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Research article

Vegetation, water infiltration, and soil carbon response to Adaptive Multi-Paddock and Conventional grazing in Southeastern USA ranches

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ABSTRACT

We examine Adaptive Multi-Paddock (AMP) grazed with short grazing events and planned recovery periods and paired ranches using Conventional Continuous Grazing (CG) at low stock density on vegetation, water infiltration, and soil carbon across SE USA. Increased vegetation standing biomass and plant species dominance-diversity were measured in AMP grazed ranches. Invasive perennial plant species richness and abundance increased with AMP grazing in the south, while in the north they increased on CG grazed ranches. Percent bare ground was significantly greater in CG at the Alabama and Mississippi sites, no different at the Kentucky and mid-Alabama sites, and greater on AMP at the Tennessee pair. On average, surface water infiltration was higher on AMP than paired CG ranches. Averaged over all locations, soil organic carbon stocks to a depth of 1 m were over 13% greater on AMP than CG ranches, and standing crop biomass was >300% higher on AMP ranches. AMP grazing supported substantially higher livestock stocking levels while providing significant improvements in vegetation, soil carbon, and water infiltration functions. AMP grazing also significantly increased available forage nutrition for key constituents, and increased soil carbon to provide significant resource and economic benefits for improving ecological health, resilience, and durability of the family ranch.

1. Introduction

Grazing ecosystems have coevolved with ruminants (Frank et al., 1998) and grasses and soil biota over the last 40 million years that has been linked to the global expansion of carbon-rich soils in grassland regions, covering ~40% of the global land area (Retallack, 2013). However, in most rangelands, free-ranging wild herbivores have been replaced by fenced-in livestock and frequently this has resulted in the degradation of vegetation and soils (Milchunas and Lauenroth, 1993; Teague et al., 2011) resulting in declines in productivity, biodiversity, and ecosystem resilience (Archer and Smeins, 1991; West, 1993; Knopf, 1994; Frank et al., 1998). Concurrently, grasslands have also declined from the conversion to row crop agriculture (Wilcove et al., 1986), and overgrazing (Wuerthner and Matteson, 2002). More recently, conversion to corn for ethanol production, especially in the US's northern Great Plains, has documented ~40,000 ha/year grassland reductions annually since 2010 (Lark et al., 2019).

Plant community composition, structure, diversity, and productivity have been extensively used to measure rangeland ecological services including soil health, soil formation, soil carbon and stability, water infiltration, including water and nutrient cycling, biodiversity, air quality, wildlife habitat and biological integrity. Rangelands comprise the largest acreage of the Earth able to produce food, fiber and fuel (Daily, 1997; Kimble et al., 2007). However, these extensive ecosystems are have been challenged for growing crops and to provide habitat for the wild grazing herbivores they depend on for their livelihoods. Ruminants coevolved with the biota of these ecosystems and they play a valuable role in sustaining ecosystem function and biodiversity of grassland ecosystems globally.

In the Southeastern USA, where there are no extensive remaining

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grasslands, a documented decline from historic grasslands and savanna systems is only now being recognized (Southeast Grasslands Initiative 2019). Now pine plantations, or succession to red maple (*Acer rubrum*), tulip poplar (*Liriodendron tulipifera*) or other early colonizing and often invasive woody plant species has occurred (Apfelbaum and Haney, 2010; Ryan, 1986). Past studies of Southeastern USA vegetation systems did not recognize the extensiveness of grasslands, barrens and savannas at ~100 M acres (~41 M ha) across 23 states they occupied, (Southeast Grasslands Initiative 2019) and now ~1%, remains.

Wildfire and native ungulate grazing suppression caused increased runoff and soil erosion, and drainage, proliferation of invasive plants, and exotic wildlife introductions contributing to biodiversity collapse (Apfelbaum and Haney, 2010; Saab and Powell, 2005; Samson et al., 2004; Waters, 2019; Chesser et al., 2019; Rosenberg et al., 2019). These sparse estimates mirror the better documented declines in western grassland vegetation systems and wildlife (Wuerthner and Matteson, 2002), but at this time, only estimates of Southeastern USA acreage of historic grasslands exists.

Livestock grazing involves the interaction of livestock, vegetation, soil, water, and human decisions, resulting in ecosystem structure and functional changes (Conant et al., 2017; Godde et al., 2020; Hewins et al., 2018). Changes have resulted from altered frequency and intensity, seasonality, duration, stocking density and stocking rates with the introduction of domestic livestock. Various grazing management strategies have been developed to provide sustainable resource and economic outcomes. These include continuous grazing (*CG*), rotational grazing (*RG*), and adaptive multi-paddock grazing (*AMP*) and involve use of different numbers of paddocks per herd, provision of planned post-grazing recovery periods, and different stocking rates and densities (Teague et al., 2013; Teague and Barnes, 2017). For CG and RG there are well documented impacts to vegetation composition and structure (Souther et al., 2019; Su et al., 2017), plant productivity and biomass (Biondini et al., 1998; Hillenbrand et al., 2019; Su et al., 2017), root productivity (Hao and He, 2019), decomposition and soil microbial community (Kooch et al., 2020; Wang et al., 2018; Xun et al., 2018), hydrological responses and soil carbon and mineral cycles (Abdalla et al., 2018; Conant et al., 2017; Godde et al., 2020; Hao and He, 2019; Hewins et al., 2018; Lu et al., 2017; Ritchie, 2020; Wagle and Gowda, 2018). This paper is focused on comparing CG and AMP grazing in the SE USA.

Resource degradation, due to constant grazing pressure on preferred areas and plants, with no planned recovery after grazing, especially under heavy continuous grazing (HCG), becomes more prevalent and damaging (Fuls, 1992; Mü;ller et al., 2014). A higher percentage of bare ground, a low proportion of high seral and desirable grasses and forbs and high proportions of less desirable short grasses, cool C_3 grasses, and annual forbs, and the lowest standing crop biomass, compared to AMP grazing management damages the soil, vegetation and economic viability (Müller et al., 2014).

In this study we examine the effect of *AMP* and *CG* grazing management on 1) plant species richness, diversity, dominance, and cover as a measure of abundance on paired "across the fence" AMP and CG ranches, and where possible within a Reference Natural Area (RNA) context; 2) vegetation standing crop biomass, and 4) water infiltration, soil carbon levels, bare ground, fine litter cover and nutrient cycling indicated by cow pat % cover under these grazing practices.

2. Methods

2.1. Experimental design

To understand the impacts of different grazing management on commercial scale ranches, we avoided the challenges of attempting to conduct controlled, small-scale replicated evaluations of variables and treatments because landscape-scale variability, year to year control over management have been misleading at best (Teague and Barnes, 2017). This study has focused on providing results of utility to the science and ranching community from large heterogenous landscapes managed under often highly variable weather conditions, with designed sample sizes over representative land and time periods and supporting re-measurement (Hargrove and Pickering, 1992; Teague et al., 2011). The resulting focus on science and practice understandings on real commercial operations, where adaptive treatments, and scale and heterogeneity effects of grazing animal resulted in this study being focused with the leading AMP ranchers in the South-eastern USA, and neighboring CG ranches representative of local conventionally managed ranches.

This study consequently i) addresses questions at commercial ranch scales; ii) use a whole-system framework to integrate component science elements; iii) incorporated pro-active management to achieve desired rancher goals under changing circumstances; iv) to identify emergent properties in an attempt to encompass and inform of any unintended consequences; and v) extend the usefulness of information developed in research to land managers (Teague et al., 2013; Van der Ploeg et al., 2006) for grazing management categories outlined by Hargrove and Pickering (1992) and Teague et al. (2011).

To achieve this, we compare AMP and CG "across the fence" in ranch pairs located in Kentucky, Tennessee, Alabama, and Mississippi. We have biophysically stratified for soil texture, slope, aspect, slope position, depth to bedrock, depth to ground water table, land use, and grazing practices and use this process to identify "paired soil catena's on AMP and neighboring CG ranches.

