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Managing grazing lands to improve soils and promote climate change adaptation and mitigation: a global synthesis

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Abstract

The potential to improve soils to help farmers and ranchers adapt to and mitigate climate change has generated significant enthusiasm. Within this discussion, grasslands have surfaced as being particularly important, due to their geographic range, their capacity to store substantial quantities of carbon relative to cultivated croplands and their potential role in mitigating droughts and floods. However, leveraging grasslands for climate change mitigation and adaptation will require a better understanding of how farmers and ranchers who rely on them for their livelihoods can improve management and related outcomes. To investigate opportunities for such improvements, we conducted a meta-analysis of field experiments that investigated how soil water infiltration rates are affected by a range of management options: adding complexity to grazing patterns, reducing stocking rates or extended rest from grazing. Further, to explore the relationships between observed changes in soil water infiltration and soil carbon, we identified papers that reported data on both metrics. We found that in 81.9% of all cases, responses of infiltration rates to identified management treatments (response ratios) were above zero, with infiltration rates increasing by $59.3 \pm 7.3\%$. Mean response ratios from unique management categories were not significantly different, although the effect of extended rest ($67.9 \pm 8.5\%$, $n = 140$ from 31 experiments) was slightly higher than from reducing stocking rates ($42.0 \pm 10.8\%$; $n = 63$ from 17 experiments) or adding complexity ($34.0 \pm 14.1\%$, $n = 17$ from 11 experiments). We did not find a significant effect of several other variables, including treatment duration, mean annual precipitation or soil texture; however, analysis of aridity indices suggested that grazing management may have a slightly larger effect in more humid environments. Within our database, we found that 42% of complexity studies, 41% of stocking rate studies and 29% of extended rest studies also reported at least some measure of soil carbon. Within the subset of cases where both infiltration rates and carbon were reported, response ratios were largely positive for both variables (at least 64% of cases had positive mean response ratios in all management categories). Overall, our findings reveal that a variety of management strategies have the potential to improve soil water infiltration rates, with possible benefits for soil carbon as well. However, we identified a shortage of well-replicated and detailed experiments in all grazing management categories, and call for additional research of both soil water and soil carbon properties for these critical agroecosystems.

Introduction

The potential for improved soil health to help farmers and ranchers adapt to and mitigate climate change has generated substantial enthusiasm among various stakeholders. While much of this conversation has centered on croplands and related conservation agriculture practices (Poeplau and Don, 2015; VandenBygaart, 2016), grasslands and grazing lands have gained increasing attention (Paustian *et al.*, 2016; Teague *et al.*, 2016). The significance of these grass and grazing-based systems is in part due to their wide geographic range; in the USA, there are about 777 million acres of grazing land (Nickerson *et al.*, 2011), and about 25% of the global land surface is managed as grazing land (Asner *et al.*, 2004). Further, grazing systems are the foundation of millions of livelihoods in the USA and hundreds of millions globally, and these lands and livelihoods are very vulnerable to climate change (Thornton *et al.*, 2009; Sayre *et al.*, 2013; Briske *et al.*, 2015). Therefore, these areas represent a significant opportunity to address land sector solutions for climate adaptation and mitigation.

Grasslands provide numerous ecosystem services, including the capacity to store substantial quantities of soil carbon, reduce runoff and erosion, protect water quality, store water, reduce drought and flood risk, provide wildlife habitat and recreational areas, and support biodiversity (Franzluebbers *et al.*, 2012; Werling *et al.*, 2014; Yahdjian *et al.*, 2015). Together, these services contribute to both climate change mitigation and adaptation, in addition to many other co-benefits. Despite their value, grasslands are being degraded and converted around the

world, frequently to crop production systems (Wright and Wimberly, 2013; Gibbs and Salmon, 2014; Lark *et al.*, 2015; Gage *et al.*, 2016). Notably, many of these ecosystems are highly prone to erosion under cropland management and may be better ecologically suited to production of animal products in well-managed grazing systems (Peters *et al.*, 2016). Identifying the best management practices that can maximize ecosystem services while maintaining farm profitability may be one way to protect and improve the ecological function of grasslands.

While uncertainties remain, several approaches to improve grazing land management have been proposed. These include identifying optimal stocking rates and adopting more complex grazing management strategies, for example, through rotational grazing, adaptive management practices (e.g., adaptive multipaddock grazing) or silvopasture (Myserud, 2006; Heckman, 2015; Teague *et al.*, 2016; Teague and Barnes, 2017). Other strategies involve integrating grazing and pastures into more intensively managed diverse cropping systems (Russelle *et al.*, 2007; Sulc and Franzluebbers, 2014). Extended rest from grazing has also been adopted in an effort to restore lands and ecosystem services (Bock *et al.*, 1993; Castellano and Valone, 2007; Jeddi and Chaieb, 2010; Allington and Valone, 2011). These strategies can have different impacts and tradeoffs related to ecosystems, livelihoods and other socio-economic factors (Rivera-Ferre *et al.*, 2016).

Among the many ecosystem services affected by grazing land management, climate change resilience is especially critical given increasing rainfall variability (Pryor *et al.*, 2014). One approach to adapting to rainfall variability is to improve conditions for effective water management in soils, enabling them to capture more rainfall and make it available to plants during drier times (Stroosnijder *et al.*, 2012; Stewart and Peterson, 2015). A variety of chemical, physical and biological soil processes affect soil water storage, but a key driver is infiltration rate, the rate of water entry into the soil (Hillel, 1998). Soil water content also has strong links to soil carbon and soil organic matter contents (Hudson, 1994; Emerson, 1995), variables that can be affected in response to both crop and grazing land management (Conant *et al.*, 2001; Wright *et al.*, 2004; Franzluebbers *et al.*, 2012; McSherry and Ritchie, 2013; McDaniel *et al.*, 2014; Poeplau and Don, 2015; Paustian *et al.*, 2016). Other factors affecting soil water content include hydrological properties such as porosity and plant available water, which can also be improved in agricultural systems, such as by cover crops, perennial grasses and agroforestry (Basche and DeLonge, 2017).

