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Compost amendment to enhance carbon sequestration in rangelands

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Abstract: Rangelands contain 20% of global soil carbon (C). Past management of rangelands has resulted in significant losses of soil C, threatening the long-term productivity and sustainability of these ecosystems. Compost amendments have been proposed as a means to increase soil C sequestration while providing important cobenefits to rangeland ecosystems and land managers. Here, we review the literature on the effects of compost amendments on soil and plant characteristics and rates of soil C storage. We extracted values related to biological, physical, and chemical responses to compost applications in rangelands in eight countries and on five continents. Studies reported both short (<1 y) and long-term (>12 y) effects with compost types derived from green waste, food waste, manure, and biosolids. Generally, we found that compost amendments improved aboveground production by >40%, and belowground C content by 50%. Further benefits of compost additions included increasing aggregate stability (~42%), water retention (~18%), nutrient availability (~37% and 126% for nitrogen [N] and phosphorus [P], respectively), as well as generally reducing erosion but with high variability. We found little to no effect of compost amendments on plant diversity and very few studies investigated effects on soil microbial community and function. Both field and modeling studies demonstrated that the changes in soil C from compost amendments can result in long-term C storage. Overall, results suggest that compost amendments may contribute to rangeland resilience to climate change with the additional benefit of climate mitigation via soil C sequestration.

Key words: carbon sequestration—climate mitigation—compost—rangelands

Rangeland ecosystems provide vital ecological services and societal goods but are under threat from climate change. Rangelands are seminatural ecosystems that are used primarily for livestock grazing, and in many cases without direct irrigation or nutrient management (Stoddart and Smith 1955). These ecosystems directly support subsistence and commercial livelihoods of a substantial proportion of the world's rural populations (Godde et al. 2020), and maintain wildlife diversity, water and nutrient cycling, and other key ecosystem services (Havstad et al. 2007; Sala et al. 2017). Rangelands cover approximately 25% of the terrestrial land area (Asner et al. 2004) and store approximately 20% of global soil organic carbon (SOC) (Follett and Reed 2010), and many areas globally are considered degraded with regard to soil C content (Sanderman et al. 2017). Rangelands are threatened by climate-driven changes in temperature, rainfall (including drought frequency and event intensity), and fire regimes, as well as management impacts such as land-use change and overgrazing (Fleischner 1994; Knapp and Smith 2001; Reynolds et al. 2007; Polley et al. 2013; McCollum et al. 2017; Godde et al. 2020; Barnes et al. 2021; IPCC 2022). The protection of existing soil C stocks and management interventions that enhance soil C across the large global rangeland area could make a significant contribution to climate change mitigation (Paustian et al. 2016; Mayer et al. 2018) and in turn support the ecosystem services provided by rangelands.

Maintaining or building soil organic matter content is key to enhancing resilience to climate change impacts as well as helping to mitigate future effects of climate change. Organic matter is a complex mixture of organic C compounds and inorganic nutrient and nonnutrient molecules, consisting of decaying plant, animal, and microbial material. Organic material can be divided into distinct pools according to its formation, persistence, and functional relevance. Soil organic matter can be associated to clay minerals or trapped within aggregates, which reduce accessibility to microbial decomposers and thus tends to remain in the soil for much longer than particulate organic matter (Swift 1996; Cotrufo et al. 2019). Previously, the fate of C in organic matter in a soil system was thought to be primarily controlled by chemical characteristics (e.g., cellulose, chitin, and lignin) that determine the ability of SOC to withstand microbial mineralization (Schlesinger 2005; Lal 2008). However, recent work suggests that SOC dynamics and turnover are also sensitive to soil type (including soil physical characteristics of pH and texture), moisture, temperature, and microbial community structure (Luo et al. 2019; Dynarski et al. 2020). The field has transitioned to the use of the term "soil C persistence" instead of the concept of recalcitrance, as persistence refers to long-term preservation of SOC influenced by ecological, biological, and physicochemical conditions and interactions that increase or decrease the vulnerability of SOC to microbial decomposition (Schmidt et al. 2011; Lehmann et al. 2020a). Ultimately all these site and soil specific factors have the potential to influence the turnover rate of SOC and should be accounted for in any assessment

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of the effects of land management meant to enhance SOC storage.

Compost amendment of rangeland soils has been proposed as a management intervention to increase plant productivity, reduce erosion, enhance water availability, and promote long-term soil C sequestration (Tongway 1990; Ryals and Silver 2013; Ryals et al. 2015; Silver et al. 2018; Grauver et al. 2019). We define compost as organic material that has been biochemically transformed by microbial enzymatic activity under managed, aerobic, and thermophilic conditions (Agnew and Leonard 2003; Rynk 2022). Compared to initial feedstocks, composted material has less biomass (due to evolution of carbon dioxide [CO_2]), lower water-soluble C concentrations, a lower C:nitrogen (N) ratio, and generally higher populations of mesophilic bacteria and fungi and humic substances (Goyal et al. 2005). However, the differences in physical, chemical, and biological characteristics between compost and other organic amendments warrant further investigation into the use of compost specifically to build positive feedbacks between the C, water, and nutrient cycles to support the ecosystem services including climate change mitigation and resilience.

In this paper, we reviewed the literature on compost applications on rangeland or other nonirrigated natural system soils across five continents to determine impacts on C, water, and nutrient cycling, and plant biodiversity. We first discuss how compost may relate to long-term sequestration of atmospheric C and thus combat climate and discuss outstanding questions regarding the mechanisms and processes controlling responses to compost amendments. We also discuss the potential for compost amendments to contribute to other ecosystem services. Finally, we discuss the economics of compost additions to rangelands. We identify gaps in knowledge as well as patterns that emerge across the broad range of soils, climates, and compost characteristics that have been studied thus far.

Materials and Methods

Rangeland Compost Studies. We compiled the results from 27 publications from 2000 (earliest identified) to 2022 that followed the effects of compost amendment to rangelands and other nonirrigated natural lands (table 1) including studies conducted in field soils, mesocosms (rows or planter boxes outdoors), greenhouses, and one laboratory incubation of soils. Studies encompassed research that was conducted in eight countries across a wide range of bioclimatic and soil conditions and diverse mix of annual and perennial vegetation. The studied experimental sites were mainly managed for cattle grazing, in postfire shrublands, or degraded forest and agricultural sites. Mean annual precipitation ranged from <250 to >900 mm y^{-1} and mean annual temperature ranged from 0.2°C to 20°C.