2.2. Site screening and selection

We used the "across-the-fence" comparison framework used by Teague et al. (2011) to compare "best in class" comparisons of AMP grazed and well-managed CG (conventional continuous) paired neighbors. We obtained a list of potential AMP managed ranches from regional Natural Resource Conservation Service (USDA-NRCS) agency technical staff, grazing consultants and rancher organizations (e.g., Grassfed Exchange, others). Candidate AMP ranchers we solicited to participate in an online survey, to begin a multi-stage screening process to understand the details of their ranch management history over the previous ten years, including cattle stocking rates, typical stocking density, history of planting, fertilization, liming, mowing, herbicide use, worming use, cropping, size and number of paddocks per herd, frequency of moves (multiple times per day, once a day, once a week, once a month, etc.), and recovery period length. Each prospective AMP rancher was queried to find a well-managed CG grazer in the same location. Ranch pairs (Fig. 1) required matched soils, slope, aspect, and land use history with the primary deviation being the conversion of a former CG managed ranch to AMP grazing management (Table 2).

Step 2 in the process involved an independent review of responses by AMP grazing scientists Drs. Richard Teague and Allen Williams, culminating in a sort of ranches meeting AMP criteria including a representative well-managed CG neighbor. Step 3 involved a telephonic follow-up to clarify on-line survey responses. Step 4 involved a field validation visit during Spring 2018 when ecologists, grazing expert Dr. Richard Teague, and soil scientist Dr. Tom Hunt confirmed the AMP and CG grazing details, land-use history, and comparable biophysical details and rancher willingness to share socioeconomic, production, and land management details and data. At each ranch during this pre-study visit, soil cores were sampled to assess the accuracy of soil maps, including comparability of primary shared soil catenas between available AMP and CG ranches, followed by a determination that randomized measurements of all variables to be measured could be spatially accommodated. We also sought the nearest reference natural areas (RNA's) meeting the same biophysical conditions through inquires with The Nature Conservancy, State Departments of Natural Resources, US Forest Service, Southeast Grasslands Initiative, US Military, and others, and screened to ensure they were native grasslands/savanna systems, and

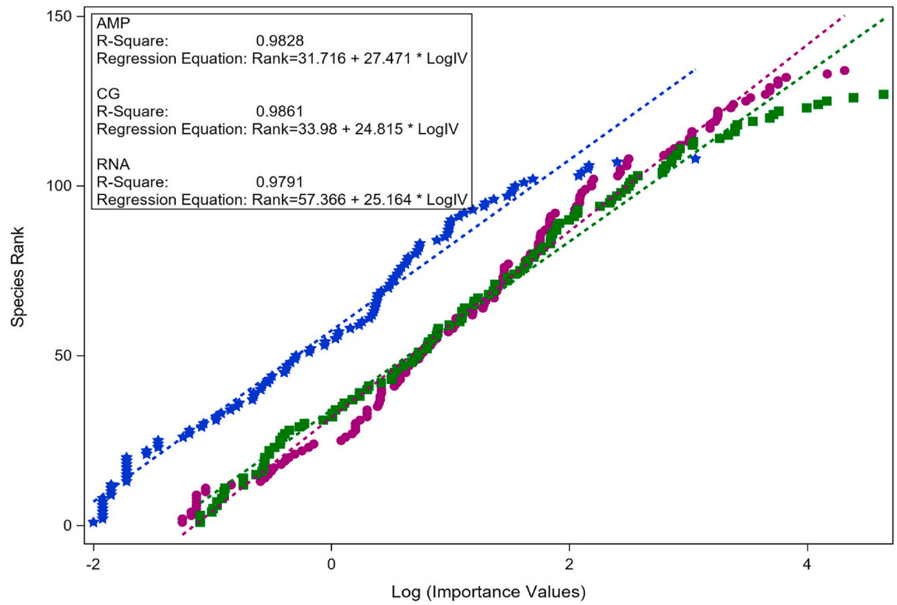

Fig. 1. Plant species importance values for paired AMP, CG and Reference Natural Areas.

Table 2
Soil series and hydrological properties of soils (USDA-Natural Resource Conservation Service, 2009) by farm pair for AMP and CG farm pairs.

Farm pair	Catenal position	Soil series	Map unit	Slope %	Taxonomic classification
Pair 1	Flat Slope	Trimble gravelly silt loam	TrB2 TrC2	2–6 6–12	Fine-loamy, siliceous, semiactive, mesic Typic Paleudults
Pair 2	Flat Slope	Emory silt loam Cumberland silty clay loam	Ea Cm	0–2 2–5	Fine-loamy, siliceous, semiactive, thermic Typic Paleudults Fine, mixed, semiactive, thermic Rhodic Paleudalfs
Pair 3	Flat Slope	Hartsell fine sandy loam	Hc Hd	2–6 6–10	Fine-loamy, siliceous, subactive, thermic Typic Hapludults
Pair 4	Flat Slope	Cumberland gravelly loam Cumberland gravelly clay loam	CoB2 CrC3	2–6 6–10	Fine, kaolinitic, thermic Rhodic Paledudults Fine, mixed, semiactive, thermic Rhodic Paleudalfs
Pair 5	Flat Slope	Loring silt loam	12B2 12C2	2–5 5–8	Fine-silty, mixed, active, thermic Oxyaquic Fragiudalfs

we had access approvals this study.

2.3. Study ranches and reference natural areas

Five paired *AMP* and *CG* ranches and three RNAs were selected in the Southeastern USA with closely comparable biophysical conditions on neighboring ranches, and with nearest reference natural area.

2.4. Study layout

Detailed GIS biophysical mapping and a randomized study area layout of the replicated, nested design in two primary soil catenal positions on each ranch pair was evaluated, to ensure the statistical design for soil carbon and vegetation (and other study modules: soil microbiology and genomics, hydrology (water infiltration), insects, breeding birds, greenhouse gas (GHG) Flux tower emissions measurements could be achieved. In this paper, we report on vegetation, hydrology, and summarize soil carbon findings. We attempted to "pair" reference natural areas with each grazing study site, but we were unable to find remaining natural areas for each grazed site meeting the biophysical match requirements. Consequently, natural area data only provides a context to the livestock grazing study findings.

2.5. Vegetation measurements

2.5.1. Macro-regional scale

Two of the primary shared soil catenas present in the AMP and CG ranches were sampled in each ranch with random 1-m square quadrats located within three slope position zones – upper, middle, and lower areas – in each catena. Thus, in each ~30–50 m width slope position zone, seven randomly located 1-m square quadrats were established for vegetation data collection. Each zone and its random array of quadrats by slope position zone, have been designated for nomenclature and computer coding ease as being present within zones, or belt transects, we refer simply to as transects. In each sample quadrat, plant species, % cover and % frequency of each species over all quadrats, % bare soil, % fine (dead stem litter) and % coarse litter (>4 cm in any dimension), % rock, % cow pat cover. Shrub (<1 m height and <4 cm DBH) and tree intercept (cover >1 m height and >4 cm DBH) were measured within the same quadrats with all measurements in late-April through early-May 2018.

Specifically, each plant species and other variables were measured for percent coverage in 1 m^2 circular quadrats. Herbaceous species frequency was calculated as the percentage of the total number of quadrats occupied by each plant species, and plant cover was averaged across all quadrats in each of three slope position zones established in contour zones in the upper, middle and lower slope position, in the two soil catena on each ranch.

Plant species richness (the number of different species) was calculated as the total and average number of plant species per quadrat in each slope position zone by catena. We calculated plant species dominance using the % cover and % frequency of each species across all quadrats in each slope position. Then, the absolute cover and frequency were relativized, expressed as a percent of 100%. To compare species, we summed relative frequency (RF) and relative cover (RC) to create an Importance Value (IV) equal to 200% across all species within each catena (Apfelbaum and Haney, 2010). Plant taxonomy follows Gleason and Cronquist (1991).