Understanding soil water infiltration rates and how they change is useful given their role in enhancing soil water storage and because they are an indicator of soil health (Moebius-Clune *et al.*, 2016). Importantly, infiltration rates differ between and among ecosystems; for example, infiltration rates are often higher on grasslands than croplands (Bharati *et al.*, 2002; Ghosh *et al.*, 2009), and can be even higher in agroforestry systems (Ketema and Yimer, 2014; Bayala and Wallace, 2015). Within grasslands, grazing management can influence infiltration rates; studies have found that rates tend to decrease as grazing pressure increases (Radke and Berry, 1993; Holechek *et al.*, 2000; Bell *et al.*, 2011; Kumar *et al.*, 2012), and some comparisons of well-managed grazing systems have suggested that adding complexity to grazing patterns can improve or maintain infiltration rates relative to continuous grazing (Thurow, 1991; Teague *et al.*, 2011). Areas where grazing has been excluded can also have higher infiltration rates. For example, a recent analysis of Australian grazing lands found significant declines in ecosystem structure and

function, including hydrological processes such as water infiltration and soil water, when cattle or sheep were introduced to previously ungrazed fields; however, this analysis did not focus on opportunities to improve outcomes with grazing management (Eldridge *et al.*, 2016).

While many individual studies exist, to our knowledge, there are no quantitative reviews of the effect of improved grazing land management practices on soil water, particularly for infiltration rates. Furthermore, we know of no reviews that evaluate how soil water properties and soil carbon sequestration may be jointly affected by management changes in grazing systems. The primary goal of this study is to investigate the potential of different management practices on grass-based grazing systems to improve water infiltration rates. A secondary goal was to evaluate the degree to which experiments on this topic have also explored relationships between soil water infiltration rates and soil carbon. This analysis builds on other recent work investigating impacts of cropland management practices (no-till, cover crops, crop rotations, perennials, cropland grazing) on infiltration rates, porosity and water retained at field capacity (Basche and DeLonge, 2017; Basche and DeLonge, *In Preparation*). In this analysis, we focus on management options for grass-based systems with a history of grazing.

Methods

Literature search

To investigate how soil water is affected by grazing management, we conducted a meta-analysis of grass-based field studies. We identified papers with the EBSCO Discovery Service™ using the keyword string 'infiltration AND graz*', and secondarily searched the USDA-NRCS Soil Health Literature database (USDA-NRCS, 2016), as detailed in Basche and DeLonge (2017). Ultimately, 37 papers (representing 221 paired comparisons) were included in the database.

Defining management practice categories

Three management categories were used to group the studies in this analysis (Table 1), and these categories were defined as described below.

Increased grazing pattern complexity (12 experiments): Experiments were included in this category if they represented a switch from a continuous grazing system to a more complex or strategically managed system (online Supplemental Material Table S1). This category primarily included cases where grazing was changed from continuous (year-round or seasonal) to complex (e.g., rotational, mob, adaptive, etc.) management. We also searched for cases of increasing management complexity through other variables, such as by moving from a fully grass-based system to silvopasture, but we only found one paper that met those criteria (Sharrow, 2007). This category generally included comparisons that added complexity while kept stocking rates ($\text{ha AU}^{-1} \text{yr}^{-1}$) similar (see online Supplemental Material Table S1).

Reduced stocking rates (17 experiments): Treatments were included in this category if they represented a reduction in grazing pressure without any clear changes to grazing land or grazing management complexity. Changes in stocking rates or densities were reported in database studies using a variety of variables (stocking rate, stocking density, residual phytomass, degradation, vegetation type; see online Supplemental Material Table S2).

Table 1. Overview of experiments. All systems include either continuous (C) or rotational (R) grazing with stocking rates that are low (L), moderate (M), high (H), very high (VH) or uncertain (n/a, considered to be moderate for analysis). Studies are categorized overall as (a) grazing pattern complexity studies, where treatments are agroforestry (For), rotational grazing (R) or adaptive grazing (Ada); (b) stocking rate studies, where treatments are reduced grazing (represented as L, M or H); and (c) extended rest studies, with exclosure treatment(s) only. Studies in (a) or (b) that also have exclosure treatments are noted with an 'E'

