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Adaptive multi-paddock grazing improves water infiltration in Canadian grassland soils

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ABSTRACT

The maintenance of hydrologic function on grazing lands is an important management objective to sustain forage production during low moisture supply, safeguard other ecosystem goods and services and build resilience to a warming climate. Hydrologic function can be influenced by grazing patterns, as represented by variation in the timing, intensity and frequency of livestock use. While rotational, adaptive grazing (a short-duration, multi-paddock grazing system that emphasises plant recovery between grazing events) is growing in popularity and has the potential to influence grassland hydrological processes such as water infiltration, few studies have comprehensively examined infiltration in relation to on-ranch grazing practices. We examined water infiltration in grasslands on 52 ranches (set up as matched pairs) to examine whether adaptive grazing alters water infiltration in the Great Plains of western Canada, as compared to conventional grazing management employed on neighbouring ranches. We also used producer survey information to test for the influence of ongoing nuanced grazing practices on water infiltration rates, over and above the biophysical effects of soil texture, soil bulk density and plant litter, as well as cultivation history and climate. Overall, adaptive grazing, and specifically the use of higher rest-to-grazing ratios early in the growing season (prior to August 1), led to increased water infiltration in grassland soils. Water infiltration was positively associated with increased litter mass under adaptive grazing, whereas higher bulk density (and sandier) soils were associated with decreased infiltration rates. This study highlights the potential of specialised rotational grazing systems using cattle to improve soil hydrologic function in grazed grasslands.

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1. Introduction

Grasslands cover over 30% of the world's terrestrial surface, the majority of which are grazed by livestock (Dixon et al., 2014; Jones, 2019). Degradation of grasslands due to improper grazing management, along with the ecological footprint of the livestock sector in general, is of global concern (Chang et al., 2021; Geist and Lambin, 2004). Hence, more sustainable grazing practices are key to ensuring food security for a growing human population, whilst safeguarding ecosystem function, protecting biodiversity and building resilience to a warming climate (Delgado et al., 2011; Janzen, 2011).

Grassland ecosystem function is largely driven by hydrological processes (Weng and Luo, 2008), including the regulating influence of available soil moisture on plant productivity, thus underpinning the capacity of grasslands to provide ecosystem goods and services, including forage for livestock (Arshad and Martin, 2002; Sala et al., 1988; Teague and Barnes, 2017). Available soil moisture is heavily influenced by water infiltration, which in turn is determined by climatic conditions, edaphic properties and vegetation patterns (Bradford et al., 2019; Noy-Meir, 1973). At the ecosite scale, the primary biophysical drivers of soil water infiltration include intrinsic soil properties such as organic matter content, texture and bulk density, as well as plant litter (Naeth et al., 1991a; Salve and Allen-Diaz, 2001).

Water infiltration and moisture holding capacity of soils are largely determined by soil texture (Epstein et al., 1997). While fine-textured soils have a higher water-holding capacity, sandy soils hold less water and generally have higher infiltration rates due to large soil pore sizes (Rahmati et al., 2018). Similarly, soil bulk density is an important physical property regulating hydrological processes (Deutsch et al., 2010b), which in turn, is influenced by both soil organic matter content and texture (Martín et al., 2017). In addition, plant litter plays an important role on hydrologic function, as has been extensively shown in Canadian grasslands (e.g. Bork and Irving, 2015; Deutsch et al., 2010a, 2010b). The litter layer reduces runoff and evaporation (Meeuwig, 1970), and increases the soil moisture content in spring by trapping snow (Naeth and Chanasyk, 1995), thereby enhancing forage production (Deutsch et al., 2010b; Willms et al., 1986). On the other hand, very high litter levels can reduce soil moisture content by intercepting rainfall and reducing the amount of water reaching the mineral soil (Knapp and Seastedt, 1986; Naeth et al., 1991a). Litter decomposition enriches the soil with organic matter (SOM), which in turn improves soil structure and its hydrological properties (Parton et al., 1987), with direct benefits to plant productivity (Franzluebbers, 2002).

Finally, grazing patterns such as the timing, intensity and frequency of livestock use can influence soil hydrological properties by affecting vegetation dynamics and soil properties (Naeth et al., 1991b; Niraula et al., 2020; Teague et al., 2011). While conventional grazing typically reduces soil water infiltration (Sirimarco et al., 2018), the use of rest-rotation grazing can enhance infiltration (Hillenbrand et al., 2019).

One grassland management approach suggested to enhance hydrological properties, improve plant productivity, restore ecosystem processes and mitigate the effects of climate change, is adaptive multi-paddock grazing (hereafter 'adaptive grazing') (Teague and Kreuter, 2020). The conceptual foundation of this adaptive grazing method is the strategic use of animal impact, similar to the 'herd effect' in Holistic Management (Savory, 1983; Savory and Parsons, 1980), referencing natural rotational grazing dynamics by large keystone herbivores in grasslands, e.g. migratory bison in North America (Hillenbrand et al., 2019). Adaptive grazing is characterised by the use of very short grazing periods at high stock densities, followed by an extended rest period considered adequate for plants to regenerate (Holechek et al., 2000; Savory and Butterfield, 2016). Such intense but brief animal impacts can break up physical soil crusts and facilitate the integration of dead plant material into the soil (Butterfield et al., 2019; Geremia et al., 2019; Knapp et al., 1999). This process, in turn, is thought to have positive effects on hydrological processes through enhanced water infiltration and retention, as well as reduced runoff and associated soil erosion (Savory, 1983; Teague and Barnes, 2017).