Mapping the vegetation community and standing crop biomass was conducted using on-the-ground field mapping and measurement procedures and with remote sensing (Hillenbrand et al., 2019) using high-resolution multi-temporal and multi-spectral airborne aerial photography and satellite imagery and an assisted classification of land cover/vegetation and biomass measurements in each ranch. This mapping used field calibrated spectral signatures of on-the-ground identified and GPS geo-referenced sampled quadrat locations and targeted georeferenced stands of dominant native plant species, planted forage species, and invasive and native weedy plant species following the procedure in Hillenbrand et al. (2019). Remote sensing classification of vegetation, plant species mapping, and standing crop biomass estimation utilized WorldView-3 Satellite imagery.[1] Additionally, whole plot biomass clips to 2.54 cm of the ground surface in1-meter square quadrats randomly allocated across the vegetation communities and standing crop biomass mapped zones.

Dominance Diversity Analysis (DDA) was completed for the plant community using the seven 1 m-square sample quadrats from each of the transects used Importance Values calculated as described above and used SAS GENMOD, and log transformations to linearize regressions. Regression equations and R-Squared values for all DDA regressions were plotted on a single graph to understand dominance diversity relationships among AMP, CG and RNAs. Clusters of linear regressed plots were then characterized with a centroid (mean) linear regression for AMP, CG and RNAs, using 95% confidence limits.

2.5.2. Micro scale sampling

2.5.2.1. Vegetation measurements. We sampled herbaceous vegetation composition and biomass during three periods - spring, summer, and fall – for the 5 AMP and CG pairs. For grazing pairs, soils of 2 slope positions—ridge & mid-slopes in the same two catenas and transects where the macro-scale sampling of vegetation and soils was conducted. During the three sampling periods fifteen 0.10 m^2 quadrats were measured for bare ground, dead vegetation litter cover, and herbaceous coverage. Additionally, the proportion of live leaf, forb weight, and grass weight were estimated and ranked for the top 3 grass and top 3 forb species, yielding herbaceous composition using the dry-weight-rank method (Dowhower et al., 2001). Biomass was clipped at the ground level and wet weight recorded and subsamples for forage nutritional quality were drawn from composited samples across each slope zone. Biomass results were further summarized by functional groups: annual forbs, perennial forbs, annual C_3 grasses, perennial C_3 grasses, perennial C_4 grasses and dry weight was recorded.

2.5.2.2. Water infiltration measurements. Grazing treatment relations with soil water infiltration were measured using a SATURO dual head infiltrometers,[2] which measures field saturated hydraulic conductivity. Four points were randomly allocated along the 3 transects in each catena ($n = 4$). This resulted in 8 infiltrometer tests per ranch treatment ($n = 8$). Because only one study catena was selected in each RNA, only 4 infiltrometer tests were completed ($n = 4$). The infiltrometer set-up followed the procedures manual for antecedent soil conditions of moisture and texture. Dry or clay soils required a long pre-soak period to standardize for soil moisture. Once the appropriate settings were keyed into the infiltrometer, water levels maintained the constant test "water level" and head pressures established as a part of the standard test. After the machine ran for 90 min to over 3 h, depending on site settings, saturated field conductivity results were downloaded. These were collated in excel spreadsheets and student "t" tests of mean infiltration rates ("k") values were evaluated.

2.5.2.3. Soil carbon measurements. Soil sampling followed VM0021 "Soil Carbon Quantification Method" (Verra, 2011), an approved technical method designed and approved for the carbon marketplace. At the two selected soil catenas in each ranch, the same 42 randomly located macro-scale vegetation sample points were also sampled for soil carbon, and a subset were sampled for infiltration.

At each georeferenced random point along the transect, a 1-m depth soil core was extracted with a Giddings[3] hydraulic sampler mounted on a Polaris Ranger 6 × 6. The 2" (~5 cm) diameter soil cores were extracted in plastic sleeves, which were capped at both ends, labeled with a bar code label, stored in a large heavy duty wood crate and shipped to the Colorado State University Natural Resources Ecology Laboratory (NREL) for all soil carbon and soil health analyses.

At the laboratory, the sampled were divided into strata (e.g. topsoil-"A" horizon) and depth increments (bottom of topsoil to 30 cm, 30–50 cm, 50–100 cm) which were separated, homogenized, and sieved to remove and quantify materials such as roots, rocks, and litter. A subsample of each core depth increment was dried and measured for gravimetric water content. Bulk density was determined by weighing a standard volume, subtracting the mass of the removed materials for each depth increment, after oven drying at 60 °C. Soils were analyzed for total soil carbon, and organic and inorganic carbon levels.

2.5.2.4. Ecological function assessments. The percent cover of key ecological parameters was measured, including bare ground, cow pat cover, percent exposed rock, bryophytes, coarse litter (diameter >5 cm), fine litter (diameter <5 cm), and cover of cattle dung. Where fire ant (*Solenopsis* spp.) mounds were encountered, these were also summarized by creating averages for each transect. The randomly placed quadrats for the detailed vegetation sampling were GPS surveyed to submeter accuracy.

2.6. Statistical analyses

Data analysis assumptions for use of various statistics were tested, followed by the creation of summary statistics. An "outlier analysis" was applied equally to AMP and CG data. A generalized linear model was fit to the data to evaluate if plant and vegetation metrics were statistically different across paired grazing sites. Regression analysis was also used to evaluate spatial trends measured from aerial photography and satellite imagery with the on-the-ground measures of soils, vegetation, biomass, infiltration, land cover and plant species identifications. All statistical tests were run using a 95% ($p < 0.05$) probability level using SAS[4] software.

Effect of grazing practices on vegetation species richness was analyzed by using SAS GENMOD procedure. It fits generalized linear models to data by allowing the mean of a population to depend on a linear predictor through a nonlinear link function and allows the response probability distribution to be any member of an exponential family of distributions. Since the richness was a count data type, a Poisson distribution and a Log link function we adjusted for a zero inflated dataset, Tweedie distribution and a Log link function were used in model fitting.

For water infiltration, the statistical analysis compared mean "k" values for each paired treatment (AMP/CG pairs) and RNAs were summarized as a point of reference. Gaussian response distributions and

[1] http://www.satimagingcorp.com/satellite-sensors/worldview-3/.
[2] https://www.metergroup.com/environment/products/saturo/.
[3] Giddings Machine Company, Windsor, CO (www.soilsample.com).
[4] www.sas.org.

Kenward-Roger degrees of freedom and Fixed effects standard error adjustment procedures were used.

Soils data analysis was initiated after evaluating if the data met distributional assumptions required to use various statistical tests, followed by generating simple summary statistics. Paired treatment effects within and among pairs, and for RNAs were tested at $p < 0.05$.

The micro-scale vegetation data were analyzed using the MIXED MODEL (SAS Institute, 2016). A randomized block design was used with the main effects of Grazing treatment and Location and Month. Slope position was treated as a replication so the random variables in model were Grazing × Location × Slope. Month was a repeated measure. Means and probabilities of differences were based on LS-means comparisons.

3. Results

3.1. Vegetation percent cover

Under the CG grazing treatment, the total perennial plant cover (%) at the two northerly sites (P1-KY, P2-TN) had 30–40% higher average cover than in the paired AMP ranch (Table 3). Conversely, in the southerly sites (P3-AL, P4-AL, P5-MS), plant cover in the AMP ranch had 60–100% greater plant cover than the paired CG sites.

Plant cover of C_4 photosynthetic pathway plant species (Table 3) was higher in the southern CG than AMP ranch pairs (P4 and P5). Conversely, in the northern ranches (P1, P2, and P3) there was little difference in C_4 plant cover among CG and AMP ranch pairs despite some significant differences.

C_3 plant cover was higher in the AMP than paired CG sites at P4 and P5, while in the two most northerly locations (P1-KY and P2-TN), CG had higher C_3 cover than AMP paired sites. At the midway between north and south in P3 the C_3 plants were equally abundant.

Cover of exotic perennial plants was significantly higher in CG than AMP ranches in Kentucky (P1) and Tennessee (P2) and marginally higher in the central location in northern Alabama (P3). In the two southerly locations in Alabama (P4) and Mississippi (P5), exotic perennial cover was higher in AMP than CG ranch pairs by a factor of 2 to over 60 times.

