 2017). Initial values for other parameters were based on ALMANAC recommendations (Kiniry et al., 1992) or set to APEX default values. The final forage parameter values used in the model are shown in Supplementary Materials (Table 2A).

2.3. Model evaluation

Model simulation results for total peak forage production and for the six functional groups were compared to measured data from the CARM and TRM treatments. Root Mean Squared Error (RMSE), coefficient of determination (R^2), Willmott agreement index (d), Nash-Sutcliffe efficiency (NSE), Mean Error (ME), and Mean Absolute Error (MAE) were used to quantify model goodness-of-fit (Bosi et al., 2020). The modified F-test was also used to evaluate model performance considering measurement uncertainties (Sima et al., 2018). Mean separation for significant factors was conducted with Fisher's least significant difference using the LSD.TEST function provided in the 'agricolae' package (version 1.3–2) in R (v 4.0.0).

2.4. Model application for alternative grazing management scenarios

Once calibrated, APEX was used to simulate forage production for three alternative grazing management practices: (1) ±25% and ± 50% stocking rate changes for both CARM and TRM; (2) consistent 7-day and 14-day grazing durations in each pasture under the CARM rotation sequence; and (3) automatic-rotation every 14 days for CARM to either the pasture with highest simulated forage biomass or to a random pasture (rotation sequences shown in Supplementary Material Fig. 2A).

3. Results and discussion

3.1. Effects of annual precipitation

Total aboveground biomass measured inside grazing exclusion cages at the beginning of August varied considerably as influenced by precipitation (Fig. 1a, b). Total aboveground biomass was highest in 2015 (1699 ± 730 kg ha^{-1}), followed by 2014 (1461 ± 586 kg ha^{-1}), 2016 (1414 ± 639 kg ha^{-1}), 2017 (1369 ± 685 kg ha^{-1}), and 2018 (1186 ± 568 kg ha^{-1}). Simulated aboveground biomass was highest in 2014 (1798 kg ha^{-1}) and lowest in 2018 (865 kg ha^{-1}), with values of 1276 kg ha^{-1}, 1117 kg ha^{-1}, and 1009 kg ha^{-1} in 2015, 2016, and 2017, respectively. These results indicate that APEX adequately simulated total aboveground biomass given the relatively high temporal variation in precipitation. The F-test showed no significant difference between measured and simulated total aboveground biomass ($p = 1.0$, Supplementary Material Table 3A). Both measured and simulated above ground biomass showed decreasing trends from 2015 to 2018, although the biomass was consistently under-simulated. In 2014, the model overestimated total aboveground biomass because simulated cool-season perennial grass biomass was higher (Fig. 1d) due to high precipitation in August 2013 (data not shown). Although cool-season perennial grass biomass was overestimated in 2014, APEX correctly predicted exceptionally high production for this plant functional group in 2014 and 2016.

Dynamic changes in aboveground biomass for each plant functional group are shown in Fig. 1e-g. At the beginning of each year, sub-shrubs were the dominant functional group in terms of aboveground biomass. Then in February, cool season annual and perennial grass species began to grow. Warm season perennial grass growth began in March and reached peak biomass in August and September. Due to greater water-use efficiency, warm season grasses should maintain high productivity in the hotter, drier months (July–September) and compensate for the decline in cool season grass production (Bleier and Jackson, 2007; Moore et al., 2004). APEX effectively simulated the aboveground biomass of cool-season perennial grasses, forbs, and sub-shrubs with RMSE values of 232, 188, and 75 kg ha^{-1} under CARM and 229, 101, and 93 kg ha^{-1} under TRM. For both CARM and TRM, R^2 ranged from 0.01 (sub-shrubs) to 0.56 (cool-season perennial grass), the d-index ranged from 0.21 (sub-shrubs under TRM) to 0.83 (cool-season perennial grass under TRM), and NSE was always lower than 0.5 (Supplementary Material Table 3A). However, the F-test showed no significant differences between measured and simulated biomass when considering the experimental uncertainties ($p > 0.5$, Supplementary Material Table 3A).