Across North America, adaptive grazing is being increasingly adopted by the ranching community, and yet while several studies have noted the environmental benefits of this practice (e.g. Mosier et al., 2021; Stanley et al., 2018; Teague and Kreuter, 2020), there remains debate on the scientific merits of adaptive grazing, in part due to limited evidence from large-scale studies and the failure of low sample sizes to capture the broad gradients in management practices and biophysical environments used for cattle grazing (e.g. Briske et al., 2013; Carter et al., 2014; Gosnell et al., 2020; Nordborg and Röös, 2016; Teague et al., 2013). Furthermore, few studies account for detailed ranch-level management practices when evaluating agro-environmental metrics (Nordborg and Röös, 2016).

To better understand the relationship between grazing practices and grassland hydrology, we investigated whether water infiltration rates of grassland soils under adaptive grazing differed from those of neighbouring properties (hereafter 'conventional grazing'), where the latter were assumed to represent a regionally representative sample of beef cattle ranches across Canada's prairies (Bork et al., 2021). Moreover, we assessed the influence of various grazing practices on water infiltration rates, in addition to the effects of cultivation, the biophysical environment and climate. Overall, we hypothesised that extended rest periods following early-season grazing, as well as high animal unit densities resembling 'herd effect dynamics', would enhance water infiltration rates. We discuss the implications of our findings in the wider context of sustainable grazing management practices and resilient agricultural production landscapes in a changing climate.

2. Methods and materials

2.1. Study area

This study was conducted on grasslands associated with 52 beef cattle ranches across western Canada's prairie provinces, namely Alberta ($n = 20$), Saskatchewan ($n = 24$), and Manitoba ($n = 8$), as part of a larger interdisciplinary grazing management project (Fig. S1). Ranches were distributed across several ecoregions spanning wide gradients in climate, soil type, vegetation type and land management. These areas included the Mixedgrass Prairie ($n = 6$ ranches), which is characterised by grasses of varying height including spear grass (*Hesperostipa* spp.), blue grama grass (*Bouteloua gracilis*), junegrass (*Koeleria macrantha*) and wheat grasses (*Pascopyrum smithii* and *Elymus lanceolatus*). Many sites were in the Fescue Grasslands of the foothill and parkland regions ($n = 36$ ranches), which were either dominated by native rough fescue (*Festuca campestris* and *F. hallii*) on non-cultivated soil, or more commonly, were comprised of agronomic seeded grasses such as smooth brome (*Bromus inermis*), Kentucky bluegrass (*Poa pratensis*) and timothy (*Phleum pratense*) together with the introduced legumes alfalfa (*Medicago sativa*) and clover (*Trifolium* spp.). Our study area also included the Boreal Transition ($n = 10$ ranches), which is dominated by introduced grasslands (largely seeded following prior cropping) interspersed with forest (Fig. S1). Climatic conditions ranged from 326.2 to 629.2 mm for mean annual precipitation (MAP), and -1.2 to 4.8 °C for mean annual temperature (MAT) based on 30-year normal (1989–2018) data, whereby the Mixedgrass Prairie, on average, receives the lowest rainfall and has the mildest mean annual temperature, while the Boreal Transition receives the highest rainfall and has the coldest mean annual temperature. Predominant soils vary from low-fertility Brown Chernozems (Mixedgrass Prairie) and Gray Luvisols (Boreal Transition), to Dark-Gray Chernozems and well-humified Black Chernozems (Fescue Grasslands) (Fig. S2).

We used a paired design in which adaptively grazed ranches were initially identified through select grazing criteria, with each adaptively grazed ranch matched to a neighbouring conventional ranch employing regionally representative grazing for comparison (within 5 km typically) on similar ecosites (e.g. landform, slope, soil texture and soil series). Ranch pairs were sought with comparable cultivation history (i.e. both non-cultivated or both cultivated in the past).

Across all ranches, the majority had been cultivated (42/52) and previously seeded, with on average about 19 years since cultivation ended (Bork et al., 2021). To identify a ranch as adaptive, this grazing system had to be in place for a minimum of ten years. A three-step selection process was used to identify adaptive grazing ranches that met the criteria for participation in this study, including 1) initial self-identification of adaptive grazing ranchers via an online questionnaire, 2) subsequent phone interviews and ensuing field reconnaissance assessment and 3) the identification of an available conventional grazing ranch for comparison. Paddocks were eliminated from our sample if winter bale feeding had occurred. A more detailed account of the ranch selection process can be found in the Supplementary Materials (Appendix S1).