Native perennial plant cover was significantly higher in CG ranches in P1 and P4, while in P5, AMP was greater than in the CG ranch pair.

Exotic annual/biennial plants were only present in small amounts and higher cover in AMP than CG ranch pairs at sites P1 and P4. Exotic annual and biennial plant cover generally averaged less than 10% except in the P5 where there was no significant difference and both AMP and CG, where it averaged 50–60% average coverage.

Cover of native annual/biennial plants was higher in P1, P2 and P5, while *CG* had higher cover than *AMP* in pair P4.

Total native graminoid percent cover was significantly higher in all CG sites except not significantly different with AMP percent cover in Pairs 1 and 3. AMP pairs had significantly higher native graminoid percent cover only in Pair 5. Native graminoid percent cover ranged from 1.5 to slightly over 10% in the CG ranch at P5, while at P4 the CG ranch pair coverage of native graminoids ranged from 50 to 70%. In P5, AMP ranch native graminoid percent coverage was ~45%. Total native graminoid percent cover in CG was up to 25 x greater total native graminoid cover than AMP in the other ranch Pairs (P1, P3, P4).

Total native forb percent cover was 3–4 x higher in northern AMP ranches, and significantly higher in AMP P1 and P2. AMP P3 was numerically higher, but not significant. The CG ranch at P4 was significantly higher than AMP % cover.

Exotic graminoid percent cover was higher in CG than AMP ranch in P1, P2, and P5. In Pair 2, exotic graminoid cover was higher in CG than the paired AMP site.

Bryophytes and surface algal growths (e.g. *Nostoc* spp.) were present in only one of the of the CG sites (Table 2).

3.2. Non-vegetation cover

In RNAs bare soil ranged from 0.7 to 3.6% (average = 2.2%) (Table 4). *AMP* sites ranged from 2.7 to 21% in P3 and P2, respectively, while at P2 and P5 *CG* ranch pairs it ranged from 3.3 to 25%. *AMP* and *CG* sites generally greatly exceeded the percent bare soil of reference natural areas. Bare soil was greater with *CG* than *AMP* at P3 and P5, not significantly different at P1 and P4, and greater with *AMP* than *CG* at site P2 (Table 4).

Fine litter percentage in *AMP* sites ranged from 76 to 94% over all sites. In *CG* ranches fine litter ranged from 4.6 to 96% in P5 and P2. Reference natural areas averaged 94% and ranged from 94 to 99%. Fine litter was more consistently higher in the reference natural areas. Fine litter cover was greater with *AMP* than *CG* at site P1, P3, and P5 but greater in CG in site P2, and not significantly different at P4 (Table 4). Fine litter in all reference areas exceed 89%.

Rock and coarse litter cover approximated 1% in the reference natural areas. Only in AMP P4 was coarse litter significantly higher than the corresponding CG pair; 7.6 vs 1.3%. Rock was not represented across any of the treatments or natural areas.

Livestock dung was measured at zero in the reference natural areas and also in the AMP P4 treatment but was <3% in all treatments except in the *CG* treatment in P3 where it was measured at 8%. Livestock dung cover was greater with *CG* than *AMP* at P1, P3, P4 and P5 and was not significantly different at P2 (Table 4).

Table 3
Vegetation cover (%) for paired AMP (n = 42), CG (n = 42) and Reference Natural Areas (Significance at $p < 0.05$).

Ranch pairing	Pair 1			Pair 2			Pair 3			Pair 4			Pair 5			RNA		
	Amp	CG	Sig	Amp	CG	Sig	Amp	CG	Sig	Amp	CG	Sig	Amp	CG	Sig	Site 1 n = 21	Site 2 n = 21	Site 3 n = 2
Bryophyte,	0.0	0.0		0.0	0.0		0.0	0.0		0.0	0.0		0.0	0.0		1.5	0.0	0.0
Total perennial	13	182	*	111	143	*	121	112	*	138	75	*	79	31	*	128	140	163
C4 perennials	1	3	*	0.6	0.0	*	0.0	0.8		1.8	52	*	0.1	13	*	55	55	63
C3 perennials	148	182	*	118	144	*	125	119		149	35	*	181	73	*	76	87	102
Exotic perennials	119	169	*	109	140	*	115	104	*	135	16	*	70	29	*	30	0	3
Native perennials	7	13	*	27	3	*	6	8		3	59	*	9	2	*	98	139	160
Non-perennials	3	0	*	0.5	0.5	*	0.0	7	*	8	0.	*	62	54		0.0	0.0	0.0
Native annual	20	2	*	79	3	*	4	2		5	12	*	40	1	*	3	2	2
Native graminoids	9	13		2	4		5	7		3	52	*	46	0.0	*	62	79	86
Native forbs	17	3	*	7	2	*	4	2		4	19	*	4	3		36	56	67
Exotic graminoids	55	103	*	67	74	*	98	88	*	49	12	*	52	62	*	20	0.0	0.0
Total herb cover	149	192	*	126	155	*	131	123		154	89	*	190	88	*			

Table 4
Non-vegetation cover for paired AMP, CG and Reference Natural Areas. For grazing sites (n = 46 and for Reference Natural Area sites n = 21).

Location	Non-vegetation cover (%)														
	Bare soil			Fine litter			Coarse litter			Rock			Livestock dung		
	AMP	CG	p > F	AMP	CG	p > F	AMP	CG	p > F	AMP	CG	p > F	AMP	CG	p > F
Pair 1	6.2	8.3	0.2	93.1	86.4	0.01	0	0	0	0.0	0.0		0.7	3.1	0.001
Pair 2	20.7	3.3	0.001	77.5	95.8	0.001	0.3	0.0	0.1	0.0	0.0		1.4	1.0	0.6
Pair 3	2.7	13.9	0.001	95.8	80.3	0.001	0.1	0.0	0.1	1.2	0.0	0.3	0.7	8.2	0.001
Pair 4	15.7	15.5	0.9	76.4	0.0	0.001	7.6	0.0	0.001	0.0	0.0		7.6	1.3	0.001
Pair 5	3.2	25.1	0.001	96.2	4.6	0.001	0.0	0.0		0.0	0.1		0.5	3.5	0.001
RNA 1	2.4			89.5			1.1			0.2			0.0		
RNA 2	0.7			99.3			0.0			0.0			0.0		
RNA 3	3.6			93.6			2.9			0.0			0.0		

3.3. Plant species richness

Average perennial species richness per square meter, ranged from 2 to 7 species across *CG* and AMP pairs. The average was significantly higher in the southern *AMP* grazed ranch pairs (P4, and P5) and in *CG* ranches in P1, P2, and P3. However, the difference between *AMP* and *CG* ranches across the sampled pairs ranged from the biggest difference in P5, where 2 species were found in the *CG* and 5 species on average in the AMP, to a more typical difference of 1 species difference in the other pairs (Table 5).

The average number of annual species richness present were significantly different across all AMP and *CG* pairs. With the exception of P3 in which the *CG* treatment had the higher annual plant species richness, at all other locations *AMP* ranch pairs (P1, P2, P4, and P5) had the greatest annual species richness (Table 5). The differences ranged from 1 to 2 species more in the *AMP* treatments than the *CG*.

Average native species richness was found to have no differences between *AMP* and *CG* at P1, while at P2 and P5 there were more native species present with *AMP* than *CG* with ~1 species present (Table 5). At site P4, *CG* had higher native species richness than the *AMP* site.

Invasive exotic plant species richness ranged from a low of 1 species in *CG* at P4, which was significantly different from the ~7 species present in the AMP in the same pair. The *AMP* treatment in P1 and P5 had statistically higher invasive plant species richness by 1–2 species, while *CG* had greater exotic species richness than the paired *AMP* treatment at P2 and P3 (Table 5).

3.4. Dominance and diversity patterns

Plant community dominance-diversity used species Importance Values in each AMP and CG ranch pair across each of the six transects (Fig. 1; Table 6) which were plotted to evaluate dominance within the plant community. This analysis suggested the RNAs were by far more diverse with more species sharing the Importance Value. It also suggests CG ranches were the least diverse and that AMP ranches were transitioning ("diverging") toward a higher dominance diversity condition, away from the CG plant community.