	(Author, year)	Site	Prec (mm)	Duration (years)	System	Stocking rate	Treatment
(a)	Sharrow (2007)	USA, OR	1085	11	C	n/a	For
E	Dedjir Gamougoun <i>et al.</i> (1984)	USA, NM	384	12	C	H	R
	Kumar <i>et al.</i> (2012)	USA, MO	967	3	C	M	R
E	McGinty <i>et al.</i> (1979)	USA, TX	572	7	C	H	R
E	Pluhar <i>et al.</i> (1987)	USA, TX	680	24	C	M	R
	Proffitt <i>et al.</i> (1995)	Australia	307	1	C	n/a	Ada
E	Tadesse (2002a)	Ethiopia	1360	4	C	H	R
	Teague <i>et al.</i> (2010)	USA, TX	648	3	C	M	R
E	Teague <i>et al.</i> (2011)	USA, TX	820	9	C	H	R
E	Thurrow <i>et al.</i> (1986)	USA, TX	609	4	C	H	R
E	Weltz and Wood (1986)	USA, NM	426	2, 3	C	H, M	R
E	Wood <i>et al.</i> (1981)	USA, TX	680	4, 20	C	M, M	R
(b)	E Bari <i>et al.</i> (1993)	Pakistan	625	2	C	H	M, L
	Chartier <i>et al.</i> (2011)	Argentina	258	-	C	H	M, L
E	Dedjir Gamougoun <i>et al.</i> (1984)	USA, NM	384	3	C	H	M
E	du Toit <i>et al.</i> (2009)	South Africa	366	2	C	H	M, L
E	Franzluebbbers <i>et al.</i> (2011)	USA, GA	1250	12	C	H	L
E	Mwendera and Saleem (1997)	Ethiopia	1000	1	C	V	L, M, H
E	Pluhar <i>et al.</i> (1987)	USA, TX	680	1	R	V	H
E	Savadogo <i>et al.</i> (2007)	Burkina Faso	841	1	R	V	L, M, H
E	Taddese <i>et al.</i> (2002b)	Ethiopia	1000	1	C	V	L, M, H
E	Tadesse <i>et al.</i> (2003)	Ethiopia	1095	2	C	H	M
E	Teague <i>et al.</i> (2011)	USA, TX	820	9	C	H	L
E	Thurrow <i>et al.</i> (1986)	USA, TX	609	6	C	H	M
E	Warren <i>et al.</i> (1986a)	USA, TX	609	1	R	V	M, H
	Warren <i>et al.</i> (1986b)	USA, TX	609	2	R	H	M, L
E	Weltz and Wood (1986)	USA, NM	426	18	C	H	M
E	Wood <i>et al.</i> (1981)	USA, TX	680	20	C	H	M
E	Zhou <i>et al.</i> (2010)	China	505	13	C	H	M
(c)	Achouri and Gifford (1984)	USA, UT	250	20	C	M	
	Allington and Valone (2011)	USA, AZ	395	40	R	n/a	
	Bharati <i>et al.</i> (2002)	USA, IA	851	6	C	-	
	Busby and Gifford (1981)	USA, UT	345	5,1	R	M	
	Castellano and Valone (2007)	USA, AZ	350	52, 25, 10	C	-	
	Gifford (1982)	USA, ID	305	1, 2, 4, 6	C	-	
	Jeddi and Chaieb (2010)	Tunisia	196	6, 12	C	-	
	Kato <i>et al.</i> (2009)	Mongolia	181, 213, 162	4	C	V, H, M	
	Kauffman <i>et al.</i> (2004)	USA, OR	320	7	C	n/a	
	Lavado and Alconada (1994)	Argentina	950	3, 12	C	H	
	Takar <i>et al.</i> (1990)	Somalia	446	3	C	H	

(Continued)

Table 1. (Continued.)

(Author, year)	Site	Prec (mm)	Duration (years)	System	Stocking rate	Treatment
Tukel (1984)	Turkey	362	30	C	H	
Tromble <i>et al.</i> (1974)	USA, AZ	312	9	–	–	
Wheeler <i>et al.</i> (2002)	USA, CO	407.7	39	C	H	

Extended rest from grazing (31 experiments): Numerous experiments from our search included treatments where livestock were excluded from grazing areas. In fact, 58% (10/17) of the grazing pattern complexity studies and 88% (15/17) of the stocking rate studies also included grazing enclosure measurements (online Supplemental Material Tables S1 and S2). Additionally, 15 studies from our keyword search had measurements on enclosure only (online Supplemental Material Table S3). While not the focus of our analysis, we included these studies to provide insight into the potential effects on land from extended rest from grazing. For these studies, we defined the experimental treatment as the enclosures (i.e., rested areas) and the controls to be the grazed treatments. We further categorized these studies based on what type of grazing the treatments were being rested from (complex versus continuous grazing patterns, and light, moderate, heavy or very heavy stocking rates). Treatment duration was defined as the time since rest from grazing began; this was not always equivalent to the time since introduction of the control grazing pattern, so in some cases the control treatment should be considered only a proxy for the grazed condition. This artifact of the available data also means that the responses to rest estimated here could be larger or smaller than what would likely be found in a well-controlled experiment.

Database development

Data from studies were extracted and analyzed as systematically as possible, as described in Basche and DeLonge (2017). Our analysis only included values of steady-state infiltration (e.g., total volume of water infiltrated over a defined period). Further, multiple measurements reported in 1 yr were averaged, unless those measurements were distinctly different (due to experimental differences related to grazing management, slopes, soil textures, etc.). Additional variables were identified to assess the influence of different environmental or management factors. These included soil texture (percent sand, silt, clay), mean annual precipitation, treatment duration (number of years that a treatment was in place) and information on grazing (animal type, stocking rates and densities, annual days of grazing, days of rest between grazing, residual dry matter) (see Appendices 1–4). When available for both control and treatment conditions, we also extracted data on soil carbon or organic matter (concentrations or contents).

To supplement reported values, annual precipitation and temperature data were obtained from NOAA (Menne *et al.*, 2012; <https://www.ncdc.noaa.gov/cdo-web/datatools/normals>), and soil texture was retrieved from the US Department of Agriculture (Soil Survey Staff, 2017) for US locations only. When soil texture data were unavailable (seven of 37 studies), broader texture categories were defined if possible, based on soil textural descriptions (e.g., clay loam, loamy sand, etc.). Finally, we estimated aridity indices for all study sites using geographic coordinates, based

on the CGIAR-CSI Global-Aridity Database (Zomer *et al.*, 2006; Zomer *et al.*, 2008).

Statistical analysis

The meta-analysis was conducted by calculating response ratios, representing a standardized comparison of the experimental to control treatments (Hedges *et al.*, 1999). We calculated the natural log of the infiltration rate measured in the experimental treatment divided by the infiltration rate in the control treatment [Equation (1), e.g., more complex compared with more continuous management; reduced compared with greater stocking rates and extended rest from grazing compared with continued grazing]. Natural log results were back transformed to a percent change to ease interpretation, and results were considered significant if the 95% confidence intervals did not cross zero.

$$\text{LRR} = \ln \frac{\text{Experimental Infiltration Rate}}{\text{Control Infiltration Rate}}. \quad (1)$$

Many meta-analyses use weighting factors in statistical models to calculate mean treatment effects, which can include standard errors, standard deviations or experimental replications (Philibert *et al.*, 2012). However, due to the limited reporting of standard errors or standard deviations, as well as the fact that many grazing studies did not include true replications (experimental designs frequently included only subsamples from larger areas or transects, as opposed to a true randomized block design), we performed an unweighted meta-analysis (Eldridge *et al.*, 2016). Categories of grazing management (pattern complexity, stocking rates, extended rest) were analyzed separately, due to differences in experimental designs. A mixed model (lme4 package in R) was used to calculate category means and standard errors, including a random effect of study to account for similar study environments when experimental designs allowed for multiple paired observations (St-Pierre, 2001; Eldridge *et al.*, 2016). For several of the continuous environmental variables (soil texture, mean annual precipitation and aridity index), regression coefficients were generated from a similar statistical model where environmental variables were considered fixed effects.