Aboveground warm-season perennial grass biomass, which is more dependent on summer precipitation (Augustine et al., 2020), was accurately simulated in 2014, 2016, and 2018 but was underestimated in 2015 and 2017 (Fig. 1c). Biomass is constrained in APEX by the growth regulating factor, which is the minimum of the water, nutrient,

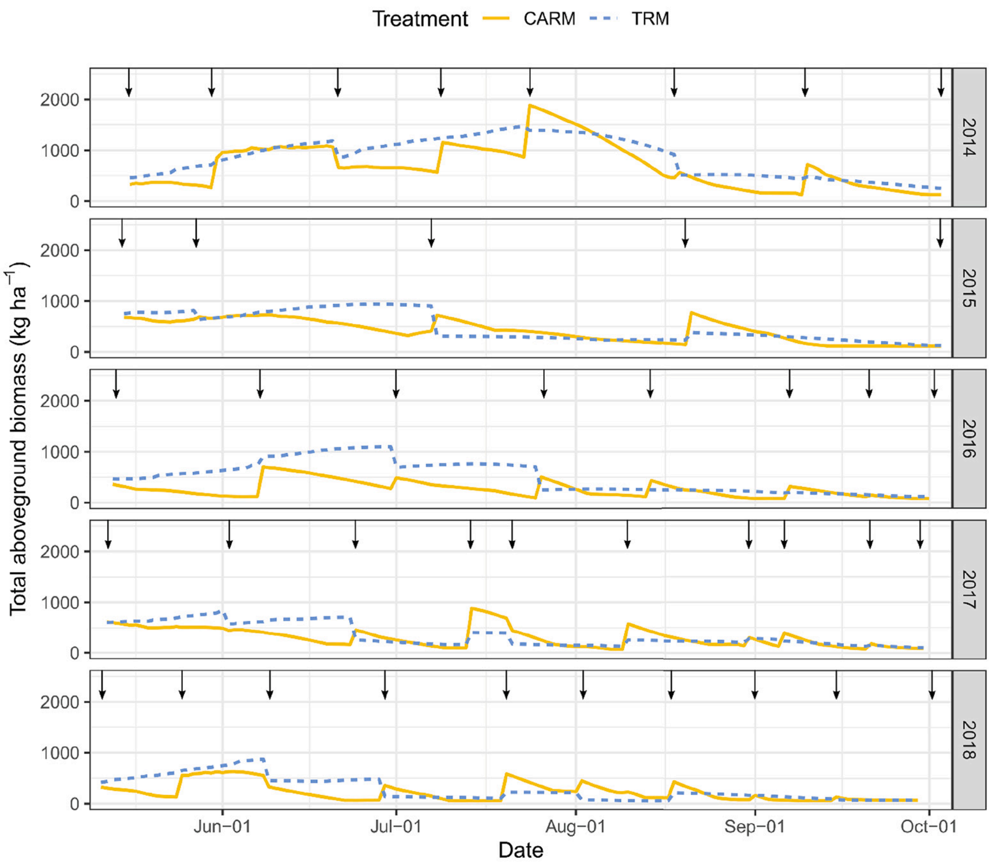

Fig. 2. Simulated total aboveground biomass in paired pastures under collaborative adaptive rangeland management, CARM (yellow line) and traditional rangeland management, TRM (dotted blue line). The CARM herd moved to a new pasture on dates indicated by black arrows. Sudden changes in biomass on the blue lines are due to spatial differences in simulated biomass among TRM pastures, largely associated with variation in soil type.

temperature, and aeration stresses (ranging from 0.0 under maximum stress to 1.0 under minimum stress) (Williams and Izaurralde, 2006). Warm-season perennial grass growth was limited each year by cool temperature stress before June and then by drought stress from June to the end of the growing season (Fig. 1c). Low precipitation in June and July of 2015 increased drought stress from mid-June to August, which constrained the biomass growth in August. Both the timing and amount of rainfall influence soil moisture dynamics and therefore above-ground net primary productivity in shortgrass steppe (Heisler-White et al., 2009). It is difficult for rangeland models to accurately simulate the effects of high intra-annual precipitation variation on forage dynamics (Ma et al., 2019) possibly due to poor simulation of the dynamics of drought stress during the wet-dry cycles. For example, the APEX model failed to accurately simulate warm-season perennial grass growth in drought-prone soils during drought periods with low LAI (Kiniry et al., 2002). This result for APEX was consistent with that reported for GPFARM-Range, which overestimated the effects of dry conditions (Ma et al., 2019). Annual and spring precipitation were higher in 2017 than in 2016, but APEX underestimated warm-season perennial grass biomass in 2017 because it did not adequately represent the effects of limited precipitation in June 2017 (9 mm). Due to drought conditions beginning in November 2016, drought stress was severe in the beginning of the 2017 growing season, which reduced warm-season perennial grass biomass production.