The native C_4 grass, broom sedge (*Andropogon virginicus*), was highest in *CG* at P4 and not present in other ranches. The non-native C_3 grass, orchard grass, (*Dactylis glomerata*) had greater cover in *AMP* paired sites in P1, P3 and P4 but was not present in P5 with either *AMP* or *CG* management. Orchard grass was a dominant plant species with CG in P2.

Tall fescue (*Festuca elatior*) had a highly significant percent cover in all *AMP* and *CG* pairs P1, P2, P3, and P4, but was not present in P5. Wherever present, it had higher cover in *AMP* than *CG* paired ranches.

Kentucky bluegrass (*Poa pratensis*) was only present in northern ranch pairs P1, P2 and P3, and had higher cover in the *CG* than *AMP* ranch pairs at P1 and P2, but in P3, it had higher cover in *AMP* than *CG* grazing treatments.

Clovers showed a variable response across treatments and locations. Hybrid clover (*Trifolium hybridum*) was significantly higher in AMP than CG paired ranches in P4 and P5, and was not present in P1, P2, and P3. White clover (*Trifolium repens*) was significantly higher in the CG than AMP treatment in P1, but it was higher in the AMP than CG treatment in P2. It was not present in the other pairs. Red clover (*Trifolium pratense*) was only present in the AMP in P5 where it was significantly higher than in the CG than AMP treatment.

Bermuda grass (*Cynodon dactylon*) only had a meaningful presence with *CG* management at P5.

Annual rye grass (*Lolium multiflorum*) only had a meaningful presence with *CG* management at P5 and was present in equal amounts with *AMP* and *CG* with an average of 48–49% coverage.

The invasive weedy species buttercup (*Ranunculus bulbosus*), path rush (*Juncus tenuis*), and lance-leaved plantain (*Plantago lanceolata*) are indicators of impoverished, compacted and often overgrazed paddocks. They were significantly higher in *CG* treatments in P3 and P2 and were present as a dominant species in the AMP treatment in P4.

3.5. Plant biomass and composition in the vicinity of soil sampling

Standing crop biomass in the close proximity of the soil sampling sites at each location are presented in Table 7. There were no differences between flat and slope catenal positions at each location ($p > 0.8$) so they were used as replicates in the statistical analysis. Over all sites, the mean herbaceous standing crop for the year we sampled (2018) was

Table 5
Herbaceous species richness (# species/m^2) for paired AMP, CG sites (Significance at $p < 0.05$).

Location	Perennial species			Annual species			Native species			Exotic species		
	AMP	CG	Sig.	AMP	CG	Sig.	AMP	CG	Sig.	AMP	CG	Sig.
Pair 1	6.3	7.1		2.3	0.3	*	2.8	2.4		6.6	5.4	*
Pair 2	5.0	6.0	*	1.2	0.8	*	1.8	1.1	*	4.7	5.7	*
Pair 3	4.1	5.2	*	0.3	1.3	*	0.3	1.3	*	3.5	5.1	*
Pair 4 A	5.5	3.4	*	3.0	0.4	*	2.1	4.2	*	6.6	1.4	*
Pair 4 B	5.5	3.4	*	3.0	1.1	*	2.1	4.0	*	6.6	0.6	*
Pair 5	4.8	2.4	*	3.6	2.0	*	2.5	1.0	*	5.9	3.4	*
RNA 1	11.6			0.2			9.6			2.6		
RNA 2	16.8			0.0			17.1			0.0		
RNA 3	8.7			0.0			8.4			0.5		

Table 6
Comparison of dominance of the most abundant plant species (% cover) by farm pair for AMP and CG farm pairs (Significance at $p < 0.05$).

Species		Pair 1		Pair 2		Pair 3		Pair 4		Pair 5	
		Cover	Sig.	Cover	Sig.	Cover	Sig.	Cover	Sig.	Cover	Sig.
Andropogon virginicus	AMP	0.0		0.0		0.0		0.0	*	0.0	*
	CG	0.0		0.0		0.0		40.5			
Dactylis glomerata	AMP	23.0	*	9.6	*	9.8	*	21.9	*	0.0	*
	CG	5.0		22.0		1.4		0.1		0.0	
Festuca elatior	AMP	29.1	*	58.0	*	66.3	*	43.2	*	0.0	*
	CG	12.6		32.7		53.6		10.8		0.0	
Poa pratensis	AMP	22.4	*	8.5	*	31.4	*	0.0	*	0.0	*
	CG	77.1		41.4		29.3		0.0		0.0	
Trifolium hybridum	AMP	0.0	*	0.0	*	0.0		47.5	*	40.0	*
	CG	0.0		19.9		0.0		0.0		1.5	
Trifolium repens	AMP	30.4	*	15.3	*	0.0		0.0		0.0	
	CG	53.8		0.0		0.0		0.0		0.0	
Trifolium pratense	AMP	0.0		0.0		0.0		0.0		18.0	*
	CG	0.0		0.0		0.0		0.0		0.0	
Ranunculus bulbosus	AMP	0.0		0.0		2.3		0.0		0.0	
	CG	0.0		0.0		7.3		0.0		0.0	
Juncus tenuis	AMP	0.0		0.0		2.1		0.0		0.0	
	CG	0.0		0.0		6.1		0.0		0.0	
Veronica peregrina	AMP	14.5	*	0.0		0.0		0.0		0.0	
	CG	0.0		0.0		0.0		0.0		0.0	
Lolium multiflorum	AMP	0.0		0.0		0.0		0.0		48.1	
	CG	0.0		0.0		0.0		0.0		49.8	
Cynodon dactylon	AMP	0.0		0.0		0.0		0.0		0.0	*
	CG	0.0		0.0		0.0		0.0		12.6	
Hordeum pusillum	AMP	0.0		0.0		0.0		0.0		39.9	*
	CG	0.0		0.0		0.0		0.0		0.0	
Plantago lanceolata	AMP	0.0		0.0		0.0		19.9	*	0.0	
	CG	0.0		0.0		0.0		0.2		0.0	

Table 7
Herbaceous standing crop biomass and ANPP (cage production) (g m^{-2}) on combined flat and slope catena positions from paired AMP and CG farms in the immediate vicinity of soil sampling points. Probabilities are based on untransformed data. Combined AMP site ANPP exceeded CG farms (1073 vs 894 g m^{-2}, $p = 0.020$). Mean standing crop was AMP 373 vs 322 CG g m-2, $p = 0.019$.

Farm pair	Sample month	AMP	CG	p < F
Pair 1	May	283	212	0.272
KY	Jul	556	407	0.050
	Nov	786	494	0.000
	Mean	541	371	0.002
	Total	1696	1107	0.005
Pair 2	May	257	397	0.018
TN	Jul	377	179	0.011
	Nov	593	689	0.196
	Mean	409	422	0.755
	Total	411	388	0.644
Pair 3	May	414	186	0.000
AL (Ft P)	Jul	567	588	0.776
	Nov	563	326	0.003
	Mean	515	367	0.004
	Total	1119	1017	0.485
Pair 4	May	256	97	0.004
Al (P)	Jul	139	139	0.995
	Nov	80	138	0.433
	Mean	158	125	0.411
	Total	733	496	0.058
Pair 5	May	350	216	0.075
MS	Jul	247	271	0.750
	Nov	128	495	0.000
	Mean	242	327	0.074
	Total	924	891	0.831

higher under *AMP* than *CG* management ($p < 0.02$), and this was mainly due to greater forage growth before summer under *AMP* management. This was not the case at P2 and the most southerly locations P4 and P5. At P2, the CG rancher decision to grow his forage out in spring for hay production increased the standing crop biomass sampled under this analysis. In P4 and P5, forage biomass was substantially lower at the end of summer with *AMP* relative to *CG* management as a direct function of the goals of *AMP* management at these two locations. The *AMP* grazers at these locations overseeded their summer pastures with winter growing, mixed species cover crops in fall that required heavy fall defoliation to facilitate successful establishment of the overseeded cover crops. Also, the rancher at P5 occupied the paddock we sampled for a month in midsummer and not the usual 1–2 days while his cows were calving. We only learned of this after it had happened.