2.2. *Experimental design and sampling*

Within each of the 52 ranches, a 10-ha study area was identified for comprehensive assessment; here we report only on water infiltration. Three sampling points were established in grasslands on each ranch within this area following a random stratification design using random number charts and grids of the site, and aligned with three soil core sampling locations. Fieldwork took place during the months of July and August of two consecutive seasons, with 24 of the ranches sampled in 2017 and the remaining 28 in the following year. All sampling was conducted by the same team of hydrologists and followed standard sampling methods (VCS, 2011). Field saturated hydraulic conductivity (K_{fs}), a measure of the ease with which water moves into the soil (cm s^{-1}) (Bouwer, 1986), was quantified with a Saturo Dual Head Infiltrometer (DHI) (SATURO, METER Group Inc., formerly Decagon Devices Inc.) (Meter Group Inc, 2019), and converted into a vertical flow rate (mm h^{-1}; hereafter ‘water infiltration rate’).

Prior to conductivity testing, live vegetation was clipped at ground level and cleared from the sampling area along with (partially decomposed) leaf litter and branches. Next, a 14.4 cm wide stainless steel ring was inserted into the topsoil using a dead blow mallet, on top of which the infiltrometer (computer, water pump and pressure measurement unit) was attached, using a 5 cm deep vertical collar for clay and silt clay soils, and a 10 cm deep collar for soils with high infiltration rates (Meter Group Inc, 2019). The infiltrometer was connected to a sealed water bucket via hosing, so that water could be pumped into the infiltrometer chamber above the ring at a specified rate to maintain constant head pressure. The soil in the ring was first pre-soaked for 10–30 min to ensure a standard saturation level, followed by 3 measurement cycles (rarely 2 or 4), during which alternate periods of low and high pressure were applied to a column of water maintained above the sampling area (Döbert et al., 2021). The length of time the automated equipment operated to obtain estimates of saturated infiltration was determined by soil texture and antecedent moisture as directed by the Saturo operations manual (Meter Group Inc, 2019).

The collar directed the saturation cycle water vertically into the soil and minimised seepage around the collar. Where macropores (i.e. large soil openings such as ground squirrel burrows) prevented accurate sampling, sample locations were offset by no more than a meter along a cardinal compass direction to the nearest suitable spot. Sampling tests varied in duration from 75 to 180 min resulting in a single output value based on the last cycle of the test. Initial test result verification was done in the field and was followed by a more detailed QA/QC assessment of water pressures and k estimates following the Saturo procedures manual (Meter Group Inc, 2020).

Across all ranches, a total of 780 soil core samples were collected (100 cm depth × 5 cm diameter) as part of the larger study (n = 15 per ranch). Of those, 156 coincided spatially (three samples per ranch) with the individual water infiltration sampling locations (within 0.1 m), thus providing the complementary soil data used for the water infiltration study. About 5% of each sample was randomly extracted and used to determine the bulk density of the Ah layer. Soils were air-dried at room temperature for four days, and subsequently sieved (2 mm) to remove coarse fragments and roots, which were then weighed. Soil samples (20 g) were oven-dried at 105 °C for 27 h and then weighed to determine bulk density. The water displacement method was used to quantify coarse fragment volumes. Soil bulk density was calculated as:

Bulk density (g cm^{-3}) = (dry soil mass [g] − coarse fragment mass [g])/(soil sample volume [cm^3] − coarse fragment volume [cm^3])

Soil samples were also used to quantify the clay, silt and sand content of soil on 38 of the study ranches using the Bouyoucos hydrometer method (Bouyoucos, 1962). *In-situ* litter biomass samples were collected from 34 of the study ranches within 50 × 50 cm sample areas adjacent to the DHI. Root biomass samples were collected from the same 34 study ranches using separately collected 15 cm deep × 6.35 cm wide cores. Litter and root sample dry weights were recorded after oven drying at 200 °C to stable water mass. Soil, biomass and infiltration rate data from each sampling point were considered subsamples and averaged to the ranch level for analytical purposes, particularly for association with the ranch-management data (Table S1).

2.3. *Grazing metrics*

For each ranch, we recorded variables that reflected the biophysical environment, as well as those that account for nuanced grazing practices that made each individual operation unique, regardless of its broadly defined grazing system. We characterised grazing management practices and the land use history of individual ranches through detailed rancher surveys. Surveys addressed long-term land use patterns such as cultivation history, and typical grazing practices for a minimum of 10 years prior, as verified by field surveys. The following key metrics were identified: rest-to-grazing ratio, stocking rate, animal unit density, start of the grazing season and cultivation history (Table S1) (see Bork et al., 2021 for details). The rest-to-grazing ratio was defined as the number of days of rest per day of early-season grazing (where early grazing occurred prior to August 1). Stocking rates (in animal-unit-months ha^{-1}) for each ranch were calculated based on the number of cattle, stock class (mature cows/bulls vs yearlings) and entry and exit dates. Mean paddock size and herd sizes were used to compute mean cattle densities while grazing (animal-units ha^{-1}). Start of the grazing season was defined as the first day of early-season grazing (Julian d), with the earliest possible start date set to March 15 to avoid the inclusion of winter (dormant-season) grazing. The binary cultivation history metric (yes/no) indicated whether a grassland had previously been cultivated (and seeded). The annual heat-moisture index (AHM) was included as the primary climatic variable, which was derived from MAP and MAT, and represented increasing levels of aridity. Binary metrics were used for grazing system (adaptive = 1; conventional = 0).