Results

Infiltration database description

We located 37 total experiments representing 221 paired observations from five continents that met the criteria for this analysis (Fig. 1a). The number of suitable experiments for this analysis was smaller, but comparable, to the number of experiments available for a companion study investigating impacts conservation agriculture techniques on infiltration rates in cropping systems (e.g., 52 experiments for no-till, 23 for cover cropping; Basche

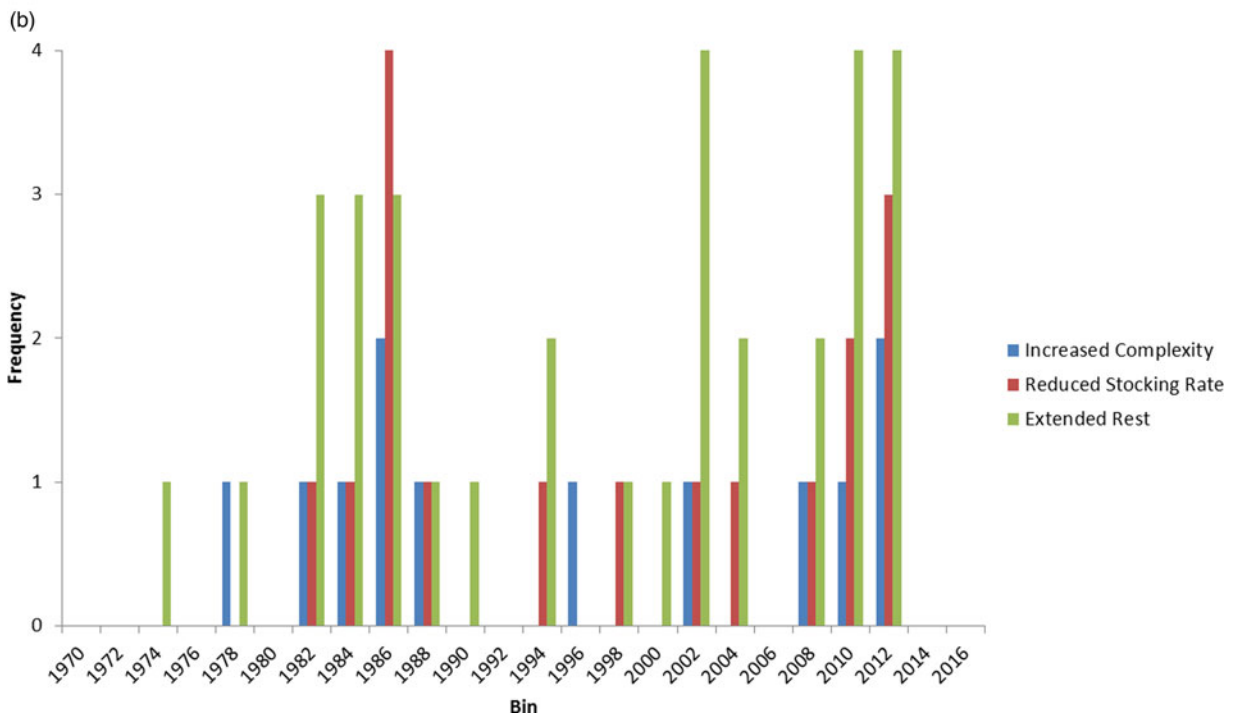
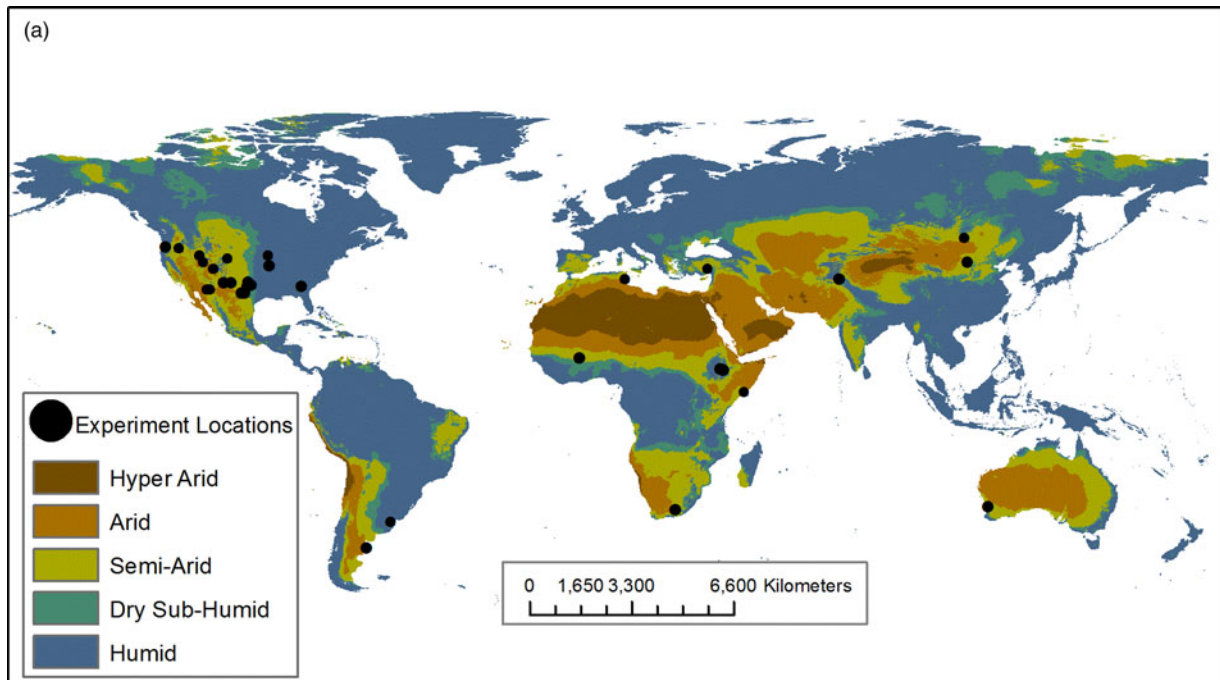