As mentioned by Zilverberg et al. (2017), APEX is not flexible enough to simulate dramatic temporal shifts in plant drought stress. Likewise, GPFARM-Range failed to simulate rapid vegetation recovery after a severe drought in the Great Plains (Andales et al., 2006; Fang et al., 2014; Qi et al., 2012). In APEX, biomass and leaf area gradually decline after maturity, and the transfer from belowground biomass to aboveground biomass reinitiates with plants growth in the spring (Zilverberg et al., 2017). Since APEX does not reset plant densities each year, we used average plant densities to initialize each plant functional group.

Measured total aboveground biomass was not significantly different between CARM and TRM treatments in each year ($p = 0.89$) (Fig. 1b; see also Augustine et al., 2020). Simulated peak biomass inside exclusion cages ranged from 667 to 1230 kg ha^{-1} under CARM and from 723 to 1357 kg ha^{-1} under TRM across the study years. Seasonal dynamics across years in simulated total aboveground biomass were similar between CARM and TRM inside the exclusion cages. This result supports the idea that season-long and rotational grazing regimes may not differ in overall forage production (Briske et al., 2008, 2011). Temporally variable precipitation inputs and high allocation to root biomass in this ecosystem with a long co-evolutionary history of grazing by large herbivores (Milchunas et al., 1994) may influence forage production more than temporal grazing patterns (Augustine et al., 2020; Briske et al., 2008; Ellis and Swift, 1988). With grazing, simulated peak biomass values outside exclusion cages were lower than inside cages in each year (Fig. 1b), ranging from 478 to 964 kg ha^{-1} for CARM and 477–994 kg ha^{-1} for TRM. Previous studies have also shown that rotational grazing did not affect vegetation growth during the grazing period on North American prairies (Teague and Dowhower, 2003; Teague et al., 2004) and other locations (Briske et al., 2008; Venter et al., 2019).

3.2. Effects of grazing treatment

APEX accurately simulated relative differences in total aboveground biomass outside exclusion cages between grazing treatments. Total aboveground biomass inside cages did not differ between CARM and TRM treatments for either measurements or simulations ($p > 0.05$, as

