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RESEARCH ARTICLE

Soil restoration increases soil health across global drylands: A meta-analysis

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Abstract

1. Soil degradation is one of the greatest environmental issues our planet faces today, with over 33% of Earth's soils currently degraded. Drylands are especially vulnerable to soil degradation given their history of intensive land use and desertification. Active soil restoration has been identified as a leading strategy to combat soil degradation and promote ecosystem recovery. However, soil-based dryland restoration techniques have shown varying success, potentially due to a lack of understanding of the ecological contexts in which soil-based treatments are most beneficial.
2. To improve our understanding of how to best use active soil restoration to restore degraded drylands, we conducted a global meta-analysis of soil treatment effectiveness at improving soil health across varying environmental gradients. The soil health metrics we analysed were aggregate stability, bulk density, soil moisture, soil organic carbon (SOC), soil nitrogen, mycorrhizal colonization and basal respiration. For this meta-analysis we collected 155 publications, yielding 1403 unique studies spanning six continents.
3. We found that overall, soil restoration had a beneficial effect on all measures of soil health ranging from a +11% increase in bulk density (inverse) to a +6967% increase in mycorrhizal colonization. Aridity and soil texture greatly influenced restoration effectiveness for certain soil health metrics. Specifically, for soil carbon and nitrogen, restoration was found to be most effective in arid, fine-textured soils and mesic, coarse-textured soils. Additionally, we found that organic amendments were most effective at increasing SOC, while fungi inoculation was most effective at increasing mycorrhizal colonization.
4. *Synthesis and applications*: Our findings indicate that active soil restoration is an effective tool for increasing soil health and provide information on optimal treatments and site conditions for improving certain aspects of soil health. This could greatly help inform decision-making, and thus improve outcomes, in dryland restoration worldwide.

KEYWORDS
drylands, ecological restoration, land degradation, meta-analysis, soil ecology, soil health

1 | INTRODUCTION

Land degradation, the deterioration or loss of the productive capacity of the soils, is one of the greatest environmental issues our planet faces today (IPBES, 2018). Over 33% of Earth's soils are currently degraded with the potential for over 90% to become degraded by 2050 (FAO & ITPS, 2015). Earth's drylands (semi-arid and arid ecosystems) (Chambers & Wisdom, 2009), which cover ~46% of Earth's land surface and contain half of the world's agricultural systems (Maestre et al., 2021), are especially vulnerable to land degradation. Drylands have a long history of intensive agriculture, urbanization, resource extraction, and water limitation, making land degradation particularly pervasive (IPBES, 2018). This directly impacts at least 3.2 billion people worldwide whose livelihoods depend on agriculture, natural resource use, and functioning ecosystems (IPBES, 2018). Once degraded, dryland functionality often cannot be recovered within human timescales in the absence of active ecological restoration, broadly defined as the process of applying active management techniques to overcome physical and biotic barriers that limit ecosystem recovery (Gann et al., 2019).

Restoration of degraded landscapes is of urgent need to help sustain livelihoods (George et al., 2018), enhance natural carbon sequestration (Di Sacco et al., 2021), and mitigate other impending environmental crises such as poor water quality and loss of biodiversity (Rey Benayas et al., 2009). However, drylands are particularly difficult to restore. Dryland restoration has historically focused on revegetation through native plant seeding (Palma & Laurance, 2015), though seeding alone is often ineffective in recovering ecosystem functioning in degraded drylands (Shackelford et al., 2021). Even when native plant seeding is successful in increasing plant establishment, it may not improve soil health conditions without additional intervention (Yang et al., 2021). Other methods, such as active soil-based restoration, meaning non-vegetation restoration treatments that specifically target soil health, may be needed (Farrell et al., 2020). Active soil restoration treatments include anything that can be applied to the soil that is not just a plant or seed, such as organic amendments, erosion control structures, water retention agents, microbial inoculations and more (Figure A2 in Appendix S1). Soil restoration addresses various abiotic and biotic barriers to ecosystem recovery in drylands, while seeding alone only addresses the barrier of a lack of plant propagules. *Abiotic* barriers include low moisture and nutrient availability, as well as soil erodibility, while *biotic* barriers include diminished beneficial soil microbial communities, which commonly limit ecosystem recovery in degraded dryland systems (Anaya-Romero et al., 2015). Despite this growing need for active soil restoration, we have a limited understanding of how these techniques can be best used to improve soil health across environmental gradients in degraded drylands.

In recent decades, soil-based restoration techniques have been increasingly used with the goal of re-establishing soil health in degraded drylands (Chaudhary et al., 2020; Faist et al., 2020; Román et al., 2021). However, these soil treatments have shown varying degrees of success in promoting recovery of soil function. Some studies suggest that certain treatments may work better than others at improving soil health, such as Antoninka et al. (2019), which found that biocrust inoculation increased aggregate stability but straw barriers and soil tackifiers did not. Additionally, Luna et al. (2016) found that organic amendments were more effective than mulch at improving multiple aspects of soil health. Other studies suggest that environmental conditions largely control whether restoration efforts are successful. For example, a study by Bateman et al. (2019) suggests that the effectiveness of restoration treatments depends on how water-limited the system is. Similarly, Chua et al. (2019) found that soil type was a more important determinant of soil health than whether a plot was treated or not. Such variability in restoration outcomes highlights a current lack of a predictive understanding of the ecological contexts in which soil-based restoration treatments may be most beneficial for improving soil health.

To address this knowledge gap of how to best use soil-based restoration to improve soil health in drylands, we compiled available literature on soil-based restoration in drylands and conducted meta-analyses to determine how the effects of soil-based restoration vary across ecological and restoration context factors. We used results from this analysis to answer the following questions:

1. How does soil restoration affect various measures of soil health?
2. Do these effects of soil restoration vary across environmental stress gradients of aridity and soil texture?
3. Could other restoration intervention factors, such as the type of treatment used, additional revegetation, and time since restoration, impact the effect of soil restoration?
4. What information on soil restoration in drylands are we still lacking and where should future research focus?

We predicted that overall, soil restoration would benefit soil health, and that the effectiveness of soil restoration would increase with aridity and percent soil sand. We made this prediction under the assumption that soil health could improve by larger margins in areas facing more limited moisture and nutrient availability (typical of arid and sandy soils) than it would in areas that already had higher levels of moisture and nutrients (Augustin & Cihacek, 2016; Klemmedson, 2009). Additionally, we predicted that treatment type, revegetation, and time since restoration would all impact soil restoration effectiveness.