Differences in species group composition in the close proximity of the soil sampling sites at each location are presented in Fig. 2. At P1, P2 and P3 there were no significant differences between *AMP* and *CG* paired sites ($p > 0.05$). In contrast, at the more southerly locations (P4 and P5)

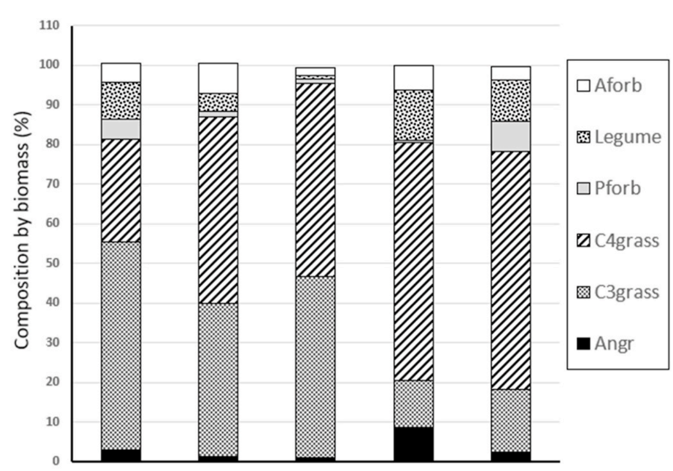

Fig. 2. Mean composition of herbaceous vegetation for AMP and CG pairs in the proximity of the soil sampling sites represented by the different herbaceous plant groups at each location.

there were differences ($p < 0.05$) due to management that did not occur at the northerly locations to take advantage of more growing days in the south as noted above.

Legumes were most prevalent at P1, P4 and P5 while annual forbs were present in lower abundance at Pairs 3 and 5. Annual grasses were more abundant at Pair 4 AMP where they were intentionally planted in a diverse cover crop mix as the forage base and for this reason, they were a minor component of total herbaceous biomass at all other sites. There were low amounts of perennial forbs at all sites, with P5 having the most ($p < 0.05$).

3.6. Ground cover in the immediate vicinity of soil sampling points

Differences in non-vegetative cover composition in the close proximity of the soil sampling points at each location are presented in Table 8. Bare ground was greater with *AMP* than *CG* at P2 and P4, but the bare ground cover was no different at the other locations.

Fine litter was significantly higher with *CG* than *AMP* at only P2. At AMP sites, P1, P3, and P5, fine litter was significantly higher; no significant difference was measured at P4.

Similarly, plant canopy cover was greater with *CG* than *AMP* at P1, P2, P4 and P5, while *AMP* plant cover was greater than *CG* at only P3.

3.7. Water infiltration

Three *AMP* treatments, at Pair 2, Pair 4, and Pair 5 had significantly higher water infiltration rates compared to *CG* pairs ($p < 0.05$), while at Pair 1 and Pair 3, differences were not significant ($p > 0.06$) (Table 9). AMP water infiltration rates ranged from 2.54 to 14.4 cm/h, averaging 7.2 cm/h, while *CG* treatment rates varied from 0.5 to 11.7 cm/h, averaging 5.0 cm/h.

3.8. Soil carbon and C_3/C_4 plant composition

Averaged over all locations, soil organic carbon stocks to a depth of 1 m were over 13% greater on *AMP* than *CG* ranches (Fig. 3; $p < 0.02$). AMP grazing did not have significantly more soil C than *CG* at P1 and P4 ($p > 0.05$) but at the other 3 ranch pair sites (P2, P3 and P5) soil organic carbon was greater at each depth increment with *AMP* than *CG* paired sites ($p < 0.05$).

4. Discussion

We have compared CG and AMP grazed vegetation systems, water infiltration and soil carbons stocks. Simply put, AMP grazing quickly moves a higher stocked herd quickly across a series of paddocks and provides sufficiently long recovery periods for the plants. CG grazing typically under stocks and allows livestock continuous access to the paddock and plants, and no planned recovery period during the growing season. AMP grazing management is focused on improving ecological function by emulating the evolved grazing land ecology of constant movement of large herds of multispecies grazing ungulates (Frank et al., 1998; Retallack, 2013; Teague et al., 2013). *AMP* grazing also involves adjusting animal numbers to match available forage, using short grazing periods of <1 to several days, retaining sufficient post-herbivory plant residue for regrowth, and providing long recovery periods to adaptively accommodate intra- and inter-seasonal variation in herbaceous plant growth. Incorporating multiple livestock species into enterprises gives multiple benefits and increases biodiversity, business benefits from multiple enterprises (animals and crops), and disease and parasite management control (Earl and Jones, 1996; Murphy, 1998; Jacobo et al., 2006; Provenza, 2008; Ferguson et al., 2013; Teague et al., 2013; Flack, 2016; Rowntree et al., 2016; Wang et al., 2016; Hillenbrand et al., 2019).

AMP grazing has been shown to be a promising regenerative grazing strategy (Teague et al., 2013; Savory and Butterfield, 2016; Wang et al., 2020) and avoids overgrazing and overstocking by incorporating management adjustments to respond to changing weather conditions and

Table 9
Infiltration measurements from paired AMP and CG farms in the immediate vicinity of soil sampling points (Significance at $p < 0.05$).

Farm pair	Grazing	n	Mean (cm/hour)	Std Dev	p > F
Pair 1	AMP	5	2.5	0.55	
	CG	6	11.7	3.73	0.063
Pair 2	AMP	5	14.4	2.16	
	CG	7	8.1	1.46	0.032
Pair 3	AMP	7	7.6	1.54	
	CG	6	4.1	1.28	0.107
Pair 4	AMP	6	6.6	1.29	
	CG	7	1.0	0.17	0.008
Pair 5	AMP	8	4.7	2.04	
	CG	8	0.5	0.16	0.056

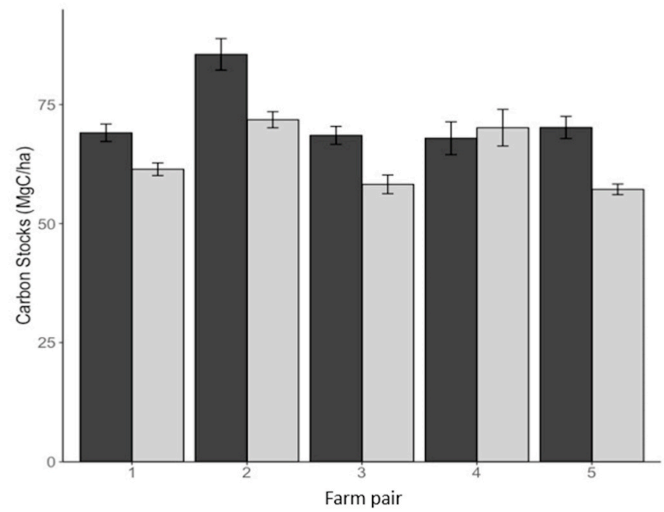

Fig. 3. Mean carbon stocks for AMP and CG pairs to a depth of 1 m (Significant differences among AMP and CG at each farm pair ($p < 0.05$).

Table 8
Ground cover (%) from paired AMP and CG farms in the immediate vicinity of soil sampling points (Significance at $p < 0.05$).

Location	Bare ground			Fine litter			Plant canopy		
	AMP	CG	p > F	AMP	CG	p > F	AMP	CG	p > F
Pair 1 KY	0.8	1.5	0.746	87.7	88.0	0.958	92.6	89.2	0.297
Pair 2 TN	4.6	0.4	0.074	72.4	96.0	0.001	83.9	93.6	0.005
Pair 3 AL (F)	0.3	2.4	0.364	96.2	93.0	0.542	90.4	81.7	0.009
Pair 4 AL (P)	12.0	6.3	0.016	74.4	90.6	0.002	52.8	64.3	0.001
Pair 5 MS	7.2	6.3	0.731	91.3	88.6	0.619	69.7	87.8	0.001
Mean	5.0	3.4	0.134	84.4	91.2	0.006	77.9	83.3	0.001

available forage, including varying stocking rate, density, animal size and nutritional needs to achieve ranchers' forage quality and quantity goals (Teague et al., 2013).