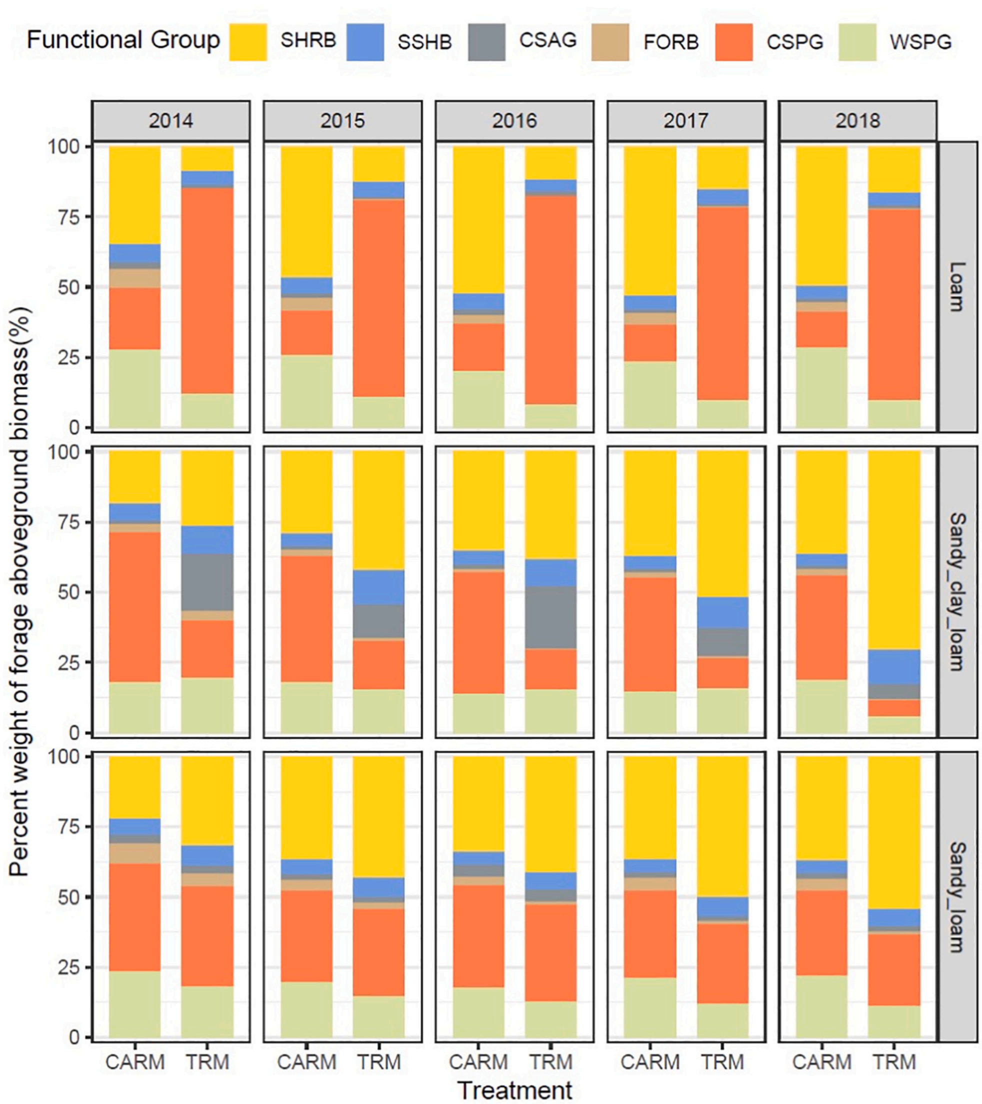

Fig. 3. Simulated forage composition for collaborative adaptive rangeland management (CARM) and traditional rangeland management (TRM). SHRB, shrub; SSHB, sub-shrub; CSAG, cool-season annual grass; FORB, forbs; CSPG, cool-season perennial grass; WSPG, warm-season perennial grass.

tested by LSD, Fig. 1b).

Warm- and cool-season perennial grasses were dominant on this shortgrass steppe site and accounted for 83% of the simulated total aboveground biomass compared to 75% of the measured biomass. There were no significant differences between CARM and TRM treatments in simulated aboveground biomass for warm-season perennial grasses (Fig. 1c), cool-season perennial grasses (Fig. 1d), forbs (Fig. 1e), or cool-season annual grasses (Fig. 1g) ($p > 0.05$), which was consistent with the measured results. The model predicted that CARM decreased sub-shrub biomass by 13% ($p = 0.03$) compared with TRM, whereas field measurements of vegetation responses did not sample this functional group at a sufficient intensity to make such a comparison.

Changes in total aboveground biomass for paired CARM and TRM pastures are shown in Fig. 2. As the grazing season progressed, total aboveground biomass under CARM decreased because of higher stocking density than TRM (keep in mind that annual stocking rates are the same between the two treatments, but stocking density at a given time was much higher with the single CARM herd grazing one pasture). Total aboveground biomass for the corresponding TRM pasture generally increased in the beginning of the grazing season and decreased at the end of the grazing season. These results indicated that total aboveground biomass under the CARM treatment was lower at times relative to the corresponding TRM pasture even though the average total aboveground biomass among 10 pasture pairs was similar (Fig. 1b).

3.3. Effects of soil texture

Simulated warm-season perennial grass biomass on sandy loam soil (403 kg ha^{-1}) was significantly higher than on other soils (302 kg ha^{-1} for loam soil and 270 kg ha^{-1} for sandy clay loam soil), but measured values were similar among soil types (Supplementary Material Table 4A). Sandy loam soils had deeper water infiltration and less evaporation during the grazing season, which increased the simulated water availability. The inverse texture hypothesis assumes that in arid and semi-arid regions, soils with high sand content lose less evaporative water than soils with greater clay and silt content, and thus have deeper water infiltration and ultimately higher water availability for plant growth and development (Augustine et al., 2017). Renne et al. (2019) found that coarse-textured soils supported greater plant cover than fine-textured soils in the North American temperate semi-arid steppe. There was no significant difference among soil textures in simulated total aboveground biomass and in simulated biomass for cool-season perennial grasses ($p > 0.05$, Supplementary Material Table 4A), which was consistent with the measured results. Simulated forb and sub-shrub