Fig. 1. (a) Geographic distribution of included studies (Africa: eight, Australia/New Zealand: one, Asia: four, South America: two, North America: 23 (22 in the USA)). Aridity indices are also shown for context. (b) Histogram showing timeline of publication of studies from each grazing management category.

and DeLonge, *In Preparation*). The management practice that was most represented within the database was extended rest from grazing ($n = 140$ paired comparisons), followed by reduced stocking rates ($n = 63$) and changes to pattern complexity ($n = 18$).

The studies within the database were diverse in several ways. For example, the types of grazing animals varied among experiments. For the complexity studies, six were cattle, two were sheep, three were mixed (including cattle, sheep and goats) and

one was described as livestock only. For the stocking rate studies, nine were cattle, two were sheep, four were mixed and two were livestock, whereas studies investigating the effects of extended rest included nine focused on cattle, four on mixed systems and two on livestock. Additional variability occurred with respect to vegetation (ranging from annual to perennial grasses, shrubs and forested areas); grazing management systems (including seasonal, rotational and adaptive grazing); and experimental design

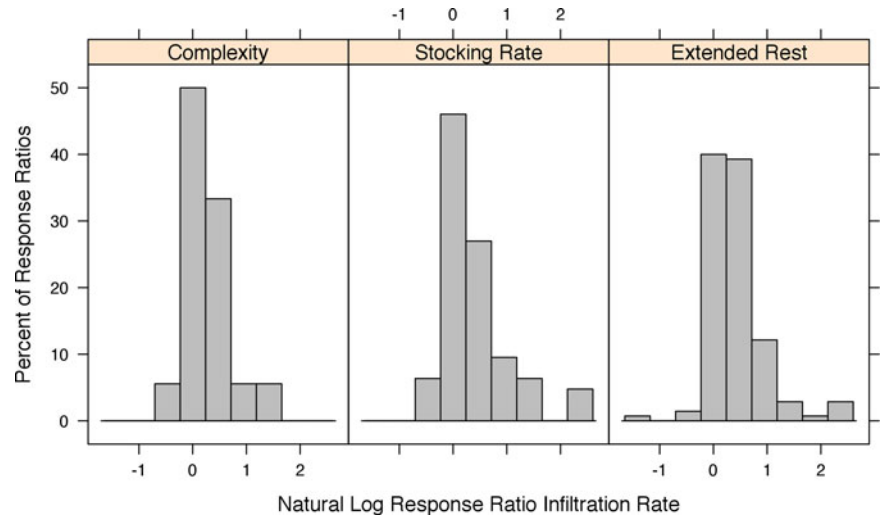


Fig. 2. Histograms of the natural log of response ratios to test for publication bias, separated by studies evaluating impacts of adding complexity to grazing patterns, reducing stocking rates or extended rest from grazing.

(ranging from replicated plots to cross-fence transects) (see online Supplemental Material Tables S1–S3). Several studies were published over a decade ago (the first three were published between 1974 and 1980), but overall papers have been published at a steady rate (1–4 papers every 2 yr) for all management categories (Fig. 1b, online Supplemental Material Tables S1–S3). Histograms of response ratios for the database, separated by grazing management categories, did not reveal evidence of publication bias (Fig. 2).

Response of infiltration rates to management changes

Of the full dataset representing all practices, 81.9% of response ratios were above zero, indicating an increase in infiltration rates (Fig. 3a). Of the grazing management response ratios that included either changes to pattern complexity or stocking rate, 72.8% were above zero (66.7 and 74.6% from adding complexity and reducing stocking rates, respectively). An even larger percentage of studies investigating the impacts of extended rest had positive response ratios (87.1%). Overall, results indicate that infiltration rates improved by $59.3 \pm 7.3\%$ following the implementation of the considered management practices (including adding complexity, reducing stocking rate and adopting extended rest from grazing; Fig. 3b). All individual management categories had mean response ratios significantly different from zero, including the categories with smaller sample sizes (changes to pattern complexity or stocking rate). There was no clear effect of treatment duration in any of the experiments, although several of the extended rest studies continued over relatively long periods; however, some studies suggested that relatively large differences could be possible within a short timeframe (Table 2, online Supplemental Material Fig. S1).

We found no significant differences between or within the complexity, stocking rate and extended rest treatments, although the mean values and confidence intervals differed. The mean response ratios for the added complexity and reduced stocking rate studies ($33.8 \pm 13.0\%$, $n = 18$ from 12 experiments, and $42.0 \pm 10.8\%$, $n = 63$ from 17 experiments, respectively) were slightly lower than those from the extended rest studies ($67.9 \pm 8.5\%$, $n = 140$ from 31 experiments) (Fig. 3b). There was no significant difference between the effect of reducing stocking rate ($42.0 \pm 10.8\%$; $n = 63$ from 17 experiments) and increasing

complexity ($33.8 \pm 13.0\%$, $n = 18$ from 12 experiments). Likewise, we did not detect any significant differences when grazing was prevented from continuous versus more complex (rotational, adaptive, etc.) managed grazing systems (Fig. 4). Treatments that reported an enclosure from continuous grazing had slightly higher mean response ratios ($73.7 \pm 10.1\%$) and represented a greater number of the available studies ($n = 119$) as compared