2 | MATERIALS AND METHODS

2.1 | Literature search

To identify relevant literature, we searched the Web of Science Core Collection database (http://www.webofknowledge.com/) using the following search terms:

dryland OR desert* OR arid* OR shrubland* OR rangeland* AND restor* OR rehabilitat* OR reclamation* OR revegetat* AND soil*.*

From the records that came up from our search, we only selected articles that

1. examined some type of active, soil-based restoration treatment, as opposed to passive restoration (i.e. letting land regenerate naturally by providing protection only), or restoration through seeding or revegetation only,
2. took place in a dryland, defined by having an aridity index of less than 0.65 (Cherlet et al., 2018), on land that was not being currently cultivated (previous meta-analyses have covered agroecosystems), and
3. quantified at least one of the chosen soil health metrics (aggregate stability, bulk density), volumetric water content (%VWC) (as a measure of soil moisture), soil organic carbon (SOC), soil nitrogen (N), mycorrhizal colonization or basal respiration (see Appendix S1).

These soil health metrics were chosen based on their representation of physical, chemical, and biological properties of soils, as well as their common presence in the literature. Specifically, aggregate stability and bulk density are useful in determining nutrient holding capacity, aeration and infiltration, and susceptibility to erosion or compaction (Raghavendra et al., 2020). Volumetric water content, which was the most reported measure of soil moisture, indicates water availability to plants and microbes and influences aeration (Voroney, 2019). Organic carbon and nitrogen are essential nutrients for plants and microbes, and are therefore major aspects of soil health (Raghavendra et al., 2020). Lastly, mycorrhizal colonization and basal respiration are both ways to quantify the presence of beneficial microbes in the soil that can be integral in aiding plant nutrient uptake (Raghavendra et al., 2020). Other biotic soil health metrics, such as microbial diversity, were considered but were not reported enough in the literature to yield sufficient data for meta-analysis.

The initial literature search only included publications written in or previously translated into English, so we also conducted a separate multilingual literature search to identify publications written in languages other than English, using guidance from a recent study on multilingual literature searches for ecological reviews (Zenni et al., 2023). First, we used the same search described above from Web of Science and selected to view only publications in languages other than English. We also searched the multilingual databases Periodica, Francis, E-Marefa, Al-Manhal and AskZad with combinations of the search terms: restoration, revegetation, reclamation, dry, desert, arid and soil. We chose to search these databases as Periodica specializes in Spanish and Portuguese literature from Latin America, Francis specializes in French literature, and E-Marefa, Al-Manhal and AskZad specialize in Arabic literature. We chose to focus on Spanish, French and Arabic literature as these are the most common languages spoken in Latin America, North Africa and the Middle East, which all contain large areas of drylands and had relatively low representation from our English literature search (Figure A5 in Appendix S1). We also considered using the Scopus and Ebsco databases, but unfortunately could not access these databases from our university. From these searches, we identified six publications that met search criteria. Due to translation constraints, we were only able to screen titles and abstracts of these publications for eligibility but were not able to analyse the full texts to be included in the final meta-analysis (see Appendix S1).

2.2 | Database creation

After identifying publications to be included in the analysis, we extracted the mean, standard deviation or standard error, and the number of replicates for the treatment and control groups from each unique study, meaning any report of a treatment compared to an untreated control. When data were represented in figures rather than numerical values, we used the online tool *graphreader* to extract values from figure images (Graphreader, 2022). We also recorded information on candidate moderator variables. These included what type of restoration treatment was used in the study (i.e. Treatment_Type; Table 1, Figure 1), as well as the aridity index (Aridity_Index) and soil texture (Percent_Sand) of the study site. We chose aridity and soil texture as representative environmental stress variables because these are two of the most influential variables in controlling ecosystem functioning in drylands, given that both are related to water availability (Maestre et al., 2021). These two variables were found to be only weakly correlated (24%) from a correlation analysis using the corrplot() function in R. To calculate Aridity_Index for each study, we extrapolated precipitation and potential evaporation data from the geographic coordinates of each study using the TerraClimate dataset (Abatzoglou et al., 2018). When soil texture data were not reported for a given study, we extrapolated sand percentages using SoilGrid spatial data from the World Soil Information Service database (Hengl et al., 2014). Lastly, we extracted data on whether treated plots were seeded or revegetated in addition to a soil treatment (Revegetation), and how long it had been since the treatment(s) were implemented when data were collected (Time) (see Appendix S1).

2.3 | Calculation of meta-analysis metrics

To obtain the metrics needed for meta-analysis, we calculated the log response ratio (LnRR) as a measure of the effect size of soil restoration on each soil health metric, using Equation (1) (Hedges et al., 1999):

$$\text{LnRR} = \ln\left(\frac{X_{\text{treatment}}}{X_{\text{control}}}\right). \tag{1}$$

In this equation *Xtreatment* signifies the mean of the treatment group, and *Xcontrol* signifies the mean of the control group. For bulk density, we took the inverse of the LnRR, as lower values for bulk density indicate better soil health, given that high bulk density usually means lower soil porosity, which limits nutrient and water holding capacity and can lead to soil compaction (Raghavendra et al., 2020). We calculated within-study variance using Equation (2) (Hedges et al., 1999, Appendix S1):

TABLE 1 Descriptions of each moderator variable.

Variable name	Variable type	Variable description
Treatment_Type	Categorical	Type of treatment used; seven levels: organic amendment, inorganic NPK fertilizer, water retention treatment, erosion control structure, soil tackifier, bacteria inoculation, fungi inoculation (Figure A2 in Appendix S1)
Aridity_Index	Continuous	The calculated aridity index of the site from 0 to 0.65 (low values meaning more arid, high values meaning more mesic)
Percent_Sand	Continuous	Percent of sand particles (0.5–2 mm diameter) of the study site's soil (Soil Survey Staff, 1999)
Revegetation	Categorical	Whether or not treatment plots were seeded or revegetated in addition to soil treatment(s); two levels: yes, no
Time	Continuous	Time since restoration treatment application in years