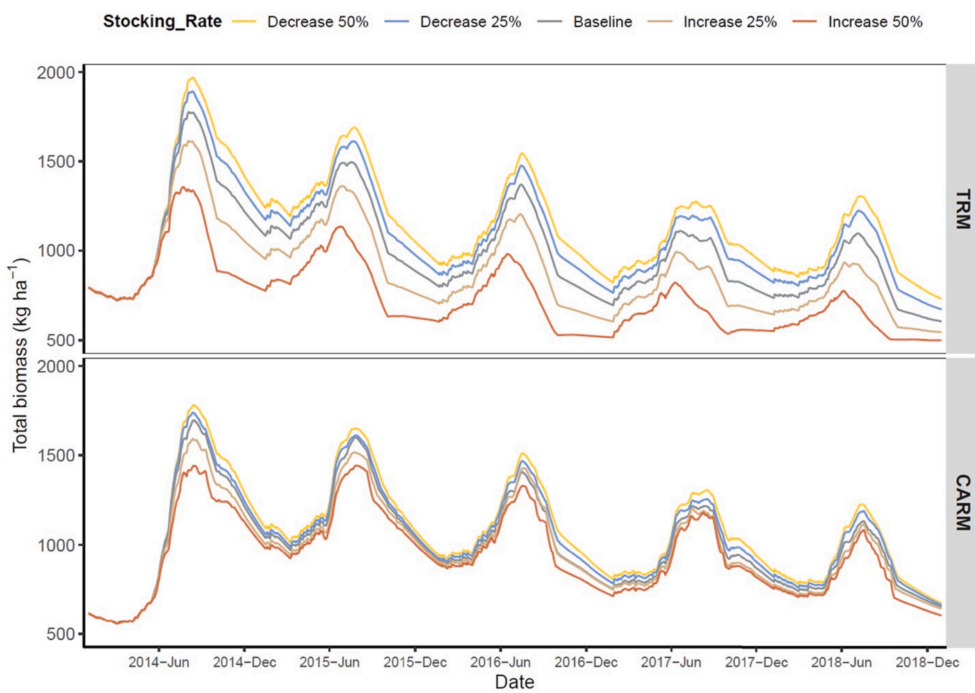

Fig. 4. Average simulated total aboveground biomass across 10 pastures for different stocking rates [actual/experimental (baseline), ±25%, ±50%] under collaborative adaptive rangeland management (CARM) and traditional rangeland management (TRM).

biomass were highest for sandy loam soils (88 kg ha^{-1} for forb and 98 kg ha^{-1} for sub-shrub), which is consistent with measured results (145 kg ha^{-1} for forb and 82 kg ha^{-1} for sub-shrub), although the measured forb biomass did not differ among soil types. These results indicated that APEX was able to simulate relative differences in aboveground biomass of cool-season perennial grasses, forbs, and sub-shrubs among soil textures. Measured biomass for cool-season annual grass was similar among soil textures, but simulated biomass for cool-season annual grass on the sandy clay loam (81 kg ha^{-1}) was higher than on the loam soil (19 kg ha^{-1}).

Simulated forage composition was affected by weather, grazing management, and soil texture. Forage composition was similar among years under the TRM treatment on the loam soil, which produced more cool-season perennial grass aboveground biomass than other soils. Cool-season perennial grass was dominant in all five years on loam soils accounting for 68–74% of total aboveground biomass under TRM (Fig. 3); however, this percentage decreased from 22% to 13% from 2014 to 2018 under CARM while shrub increased from 35% to 50%. This is attributed to higher palatability and grazing preference of cool-season perennial grasses (C_3) than warm-season perennial (C_4) grasses (Augustine et al., 2017; Scheirs et al., 2001).

On the other hand, the percent of cool-season perennial grass decreased as shrub biomass increased under both grazing treatments on sandy clay loam soils. The proportion of warm-season perennial grass, cool-season perennial grass, and cool-season annual grass decreased by 13%, 15%, and 15% relative to total forage under TRM. In contrast, CARM maintained the same proportion of warm-season perennial biomass for the sandy clay loam soil from 2014 to 2018. For TRM on sandy loam soil, the percentage of cool-season perennial grass and warm-season perennial grass decreased by 10% and 7%, respectively, after five years, while the percentage of shrub biomass increased by 22%. For CARM on sandy loam soil, the percentage of cool-season perennial grass and warm-season perennial grass biomass decreased by 9% and 2%, respectively, after five years, while the percentage of

Table 1
Simulated aboveground biomass (kg ha^{-1}) for plant functional groups in response to ±25% and ± 50% changes in stocking rate[a] for collaborative adaptive rangeland management (CARM) and traditional rangeland management (TRM).