The method of compost application varied considerably across studies. The rate of compost application to soils ranged from <0.1 to >33 kg m^{-2}; some studies reported application depth (2.5 or 5 cm) (Crohn et al. 2013) or volume (Pease et al. 2000; Alguacil et al. 2004) rather than the mass added. All studies reported on a single compost amendment, and three studies (Albiach et al. 2000; Crohn et al. 2013; Blumenthal et al. 2017) compared composts from different initial feedstocks. The majority of studies focused on composted municipal solid waste/biosolids, but some studies used composted green wastes or composted manure. Relatively few (n = 5) publications reported C:N ratio of the compost added.

The responses included aboveground production and cover, belowground C responses, C and N fluxes, erosion impacts, water retention, soil chemical properties, soil N, and other nutrients. Several studies also addressed plant N, heavy metals, and other responses of interest to managers. Soils were sampled at various depths including 0 to 10, 0 to 15, and 0 to 20 cm; one study sampled from 0 to 50 cm (McClelland et al. 2022), while another sampled depth intervals from 0 to 100 cm (Ryals et al. 2014). The time period of postamendment data collection spanned from less than one month to 12 years.

We focused on the earliest and latest observations recorded for each response rather than including intermediate observations for the purpose of this review; this reduced the weight of a few studies with many intermediate time points compared to studies that only measured one or two time points. We calculated effect size as equation 1:

$$(\text{compost treatment} - \text{control})/\text{control}, \quad (1)$$

such that values greater than zero indicate values higher in the compost treatment, and values less than zero indicate values higher in the control treatment (for log response ratio tables and figures, see supplemental materials). Multiplying by 100 gives the percentage increase or decrease of a response with compost addition compared to control. We used linear mixed effects models to generate summary values (mean and SE) and study ID was included as a random effect to account for repeated measures. For above- and belowground C responses, we included fixed effects of duration, annual precipitation, annual temperature, feedstock, amount of compost, and compost C:N when available to identify patterns related to site context or management.

Results and Discussion

Compost and Carbon. Overall, compost application had the potential to increase plant productivity and associated C storage (tables 1 and 2). Compost amendments, even a single application, generally increased net primary productivity (NPP); studies reviewed here found that compost amendments increased aboveground NPP and cover by an average of 43% ± 14% (± SE throughout; removed one outlier value with effect size >2,200%), and nearly all studies that reported results over at least 24 months showed positive responses (effect size >0.1) (figure 1a). Increases in belowground plant biomass can promote higher root turnover rates, along with increased root area for exudation of C to the rhizosphere (Bruce et al. 1999; Derner and Schuman 2007). Total belowground C (considering all forms) was 50% ± 22% higher overall in compost amended plots relative to controls (figure 1b and table 1).

Understanding the above- and belowground mechanisms driving the patterns observed across different environmental conditions (e.g., aridity gradients) and management contexts (e.g., type and amount of soil amendments through time) help determine how compost could be most effectively used as a natural and working lands solution to climate change (Griscom et al. 2017). However, the above- and belowground C responses to compost additions did not vary significantly by temperature or precipitation (P > 0.05; figure 2). Notably, compost generally increased soil C stocks in sites with annual precipitation >400 mm (figure 2a). For compost types, manure and biosolid compost were more likely to lead to negative C responses than green waste compost or green waste + biosolids (figure 3a). Additionally, there were no strong patterns in C with different compost application

Table 1

Site and compost characteristics for studies collected for review. Note that some studies had multiple manuscripts, and study ID is separated for reference in tables 2 and 3.

Location		Study ID	MAT (°C)	MAP (mm)	Dominant vegetation + management	Compost feedstock(s)	Amount added	Compost C:N	Manuscript ID
South America	Argentina	A	10.2	270	Postfire shrub steppe	Biosolid	4 kg m^2	Not reported	Kowaljow et al. (2010)
North America	Arizona	B	19.1	375	Shrubs and grassland, not reported	Green waste	1 cm	Not reported	Pease et al. (2000)
(all United States)		C	19.1	330	Mesquite grassland; cattle grazing	Manure + green	16, 33.6 kg m^2	11.5	Leger et al. (2022)
	California	D	18.6	260	Coastal scrub; postfire	Biosolid + stable bedding, green waste	2.5, 5 cm;	Not reported	Crohn et al. (2013)
		E	18.5, 13	725, 950	Annual grassland, coastal grassland; cattle grazing	Green waste	7 kg m^2	Not reported	Ryals et al. (2013, 2014, 2016)
	Colorado	H	9.5	420	Degraded rangeland, cattle and elk grazing	Manure	0.67 kg m^2	Not reported	McClelland et al. (2022)
	Texas	U	19.4	870	Oak/Juniper savannah, cattle grazing	Manure	0.4, 1.2 kg m^2	Not reported	Wilcox et al. (2012)
	Wyoming	V	7.6	380	Perennial grassland	Biosolid, manure	2.24 kg m^2	Not reported	Blumenthal et al. (2017)
Europe	Spain	M	18.4	450	Shrubland, not reported	Biosolid	2.4 kg m^2	Not reported	Albiach et al. (2000)
		N	19.2	300	Shrubland, not reported	Biosolid	1% mixed with soil	Not reported	Alguacil et al. (2004)
		O	17	330	Shrubland, not reported	Biosolid + bedding	12 kg m^2	13.5	Bastida et al. (2008, 2009)
		P	20	230	Shrubland, afforestation	Biosolid	6.7 kg m^2	Not reported	Caravaca et al. (2003)
		Q	16.8	350	Postfire shrubland	Biosolid	4, 8, 12 kg m^2	Not reported	Cuevas et al. (2000), Martinez et al. (2003), Walter et al. (2006)
		R	12	750	Postfire shrubland	Biosolid	1 kg m^2	12.9	Tarrasón et al. (2007, 2014)
		S	12.7	480	Postfire shrubland	Biosolid	1.5, 3, 6 kg m^2	Not reported	Valdecantos and Fuentes (2018)
	France	I	13.6	740	Postfire shrubland	Biosolid + green	3.6 kg m^2	Not reported	Cellier et al. (2014)
		J	15	900	Shrubland, not reported	Biosolid + green	5, 10 kg m^2	13.4	Ormeno et al. (2006)
	Italy	K	15	870	Degraded urban-adjacent seminatural soil	Biosolid	2 kg m^2	Not reported	Vannucchi et al. (2015)
	Portugal	L	17.8	480	Organic farm soil	Manure	2 kg m^2	16.8	Ribeiro et al. (2010)
Africa	Canary Islands	F	14	450	Pasture; cattle/goat grazing	Biosolid	0.0006 kg m^2	Not reported	Chinea and Arevalo (2014)
Asia	China	G	0.2	375	Grassland; agro-ecosystem station	Manure	0.3, 0.6, 0.9 kg m^2	Not reported	Zhang et al. (2018)

Notes: MAT = mean annual temperature. MAP = total mean annual precipitation. C = carbon. N = nitrogen.

rates (note the lower C accumulation aboveground with compost additions >15 kg m^{-2} [figure 3b]) or compost C:N ratio (figure 3c). These results spanned locations and time periods, suggesting that compost additions may positively affect C persistence in rangeland soils.