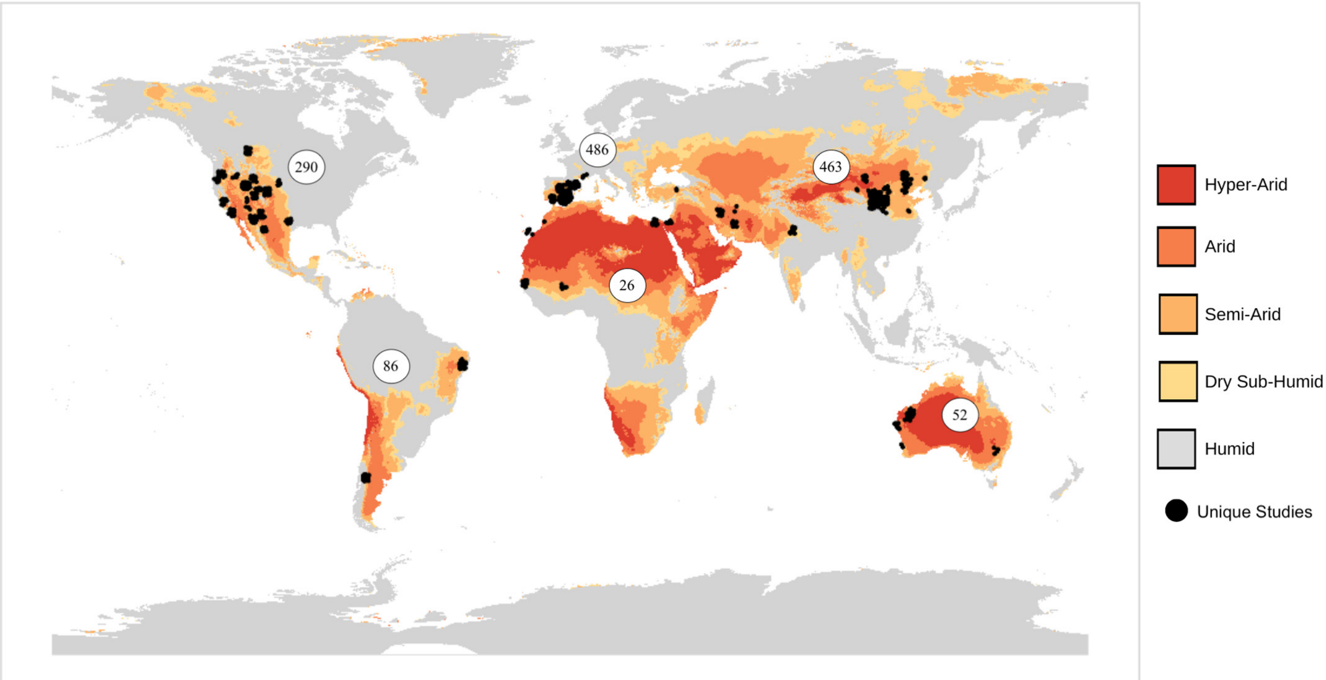

FIGURE 1 Geographic locations of the 1403 unique studies from 155 publications included in this meta-analysis, with dryland zones based on aridity index. See Figure A3 in Appendix S1 for a map of study locations for each individual soil health metric.

$$\sigma^2 = \left[\frac{\mathrm{SD}^2_{\mathrm{treatment}}}{\left(n_{\mathrm{treatment}} \times X^2_{\mathrm{treatment}}\right)}\right] + \left[\frac{\mathrm{SD}^2_{\mathrm{control}}}{\left(n_{\mathrm{control}} \times X^2_{\mathrm{control}}\right)}\right]. \quad (2)$$

When standard deviation (or standard error) was not reported (45% of studies), we used Taylor's Law, which describes the linear relationship between the natural log of the mean and standard deviation within a given dataset (Nakagawa, 2015). Equation (3) describes this relationship for our dataset:

$$\log\left(\mathrm{SD}_{\mathrm{pooled}}\right) = \left(\log\left(X_{\mathrm{pooled}}\right) \times 0.8878\right) - 1.951; R^2 = 0.6143. \quad (3)$$

2.4 | Publication bias

To determine whether publication bias was detected in our data, we performed a p-curve analysis using the pcurve() function from the METASENS package in R (Schwarzer et al., 2022). This p-curve is an alternative to the trim-fill method, as the p-curve tests for bias towards studies with low p values, rather than just for effect sizes (Harrer et al., 2021). During this analysis, a curve of p values is created for all studies and then right and left skewness are measured to test for bias towards studies with low p values (Harrer et al., 2021). The results from this test indicated that evidential value was present in our study, meaning that publication bias was unlikely a main driver of the observed effect sizes produced from our models (Harrer et al., 2021).

2.5 | Meta-analysis

We performed a separate meta-analysis for each soil health metric, totaling seven separate meta-analyses. All analyses were conducted in R version 1.4.1103 (RStudio Team, 2022) using the METAFOR package (Viechtbauer, 2022). First, we used pure random effects models to determine the overall effect size of soil restoration on each soil health metric without the influence of moderator variables using the rma() function. (2) Next, we used the rma.mv()

function to run multivariate mixed-effects models for each response variable using the five moderator variables listed in Table 1. In these models, we included interaction terms that were found to be significant from a boosted regression tree analysis using the gbm.interactions() function from the GBM package (Greenwell et al., 2020). From the multivariate models, we determined which moderator variables had a significant effect on LnRR in the presence of other moderator variables ($p < 0.05$), which then allowed us to select moderator variables to run in univariate mixed-effects models (Havrilla et al., 2019; Hoeksema et al., 2010). We chose to analyse univariate models because this allowed us to maximize the number of studies that could be analysed as not all moderator variables were reported in every study. Using univariate models also allowed us to calculate the intercept and slope or mean effect size values that described the relationship between each moderator variable and its effect on the LnRR of soil restoration. This approach allowed us to calculate these values while still accounting for the effects of all moderator variables to ensure that each moderator variable analysed still had a significant effect on LnRR in the presence of other moderators. In all models, studies were nested within publications as well as within independent observations, where repeated observations of the same treatment made over multiple time points were analysed as one group of observations (Fernández-Castilla et al., 2020; Harrer et al., 2021).

3 | RESULTS

3.1 | Database summary

We identified 155 publications, yielding 1403 unique studies to include our database. These studies spanned all continents excluding Antarctica (Figure 1). The majority of studies took place in Europe ($n=486$), Asia ($n=463$) and North America ($n=290$), while fewer took place in South America ($n=86$), Australia ($n=52$) and Africa ($n=26$). Most of our studies assessed the effects of soil-based restoration on soil nutrients (SOC: $n=518$; soil N: $n=464$) and soil moisture ($n=427$), while fewer analysed effects on soil structure (aggregate stability: $n=167$; bulk density: $n=129$) and microbial communities (mycorrhizal colonization: $n=164$; basal respiration: $n=62$).