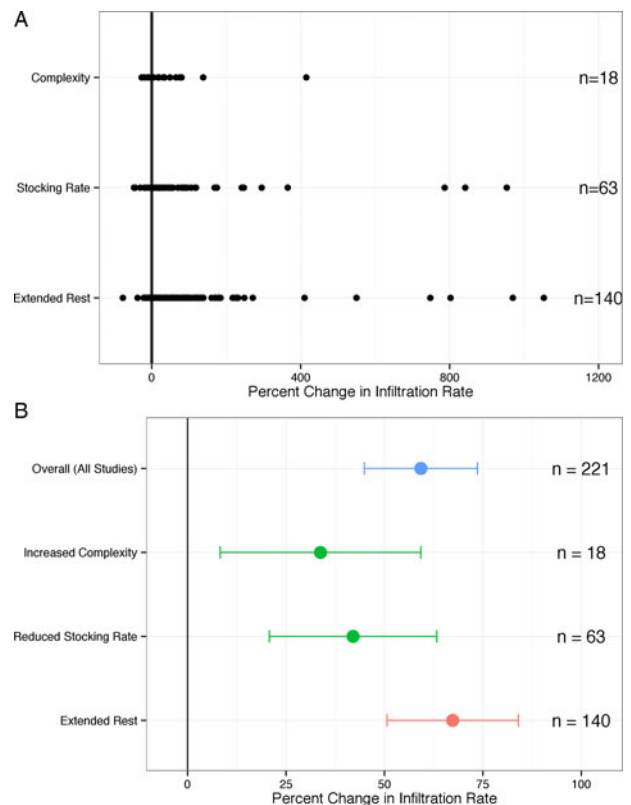


Fig. 3. (a) Influence of grazing system management on infiltration rates, separated by studies evaluating impacts of adding complexity to grazing patterns, reducing stocking rates or extended rest from grazing. (b) Mean response ratios ($\pm 95\%$ CI) for the overall database and for various subsets of grazing system management (changes to pattern complexity, changes to stocking rate, extended rest). Results were considered statistically significant if error bars did not cross zero. Numbers of response ratios per subgroup are shown for reference.

Table 2. Regression coefficients, *t*- and *P*-values from statistical model considering key environmental variables as fixed effects

		Mean annual precip.	Aridity index	% Sand	% Clay	Treatment duration
Overall database	Reg.coef.	0.000	0.242	0.006	-0.010	-0.001
	<i>t</i> -val	0.497	0.717	1.649	-2.244	-0.270,
	<i>P</i> -val	0.624	0.478	0.108	0.034	0.788
	# RRs	221	221	185	185	219
Complexity + stocking rate studies	Reg.coef.	0.001	0.278	0.006	-0.016	-0.007
	<i>t</i> -val	2.129	0.677	1.113	-2.586	-0.408
	<i>P</i> -val	0.084	0.505	0.277	0.015	0.685
	# RRs	81	81	69	69	79
Extended rest studies	Reg.coef.	0.000	0.506	0.006	-0.008	-0.004
	<i>t</i> -val	0.487	1.181	1.520	-1.464	-0.875
	<i>P</i> -val	0.631	0.249	0.143	0.160	0.384
	# RRs	140	140	116	116	140

P-values ≤ 0.1 are shown in bold for convenience. Number of available response ratios (# RRs) for each analysis shown for context.

with the enclosures from more complex grazing patterns ($50.4 \pm 9.8\%$, $n = 23$) (Fig. 4).

We did not detect a clear relationship between the percent reduction in stocking rates and changes to infiltration rates (online Supplemental Material Table S2 and Fig. S2). However, when we grouped the data in categories based on author descriptions of stocking rates, we found that the largest improvements in infiltration rates came from studies that reduced stocking rates from 'very heavy' to 'moderate' or 'low' stocking rates, as reported by authors (Fig. 5). There were relatively smaller differences in infiltration rates when the change in stocking rate was less pronounced, such as a change from 'very heavy' to 'heavy' or 'heavy' to 'moderate', and these groups exhibited changes that were not statistically different from zero.

Influence of soil and climatic factors

There were no clear patterns indicating relationships between management effects and climate variables (Table 2, online

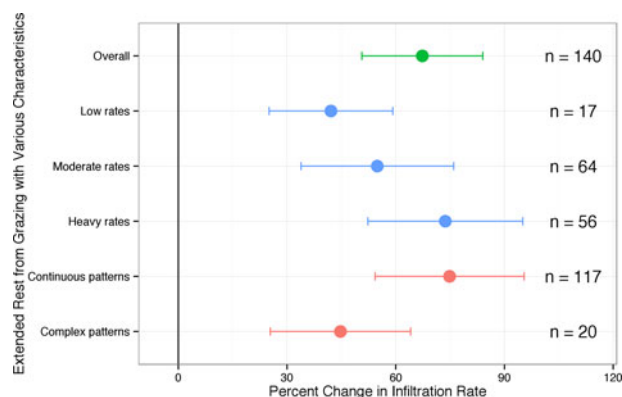


Fig. 4. Influence of extended rest on infiltration rates. Grouped mean response ratios ($\pm 95\%$ CI) are shown for all extended rest experiments (overall), as well as for sub-groups of studies based on the control treatment grazing systems (systems with continuous or complex grazing patterns; systems with low, moderate or heavy stocking rates). Results were considered statistically significant if error bars did not cross zero.

Supplemental Material Figs S3 and S4). The strongest observed relationship was a pattern in the aridity indices, where regression coefficients indicated a greater effect of grazing management in environments that are more humid. Among the relatively few studies in humid environments (aridity index > 0.65 ; $n = 25$ from seven experiments), there were no negative response ratios and there was a larger mean effect compared with the experiments in more arid environments (online Supplemental Material Fig. S3).