2.4. *Data analysis*

Prior to analyses, we removed 13 of the 156 water infiltration measurements from our dataset that were rated as ‘poor’ based on the Saturo operational manual QA/QC tests (adaptive = 5; conventional = 8; maximum of 1–2 per ranch) (Meter Group Inc, 2020). The main source for anomalous readings (i.e. ‘poor’ ratings) was that the Saturo unit failed to maintain constant pressure, an error that was usually not detected until the data could be reviewed in the office. One additional data point was removed from analyses following an outlier test on water infiltration rates using the *identify_outliers* function in the R package ‘rstatix’ (Kassambara, 2020).

We first conducted several linear regression analyses to explore the fundamental relationships between water infiltration and biophysical metrics (i.e. soil texture, bulk density, plant litter), animal impacts documented by survey data (i.e. cattle stocking rate and animal stock density) and soil bulk density, root mass and litter mass, as well as water infiltration and root mass, further separated by grazing practices at the systems level (adaptive vs conventional grazing) throughout. Effects of grazing on water infiltration rates were then tested using linear mixed-effects models (LMMs) in the 'lme4' package in R (Bates et al., 2015). As a first step, we used the subset of 34 ranches for which three biophysical variables considered important to water infiltration (i.e. soil texture, bulk density, plant litter) were available, to test whether results would differ from those based on the full 52-ranch dataset for which only bulk density data were available. We followed a two-staged analytical approach in that we separately tested for the effects of grazing at the systems level (i.e. adaptive vs conventional grazing) and other more nuanced grazing practices on water infiltration, over and above select biophysical effects (soil texture, bulk density, plant litter), essentially testing for differences in the slope of response variables between treatment groupings. Multi-collinearity between the original set of predictor variables was examined, and we retained all predictor variables based on a collinearity threshold of ($|r| < 0.7$) (Fig. S3) (Dormann et al., 2013). A similar approach was applied to the complete dataset with 52 ranches, where we tested the effects of grazing on water infiltration, over and above soil bulk density, cultivation history and AHM.

Given our primary interest in evaluating the effects of grazing management, each candidate model (other than the null model) was set to contain at least one grazing management predictor variable. No model contained more than four covariates (or three in the case of 34 ranches) to avoid model overfitting (Babyak, 2004). Null models using random-effects structure (ranch pair) only were among the candidate models, thereby accounting for regional variation in climate and soils on infiltration. Across all models, random intercepts were specified for 'ranch pair'. We specified a Gaussian distribution (identity link function), and tested model residuals for normality and homogeneity of variances. All response variables met model assumptions.

Alternative models that included adaptive vs conventional grazing and other more nuanced grazing practices, as well as soil, cultivation history, and climate covariates, were identified (Tables S2–S5). Akaike Information Criterion adjusted for small sample size (AIC_c) were used to identify the most parsimonious candidate models (i.e. those within 2 AIC units) (Tables 1 & S6) (Symonds and Moussalli, 2011). Finally, we used the *standardize_parameters* function in the 'effectsize' package of R (Ben-Shachar et al., 2020) to compute model coefficient effect sizes and confidence intervals to assess variable significance (Cumming, 2009). We tested for potential confounding spatial autocorrelation of model residuals using the *spline.correlog* function in the 'ncf' package (Bjørnstad and Falck, 2001). The LMMs did not indicate spatial autocorrelation of model residuals.

3. Results

At the ranch level, soil water infiltration rate ranged from 8 to 256 mm h^{-1} (mean of 105 mm h^{-1}) in grasslands under adaptive grazing, and 15 to 205 mm h^{-1} (mean of 74 mm h^{-1}) on neighbouring ranches (Table S1). Soil texture, expressed as the clay-to-sand ratio, ranged from <0.1 to 1.7 (mean of 0.7) on adaptive grazing ranches, and <0.1 to 1.1 (mean of 0.6) on neighbouring ranches (based on 38 ranches; Table S1). Soil bulk density at the ranch level ranged from 0.3 to 1.2 g cm^{-3} (mean 0.8 g cm^{-3}) on adaptive grazing ranches, and from 0.3 to 1.1 g cm^{-3} (mean 0.8 g cm^{-3}) on neighbouring ranches (based on 52 ranches; Table S1). The dry weight of plant litter ranged from 24.0 to 779.2 g m^{-2} (mean of 303.2 g m^{-2}) on adaptive grazing ranches, and 50.4 to 623.2 g m^{-2} (mean of 248.8 g m^{-2}) on neighbouring ranches (based on 34 ranches; Table S1).

3.1. Relationship between water infiltration and environmental variables

Linear regression between water infiltration rate and soil texture showed different patterns for the adaptive grazing as compared to the conventional grazing ranches, with a significant positive relationship for adaptive grazing ranches only (Fig. 1a). Water infiltration rate was also positively correlated with plant litter mass, albeit only on adaptive grazing ranches (Fig. 1c). The opposite trend was observed for bulk density, however, where water infiltration rates decreased significantly with increasing bulk density for both adaptive grazing and conventional grazing ranches (Fig. 1b). No significant relationships were evident between long-term reported animal impact (i.e. annual cattle stocking rates and animal stock densities) and soil bulk density within adaptive grazing ranches, though bulk densities increased with higher animal unit densities under conventional grazing (Figs. S4a–c). Moreover, there was no significant pattern between root mass and litter mass ($p = 0.288$), as well as no significant relationship between water infiltration and root mass ($p = 0.678$; data not shown).

