**Title:**

**Getting something for nothing: a synthesis of active versus passive restoration in drylands.**

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**Abstract:**

Restoration is a fundamental priority for all ecosystems. Dryland ecosystems are global biodiversity hotspots and ideal to explore different categories of restoration. These regions are facing serious threats due to agricultural intensification and land degradation. Using drylands as a case study, a formal synthesis including meta-analyses contrasted two general categories of restoration, active versus passive, and specific techniques to examine restoration outcomes. This synthesis included research from 19 countries, described almost 25 interventions and examined outcomes associated with habitats and different taxa. Active restoration practices yielded significant positive outcomes for soils, vegetation, and wildlife. Passive restoration was a viable option only for vegetation recovery but not for soils. These findings suggest that direct interventions are critical in many ecosystems specially those experiencing severe anthropogenic pressures and environmental stress.

**One Sentence Summary:**

Active restoration in dryland ecosystems yield positive ecological outcomes for soils, vegetation, and wildlife.

**Main Text:**

Restoration is a complex field of research and crucial in all ecosystems (*1*). The restoration of degraded ecosystem provide multiple benefits to people (*2*) that rely on fundamental services as food and water (*3*). Consequently, functional and healthy ecosystems are indispensable for the sustainability of humanity and all other forms of life (*4*–*6*) and ecological restoration links the interface between people and nature (*7*, *8*). As main categories of restoration (i.e. active or passive) differ in the total amount of resources invested (e.g. time, money and human assistance) (*9*) and these resources are likely to be scarce, we need to identify what interventions generate consistent and positive outcomes that support enhanced ecosystem function and services. Dryland ecosystems are great case study to evaluate the effectiveness of restoration practices, they include natural semi-arid grasslands, shrublands, and deserts (*10*) but also encompass agricultural lands that are highly extensive systems on Earth, almost 40% of terrestrial surface experiences land conversion by agriculture (*11*, *12*). Drylands are hotspots of biodiversity and support some of the most endangered species worldwide (e.g. large herbivores in Africa) (*13*). Furthermore, a great variety of ecosystem services that contribute to people´s quality of life (*14*) as food, water, energy, carbon sequestration, cultural identity and aesthetic values (*10*), are provided by drylands (*15*). However, dryland ecosystems are some of the most degraded systems in the world (*16*); the increasing land conversion (e.g. to agriculture), land degradation, and climate change (*17*) all threaten the delivery of ecosystem services (*14*). While increased land protection (e.g. conservation easements) (*18*) and better land management practices (*19*) could benefit remaining habitat in drylands, changing conditions in general and water scarcity in particular have created an opportunity to re-claim and restore degraded agricultural drylands for plants and wildlife (*19*, *20*). In order to seize the opportunity to restore dryland habitat, practitioners need clear guidance on which restoration practices will have the greatest positive outcomes given limited resources.

To examine the success of restoration practices and their outcomes, we performed a meta-analysis of 40 peer-reviewed publications that compared experimental and control groups from 19 different countries in dryland ecosystems (Fig. 1). Data collected include more than 1400 entries of independent variables measured by individual studies. Among the diverse disturbances reported in drylands globally (Fig. S1), we focused on restoration within retired agricultural lands, which included both farmland (i.e. crops) and grazing natural land. Each restoration practice was classified as either active, which involves human assistance in the restoration process, or passive, which allows for natural recovery of the system (*21*). For each study we also extracted data of the restoration outcome adopted to express the response to each restoration practice (*22*). The success of restoration practices and outcomes was assessed using the log response ratio (lrr) (*23*). We grouped active restoration practices into the following three categories based on their primary focus: soil, vegetation, and water supply (Table 1A; Table S1). Passive restoration practices were classified as soil, vegetation, and grazing exclusion. We evaluated active restoration outcomes across four categories: soil, vegetation, animals, and habitat (Table 1B). The habitat category was used when studies reported measures of both soil and vegetation. We evaluated passive restoration outcomes across the same three categories: soil, vegetation, and habitat (Table 1B). We used random effects models to account for the variability within the studies evaluated (*24*), and then applied meta-regressions to test the potential influence of aridity (*25*) and duration of studies since restoration practice implementation.