The six publications identified from our multilingual literature search took place in Colombia, Brazil, Chile, Peru, Senegal and Cameroon. Three of these publications were written in Spanish, two in French and one in Portuguese (see Appendix S1). Data were not extracted from these publications, but English-translated abstracts were qualitatively reviewed in the Appendix S1.

3.2 | Soil restoration increases soil health

Soil restoration had an overall positive effect on all soil health metrics included in our study (Figure 2). Positive effects of soil restoration were particularly large for microbial metrics, amounting to a +6967% increase in mycorrhizal colonization and a +277% increase in basal respiration following soil restoration, on average (Figure 2). These high averages may be partially due to the fact that most studies that examined microbial metrics used inoculation treatments, which in some cases could increase a condition of near 0% colonization to near 100% (e.g. Solís-Domínguez et al., 2012). Effects were also relatively large for nutrient availability (SOC: +72%; soil N: +76%), but lower for physical soil components (aggregate stability: +18%; bulk density (inverse): +11%; soil moisture: +19%).

3.3 | Effects across environmental gradients vary by soil health metric

Effects of restoration on soil health decreased with increasing aridity index for SOC and N, (Figure 3, Table 2), meaning that positive effects of restoration decrease in relatively mesic dryland systems. For aggregate stability, soil texture was a significant moderator of the effect size of soil restoration, where effect size increased with percent sand (Figure 4, Table 2).

Additionally, we found a significant interaction between Aridity_Index and Percent_Sand as moderator variables for SOC and N (Table 2). This suggests that the effect of aridity on restoration effectiveness for these two metrics is moderated by percent sand and vice versa. Using our modelled results, we calculated that when the aridity index was below 0.19 and 0.26 for SOC and N, respectively, the effect size decreased with percent sand, but when aridity index was above these values, effect size increased with percent sand. These threshold values were calculated using the modelled interaction coefficients, which were 0.0697 and 0.0850 for SOC and soil N, respectively. This means, using SOC as an example, for a one unit increase in aridity index, the slope of the relationship between LnRR and percent sand increases by 0.0697 and vice versa (Table 2). We used these coefficients to calculate the aridity index value at which the slope of the relationship between LnRR and percent sand changed from negative to positive. Using the same method, we found that when percent sand was below 68% and 78% for SOC and N, respectively, effect size decreased with aridity index but increased with the aridity index when percent sand was above these values. Combining these two results, we found that soil restoration had the greatest effect on SOC and N in fine-textured soils in more arid environments, as well as sandy soils in more mesic environments (Figure 5, Figure A4 in Appendix S1).

For just SOC, we found that the effect of Percent_Sand was also moderated by time since restoration, as there was a significant interaction between these two variables (Table 2). The coefficient for this interaction was 0.0007, meaning that as time increases, the slope describing the relationship between the LnRR and percent sand increases. Using the same method described above, we calculated that when percent sand was less than 36%, the effect size of restoration on SOC decreased with time, but when it is greater than 36%, the effect size increased with time (Figure A4 in Appendix S1).

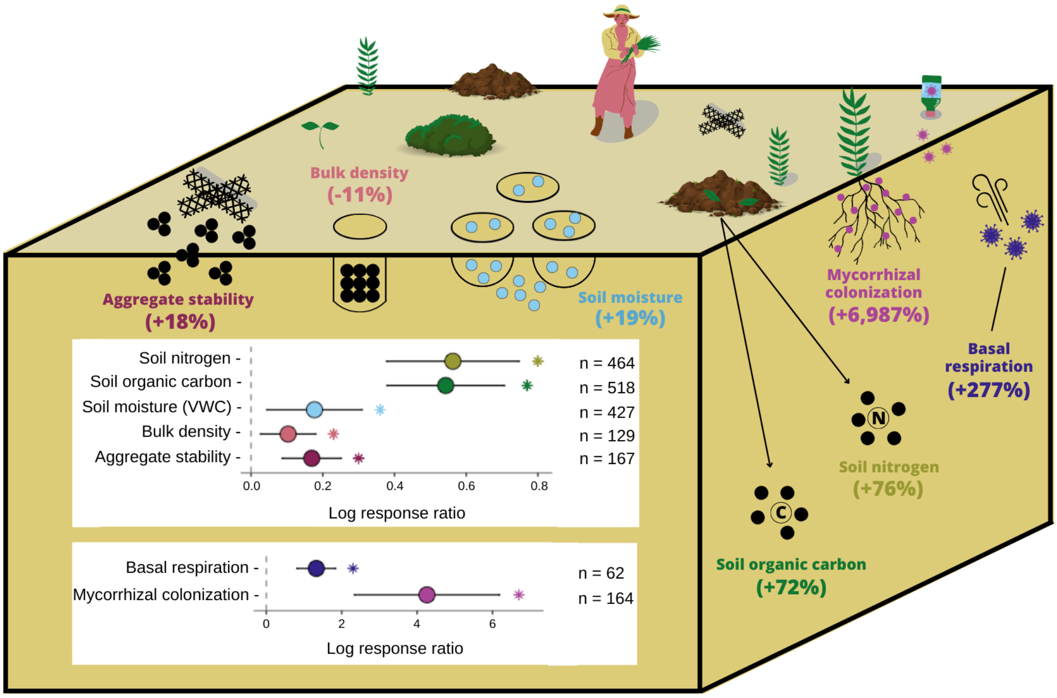

FIGURE 2 Pure random effects of soil restoration on soil health metrics (aggregate stability, bulk density, SOC, soil N, soil moisture, mycorrhizal colonization, and basal respiration). Error bars represent 95% confidence intervals. Percentages represent the average percent change of each soil health metric following soil restoration.