3.2. Linear mixed effects models of grazing management on water infiltration

Our initial comparison of the results for the subset (34 ranches) and full data set (52 ranches) indicated that among biophysical variables, bulk density (but not texture and litter amount) had a significant effect on water infiltration (Tables 2 & S7). We therefore concluded that presenting results based on analyses of the full data set from all 52 ranches was warranted. Foremost, we found a significant relationship between water infiltration and adaptive grazing management, with higher infiltration rates on adaptively grazed grasslands than on neighbouring properties (Fig. 2). In addition, water infiltration declined significantly as soil bulk density increased, a pattern that was consistent across grazing treatments (Table 2, Fig. 3a). Overall, fixed effects accounted for a lower proportion of the variance in infiltration rates (24%), than was captured by the random-effects structure (39%) of the paired-ranch study design (Table 2). Among other grazing practice characteristics, water infiltration exhibited a significantly positive association with the rest-to-grazing ratio, thereby closely reflecting the pattern observed for adaptive grazing in general (Table 2, Fig. 3b). No significant effect of cattle stocking rate on water infiltration was detected, although the latter tended to decline at higher stocking rates (Table 2, Fig. 3c). Rest-to-grazing ratio, cattle stocking rates and soil bulk density explained a substantial portion of the variation in water infiltration, while the addition of a random effect more than doubled the total variation explained, which was comparable to the overall adaptive grazing results (Table 2).

Table 1

Summary table of the most parsimonious linear mixed models (<Δ2AIC units) for water infiltration distinguished between adaptive vs conventional grazing systems (GS) and more nuanced grazing practices (GP) across the full data set of 52 ranches. We separately tested for the effects of GS and GP, over and above select biophysical effects (soil texture, bulk density, plant litter). Random intercepts were specified for 'ranch pair' to account for the paired study design. The random effect accounts for geographic variation in climate and soils. AIC_c = Akaike Information Criterion adjusted for small sample size.

Grazing management	Model	Explanatory variables	AIC_c	Delta AIC_c	log-Likelihood	AIC_c weight
Grazing system	GS	Adaptive vs conventional + Bulk density	103.51	0.00	−46.10	0.95
Grazing practice	GP1	Rest:graze ratio + Bulk density	106.04	0.00	−47.37	0.28
	GP2	Rest:graze ratio + Stocking rate + Bulk density	106.89	0.85	−46.51	0.18

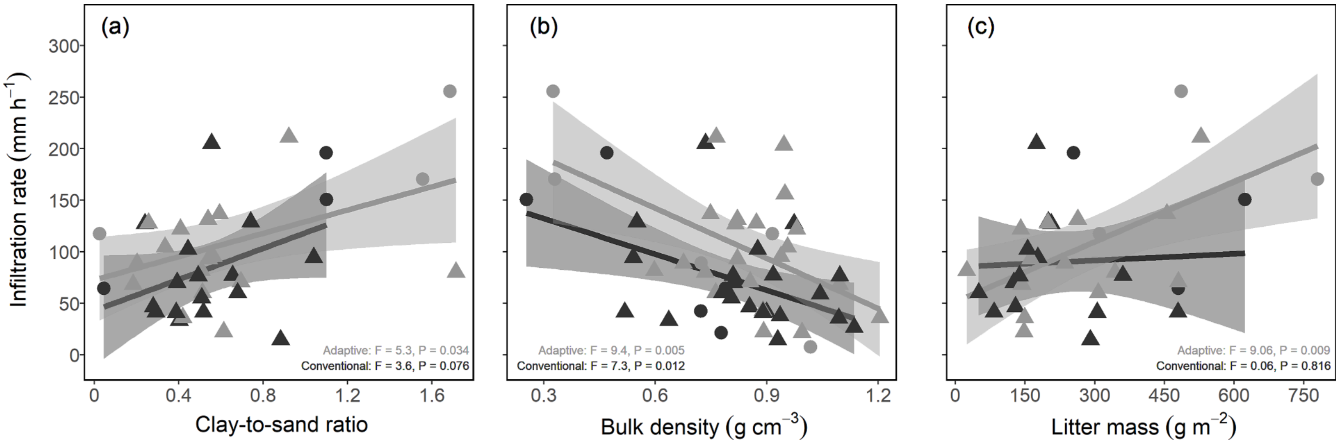

Fig. 1. Illustration of the association between clay-to-sand ratio (i.e. soil texture), bulk density (g cm^{-3}) and plant litter mass (g m^{-2}) on soil water infiltration rate (mm h^{-1}) based on 34, 38 and 60 grazed cattle ranches, respectively. Adaptively grazed ranches are indicated in light grey and conventionally grazed ranches in dark grey. Circles illustrate non-cultivated ranches and triangles cultivated ranches. Shaded areas indicate 95% confidence intervals.