Active restoration consistently led to positive responses (Table 1). All three specific categories of active restoration had net positive responses (Table 1A, Fig. 2); water supply was the most effective restoration practice followed by soil and vegetation active practices (Table 1A, Fig. 2). Passive vegetation recovery and grazing exclusion can also have positive effects on restoration (Table 1A, Fig. 2) but with lower and more variable effect sizes than active practices, while passive practices on soils led to negative responses (Table 1A, Fig. 2). Aridity and duration of studies following implementation both significantly influenced the effectiveness of active restoration practices (lrr= -0.01, 95% CI= -0.02 to -0.01; lrr= 0.003, 95% CI= 0.003 to 0.0035, respectively). Net effectiveness of active restoration practices decreased with increasing aridity. For passive approaches, only duration of recovery was significant (lrr= 0.01, 95% CI= 0.008 to 0.01). Typically, active restoration was positive for soils, vegetation and habitat, but not for animals’ outcomes (Table 1B). We found that soils cannot restore passively, but plants and habitat can recover (Table 1B). A high number of studies (n=30), classified as both active (n=16) and passive restoration (n=14), were not included in this meta-analysis due to the absence of control groups. This may highlight the lack of undisturbed reference sites or the difficulty of identifying a clear model to which compare the system to be restored (*26*) and on the other hand, the absence of specific restoration goals to be achieved (*1*). This situation entails challenges to interpret the benefits of restoration interventions (*26*) and to determine ecosystems health.

Findings from this meta-analysis support the conclusion that investment in active restoration is a more reliable strategy in meeting ecological outcomes in dryland ecosystems. In contrast, recent meta-analyses in tropical and temperate forests concluded that passive recovery through natural succession was the most effective strategy (*27*, *28*). This difference profoundly suggests that environmental limitation and stress are critical criteria to consider in weighing restoration options for an ecosystem. Rainfall, soil fertility, and productivity are severely constrained in dryland ecosystems (*10*), and results here show the success of active restoration practices decreases with aridity. The extent of land transformation and prior land use history also cannot be overlooked (*21*). Agricultural crop lands in general may need active restoration practices to overcome the former legacies of soil disturbances, nutrient inputs, and pesticides (*29*).

Resources to restore ecosystems will always be in short supply relative to need, particularly in developing countries and in those in which the reversal of environmental deterioration is not a goal of the policy agenda (*5*). This synthesis clearly demonstrates that it is likely to get something for nothing from restoration in dryland ecosystems but that an active investment in interventions will certainly lead to more consistent positive outcomes for soils, vegetation, and habitats. We are currently facing a global situation in which biodiversity, natural resources, ecosystem services and functions are under serious threats; however, considering the condition of increasing changes, we have a great opportunity to restore ecosystems, ecological processes and biodiversity (*2*) that will ultimately benefit human well-being.

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**Data and materials availability:** Include a note explaining any restrictions on materials, such as materials transfer agreements. Note accession numbers to any data relating to the paper and deposited in a public database; include a brief description of the data set or model with the number. If all data are in the paper and supplementary materials include the sentence “All data is available in the main text or the supplementary materials.” All data, code, and materials used in the analysis must be available in some form to any researcher for purposes of reproducing or extending the analysis.

Supplementary Materials:

**Materials and Methods**

Literature search and eligible criteria

PRISMA guidelines were used to structure this synthesis and meta-analysis (Preferred Reporting Items for Systematic reviews and Meta-Analyses; Fig. S2) (*30*). We systematically searched Scopus and The Web of Science using the following term combinations: [restoration\* desert\* vegetation\*] OR [restoration\* grassland\* desert\*] OR [restoration desert\* plant\*] OR [restoration "agricultural lands"] OR ["restoration techniques" desert\*] OR ["passive restoration" desert\* plant\*] OR ["active restoration" desert\* plant\*] OR [revegetation abandoned desert\*] OR [restoration "agricult\*land\*" desert\* plant\*] OR [restoration dryland\* vegetation] OR [restoration semiarid\* plant\*] OR [restoration arid\* plant\*]. The searches were done in September 2018 and returned 1504 published articles. We collected data from studies that met the following inclusion criteria: (1) research articles including results, review articles were not included; (2) agriculture as the main disturbance reported (crop and grazing lands); (3) studies with experimental (restoration practice) and control groups specifically compared; (3) reported statistical analysis and significance of treatments. After the application of the above inclusion criteria, a total of 40 studies were included in the meta-analysis (Fig. S2).