Functional group	Actual	Decrease 25%	Decrease 50%	Increase 25%	Increase 50%
CARM					
Shrub	651 a	651 a	652 a	651 a	652 a
Cool-season perennial grass	517 a	539 a	555 a	489 a	460 a
Forbs	92 a	94 a	95 a	89 a	87 a
Sub-shrubs	94 a	94 a	95 a	94 a	94 a
Cool-season annual grass	45 a	45 a	46 a	45 a	45 a
Warm-season perennial grass	321 a	326 a	334 a	315 a	312 a
TOTAL	1720 a	1749 a	1775 a	1684 a	1650 a
TRM					
Shrub	592 a	594 a	595 a	589 a	584 a
Cool-season perennial grass	559 a	603 a	633 a	492 a	382 a
Forbs	49 ab	60 ab	68 a	35 bc	18 c
Sub-shrubs	101 a	101 a	102 a	101 a	101 a
Cool-season annual grass	60 a	63 a	64 a	57 a	51 a
Warm-season perennial grass	234 bc	274 ab	304 a	179 c	100 d
TOTAL	1595 ab	1695 a	1766 a	1453 ab	1236 b

[a] Stocking rates that do not share the same lowercase letter in a row were significantly different ($P < 0.05$, as tested by LSD) in aboveground biomass within either CARM or TRM.

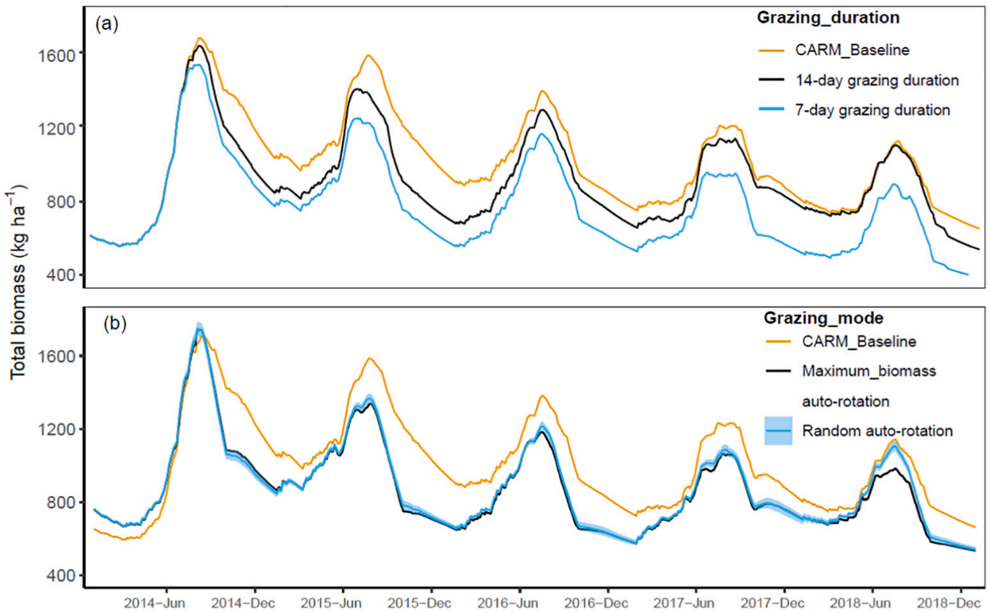

Fig. 5. Average simulated total aboveground biomass across 10 pastures under different grazing management scenarios: (a): 7-day, 14-day, and CARM-determined grazing intervals; (b) 14-day grazing interval with herds rotating to the pasture with highest simulated biomass or to a randomly selected pasture (shaded area around the random auto-rotation shows the standard deviation of 100 random rotations).

Table 2
Simulated aboveground peak biomass (kg ha^{-1}) for six plant functional groups in response to grazing duration[a].