Table 2

Summary table of the most parsimonious linear mixed models (<Δ2AIC units) for water infiltration distinguished between adaptive vs conventional grazing systems (GS) and more nuanced grazing practices (GP) across the full data set of 52 ranches. Random intercepts were specified for 'ranch pair' to account for the paired study design. We separately tested for the effects of GS and GP, over and above select biophysical (i.e. bulk density), land use (i.e. cultivation history) and climate (i.e. AHM) effects. The random effect accounts for geographic variation in soils and climate. Marginal R^2 (variance explained by just the fixed effects) and conditional R^2 (variance explained by both fixed and random effects) were calculated for the top models after Nakagawa and Schielzeth (2013). To account for model selection uncertainty we report unconditional SE. Standardised coefficients (ω_p^2) to determine effect size and 95% confidence intervals as a measure of significance are provided; bold variables have CIs that do not overlap zero.

Grazing management	Model	R^2_m	R^2_c	Explanatory variable	Estimate	SE	ω_p^2	95%
Grazing system	GS	0.24	0.63	Intercept	4.088	0.124	0.00	[0.00, 0.00]
				Adaptive vs conventional	**0.373**	**0.124**	**0.26**	**[0.09, 0.42]**
				Bulk density	**−0.729**	**0.224**	**−0.43**	**[-0.69, −0.17]**
Grazing practice	GP1	0.23	0.60	Intercept	4.279	0.109	0.00	[0.00, 0.00]
				Rest:graze ratio	**0.356**	**0.146**	**0.24**	**[0.05, 0.43]**
				Bulk density	**−0.773**	**0.231**	**−0.46**	**[-0.73, −0.19]**
	GP2	0.25	0.61	Intercept	4.281	0.106	0.00	[0.00, 0.00]
				Rest:graze ratio	**0.444**	**0.159**	**0.30**	**[0.09, 0.51]**
				Stocking rate	−0.223	0.168	−0.16	[-0.39, 0.08]
				Bulk density	**−0.788**	**0.227**	**−0.47**	**[-0.73, −0.20]**

4. Discussion

Greater water infiltration is an indication of improved hydrologic function and plant productivity potential, and is considered a core benefit of short-duration, high-intensity grazing, according to proponents of these practices (Savory, 1988; Savory and Parsons, 1980). This is supported by our result that adaptive grazing improved water infiltration within grazed grasslands of western Canada in comparison to neighbouring properties employing conventional beef cattle grazing practices (Table 2, Fig. 2). This finding is consistent with the results of a recent global synthesis that reported a positive effect of increased grazing pattern complexity, including the use of rotational, adaptive management practices, on water infiltration (DeLonge and Basche, 2018). Previous studies specifically comparing adaptive grazing with continuous grazing at the light and heavy stocking rates, albeit at a much smaller geographic scale and across substantially fewer study ranches than the present study, either found a similar trend of enhanced water infiltration under adaptive grazing (Park et al., 2017; Teague and Barnes, 2017), or reported no difference between grazing management strategies (Teague et al., 2011).

Furthermore, our more comprehensive analysis of the role of contrasting livestock management practices provides novel insight into how grazing might alter hydrologic function. This includes an assessment of those factors underpinning the 'herd effect', foremost extended rest periods in the growing season, and elevated stock density, both of which revealed distinct trajectories in their association with water infiltration (Table 2, Fig. 3). First, the adoption of extended rest following intense grazing in spring and early summer resulted in enhanced infiltration, lending support to the conclusions of a recent meta-analysis that found longer rest generally benefits water infiltration (DeLonge and Basche, 2018). Experimental accounts of the benefits of rest periods associated with rotational grazing have a long history (Voisin, 1959). In a prairie grassland context, rotational grazing systems that provide adequate rest periods allow for improved plant recovery between grazing events (Warren et al., 1986c).

In contrast to rest periods, we found no evidence that herd effect, as regulated by animal stock density, led to improved water infiltration. Proponents of adaptive grazing or similar methods (such as holistic management) claim that intense, rotational grazing at high stock density can improve hydrological properties by breaking up the soil crust (Goodloe, 1969; Savory, 1988; Savory and Parsons, 1980), which has been found to limit water infiltration (Freebairn et al., 1989). Others, however, have argued that trampling effects on soil crust would only be short-lived, while lasting effects could be achieved through increases in vegetative cover and organic matter (Thurow, 1991). Instead, numerous studies evaluating short-duration grazing in North America show intense hoof action in heavily stocked paddocks leads to soil compaction and lower (or comparable) infiltration rates relative to continuous grazing at low to moderate stocking rates (McCalla II et al., 1984; Nash et al., 2004; Pluhar et al., 1987; Thurow et al., 1986; Weltz and Wood, 1986). Moreover, high cattle densities may increase the risk of overstocking, which is widely recognised as a key driver of grassland