Data extraction

The specific restoration practice described in each study was recorded and subsequently classified as active or passive restoration. Passive restoration refers to the natural regeneration of degraded ecosystems with minimal or not human interventions which may include the cessation of the prior disturbance, for example fencing for grazing exclusion (*9*). Instead, active restoration implies direct human interventions on ecosystems to assist and accelerate their restoration (*21*). Different practices that addressed a similar restoration goal were further classified into four main categories: soil, i.e. including those practices with intervention in soils; vegetation; water supply and grazing exclusion. Soil and vegetation practices included both active and passive types of restoration, water supply was classified as an active restoration practice, and grazing exclusion as passive (Table 1A). Moreover, for each study we extracted data of the restoration outcome adopted to estimate the mean effect and relative variation for each restoration practice reported in primary studies (*24*). We grouped the different outcomes into four general categories as well: soil, vegetation, animals and habitat. These four categories were measured by studies with an active restoration approach, while evaluation of restoration outcomes on animals was not performed in passive restoration studies (Table 1B).

We collected data of all the response variables reported in each article. For each response variable, we extracted the mean and standard deviation. When these data were provided in figures, we used WebPlotDigitizer (*31*) to extract values. In addition, we collected data of the mean annual temperature and annual precipitation from the study sites of each article to calculate the aridity index (*25*) and, of the duration of studies since the implementation of the restoration practice expressed in months. When climatic data were not provided in studies, we derived them from WordClim (www.worldclim.org). The aridity index and duration of studies were used as covariates in statistical models.

Statistical analysis

To determine the effect of the restoration practice over the control group we calculated the log response ratio (lrr)(*23*) that quantifies the log-proportional change between the means of the two groups compared (*32*). A negative value of the log response ratio implies the effect of the control group was higher than that of the treatment, while a positive value indicates that a treatment leads to an increase in some responses evaluated. For each effect size we calculated the lower and upper 95% confidence intervals (CI), when the CIs did not overlap zero, we considered the effect size to be statistically significant. All figures and analyses were performed using the packages tidyverse and meta in R (*33*).

**Table 1.** Estimators of log response ratio (effect size) and 95% confidence interval (CI) from random effects models. Effect of restoration practices and outcomes were considered significant if their estimated 95% confidence intervals did not overlap 0. (A) Results of random effects models comparing categories of restoration (active versus passive) and different practices for active (water supply, soil and vegetation) and passive (soil, vegetation and grazing exclusion) restoration. (B) Results of random effects models for different outcomes for active (vegetation, soil, habitat and animals) and passive (soil, vegetation and habitat) restoration. Restoration outcomes refer to the measures adopted to estimate the effect for each restoration practice reported in primary studies.