Similarly, we were unable to identify any strong relationships between management effects and soil texture, although there was some evidence that greater clay contents were more likely to lead to lower response ratios (Table 2, online Supplemental Material Fig. S5). There was also a relatively wide range in sand content, and in experiments that altered stocking rates or grazing pattern complexity the soils with a higher sand content tended to have positive and relatively higher response ratios. For clay content, there was a slightly narrower range, and the only negative response ratios were observed in soils with higher clay contents ($> 30\%$). However, it is important to note that only limited soil texture data were available in many of the studies.

Relationship between water infiltration and soil carbon impacts

We found that very few studies rigorously investigated both soil water and soil carbon, but several of the infiltration studies in our database did include at least some measure of organic matter or carbon. Specifically, 42, 41 and 29% of the complexity, stocking rate and extended rest studies, respectively, reported at least some data related to soil carbon (a total of 42 paired observations, representing approximately 19% of the full database) (Table 3). Of the available paired comparisons, most cases were associated with increases in the soil carbon metric in response to treatments (64–73% of paired comparisons, depending on management category). Similarly, in a majority of cases, the direction of the treatment effect (positive or negative) was the same in both the infiltration rate and soil carbon measurements (at least 60% of cases within all management categories). Finally, greater increases

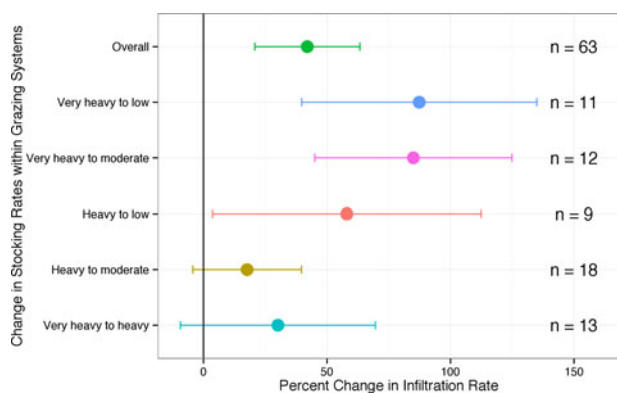


Fig. 5. Influence of changes to stocking rates on infiltration rates. Grouped means ($\pm 95\%$ CI) are shown for all studies evaluating changes to stocking rates (overall) as well as within subgroups determined by the control shown (very heavy or heavy) and treatment (heavy, moderate or low) stocking rates. Means were considered statistically significant if error bars did not cross zero.

in soil carbon tended to be associated with higher increases in infiltration rates (Fig. 6).

Discussion

Grazing management impacts on infiltration rates and soil carbon

Our analysis suggests that changes to grazing systems can increase infiltration rates, and that such improvements are possible through a variety of management strategies. These strategies include increasing grazing pattern complexity, in addition to reducing stocking rates or preventing grazing for an extended period. This finding is consistent with results from individual studies showing that infiltration rates can be increased by adding complexity to continuously grazed systems even at heavy stocking rates (Thurow, 1991), although such results have not been seen in all studies (e.g., Pluhar *et al.*, 1987, Teague *et al.*, 2010).

In addition, our results did not indicate any clear effect of treatment duration on the degree of improvements to infiltration rates. This finding is consistent with past studies that have found that high inter-annual variability in precipitation in combination with slow recovery processes could mean that over 20 yr are needed to see significant treatment effects in grazing systems (Castellano and Valone, 2007). Only select studies have documented a faster recovery of infiltration rates in grazing systems. For example, Gifford (1982) found that infiltration rates improved significantly after excluding livestock for just 6 yr. While our study

did identify select cases where relatively large improvements were achieved within short treatment durations, the lack of a significant trend and constraints in defining treatment duration (described earlier) suggested that substantial results are unlikely over short timeframes.

Our analysis of environmental factors suggests that infiltration rate improvements are possible in a wide range of climatic and soil conditions. Although there were no statistically significant differences when comparing response ratios by aridity or rainfall, there was some evidence to suggest slightly greater improvements in more humid environments. This trend was consistent with findings from another meta-analysis looking at conservation agriculture impacts on infiltration rates (Basche and DeLonge, *In Preparation*; for no-till and crop rotation practices). On the other hand, the trend conflicted with results from a meta-analysis of the effects of continuous living cover on porosity and water retained at field capacity, where treatment effects were strong in more arid environments (Basche and DeLonge, 2017). Finally, the lack of an effect of soil texture in our study could be explained in part by the limited availability of data. However, soil texture has also been shown to have only a weak effect on soil variables in other meta-analyses related to agricultural management (McDaniel *et al.*, 2014; Poeplau and Don, 2015)

Despite the importance of soil organic matter or carbon content for soil water properties (Hudson, 1994; Emerson, 1995), we found that few studies have rigorously investigated and reported results on both soil water infiltration and carbon. Nevertheless, our findings did indicate that the grazing treatments leading to improved infiltration rates were frequently associated with increases in soil organic matter or carbon content (although data were often very limited, in terms of replications, soil depth, etc.). This finding is similar to results from another study that showed that agricultural practices (e.g., cover crops, perennials) known to increase soil carbon can significantly improve infiltration rates (Basche and DeLonge, *In Preparation*). The concurrent effect of grazing management on both increased infiltration rates and soil carbon could result from enhanced biological activity that follows reduced soil disturbance. For example, it is understood that reduced soil disturbance increases earthworm activity and contributes to soil aggregation, which can increase water entry into the soil (Metting, 1993; Tomlin *et al.*, 1995; Bronick and Lal, 2005; Briones and Schmidt, 2017). Rest from grazing for long periods of time (which occurred in both the extended rest and added complexity categories) could also facilitate greater plant growth, and as a result lead to increased root development and decomposition, which is known to improve soil structure and enhance water entry into the soil (Six *et al.*, 2004).