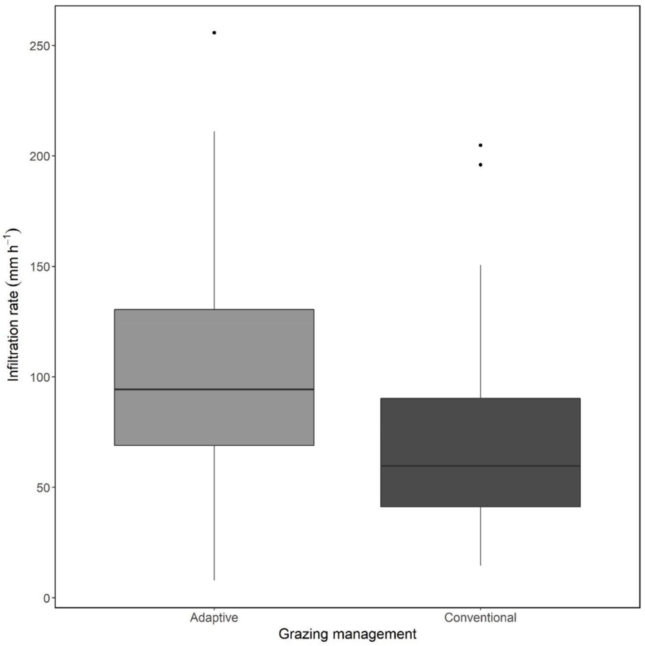

Fig. 2. Boxplot of the differences in water infiltration rate (mm h^{-1}) distinguished between adaptive and conventional grazing based on 52 grazed cattle ranches. Lower quartile, median and upper quartile are indicated by horizontal lines.

degradation and desertification (Feng et al., 2015; Fischer et al., 2009; Geist and Lambin, 2004; Mysterud, 2006).

We did observe a weak trend (albeit non-significant) for lower infiltration at higher cattle stocking rates (Table 2, Fig. 3). Throughout the scientific literature, the highest water infiltration rates are frequently reported for grasslands where livestock have been excluded (Sirimarco et al., 2018); this pattern is also consistent with a global synthesis where improvements to water infiltration followed a shift from heavy to either moderate or low stocking (DeLonge and Basche, 2018). The lack of an overall effect of stocking here might reflect the inconsistency in stocking levels (and therefore, stocking effects) among our ranches and the need for a much larger sample size. Instead, our study supports the notion that length of rest during the early growing season grazing period, rather than livestock presence directly, was the critical factor regulating water infiltration, and therefore hydrologic function, within these grasslands (Warren et al., 1986a). We postulate that lengthened rest may enhance infiltration by facilitating the growth of grazing-susceptible vegetation, leading to subsequent feedbacks on soil hydrology. For example, favourable root growth during vegetation recovery (Gould et al., 2016) could lead to an increase in soil macropores within the topsoil (Meek et al., 1992), and thereby increase opportunities for water entry and downward movement.

The two main mechanisms associated with the negative impacts of increased grazing intensity on grassland water infiltration are the modification of soil properties, including increased soil bulk densities, which could result from animal trampling, and the removal of protective cover comprised of both live and dead plant matter (Blackburn et al., 1982; Radke and Berry, 1993; Warren et al., 1986b; Wood and Blackburn, 1981; Blackburn et al., 1982). While we found no evidence for a direct livestock trampling effect on soil bulk density under adaptive grazing, there was a significant reduction in water infiltration along a gradient of increasing bulk density within these grasslands. This effect was consistent across both adaptive and conventional grazing ranches, indicating that the grazing practices under study did not alter soil physical properties. Similarly, Abdel-Magid et al. (1987) found that stocking rate did not influence bulk density, but nevertheless reduced water infiltration within a prairie grassland. The negative effect of bulk density on infiltration supports the notion that soil structural properties can strongly regulate soil water entry and movement, over and above the effects of texture (Basche and DeLonge, 2019; Castellano and Valone, 2007).

In fact, we did not find a significant overall effect of texture on water infiltration, despite the close association between bulk density and soil texture (Nawaz et al., 2013; van Haveren, 1983). The absence of a strong soil texture effect on infiltration could be due to the paired treatment design resulting in relatively uniform soil texture between adjacent ranches (Bodhinayake and Cheng Si, 2004), whereas bulk density depended not only on texture but also further modification by ongoing land use practices.

The trend towards higher rates of infiltration within clay-rich soils for both adaptive and conventional grazing practices was unexpected. This contrasts, for example, with the findings of a comparative adaptive grazing study in US grasslands, where infiltration rates were higher in coarser soils (Hillenbrand et al., 2019), as well as the usual understanding that water infiltration is enhanced by the coarse substrate of sandy soils relative to more fine-textured soils (O'Geen, 2013). A possible explanation for enhanced water infiltration within clay-rich