Plots with compost amendments have been observed to be preferentially grazed compared to control plots, and thus estimates of gross productivity may be underestimated, especially if compost amendments increased forage quality (Ryals et al. 2016). Increased forage N content was observed in Caravaca et al. (2003), Ryals et al. (2016), and McClelland et al. (2022), but Kowaljow et al. (2010) found reduced leaf N in cheatgrass (*Bromus tectorum*) and bluegrass (*Poa ligularis*) with compost addition and Cellier et al. (2014) found no effect in scarlet oak (*Quercus coccinera*) seedlings. Thus, while net productivity often shows a positive response to compost amendments, gross aboveground primary productivity is difficult to measure under field conditions unless appropriate exclosures for cattle and wildlife are used, and maybe even show a stronger response to compost additions.

Compost and Greenhouse Gas Fluxes. Long-term SOC sequestration is a balance between the C inputs and outputs via respiration, leaching, and other C losses. Compost amendments affected soil CO_2 efflux to the

Table 2

Vote counting of results about carbon (C) (above- and belowground), C fluxes, and responses related to nitrogen (N) gas fluxes. Numbers indicate the counts of studies that showed higher, no difference, and lower values for compost treatments compared to control for the longest and shortest (if more than one) duration measured. Study ID refers to table 1.

Broad response	Response	Study ID	Duration (mo)	Higher in compost than control (count)	Not different in compost and control (count)	Lower in compost than control (count)
Aboveground carbon	Aboveground productivity	A	24		1	3
			36	2	2	
		B	48		2	
		E	12	4		
			36	4		
		F	12			1
			24	1		
		G	12		3	
		H	7		1	
			24		1	
		K	12		1	
			24		1	
		N	6		1	
		P	6		1	1
			24	2		
		Q	12	6		
			60		3	
		R	12	1		
		S	48		3	
		U	2	1		1
			7	1		1
		V	12		2	
	Cover	A	3		4	
			24	4		
		C	3	1		5
			14	3		5
		O	19	1		
			36	1		
		Q	12	4		2
			18	2		1
			36	1		
			48			1
			60	3		
		R	12	2		
			2		1	
Belowground carbon	Humic C	O	3	1		
			19	1		
	Microbial biomass C	M	48		1	
			60		1	
		O	3	1		
			19	1		
			36	1		

Continued

atmosphere through an increase in respiration by 107% ± 27% across the studies in this review. Increased emissions were likely due to a combination of autotrophic and heterotrophic respiration (soil incubations: Kowaljow et al. [2010] and Bastida et al. [2008]; total respiration in situ: Ryals and Silver [2013]). Higher autotrophic respiration would be expected in sites with enhanced NPP as a result of plant growth and maintenance. Autotrophic respiration is the release of recently acquired C and thus is not considered a net C loss from ecosystems. Increases in heterotrophic respiration associated with decomposition could offset some of the plant and soil C gains (Owen et al. 2015; Silver et al. 2018; Grauver et al. 2019). However, compost amendments resulted in lower soil CO_2 emissions than alternative management such as synthetic fertilizer additions in crop systems (Alluvione et al. 2010; DeLonge et al. 2013). For rangelands, COMET-Planner, a modeling tool that provides approximations on the potential greenhouse gas (GHG) dynamics of a particular conservation practice, suggests increased sequestration benefits from compost compared to inorganic fertilizer across the range of the US-based sites where soils differ in several soil chemical and physical properties (table 3) (Swan et al. 2015). The positive feedback of higher productivity, increased soil organic matter stocks, and increased soil moisture (see below) leads to modeled projections that a single compost application increases soil C stocks compared to controls for several decades (Ryals et al. 2015).

Other GHG fluxes are little affected by compost additions. Methane (CH_4) is a GHG that is formed during methanogenesis by methanogenic archaea (Serrano-Silva et al. 2014) and has a global warming potential 25 times that of CO_2 over a 100-year period and an emission equivalent of 86 times over a 20-year period (IPCC 2022). Nitrous oxide (N_2O) is produced during either denitrification, dissimilatory NO_3^- reduction, or incomplete nitrification (Baggs 2011) and has a CO_2 emission equivalent of 298 times over a 100-year period (IPCC 2022). While data on CH_4 and N_2O fluxes are limited from compost amendment studies, Ryals and Silver (2013) found there were no significant treatment effects on soil CH_4 and N_2O emissions with compost amendments. Potential denitrification and nitrification rates were higher in compost than control plots (Bastida

Table 2 continued

Vote counting of results about carbon (C) (above- and belowground), C fluxes, and responses related to nitrogen (N) gas fluxes. Numbers indicate the counts of studies that showed higher, no difference, and lower values for compost treatments compared to control for the longest and shortest (if more than one) duration measured. Study ID refers to table 1.

Broad response	Response	Study ID	Duration (mo)	Higher in compost than control (count)	Not different in compost and control (count)	Lower in compost than control (count)
Belowground carbon	Organic C	A	12	4		
			24	4		
		E	12	1	1	
			36		2	
		H	7		3	
			24		3	
		I	6		1	
			24		1	
		K	36		2	
		O	3	1		
			19	1		
			36	1		
		P	0.75	1		
			18	4		
		Q	12	1	2	
			60	3		
		R	5	1		
	Organic matter	G	12	2	1	
		J	3	2		
			10	2		
		Q	12		3	
		S	48		3	
		U	2	2		
			7		2	
	Root biomass/ length	A	24		4	4
		E	12	2		
			36	2		
		H	7		1	
			24		1	
		P	6		2	
			24	2		
		S	48		3	
	Water-soluble C	N	6		1	
		O	3	2		
			19	2		
		P	0.75	1		
Belowground flux	C mineralization	L	0.03	1		
			3.4	1		
	Respiration	A	12	4		
			24	4		
		E	1	1		
			12	0		
			36	0		

Continued

et al. 2015), both of which can contribute to N_2O release to the atmosphere. Urease activity, an index of microbial-derived enzyme involved in N release from soils, did not differ between compost and control plots with lower compost application amounts (<0.24 kg m^2) (Albiach et al. 2000; Alguacil et al. 2004), but there was increased activity with higher amounts of compost application (>12 kg m^2) (Albiach et al. 2000; Bastida et al. 2008).