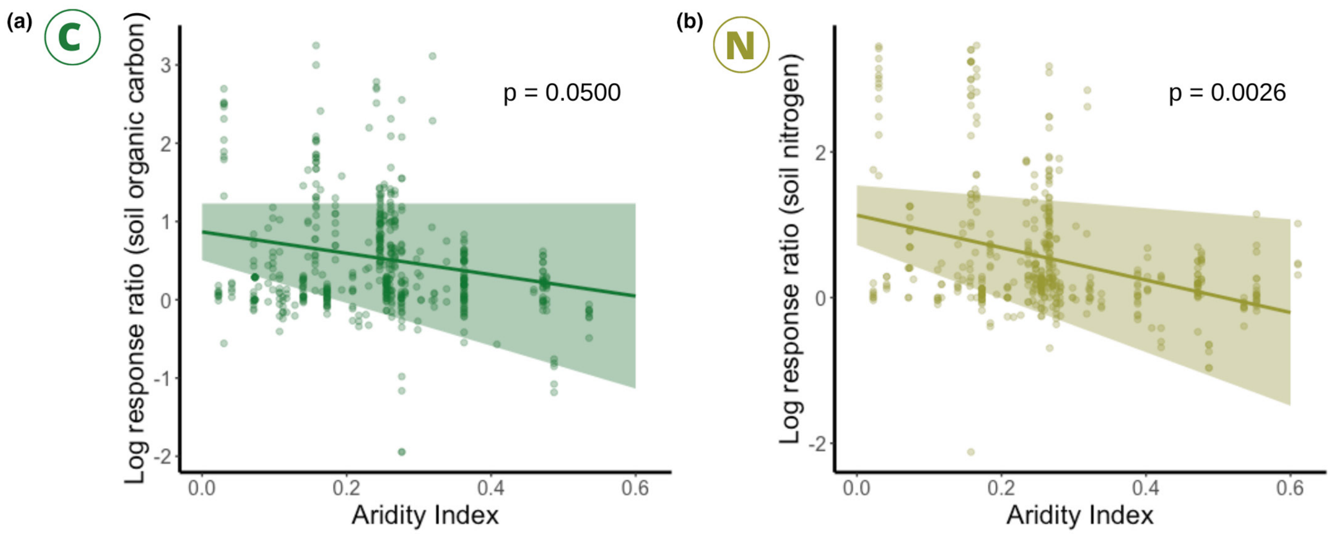

FIGURE 3 Variation in the effect of restoration across an aridity gradient for soil health metrics: (a) SOC and (b) soil N, measured as a log response ratio. Solid lines are meta-regression lines, and shaded areas represent the 95% confidence intervals.

3.4 | Treatment type influences effectiveness

Treatment type had a significant effect on restoration effectiveness for certain soil health metrics. For aggregate stability, erosion control structures had a significantly lesser effect size than all other treatments analysed. For SOC and mycorrhizal colonization, however, certain treatments had significantly higher effect sizes than others. Organic amendments significantly had the greatest effect size on SOC, while fungi inoculation had the greatest for mycorrhizal colonization. (Figure 6, Table 3). For soil N, there was no treatment that had a significant highest or lowest effect size, though organic amendments did have a significantly higher effect size than fungi inoculation. Treatment types with sample sizes of less than 20 were not included in the analysis. Revegetation did not have a significant effect on the effect size of restoration for any soil health metric.

TABLE 2 Results from univariate mixed-effects models for Aridity_Index, Percent_Sand, Time, and their interactions, when applicable. Estimates are regression line slope values. Also, 95% confidence intervals (CIs), reported as a ± value from the estimate, and *p* values are also included.

		Aridity index	Percent sand	Time	Aridity index × percent sand	Percent sand × time
Aggregate stability	Estimate	–	0.0055	–	–	–
	CI	–	0.0040	–	–	–
	p value	–	0.0062*	–	–	–
Soil organic carbon	Estimate	−1.3669	0.0005	–	0.0697	0.0007
	CI	1.3672	0.0047	–	0.0497	0.0006
	p value	0.0500*	0.8318	–	0.0060*	0.0073*
Soil nitrogen	Estimate	−2.2266	−0.0046	–	0.0850	–
	CI	1.4500	0.0059	–	0.0670	–
	p value	0.0026*	0.1171	–	0.0134*	–
Basal respiration	Estimate	−1.6883	–	−0.0771	–	–
	CI	4.3725	–	0.0852	–	–
	p value	0.4492	–	0.0766	–	–

*Indicates values that are statistically significant using an alpha of <0.05.

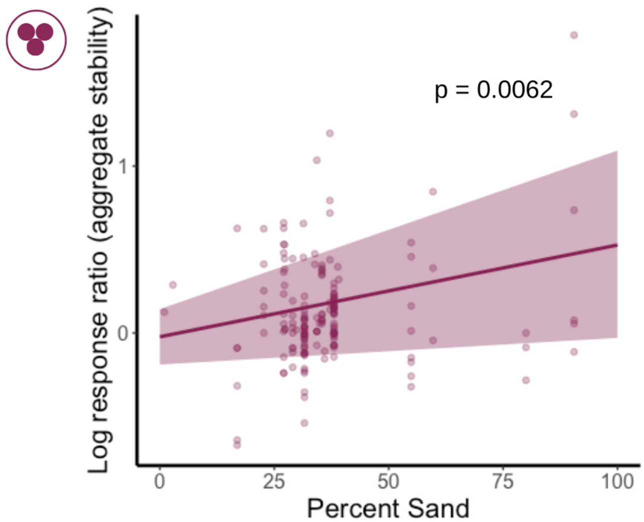

FIGURE 4 Variation in the effect of restoration across a soil texture gradient for aggregate stability, measured as a log response ratio. The solid line is a meta-regression line, and the shaded area represents the 95% confidence interval.

4 | DISCUSSION

4.1 | Soil restoration increases soil health across global drylands

Results from our meta-analysis show soil restoration had a beneficial effect on aggregate stability, bulk density, soil moisture, SOC, soil N, mycorrhizal colonization and basal respiration across global drylands. Soil restoration had very large effects on the measured microbial soil health metrics, suggesting that soil restoration is particularly effective at improving certain biotic conditions such as mycorrhizal colonization and microbial respiration (Figure 2). Collectively, results suggest that active soil restoration has the potential to improve many aspects of soil health and could be an important tool in combating dryland soil degradation.