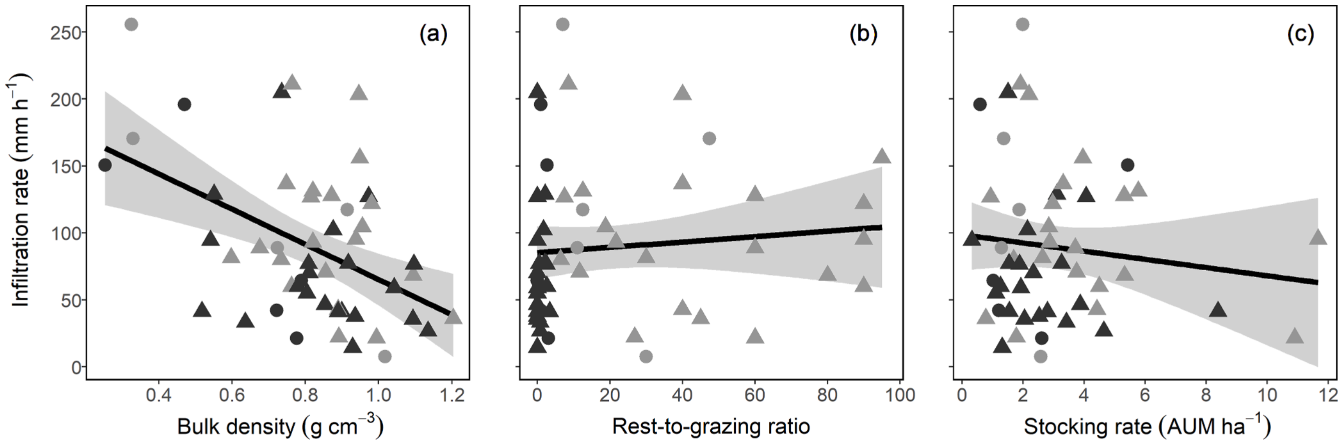

Fig. 3. a) Relationship between soil bulk density (g cm^{-3}) and water infiltration rate (mm h^{-1}) based on 52 grazed cattle ranches. b) Relationship between rest-to-grazing ratio and water infiltration rate (mm h^{-1}). The rest-to-grazing ratio was defined to be the number of days of rest per day of early season grazing (prior to August 1). c) Relationship between stocking rate (AUM ha^{-1}) and water infiltration rate (mm h^{-1}). Adaptively grazed ranches are indicated in light grey and conventionally grazed ranches in dark grey. Circles illustrate non-cultivated ranches and triangles cultivated ranches. Linear regression line and standard errors (shaded area) provided.

soils may be that fine soils have inherently higher water holding capacity than sandy soils due to higher total pore volume, which can result in higher infiltration rates under water-saturated conditions as sandy soils saturate sooner; indeed, this was the situation in the tests conducted here.

The positive correlation between infiltration rates under adaptive grazing and litter mass observed in our study provides evidence for the benefit of litter on grassland hydrological processes (Deutsch et al., 2010b). Previous studies have shown that the loss of vegetative and litter cover, for example due to overstocking, can lead to runoff and lower rates of infiltration (Castellano and Valone, 2007; Naeth et al., 1991a; Thurow et al., 1988; Warren et al., 1986b). The significant trend of greater water infiltration under adaptive grazing, but not conventional grazing, might be due to more efficient incorporation of litter into the soil surface under high-density livestock grazing, leading to improved soil structure and higher organic matter content.

Soil water infiltration is a key indicator of hydrologic function in grazed arid lands (Arshad and Martin, 2002; Keesstra et al., 2016; Teague and Barnes, 2017). Much of the Canadian Prairies is naturally moisture-limited, receiving little precipitation at high variability (Hanesiak et al., 2011; Willms and Jefferson, 1993). This limitation could be exacerbated by a warming climate, with models projecting a future increase in the frequency and magnitude of drought for western Canada, and in particular, the drought-prone Mixedgrass prairies (Bonsal et al., 2013). Livestock grazing continues to be the largest user of land globally, occurring on over 25% of the earth's terrestrial surface (Asner et al., 2004; Herrero et al., 2013), with livestock accounting for 60% of land-based vertebrate biomass (Bar-On et al., 2018). Livestock grazing will continue to be paramount to food security in many countries (Godber and Wall, 2014) and an important management strategy for safeguarding grassland ecosystems from alternative human land uses, including cultivation (Rufino et al., 2013). Grazing practices that maximise ecosystem services, including those associated with the water-carbon cycle are therefore urgently needed.

The integration of adaptive grazing with a strong focus on adequate vegetation recovery at low to medium stocking rates appears to benefit grassland soil hydrology, which will be an important puzzle piece for meeting climate, biodiversity and food security targets (McDonald et al., 2018). To maximise our ability to develop effective mitigation and adaptation strategies, however, complementary research on the effects of adaptive grazing on other ecosystem attributes is needed, such as soil carbon storage, greenhouse gas emissions and above- and belowground biology at the landscape-scale.

5. Conclusions

The world is facing the triple challenge of stabilizing the climate, ensuring food security and safeguarding ecosystem services (IPBES, 2019; WWF, 2020). These challenges are interconnected and call for concerted solutions that are scalable and economical (Hannah et al., 2013; Lenton et al., 2019; Ripple et al., 2020; Steffen et al., 2018). Our study provides one of the most comprehensive evaluations of the effects of rotational, adaptive grazing management on water infiltration in temperate grasslands. We demonstrate that adaptive grazing improves soil water infiltration in Canadian grasslands compared to conventional grazing practices. However, improvements in water infiltration are driven by extended periods of rest (and plant recovery) after growing season grazing, rather than animal impacts *per se*, such as cattle stocking rate, which had minimal to negative impacts on infiltration. Finally, we caution that as the conversion and degradation of the world's natural ecosystems continue, intensified action to protect remaining grasslands and forests is of utmost priority for stabilizing the climate, ensuring food security and safeguarding ecosystem services.

6. Data availability statement

Data can be accessed through the University of Alberta Dataverse Repository: https://doi.org/10.7939/DVN/V28LOZ (Döbert et al., 2021)

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2021.115314.

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