Indirect Effects of Compost on Soil Characteristics that Affect Carbon Storage. Compost amendments can affect physical characteristics of soils, improve soil moisture, and affect chemical properties (table 4) that in turn can affect plant and microbial processes and GHG emissions. Soil physical characteristics have been shown to change with time after a single compost application, and in turn may help to stabilize the soil from erosion and increase water holding capacity (Ryals et al. 2013). Aggregate stability generally increased with compost addition (42% ± 20%), but little change to bulk density was observed with compost addition (0% ± 3%) even up to 36 months after amendment (figure 4a). Water runoff and solids in runoff declined with compost addition within months but was highly variable (–18% ± 63% and 324% ± 453%, respectively; one extremely high value of 29,900% higher solids in runoff was excluded [figure 4b]). While infiltration rate marginally decreased 17% ± 12% (only recorded in a single study [Wilcox et al. 2012]), observed soil moisture increased 18% ± 13% (figure 4c) with compost addition. This trend makes sense because compost has a potential field capacity of ~75% (Agnew and Leonard 2003) and thus, when added to soil, promotes soil moisture retention. Soil pH, a major determinant of microbial enzyme activity and nutrient availability, did not differ greatly with compost addition (–0.003 ± 0.005) (table 4 and figure 4d), though slight acidification may have outsized effects in soils that are on the cusp of P limitations at alkaline pH. Additionally, amendments that lower pH in alkaline soils can increase the emissions of CO_2, N_2O, and CH_4, either through stimulation of microbial communities or a decrease in N_2O and CH_4 consumption (Šimek and Cooper 2002; Mosier et al. 2004; Gregorich et al. 2005). Together, these qualities can improve rooting structure, habitat for microbial communities, and availability

Table 2 continued

Vote counting of results about carbon (C) (above- and belowground), C fluxes, and responses related to nitrogen (N) gas fluxes. Numbers indicate the counts of studies that showed higher, no difference, and lower values for compost treatments compared to control for the longest and shortest (if more than one) duration measured. Study ID refers to table 1.

Broad response	Response	Study ID	Duration (mo)	Higher in compost than control (count)	Not different in compost and control (count)	Lower in compost than control (count)
Belowground flux	Respiration	O	3	1		
			19	1		
			36	1		
	Sequestration	S	48	1		
Nitrogen flux	Denitrification	O	36	1		
	N mineralization	A	12	4		
			24	4		
	N_2O emissions for first four days after compost addition	E	1	1		
	Nitrification	O	36	1		

Notes: Multiple categories of response (higher, no different, or lower) may be observed in a single study and manuscript. N_2O = nitrous oxide.

of water to prolong activity of soil organisms that affect biogeochemical cycling.

Managers are often concerned with potential contamination of compost with salts or heavy metals that may affect agricultural output. Electrical conductivity was nearly 27% ± 11% higher in compost-amended plots than controls (table 4 and figure 4d); generally, biosolids/municipal organic waste showed higher electrical conductivity than manure-based composts (Gondek et al. 2020). Thus, managers concerned with excess salts should test composts prior to amendment. Metal concentrations such as cadmium (Cd), chromium (Cr), nickel (Ni), and lead (Pb) were found to be higher in some biosolid or green waste compost amended plots compared to controls (Cuevas et al. 2000; Walter et al. 2006), but copper (Cu) was not different in runoff water in a study conducted in Spain (Martinez et al. 2003). Several metals (Cu, Cr, Cd, Ni, and Pb) were found to be significantly lower in runoff from compost-amended plots relative to control plots (Crohn et al. 2013) in California, suggesting that compost can improve water quality. These few results highlight the need for compost and soil analyses before application to avoid undesirable metal and salinity levels and also the potential for compost to improve water quality in the watershed below amendment.

Compost is widely used due to its characteristic as a slow-release fertilizer (Sullivan et al. 2003). Compost increased organic and inorganic N concentrations by 37% ± 14% (removed two values from California with

Figure 1

Effect size of responses related to (a) above- and (b) belowground carbon (C) by study duration (months) across different study locations (colors; also see table 1). Point shape defines the specific response extracted from the publications.