4.2 | Restoration effectiveness on abiotic metrics of soil health varies across environmental gradients

We found that the effectiveness of soil restoration increased with aridity for SOC and N, meaning that restoration is most effective at increasing soil nutrients in drier climates (Figure 3). This may be because in more mesic climates, soils can recover more easily on their own post-disturbance (Crouzeilles et al., 2017) as there tends to be a greater availability of moisture and nutrients. In drier climates, there are likely more barriers to natural recovery, such as a lack of soil moisture and nutrients (Klemmedson, 2009), meaning that replenishing soil nutrients through active restoration could have a greater impact. Soil texture also influenced restoration effectiveness on aggregate stability. For aggregate stability, restoration effectiveness increased with percent sand, meaning restoration was most effective at improving aggregate stability in sandier soils (Figure 4). This may be because aggregate stability is usually low in sandier soils, so it is possible for aggregate stability to increase by larger margins following restoration than it would be for soils that already have high aggregate stability (Almajmaie et al., 2017).

However, we did not find any significant influences of environmental variables on the effect size of restoration for biotic soil health metrics. Given the relatively smaller number of studies that examine biotic soil health metrics, more studies that test restoration effectiveness on biotic soil health across environmental

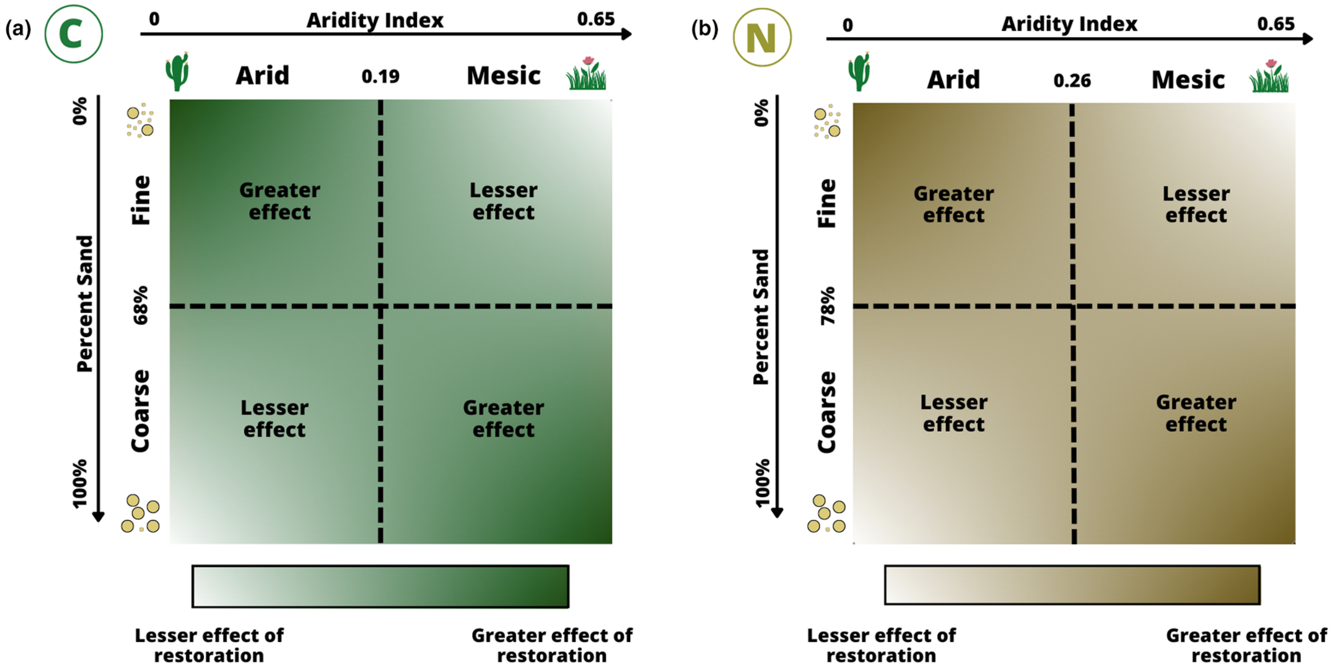

FIGURE 5 The combined influence of aridity and percent soil sand on the effect of soil restoration on SOC (a) and soil N (b). Darker colours represent conditions where soil restoration has a greater effect size, and lighter colours represent conditions where soil restoration has a lesser effect size. The values next to the dotted lines represent threshold values for aridity index and percent sand above and below which soil restoration has a greater or lesser effect.

gradients will need to be conducted to better determine these relationships.

4.3 | Effects of aridity and soil texture are moderated by other variables

Soil nutrient responses to restoration were mediated by interactions between aridity and soil texture. While we found that overall restoration effectiveness increased with aridity, this relationship was contextualized by soil texture. Overall, restoration was most effective at increasing SOC and N in finer-textured soils in drier environments, and coarser-textured soils in more mesic environments (Figure 5).

One explanation for this could be that soil restoration may be most effective at increasing soil nutrients when a site is facing just one major barrier to nutrient accumulation, rather than multiple at once. As discussed previously, high levels of aridity may be a barrier to nutrient accumulation due to a lack of organic matter in these environments (Klemmedson, 2009). Additionally, high sand content can prevent soils from holding nutrients effectively due to poor aggregation (Augustin & Cihacek, 2016). Therefore, it may be so difficult to increase nutrients in sandy soils in arid environments that restoration is not very effective. Additionally, soil restoration may also be less effective in soils that do not face any barrier associated with aridity or soil texture (i.e. mesic, fine-textured soils) because they may be able to recover nutrient levels on their own (Augustin & Cihacek, 2016; Crouzeilles et al., 2017), meaning a smaller net effect of restoration. These findings are interesting in the context of restoration decision making, as they suggest choosing a site that will likely not recover without active intervention, but is also not facing such great barriers to recovery that restoration is not possible. This also suggests that arid sites with very sandy soils may have a greater need for protection and conservation, as they are very difficult to restore post-degradation.

For SOC, the influence of soil texture was also moderated by time since restoration (Figure A4 in Appendix S1). The interaction between these two variables suggests that in less sandy soils, the effect of restoration decreases over time, but that in more sandy soils it increases over time. One possible explanation for this outcome is that restoration treatments may take longer to help sandier soils accumulate more nutrients, so that while on short time scales restoration may be less effective at increasing SOC in sandy soils, perhaps on longer time scales restoration can be effective across soil textures (De Rouw & Rajot, 2004).

4.4 | Restoration effectiveness varies by treatment type for different soil health metrics

For some soil health metrics, certain treatments showed greater effectiveness than others, meaning that treatment type was an important factor for restoration success. For SOC and mycorrhizal colonization, organic amendments and fungi inoculation had the greatest effectiveness, respectively (Figure 6). This is likely because many commonly used organic amendments, such as compost, are a direct source of carbon for the soil (Zmora-Nahum et al., 2005), and fungi inoculation directly adds colonizing fungi to the soil (Smith & Read, 2008).