Functional group	14-day grazing duration	7-day grazing duration	CARM-determined duration
Shrub	587 a	435 b	651 a
Cool-season perennial grass	501 a	503 a	517 a
Forbs	84 a	73 a	92 a
Sub-shrubs	94 a	94 a	94 a
Cool-season annual grass	46 a	45 a	45 a
Warm-season perennial grass	304 a	265 a	321 a
TOTAL	1616 a	1415 a	1720 a

[a] Grazing durations that do not share the same lowercase letter in a row were significantly different ($P < 0.05$, as tested by LSD) in aboveground biomass.

shrub biomass increased by 15%. These results suggest that CARM could mitigate shrub biomass increase relative to TRM on sandy clay loam and sandy loam soils but could increase shrub biomass on loam soils. The results suggest that pastures with loam soil under CARM should be grazed earlier in the rotational sequence to encourage cool-season perennial grass regrowth after grazing and encourage shrub consumption.

3.4. Effects of alternative grazing management scenarios

One of the primary limitations of large-scale field studies such as those comparing season-long and rotational grazing, is that only a small number (often just two) of grazing treatments are implemented and often with a single stocking rate (e.g., Augustine et al., 2020). Using the calibrated APEX model, we found that changing stocking rate relative to the actual/experimental rates by 25% or 50% had little effect (< 10% change) on total aboveground biomass for CARM (Fig. 4). In contrast, simulated total aboveground biomass under TRM decreased 11% for the 25% stocking rate increase and decreased 23% for the 50% stocking rate increase. These results suggest that despite the lack of a difference between CARM and TRM in forage production at current stocking rates, CARM could reduce interannual variation in forage production at higher stocking rates. Similarly, stocking rates under CARM did not affect simulated peak aboveground biomass for each plant functional group. For TRM, peak aboveground biomass of warm-season perennial grass decreased by 57% and that of forbs by 63% for the 50% stocking rate increase, but cool-season perennial grass, cool-season annual grass, sub-shrub, and shrub biomass were not affected (Table 1).

Grazing duration is another important component of rangeland management (Wang et al., 2016). In the field experiment, the timing of rotation between pastures (or grazing duration) for the CARM herd was determined by criteria developed by stakeholders and scientists and resulted in 3–8 rotations per year (Augustine et al., 2020). Simulation results showed that aboveground biomass was decreased for 7-day grazing durations (9–21%) and for 14-day grazing durations (3–11%), as shown in Fig. 5a. The 7-day grazing duration significantly decreased shrub peak biomass relative to the actual/experimental CARM durations (Table 2). This 33% reduction is attributed to increased cattle browsing of shrubs and the reduction of shrub LAI and subsequent growth inhibition.

In the field experiment, the rotational sequence (or pattern of rotation) among pastures under CARM was determined by the stakeholder group with triggers inducing herd movement to the next pasture (Wilmer et al., 2018). Compared with the actual CARM rotation pattern, rotating cattle every 14 days to the pasture with highest forage biomass or to randomly selected pastures reduced biomass production both at the peak and throughout the growing season (Fig. 5b). These simulations suggest the collaborative adaptive decision-making under CARM was quite effective. The success was likely due to the flexibility to match demand to forage availability within the grazing season, which capitalized on inherent spatiotemporal variation in plant communities, phenology, precipitation, and forage production (Derner et al., 2021).

4. Conclusion

In this study, we demonstrated that APEX appropriately simulated relative differences in aboveground biomass under traditional and adaptive grazing management systems. The calibrated model also was able to accurately simulate the impacts of annual precipitation, soil texture, and alternative grazing management scenarios on total biomass production and production of plant functional groups. These results indicated that APEX was capable of assessing grazing management decisions on forage production and to improve decision-support for adaptive grazing management in semiarid environments such as Western Great Plains rangelands; however, additional refinement is needed to better simulate impacts of high intra-annual precipitation variability on forage production.

Declaration of Competing Interest

I know of no conflict of interest that should be reported for "Evaluation of APEX modifications to simulate forage production for grazing management decision-support in the Western Great Plains" by G. Cheng, R. D. Harmel, L. Ma, J. D. Derner, D. J. Augustine, P. N. S. Bartling, Q. X. Fang, J. R. Williams, C. J. Zilverberg, R. B. Boone, D. Hoover, and Q. Yu for publication in Agricultural Systems.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2021.103139.

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