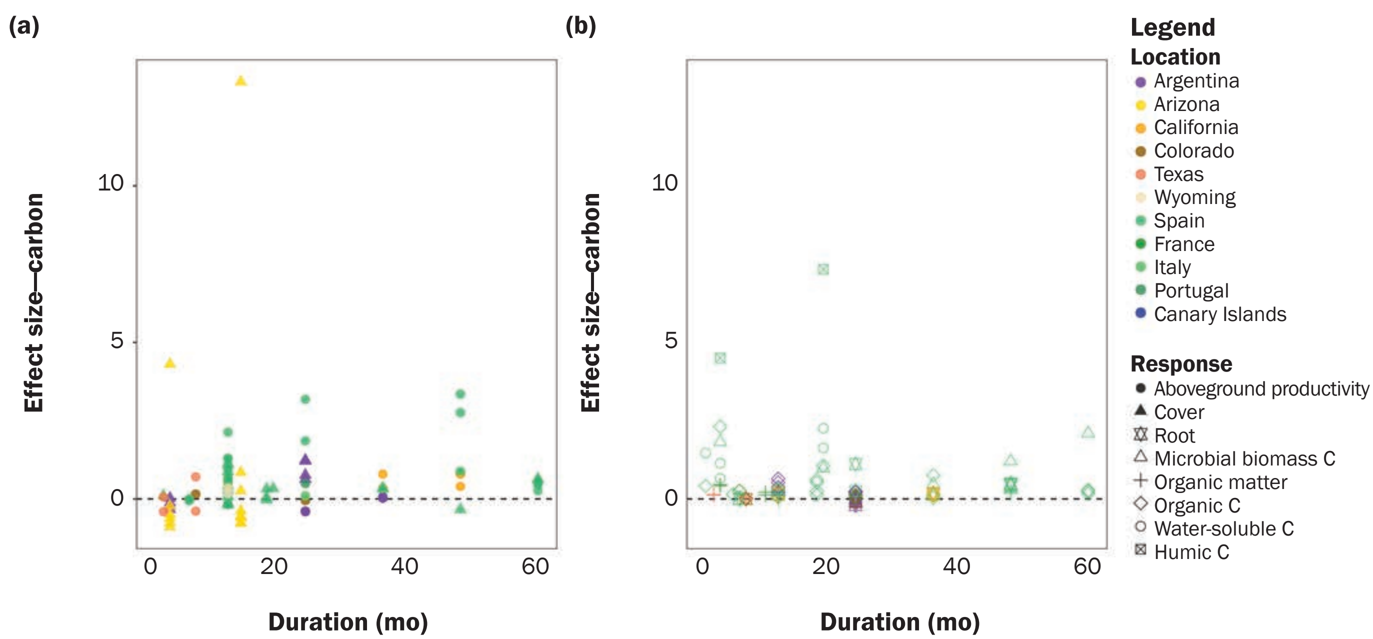
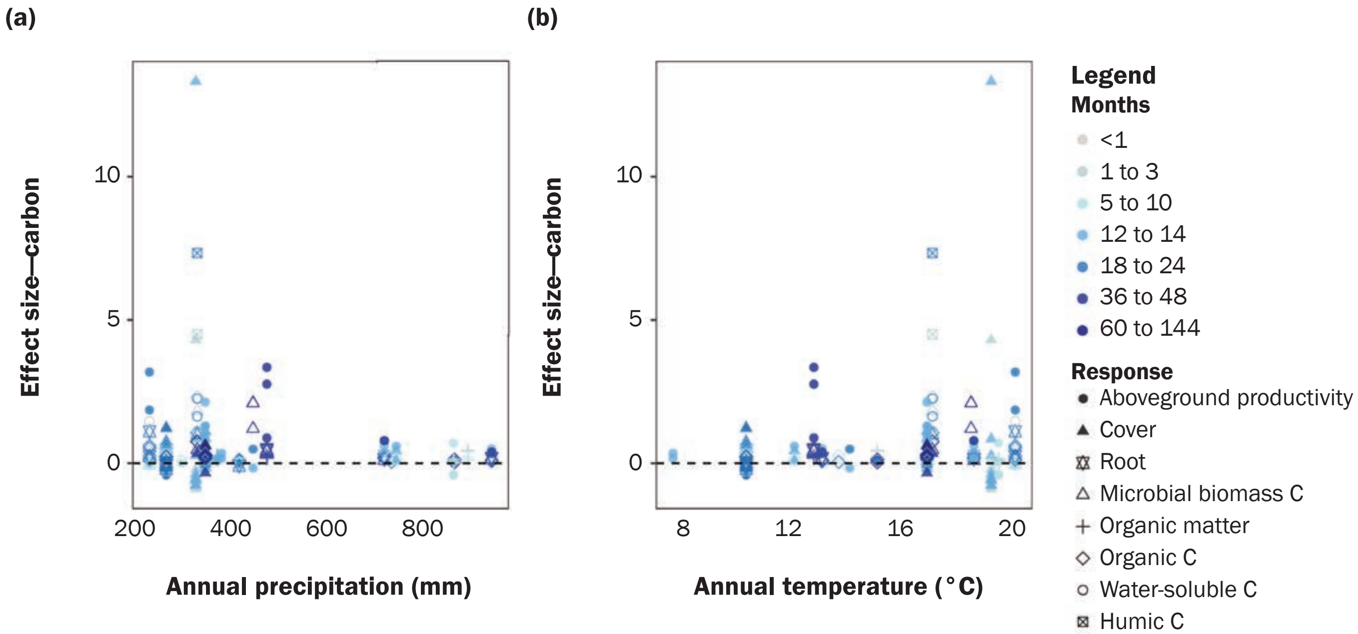


Figure 2

Effect size of responses related to above- and belowground carbon (C) by (a) annual precipitation (mm) and (b) temperature (°C). Point shape defines the specific response extracted from the publications and the color indicates duration of the study when the response was recorded.



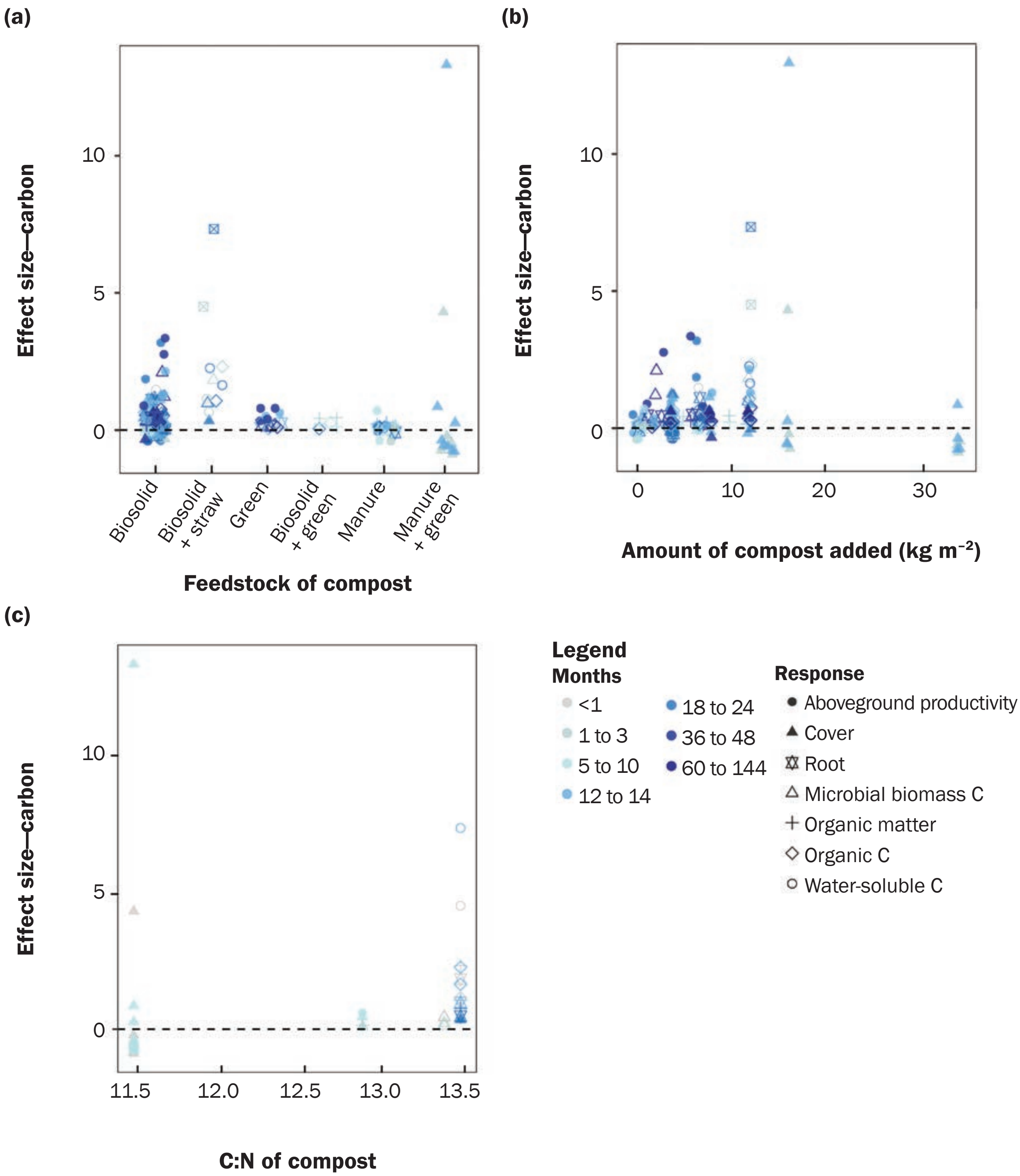
effect sizes >1,000 [figure 4e]). Potassium (K) and P were also higher with compost amendments (126% ± 54%) (figure 4f). Given that many rangelands are limited by N and P availability, the addition of compost and associated change in system nutrient dynamics may contribute to the observed increases in plant productivity and may also shift interactions among plant and microbial communities.