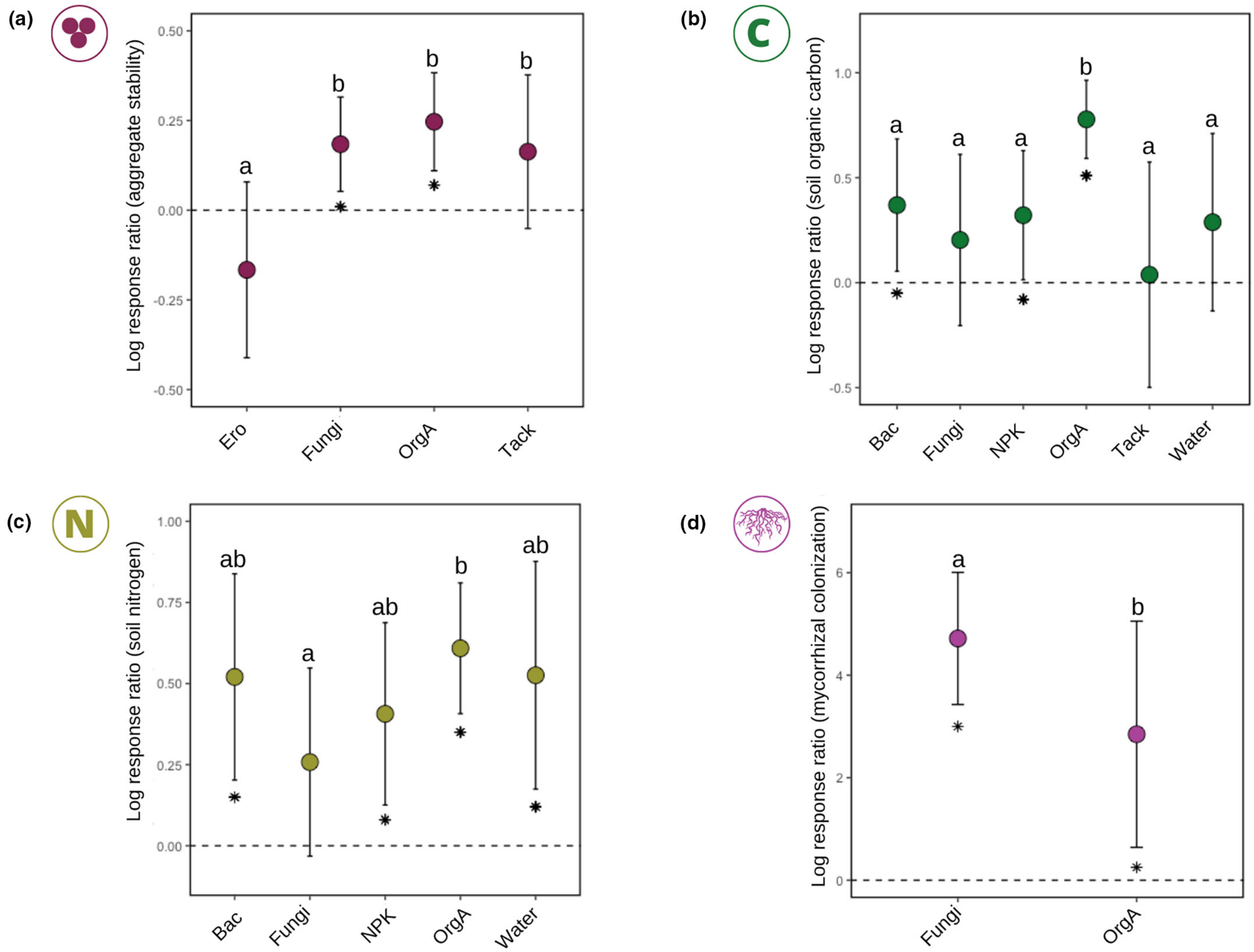

FIGURE 6 Effect sizes and differences between different soil restoration treatment types for six soil health metrics (aggregate stability (a), SOC (b), soil N (c) and mycorrhizal colonization (d)). Error bars represent 95% confidence intervals. *indicates values that are statistically significant from zero using an alpha of <0.05. Letters represent treatment types that are significantly different from each other. "Bac", bacteria inoculation; "Ero", erosion control structure; "Fungi", fungi inoculation; "NPK", inorganic NPK fertilizer; "OrgA", organic amendment; "Tack", soil tackifier; "Water", water retention treatment.

For aggregate stability and soil N, most treatments had roughly the same effectiveness, except for erosion control structures and fungi inoculation, which had the smallest effect sizes for their respective soil health metrics (Figure 6). The fact that erosion control structures were least effective for increasing aggregate stability is interesting given that aggregate stability is often associated with erodibility, which is usually what erosion control structures aim to decrease (Stanchi et al., 2015). It is possible that if aggregate stability is measured in soil adjacent to these structures, recent accumulation of loose soil will cause lower aggregate stability measurements. Additionally, our finding that fungi inoculation was the least effective treatment for soil N is noteworthy since this was found to be the most effective treatment for mycorrhizal colonization. This highlights how different aspects of soil health may respond differently to certain treatments, and that specific goals for soil health improvement are important when choosing restoration treatments. It is possible that fungi inoculation is less effective at improving soil N because, although mycorrhizal fungi can help plants acquire N from the soil, they generally do not fix atmospheric N like certain types of bacteria and are not direct sources of N like many soil amendments (Hestrin et al., 2019).

4.5 | Study limitations and future research directions

Our study had several limitations that highlight opportunities for future research:

4.5.1 | Geographic data distribution and multilingual coverage

This meta-analysis did not have global representation for all variables included. While our database included studies of SOC and

TABLE 3 Results from multivariate mixed-effects models for Treatment_Type and Revegetation. Estimates (est.) are mean effect sizes for each factor level. Also, 95% confidence intervals (CI), reported as a ± value from the estimate, and *p* values (*p*) are also included.