Table 3. Availability of soil carbon or organic matter data (content or concentration, including measurements to any depth) in the database that was reported by grazing land management treatments within any of the studies

Grazing management category	# Studies	# Studies with C measurements	# Paired comparisons		
			with C data	with C increase	C RR in same direction as IR RR
Pattern complexity	12	5	6	4	4
Stocking rate	17	7	11	8	8
Extended rest	31	9	25	16	15

The number of paired comparisons indicating an increase in the soil carbon metric is shown, as well as whether the treatment response ratio (RR) for the soil carbon metric tracked the observed response in infiltration rates (IR) (i.e., either both increased or both decreased).

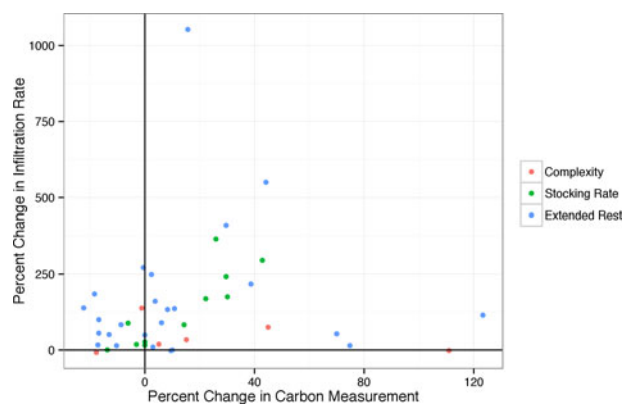


Fig. 6. Relationship between the percent changes in soil carbon or soil organic matter and infiltration rates for the subset of the database where sufficient data were reported for both properties (see Table 3).

Grazing management impacts as compared with cropland management

This study focused on grass-based grazing lands, but was part of a broader analysis that also investigated the management changes to conventional (annual) croplands. Interestingly, the improvements in soil water properties estimated in this study were on a similar order of magnitude as to what was observed in response to cropland management changes (Basche and DeLonge, 2017; Basche and DeLonge, In Preparation). Specifically, the mean improvements in this analysis were similar to the improvements in response to the introduction of perennials, and more reliably positive as compared to the implementation of crop rotations, no-till or cropland grazing. Of particular importance is the consideration that converting annual croplands to perennial systems (which are the foundation of the present study) offered the biggest overall benefit for cropland systems (Basche and DeLonge, In Preparation). With this broader perspective of agricultural lands, optimally managed grass-based grazing lands could offer even more significant water infiltration benefits relative to croplands. While we found very few studies that explicitly compared infiltration rates on croplands as compared with grass-based grazing lands (Bharati *et al.*, 2002; Liebig *et al.*, 2004; Ketema and Yimer, 2014), the available studies generally supported the idea that grazed grasslands had greater infiltration rates than nearby croplands.

Uncertainty and publication bias

Meta-analyses are inherently limited by the available published literature that fits inclusion criteria. In this analysis, there were additional limitations in the experimental details reported by many of the included studies, and this could explain some of the uncertainty in trends. For example, many of the experiments did not include any information about soil texture (12/37 experiments included numeric values of soil texture), which required using the best available public data or the creation of broader texture categories for many locations in our database, which ultimately did not reveal definitive trends. Further, we tracked whether studies reported slope (13/37) or aspect (4/37), but there were not enough experiments to perform a meaningful analysis with these variables. Some variables were reported relatively more frequently and in better detail, such as grazer type, plant communities and more specific details on stocking rates. However, given the already limited number of studies available

for the full analysis, the subcategories within such variables were too limited to be analyzed for robust results.

Our study reveals the overall need for more well-replicated, randomized research experiments exploring the effects of changes to grazing management on soil water properties, especially infiltration rates, as well as on other metrics of soil health (such as soil carbon and organic matter). Our results also emphasize the importance of including clear and detailed data in publications, especially from field experiments investigating the effects of grazing on soil water properties, as these tend to be relatively complicated and rare. Recently, Gerstner *et al.* (2017) proposed a list of useful variables that field experiments should report to improve their likelihood of being valuable for follow-up studies, including meta-analyses and other syntheses. They suggested, for example, better description of environmental characteristics related to soil and climate. Similarly, Eagle *et al.* (2017) noted the importance of standardized and consistent agricultural field experiments (and related reporting) to ensure that data syntheses, such as meta-analyses, are most insightful. For grazing systems, they highly recommended inclusion of details on species, intensity and timing of grazing. We further propose that details on historical and current management practices are particularly needed; these may include typical periods of grazing and rest, treatment durations and any specific factors that managers may consider when adjusting such parameters.

Given the complexity of experimental designs and the lack of reported standard errors in the studies within our database, we were unable to perform a weighted meta-analysis. This likely did not have a large effect on the overall findings, however. A histogram of response ratios did not reveal evidence of publication bias (Fig. 2) and given the overall similar magnitude and direction of results observed across a range of grazing management approaches and environments, the soil processes likely to be responsible for infiltration rate increases appear to be robustly captured by our analysis.

Conclusions

Overall, our findings revealed that a variety of grazing management practices can improve soil water properties, including not only extended rest from grazing but also changes to grazing pattern complexity and stocking rates. Furthermore, a lack of significance of several experimental and environmental variables (e.g., treatment duration, mean annual precipitation, aridity index, soil texture) suggested that grazing management could improve soil infiltration rates across a wide range of conditions. However, our results were constrained due to the limited availability of studies within any management category that met the criteria for inclusion into the database.

In general, the findings from this study are significant given the expansiveness of grasslands and grazing lands, their role in livelihoods and ecosystem service provisioning, and their potential connection to both climate change adaptation and mitigation. However, we note that significant uncertainties result from the shortage of well-replicated experiments in all grazing management categories. Therefore, we call for additional research on opportunities to improve grassland management and ecosystem service outcomes, especially related to climate change adaptation and mitigation, for these critical agroecosystems.

Supplementary Material. The supplementary material for this article can be found at <https://doi.org/10.1017/S1742170517000588>

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