Compost Impacts on Ecological Communities. Compost effects on plant traits may impact many aspects of ecological functioning. As mentioned previously, changes in forage quality may affect grazing patterns. Additionally, Ryals and Silver (2013) and Kowaljow et al. (2010) both found the relative increase in aboveground biomass was higher than for roots, leading to a lower root:shoot ratio in compost plots than controls. This difference in allocation may indicate less of a need for acquisitive structures for nutrients and water belowground and ability to allocate to photosynthetic machinery aboveground and could potentially shift competition among some plants from belowground to aboveground.

While the addition of compost can impact plant productivity and allocation, evidence suggests that it may have little to no impact on plant diversity (Tarrasón et al. 2014; Ryals et al. 2016). Although addition of inorganic N and P have been shown to reduce plant diversity in certain systems (De Schrijver et al. 2011; Harpole et al. 2016), most of the N and P in composts are in organic forms that may not be readily available to plants (Gravuer et al. 2019; Rynk 2022). However, there is some evidence which suggests that invasive plant species could be facilitated by the introduction of composts (Blumenthal et al. 2017). The lack of an observed shift in native plant species diversity in compost amendment studies may be confounded by other environmental and climate variables; as Gravuer et al. (2019) points out, there are still unanswered questions regarding the drivers of plant species diversity in ecosystems at a range of scales. Therefore, there is a need for compost amendment studies in different rangeland types to further understand impacts on plant community patterns through time.

Compost also introduces a novel microbial community into the resident soil community (Saison et al. 2006; Bastida et al. 2008; Heisey et al. 2022). Bacteria and fungi exist throughout the composting process (Neher et al. 2013), and not unexpectedly, different compost types, compositions, and feedstocks (which in turn include characteristics of diet, antibiotic concentrations, and gut microbiome of manure producers or biosolid-based compost) may contain a different microbial community composition and diversity, which can affect the composting process as well as the postapplication soil microbial community (Ishii and Takii 2003; Neher et al. 2013; Chen et al. 2019; Wan et al. 2021; Heisey et al. 2022). Abundance of bacterial and fungal taxa were higher in compost than control plots in Spain (Bastida et al. 2008); however, there was no difference in some dominant fungal genera in China (Zhang et al. 2018). Gravuer and Scow (2021) documented that outcomes of compost added to soil microbial communities can be complex with several factors impacting the community postapplication including environmental conditions, initial community composition, traits of the compost microbial taxa, and the response of the resident soil community. The introduced microorganisms could potentially play key roles in rangeland ecosystems due to their ecosystem benefits, as has been observed in other systems, such as reduction in pathogen activity (Bonanomi et al. 2010; Mehta et al. 2014; Zhang et al. 2018), amelioration of plant drought stress (Duo et al. 2018), and improved soil structure (Shaban et al. 2015). Different outcomes of postapplication microbial communities could also lead to a change in functional capabilities due to the shift of microbial trait distributions; however, this question requires further experimental evidence in rangeland plant-

Figure 3
Effect size of responses related to above- and belowground carbon (C) by (a) compost feedstock and (b) amount of compost added (kg m^{-2}; note that studies that used depth or volume were excluded from this analysis), and (c) C:nitrogen (N) ratio of compost. Point shape defines the specific response extracted from the publications and the color indicates duration of the study when the response was recorded.



soil microbial systems (Neher et al. 2013; Bastida et al. 2015; Graveur et al. 2019).

Addition of compost at the soil surface could affect plant-microbe interactions in the rhizosphere. For example, increases in the colonization of certain soil fungal taxa, such as arbuscular mycorrhizae, which play a critical role in the C sequestration processes to both enhance plant drawdown of CO_2 and aid in aggregate formation, could promote long-term SOC storage (Wang et al. 2016; Borie et al. 2008; Hovland et al. 2019; Frey 2019). There are limited compost application studies that focus on microbial community dynamics over time, and one study found a nonsignificant trend of increased fungal colonization of shrub seedlings after 18 months in Spain (Caravaca et al. 2003).

While more data are needed to understand microbial dynamics after compost addition, compost-related microbial taxa should be investigated for their roles in ecosystem functioning, including greenhouse gas fluxes and nutrient dynamics, in rangeland soils.

Economic Considerations of Compost Amendments. Despite the long history of compost use in agriculture and research supporting the production benefits of compost application to rangelands (Ryals and Silver 2013), lack of widespread adoption of the practice by rangeland managers can be explained by the relatively high per hectare costs of compost application and the relatively low per hectare production value of rangelands. One way that managers can mitigate costs for compost amendments is to produce compost on their operation. On-farm production of compost offers the potential to optimize reuse of on-farm organic materials (such as manure, spoiled hay, and other feed and harvest residues), conserving C and nutrients and avoiding costs associated with compost purchasing and avoiding GHG emissions associated with uncontrolled decomposition of these materials on farm. If assembled in appropriate proportions and managed according to well established principles of composting (Rynk 2022), these resources can be returned to rangelands as finished compost.

As policy makers and citizens have become aware of the significant contribution of compost production and use to mitigate GHG emissions through enhanced soil C sequestration, several programs to support compost use have emerged. For example, in 2021, the USDA Natural Resources Conservation Service (NRCS) released Draft Conservation Practice Standard (CPS) 808, "Soil Carbon Amendment." Under the national standard, NRCS provides cost sharing payment for compost use, typically covering ~50% of project cost. No compost quantity is specified and, while sequestration benefits are noted in the standard, no GHG quantification is currently associated with the practice. Additionally, a draft maximum slope limit of 8% for compost application ignores the widespread use of compost for erosion control on much steeper slopes (USEPA 1997). A draft version of the CPS was published in the Congressional Record in the spring of 2022.