		Treatment type						
		Bac	Fungi	NPK	OrgA	Ero	Tack	Water
Aggregate stability	Estimate	–	0.1840	–	0.2466	−0.1662	0.1632	–
	CI	–	0.1315	–	0.1366	0.2450	0.2141	–
	p value	–	0.0061*	–	0.0004*	0.1836	0.1352	–
Soil organic carbon	Estimate	0.3695	0.2033	0.3214	0.7780	–	0.0378	0.2880
	CI	0.3152	0.408	0.3075	0.1861	–	0.5366	0.4228
	p value	0.0216*	0.3288	0.0405*	<0.0001*	–	0.8902	0.1818
Soil nitrogen	Estimate	0.5204	0.2579	0.4066	0.6087	–	–	0.5256
	CI	0.3179	0.2899	0.2811	0.2017	–	–	0.351
	p value	0.0013*	0.0814	0.0046*	<0.0001*	–	–	0.0033*
Mycorrhizal colonization	Estimate	–	4.7167	–	2.8474	–	–	–
	CI	–	1.8839	–	2.2064	–	–	–
	p value	–	<0.0001*	–	0.0114*	–	–	–

*Indicates values that are statistically significant using an alpha of <0.05. See Figure 6 for treatment type codes.

N responses to restoration in drylands across six continents, the remaining five metrics only had data points from two to five continents (Figure A3 in Appendix S1). There was also much greater representation of studies from North America, Europe and East Asia, and relatively lower representation of regions such as South America, North Africa and the Middle East. Some of this may be because we were only able to include publications that were written in or had been previously translated into English. In fact, we found six publications written in languages other than English that met search criteria, but were not able to analyse the main texts due to translation constraints. However, through reviewing the English-translated abstracts of each of these publications, we found that the main findings of these studies agreed with our overall result that soil restoration benefits many aspects of soil health (see Appendix S1). Nonetheless the inclusion of these publications may have allowed us to analyse larger samples of certain treatment types and may have added some additional findings of interest as well as geographically underrepresented dryland regions in our analyses (i.e. South America and North Africa; Figure A5 in Appendix S1). Future research could focus on better incorporating multilingual publications into meta-analyses on dryland restoration, as including multilingual literature may be crucial for capturing variation and drawing global conclusions (Zenni et al., 2023).

4.5.2 | Soil health responses

This study only included seven commonly measured metrics of soil health, so is therefore not comprehensive of all aspects of soil health. Other important aspects of soil health, including pH, electrical conductivity and exoenzyme activity (Raghavendra et al., 2020), had low representation in the literature and were not included in this meta-analysis.

4.5.3 | Land use and disturbance legacies

Other potential moderator variables, such as land usage and land disturbance, were not reported in most studies, so we did not have sufficient data to include these variables in our analyses. Future work should investigate how land use or disturbance legacies could influence soil restoration effectiveness (Meli et al., 2017).

4.5.4 | Combined abiotic and biotic restoration treatments

Future work should also examine abiotic and biotic soil treatments used simultaneously. We found several publications that examined these types of treatments (e.g. Antoninka et al., 2019; Faist et al., 2020), but there were not enough unique studies to be used for meta-analysis.

4.5.5 | Microbial responses to restoration

Soil-based restoration field studies should explore the effects of restoration on microbial community metrics, as these soil health metrics were much less commonly reported than abiotic soil characteristics and are very important indicators of soil health (Raghavendra et al., 2020).

4.5.6 | Effects of soil restoration on plants

Although outside the scope of our study, future studies should examine the effects of soil restoration on plant responses like recruitment and growth.

4.6 | Key takeaways and implications

From this meta-analysis, we found that soil restoration can be an effective tool for improving physical and biological soil health in drylands. However, for certain abiotic soil health metrics, this effectiveness is dependent on environmental stress (aridity and soil texture). Soil restoration was most effective at improving nutrient levels in fine-textured soils in arid environments as well as coarse-textured soils in mesic environments. Additionally, we found that organic amendments were most effective at increasing SOC, while fungi inoculation was most effective at increasing mycorrhizal colonization. This information can be used by land managers and restoration practitioners to choose optimal treatments for improving specific aspects of soil health and prioritizing certain areas for either restoration or conservation. Reversing land degradation through ecological restoration can produce myriad environmental and social benefits, including carbon sequestration (Di Sacco et al., 2021), improved water quality (Rey Benayas et al., 2009) and long-term sustainability of natural resources (George et al., 2018). Results from our study can be used by land managers and restoration practitioners to prioritize areas for soil restoration and choose restoration treatments based on soil health targets. More informed decision-making could improve restoration effectiveness and efficiency and will help combat escalating land degradation in global drylands (IPBES, 2018).

AUTHOR CONTRIBUTIONS

Louisa B. Kimmell and Caroline A. Havrilla conceptualized and designed this study. Louisa B. Kimmell and Jessica M. Fagan extracted data from publications and created the dataset used for meta-analysis. Louisa B. Kimmell performed data analysis, created the figures, and wrote the first draft of the manuscript. Caroline A. Havrilla and Jessica M. Fagan edited and contributed to the final draft of the manuscript. Caroline A. Havrilla advised and provided guidance on all steps of the research process. All authors contributed critically to the manuscript and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

We declare no conflict of interest for this study.

DATA AVAILABILITY STATEMENT

Data available via Dryad Digital Repository https://doi.org/10.5061/dryad.63xsj3v5k (Kimmell et al., 2022).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Appendix S1. Soil restoration increases soil health across global drylands: a meta-analysis.

Figure A1. Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) diagram.

Figure A2. Categorization of treatments analysed in this meta-analysis. PAM, polyacrylamide; SAP, super absorbent polymer.

Figure A3. Geographic locations of studies used in this meta-analysis for each soil health metric. Panels a through g correspond to the following soil health metrics, in this order: aggregate stability, bulk density, soil organic carbon, soil nitrogen, soil moisture (%VWC), mycorrhizal colonization, and basal respiration.

Figure A4. Interactions between Aridity and Percent_Sand, and Time and Percent_Sand, and their influence on the log response ratio (LnRR) for soil organic carbon (SOC) and soil nitrogen (N). Panels a and b depict the relationship between Percent_Sand and the LnRR of SOC and soil N, respectively, with plotted points colored by Aridity_Index. Panels c and d depict the relationship between Aridity_Index and the LnRR of SOC and soil N, respectively, with plotted points colored by Percent_Sand. Panel e depicts the relationship between Percent_Sand and the LnRR of SOC, with plotted points colored by Time.

Figure A5. Geographic locations of English publications included in analysis and approximate locations of publications written in languages other than English that met search criteria for analysis, relative to the global distribution of drylands. Numbers indicate total numbers of publications, including all languages.

Figure A6. Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) diagram for multilingual literature search.

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