Many ranchers who have converted from CG to AMP grazing have suggested they have more available grass and water, improved livestock health, reduced veterinary costs, among other benefits (Waters, 2019; Wilsey et al., 2019; Teague et al. 2011, 2013; Teague, 2018). This study in the SE USA confirms AMP ranches to have on average more biomass, higher water infiltration rates and soil organic carbon levels. AMP grazing via word of mouth with the ranching community appears to be increasing in rancher adoption as the awareness of the benefits of AMP such as measured in this study become understood. Currently, although 78% of surveyed ranchers were familiar with the concept, 40% identified themselves as non-adopters (Clifford, 2020; Wang et al., 2020).

The use of reference natural areas with comparatively higher total plant species richness and highest average quadrat richness, % cover and richness by native perennial forbs and graminoids and the lowest % cover of bare ground and highest % fine litter may suggest these additional benefits might be considered outcomes for future improvements in AMP grazing outcomes. But due to past histories of land use, and soil types, these RNAs bear little resemblance to the grazing areas of this study. However, they do serve as a reference point of vegetation and soils that would dominate in the absence of agricultural land use in the proximity of each of the five locations within their respective soil types, where we studied the impacts of *AMP* grazing relative to locally managed *CG* management.

Perennial plant cover on the paired grazing sites was different among all locations and ranch pairs with vegetation cover in the northerly states being higher with *CG* than *AMP* paired sites and the converse occurring in the three southerly sites (Table 3). As could be expected, simply based on plant demographics, the northern sites were dominated by an equal mix of C_3 and C_4 herbaceous plant cover while warmer southerly sites were dominated by C_4 plant cover. Plant cover in *AMP* vs. *CG* pairs differed somewhat from this overall pattern with C_3 plant cover being higher under *AMP* than *CG* in the southerly locations. These differences were to a large extent due to the difference in management goals by *AMP* grazers relative to their *CG* neighbors. *CG* grazers in the region concentrate on getting the majority of their pasture production in the warmer times of the year. CG ranch managers often manage pastures by applying inorganic fertilizers to continuously grazed pastures and when summer forage growth exceeds animal demand, they cut a substantial amount of the forage to make hay or purchase and import hay that they rely on to feed their livestock during the winter months.

Conversely, the *AMP* grazers plan to have grazable forage throughout the year, use no inorganic fertilizers, and minimize use of biocides. For this they require a substantial amount of C_3 perennial and annual forage to provide cool season grazing in addition to their C_4 summer forage production, so forage supply is more even throughout the year to avoid the expense of producing hay and/or purchasing animal feed during the cooler low growth time of the year. They do this by planning forage production and time-managed grazing to keep the amount of green growing forage for as many days of the year as possible. This has numerous advantages as it increases the period of soil carbon sequestration, provides elevated forage nutritive value for much of the year and according to interviews with the *AMP* ranchers studied, this avoids the expense and capital investment of cutting, baling and moving hay. These outcomes are achieved by using short grazing periods, 1–3 days, followed by full recovery periods that increase growth rate, and rooting depth to give higher forage production and in fall, winter and spring to even out grazable forage over the year (Teague and Kreuter, 2020). In addition, *AMP* grazers avoid or minimize the use of inorganic fertilizers and biocides that have a strong negative impact on soil fungi and consequently diminish the role of fungi in building soil aggregation, improve surface water infiltration and soil water retention (Coleman and Crossley, 1996; Six et al., 2004). Fungi and soil microbial carbon also play a key role in enhancing the access of plants to soil minerals and nutrient cycling that would otherwise not be accessible (Bardgett, 2005; De Vries et al., 2012; Morriën et al., 2017).

These management choices also account for the greater number of exotic perennials with *AMP* grazing at the two southern locations. These plants are valued and planted every year for to provide grazable forage through the year. In the 3 northerly locations exotic perennials were more evident with *CG* than *AMP* management as they were mostly C_3 plants, typically known to have a more northerly distribution (Gleason and Cronquist, 1991) to also be more widely distributed and constitute the greater portion of forages abundant under *CG*, while they were more abundant with *AMP* grazing in the southern locations as they were valued by *AMP* grazers to increase growing forage for a greater proportion of the year (Table 3).

Non-vegetation and litter cover for paired AMP, CG and Reference Natural Areas.

In this study, *AMP* and *CG* did not show clear patterns, on which grazing strategy supported an increased plant cover and fine litter. However, reference natural areas had nearly continuous fine litter & plant cover, and no bare soil.

Total herbaceous plant canopy cover was greater with *CG* than *AMP* at sites P1 and P2, no different at P3, and greater with *AMP* than *CG* at P4 and P5 (Table 3). Over the larger portion of each ranch pair, bare ground was significantly greater with *CG* than the paired *AMP* ranches at P3 and P5, no different at P1 and P4, and greater with *AMP* than *CG* at only P2 (Table 4). In contrast, fine litter cover was greater with *AMP* than *CG* at P1, P3, and P5. Only at P2 was fine litter cover greater with *CG* than *AMP*. The litter cover in the immediate vicinity of soil sampling points was rather different with litter cover greater or equal at *CG* than paired *AMP* sites (Table 8). Clearly the removal of forage in the areas where soil sampling took place was greater than that for the larger portion grazed at each ranch pair with *AMP*.

Grazing practices that remove a moderate amount of forage and leave sufficient plant canopy and litter cover to provide a full recovery before the next grazing generally result in lower incidences of bare ground, facilitate soil function and improve vegetation productivity, resulting in higher levels of soil carbon, microbial biomass and function (Teague et al., 2011; De Vries et al., 2012; Morriën et al., 2017). Excessive forage removal and no planned recovery have the opposite effect (Teague and Kreuter, 2020).

In grazing and cropping ecosystems, adequate plant and litter cover must be present to maintain normal soil function to provide protection from soil loss and allow soil microorganisms to perform optimally (Rietkerk et al., 2000; Bardgett, 2005). Excessive grazing pressure, excessive trampling, and extended drought inhibit soil function processes (Thurow, 1991; Wright and Bailey, 1982), and extensive ground cover of actively growing plants is necessary to maintain soil aggregation and organic matter for a healthy water cycle (Ferguson and Veizer, 2007). The removal of transpiring vegetation diminishes the self-regulatory damping of solar radiation and temperatures in these landscapes. Bare ground is unprotected from solar radiation and gets much hotter than covered soil causing a decrease in microbial activity, accelerated loss of organic matter, and an increased erosion risk if there is insufficient cover to dissipate the energy of raindrops before they strike the soil (Blackburn et al., 1986; Thurow, 1991). Elevated soil temperature and soil loss have a direct negative effect on infiltration rates, soil evaporation, nutrient retention, and biological functions that contribute to ecosystem function (Wright and Bailey, 1982; Neary et al., 1999; Bardgett, 2005). Consequently, the amount of bare ground is a good indicator of soil and hydrological function and erosion risk (Thurow, 1991; Bardgett, 2005).

Rate of nutrient cycling is one of the key ecosystem functions that management can influence to impact ecosystem function and services (Altieri, 1999; Van der Heijden et al., 2008, De Vries et al., 2012). A number of insects, invertebrates and soil microbes are the main drivers of nutrient cycling that can be enhanced by adjusting grazing management to optimize the benefits they provide. Grazing management strategies aimed at restoring soil function tend to expand below ground microbial networks and increase the efficiency of nutrient cycling and carbon uptake by diversifying the composition and activities of fungi (Ngumbi and Kloepper, 2016; Slade et al., 2016; Morriën et al., 2017). Such beneficial management can strongly benefit soil structure and ecological functions (Herrick and Lal, 1995; Richardson and Richardson, 2000; Wardle and Bardgett, 2004; Blouin et al., 2013; Pecenka and Lundgren, 2019). Dung cover through the year is an indicator of how rapidly nutrients are cycling. In this study, the abundance of cattle dung was greater under CG than AMP management at P1, P3, and P5 implying a more rapid nutrient cycling at the AMP sites. There was no difference between *AMP* and *CG* at P2. These differences may be explained by differences among these sites and grazing management on soil microbial composition and biomass.