California serves as a useful case study for understanding how costs can be mitigated for using compost. The California Department of Agriculture's Healthy Soils Program provides funding for compost use on croplands, pastures, and rangelands. While the program covers multiple climate-beneficial agricultural conservation practices (Swan et al. 2015), compost remains the program's most widely subscribed practice (CalCAN 2021) even though agricultural producers have noted the program fails to cover the full costs of compost application. In this program, compost is directly related to climate change because GHG mitigation is quantified using a California Air Resources Board (CARB 2020) model and is based on dry tons of compost applied. The California Air Resources Board calculates emissions reduction from composting by crediting avoided emissions from landfilling factor minus fugitive emissions from the composting process. For land application to rangelands, net GHG savings is estimated using the DeNitrification-DeComposition (DNDC) model and varies by county from 3.3 to 4.7 Mt CO_2 equivalent ac^{-1} y^{-1} (CARB 2017). It is notable that these values are at least 50% to 65% lower than those measured in field trials (Ryals and Silver 2013; Silver et al. 2018).

Table 3
Comet-Planner results for 404.6 ha (1,000 ac) replacement of synthetic nitrogen (N) fertilizer with compost (carbon[C]:N ratio 15) on managed nonirrigated pasture. Negative values indicate a loss of C or increased emissions of greenhouse gasses. Sites were chosen to be illustrative of several sites that have had or currently have compost amendment trials happening with a range of temperature/precipitation/soil/management.

Location	Carbon dioxide (CO_2)	Nitrous oxide	Methane	Total CO_2 equivalents
Pima Co., Arizona	60	−28	0	32
Marin Co., California	90	−21	0	69
Larimer Co., Colorado	59	−15	0	44
Bell Co., Texas	193	−89	0	104
Laramie Co., Wyoming	77	−23	0	54

Recent climate legislation in California requires diversion of organics from landfill disposal to avoid associated CH_4 emissions and requires local jurisdictions to procure and utilize significant quantities of compost to insure beneficial use of diverted organics (California Senate Bill No. 1383). It is not yet clear how much compost so acquired will end up on rangelands, but recent work conducted for the Marin County California Climate Action Plan suggests the county's rangelands would require 1 Mt of compost over a multiyear period to apply a single amendment across all eligible grazed county rangelands. Rangeland eligibility in the county was defined based on soil type, percentage slope, vegetation type, and land use. Anticipated GHG benefits would offset a significant percentage of agricultural emissions in the county.

Emerging C or ecosystem services markets could potentially provide added financial resources to manage land for enhanced soil C with compost, which has key cobenefits for rangeland ecosystems' resilience to stressors such as drought. Note that the C added in compost may not count toward soil C accrual, but the compost that is decomposed and remains in the soil or the input from productivity may be counted toward accrual. Additionally, the potential decrease in bulk density associated with compost amendments can influence SOC calculations so that the absolute C content in that depth may decrease due to a decrease in density, when C percentage actually increased. As SOC stocks are commonly quantified at fixed depths with an equation that uses soil bulk density, depth, and organic C concentration, bulk density can greatly influence SOC calculations. Thus, physical, chemical, and biological parameters related to soil health changes should be accounted for with the equivalent soil mass method at the start of processing soil samples to provide bias free evaluation of SOC pool dynamics, and thereafter soil health parameters (Wendt and Hauser 2013). For C accounting, we suggest soil sampling protocols that assess SOC pools for both surface (within 0 to 30 cm) and subsoils (within 30 to 100 cm) to capture the changes expected from rooting or tillage depth and deeper soils. This is especially important for C credits accreditation for the C markets and provides a more accurate assessment of the influence of compost amendments on soil C storage in rangelands.

Table 4
Vote counting of studies that reported soil properties of nitrogen (N), micronutrients, water quantity, soil physical characteristics, and soil chemical characteristics. Numbers indicate the counts of higher, no difference, and lower values for compost treatments compared to control for the longest and shortest (if more than one) duration measured. Study ID refers to table 1.

Broad response	Response	Study ID	Duration (mo)	Higher in compost than control (count)	Not different in compost and control (count)	Lower in compost than control (count)
Soil physical properties	Aggregate stability	K	36		1	
		N	6	1		
		P	0.75	1		
			18	2		
	Bulk density	I	12	1		
			24	1		
		K	36		1	1
		O	36			1
		P	0.75			1
			18		2	
		U	2		2	
			7		2	
Erosion	Runoff amount	D	3			6
		Q	36			1
			48	1		
	Sediment loss; solids in runoff	Q	36			1
			48			1
		U	2		2	
			7			
		D	3			6
Water	Infiltration rate	U	2			2
			7	1		1
	Soil moisture	I	6		1	
			24	1		
		J	3		2	
			10		2	
		O	36	1		
Soil chemical properties	pH	G	12		3	
		K	36		2	
		N	6			1
		O	36		1	
		Q	12		6	
			60		3	
	Electrical conductivity	N	6	1		
		O	36	1		
		Q	12	2	4	
			60	1	2	
Nitrogen	Available nitrogen	G	12		3	
	Inorganic nitrogen	A	12	1	3	
			24		2	2
	NH_4	D	3	1	5	
		I	6		1	
			24		1	

Continued

Summary and Conclusions

Compost as an amendment has the broad potential to improve ecosystem resilience and enhance soil C sequestration in rangelands. Compost application on rangelands can also help to synergistically connect the food and waste cycles of a region, while supporting improved productivity for grazing animals. However, research in economics and total GHG accounting is needed to understand the true costs and benefits of utilizing compost in rangeland systems. The results of our review demonstrated that compost amendments in rangeland systems have the potential to have a positive influence on C, nutrient, and water dynamics. Widespread adoption of compost application to rangelands and long-term benefits may be inhibited by short-term costs.

While we found promising trends of improved soil and rangeland functioning across our selected studies, more evidence is needed about compost amendments across a wider range of rangeland ecosystems, at deeper soil depths, over longer periods of time, and using different compost types. Additionally, a better understanding of the microbial changes through the composting process and the postapplication change in soil microbial community composition is needed, as these organisms may provide vital services to both rangeland plants and C sequestration. Finally, more research is needed to identify proper rates and timing of compost application across a range of rangeland conditions and management scenarios to provide robust predictive power for managers wishing to use compost as a strategy to build SOC to lower emissions and combat climate change.

Supplemental Material

The supplementary material for this article is available in the online journal at https://doi.org/10.2489/jswc.2023.00072.

Declaration on Conflict of Interest

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Table 4 continued
Vote counting of studies that reported soil properties of nitrogen (N), micronutrients, water quantity, soil physical characteristics, and soil chemical characteristics. Numbers indicate the counts of higher, no difference, and lower values for compost treatments compared to control for the longest and shortest (if more than one) duration measured. Study ID refers to table 1.

Broad response	Response	Study ID	Duration (mo)	Higher in compost than control (count)	Not different in compost and control (count)	Lower in compost than control (count)
Nitrogen	NH_4	O	36	1		
		Q	12	1	5	
			60		3	
	NO_3	D	3			6
		O	36	1		
		Q	12	4	2	
			60	2	1	
		R		1		
		U	2	1		1
	$NO_3 + NO_2$	I	6	1		
			24		1	
	Organic nitrogen	R	5	1		
		V	12	2		
			36	2		
	Total nitrogen	A	12	4		
			24	4		
		E	12	1	1	
			36		2	
		G	12	1	2	
		H	7		3	
			24		3	
		J	3	2		
			10	2		
		K	36	1	1	
		N	6		1	
		O	36	1		
		P	0.75	1		
			18	2		
		Q	12		3	
			60	2	1	
Other nutrients	Potassium	G	12		3	
		I	24		1	
		O	36	1		
		P	0.75	1		
			18	2		
		Q	12	6		
			60	3		
	Phosphorus	A	12	4		
			24	3	1	
		D	3		1	5
		I	6	1		
			24	1		

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Table 4 continued

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Broad response	Response	Study ID	Duration (mo)	Higher in compost than control (count)	Not different in compost and control (count)	Lower in compost than control (count)
Other nutrients	Phosphorus	J	3	2		
			10	2		
		N	6	1		
		O	36	1		
		P	0.75	1		
			18	2		
		Q	12	4	2	
			60	3		
		U	2			2
		V	12	2		
			36	2		

Notes: Multiple categories of response (higher, no different, and lower) may be observed in a single study and manuscript. Available N refers to plant-available N (hydrolyzed with sodium hydroxide) (Zhang et al. 2018). NH_4 = ammonium. NO_3 = nitrate. NO_2 = nitrite.

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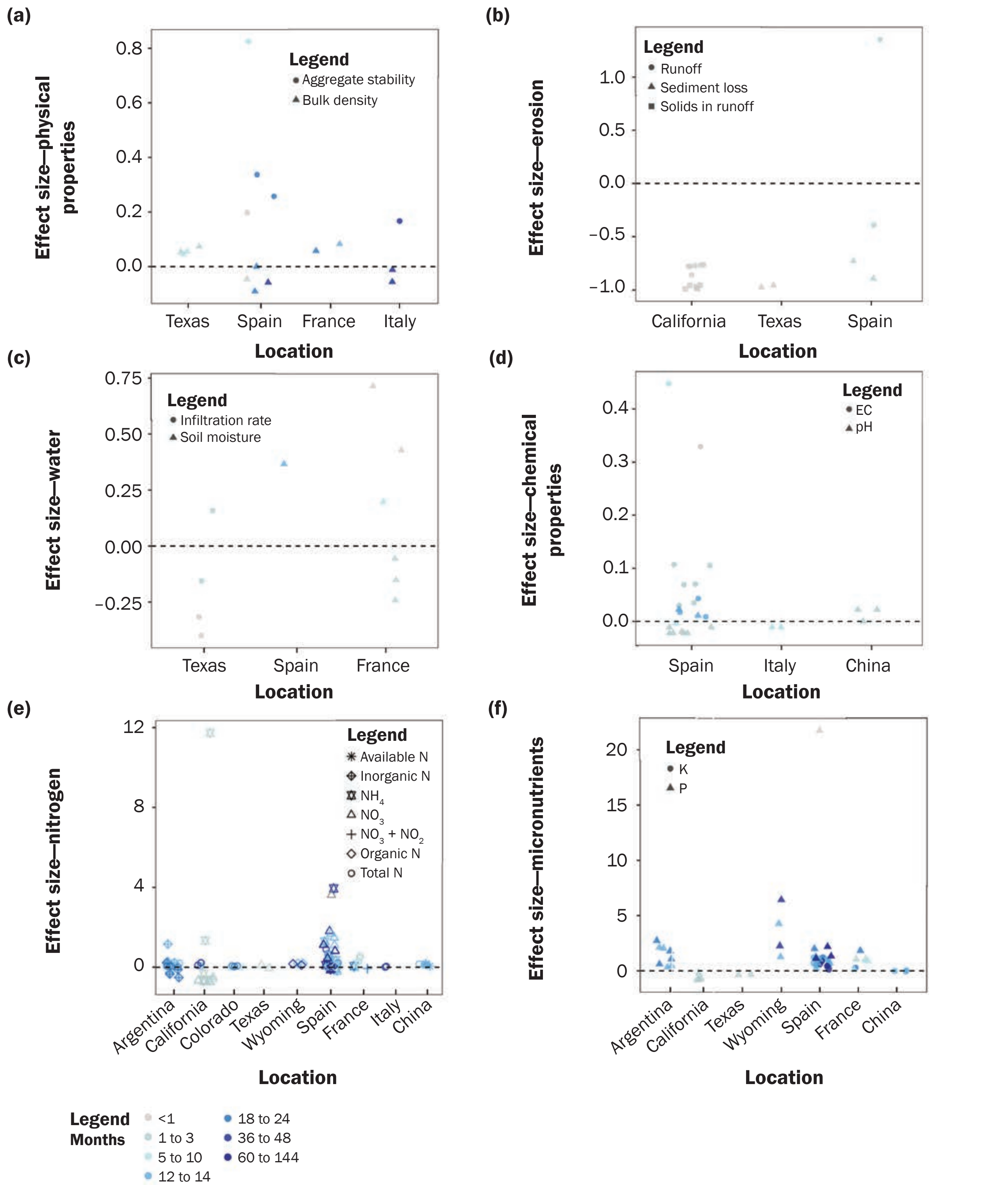
Figure 4

Effect size of responses related to soil (a) physical properties, (b) erosion responses, (c) water retention, (d) chemical properties, (e) nitrogen (N) content, and (f) other nutrient content by location of the study. Point shape defines the specific response extracted from the publications and the color indicates duration of the study when the response was recorded. EC is electrical conductivity, NH_4 is ammonium, NO_3 is nitrate, NO_2 is nitrite, K is potassium, and P is phosphorus.



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