4.1. Plant biomass and composition in the vicinity of soil sampling

To provide grazable forage through the year *AMP* grazers plan for a balanced mix of cool and warm season grasses. This entailed overseeding certain summer growing pastures with cool season annual species to provide late winter and early spring green forage to reduce or eliminate feeding of hay or purchased feed supplements. C_4 warm season grasses provided most of the forage in late spring through late summer and C_3 perennial forage species provide some spring and early summer forage and was used as stored forage for grazing inn late fall through winter. These management principles provide a good spread of forage though the year of higher forage nutritional value and lowers feed costs substantially.

As noted in the methods describing management and livestock biomass units (Table 1, AU per 10 ha) of *AMP* ranches was substantially higher than corresponding *CG* ranches because *AMP* grazing resulted in greater forage production and carrying capacity as well as a better spread of quality nutritive forage through the year. *AMP* grazers, by definition, graze their livestock for very short periods through many small paddocks and then followed by recovery periods that allow for recovery from grazing. This has multiple benefits resulting in small changes in forage nutrient intake every day and elevated forage production and nutritive value though more of each year than *CG*. Even so, the total amount of forage standing crop measured was not significantly less than on paired *CG* ranches and was often higher.

The 2 southerly locations (P4 and P5) with milder winters used overseeding management to take advantage of periods that supported cool season planted grass growth. These sites had to be grazed hard immediately before the no-till planting to minimize competition for the over sown cool season cover crops. Consequently, forage biomass, litter cover and plant cover at these sites was substantially lower in these southerly locations under *AMP* management. The differences in grazing management strategies consequently produced differences in bare ground, fine litter cover and plant canopy with *CG* generally being lower in these parameters than *AMP*. The greatest limiting factor in grazing land ecosystems is the infiltration and retention of surface water in the soil and this is negatively impacted by lower values of all three of these key elements (Thurow, 1991).

The infiltration rate of incoming rainfall is diminished by continuous grazing that removes plant cover, increases bare ground and causes soil aggregation and structure degradation. This ultimately results in lower surface water infiltration rates, less plant-available soil water, and increased surface water runoff, soil erosion, nutrient movement to downslope waterbodies impairing freshwater quality (Thurow, 1991). On average, in our overall study locations, infiltration was higher at *AMP* than paired *CG* ranches, but P1 *AMP* had lower infiltration rates than the paired *CG* ranch, with no difference between *AMP* and *CG* at P3. The infiltration rate differences for the Pair 1 location for the *AMP* ranch and *CG* ranch are only significant at the 90% level. This was mostly due to the very high standard deviation on the *CG* ranch with infiltration rates of <5 cm/h up to 58 cm/h. Two infiltrometer measurements hit these 58 cm/h levels, possibly due to bedrock fractures. If those two samples are eliminated from the analysis, the standard deviation decreases, but infiltration is still overwhelming higher for the *CG* paired ranch at site P1.

4.2. Soil carbon and C_3/C_4 plant composition in the immediate vicinity of soil sampling points

Averaged over all locations soil organic carbon stocks to a depth of 1 m were over 13% greater on *AMP* than *CG* ranches (Fig. 3). *AMP* grazing

Table 1
Farm management details for each farm and the area they had access to in 2018 by farm pair for AMP and CG farm pairs.

Farm pair	Grazing practice	Total 2018 ANPP Standing crop (g/m^2)	Average animal units carried (AU/ha)	Livestock in study area	Average paddock size (ha)	Average # Paddocks per herd	Graze period goal (days)	Recovery goal (days)	Rest vs. graze period ratio	Years of current management	Land use history
Pair 1	AMP	1696	1.53	Beef, sheep	1.2	45	2	45	22.5	13	Tobacco, grain then grazing >30 years
	CG	1108	0.79	Beef cattle	14	1	Not moved	No rest	0	6	Tobacco and grain crops
Pair 2	AMP	892	2.57	Beef cattle	1	45	2	90	45	12	Row cropped, hay and grazing
	CG	959	0.82	Beef cattle	11	8	135	82.5	0.6	>25	Row cropped, Hay and grazing
Pair 3	AMP	1119	1.55	Beef cattle	1.2	60	1	50	50	29	Small grains
	CG	1017	0.82	Beef cattle	16	50	15	82.5	5.5	17	Small grains
Pair 4	AMP	733	2.75	Beef cattle	0.4	135	1	80	80	24	Cotton
	CG	496	0.97	Beef cattle	18	2	Not moved	No rest	0	>40	Cotton
Pair 5	AMP	924	1.04	Beef cattle	1.6	150	1	70	70	10	Tobacco & grain crops then grazing >50 years
	CG	891	0.82	Beef cattle	13	7	75	90	1.2	>40	Tobacco, cotton, market gardening & grains

did not have significantly more soil C than *CG* at P1 and P4 but at the other 3 ranch pair sites (P2, P3 and P5) soil organic carbon was greater at each depth increment with *AMP* than *CG* paired sites. The soil C results cannot be explained by bare soil measurements or by the fine litter cover measurements as these findings do not parallel the soil C results (Table 4). However, one explanation for the discrepancy in soil C findings across ranch pairs could be the amount of perennial plant cover. P1 and P4 had the biggest differences in the % perennial cover between *AMP* and *CG* ranches, with *CG* ranches having significantly more % perennial cover at the time of sampling (Table 3; $p < 0.05$). At the other P2, P3, and P5 ranch pair sites there was a less pronounced difference in the amount of total perennial cover between *AMP* and *CG* ranches and in P3 and P5 the *AMP* ranches had more % perennial cover than the *CG* ranches. Perennial plants have been shown to increase soil carbon stocks compared to annual plants because perennials tend to produce more plant residues that can ultimately end up as organic matter in the soil (Ferchaud et al., 2016). Perennials also have greater root: shoot ratios as well as larger root structures and often deeper roots which can produce more root exudate carbon than annuals (Bray, 1963; Paustian et al., 1997). Additionally, there is typically less soil disturbance involved with cultivating perennials than there is with annual production (Powlson et al., 2014) which can reduce the amount of soil carbon lost during planting and maintenance. Of the perennial plants measured at P1 and P4, the *CG* ranches tended to have more C_4 perennial cover than the *AMP* ranches (Table 3). C_4 plants contain more labile components than C_3 plants which can lead to faster decomposition (Wynn and Bird, 2007) and more efficient incorporation of plant biomass into microbial biomass and soil organic matter (Cotrufo et al., 2013).

5. Conclusions

Pairing of *AMP* and *CG* managed ranches in the SE USA started by matching biophysical conditions and confirmation of rancher operating practices and land use histories. This study suggests under *AMP* grazing that increases in soil organic carbon, and % fine litter, plant cover, and standing biomass, with a concurrent decrease in bare soil, percent cow pats, compared to *CG* ranches. Additionally, *AMP* ranches typically had decreased native grass and forb composition, an increase in weedy and nonnative often invasive species, and that C_3 vs C_4 composition varies latitudinally; more C_3 representation to the north and C_4 plants southward. These measurements plus the higher AMP livestock stocking levels are important co-benefits and appear to be why AMP grazing participation by ranch owners and managers is a rapidly increasing grazing practice; ranchers both depend on and are benefiting from improving their land's ecological health.

CG ranchers passively management their land and herds, except to produce hay and any soil related fertility amendments. *AMP* grazers closely monitor and maintain their forage supply such that they could support year-round feeding, without importing hay or having to add soil fertility amendments, providing multiple resource and economic benefits. The fundamental responses of vegetation & soil systems (and soil microbial systems) we measured were closely tied to these two fundamentally different grazing practices.

Credit author statement

Apfelbaum, **Wang**, **Thompson** conducted the field work, Formal analysis and **Mosier** and **Teague** provided internal peer review and research layout and design expertise, respectively.

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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.

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