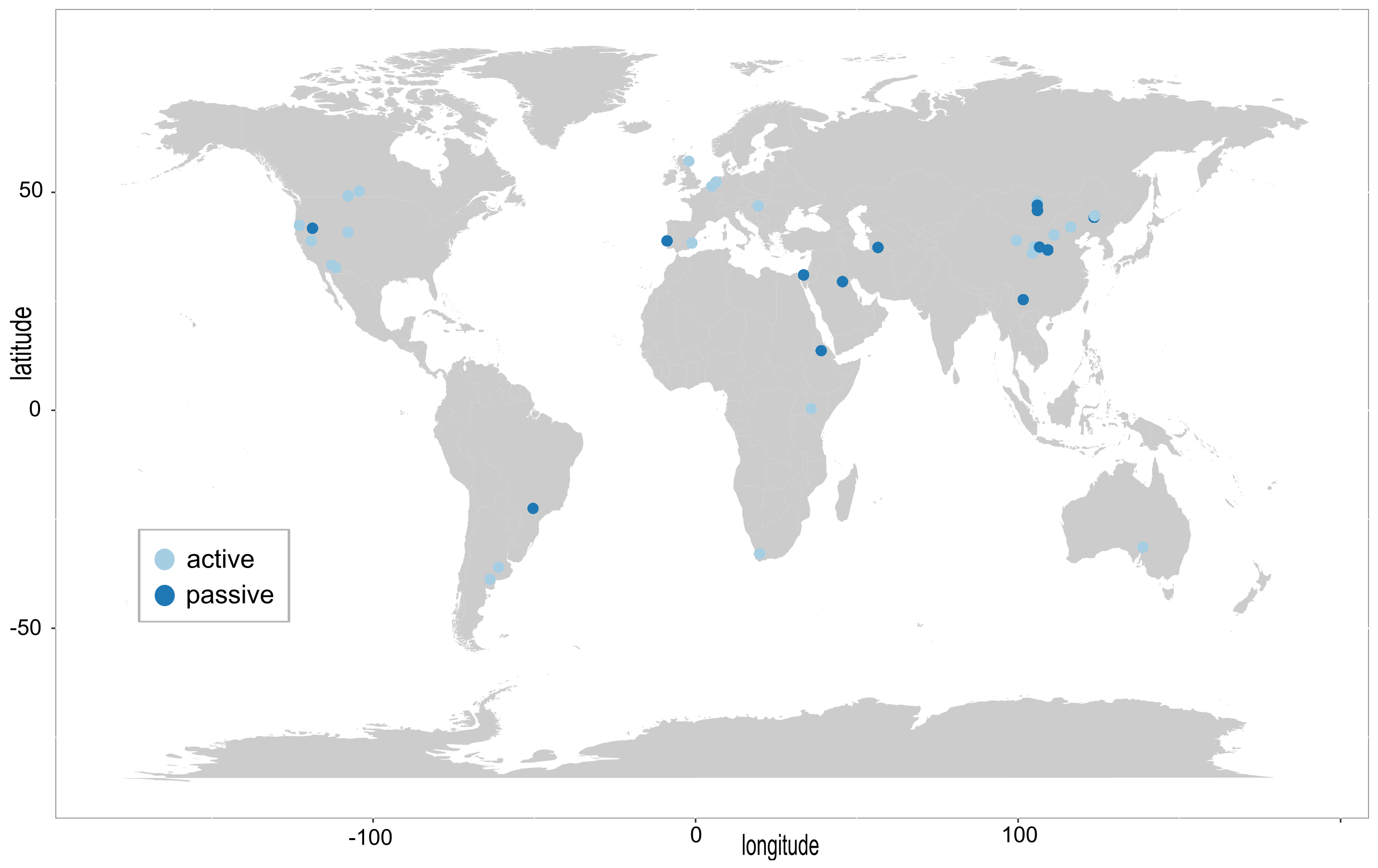
|  |  |  |
| --- | --- | --- |
| **Restoration** | **log response ratio** | **95% CI** |
| *(A)* | | |
| **Active restoration practices** | 0.22 | 0.21, 0.23 |
| Water supply | 0.64 | 0.55, 0.73 |
| Soil | 0.31 | 0.30, 0.33 |
| Vegetation | 0.18 | 0.17, 0.20 |
| **Passive restoration practices** | -0.34 | -0.37, -0.31 |
| Soil | -0.76 | -0.82, -0.70 |
| Vegetation | 0.26 | 0.21, 0.32 |
| Grazing exclusion | 0.13 | 0.03, 0.24 |
| *(B)* | | |
| **Active restoration outcomes** | | |
| Vegetation | 0.51 | 0.49, 0.52 |
| Soil | 0.22 | 0.15, 0.28 |
| Habitat | 0.06 | 0.04, 0.08 |
| Animals | -0.11 | -0.12, -0.11 |
| **Passive restoration outcomes** | | |
| Soil | -0.76 | -0.82, -0.70 |
| Vegetation | 0.44 | 0.03, 0.85 |
| Habitat | 0.16 | 0.1, 0.22 |

Figures S1-S2

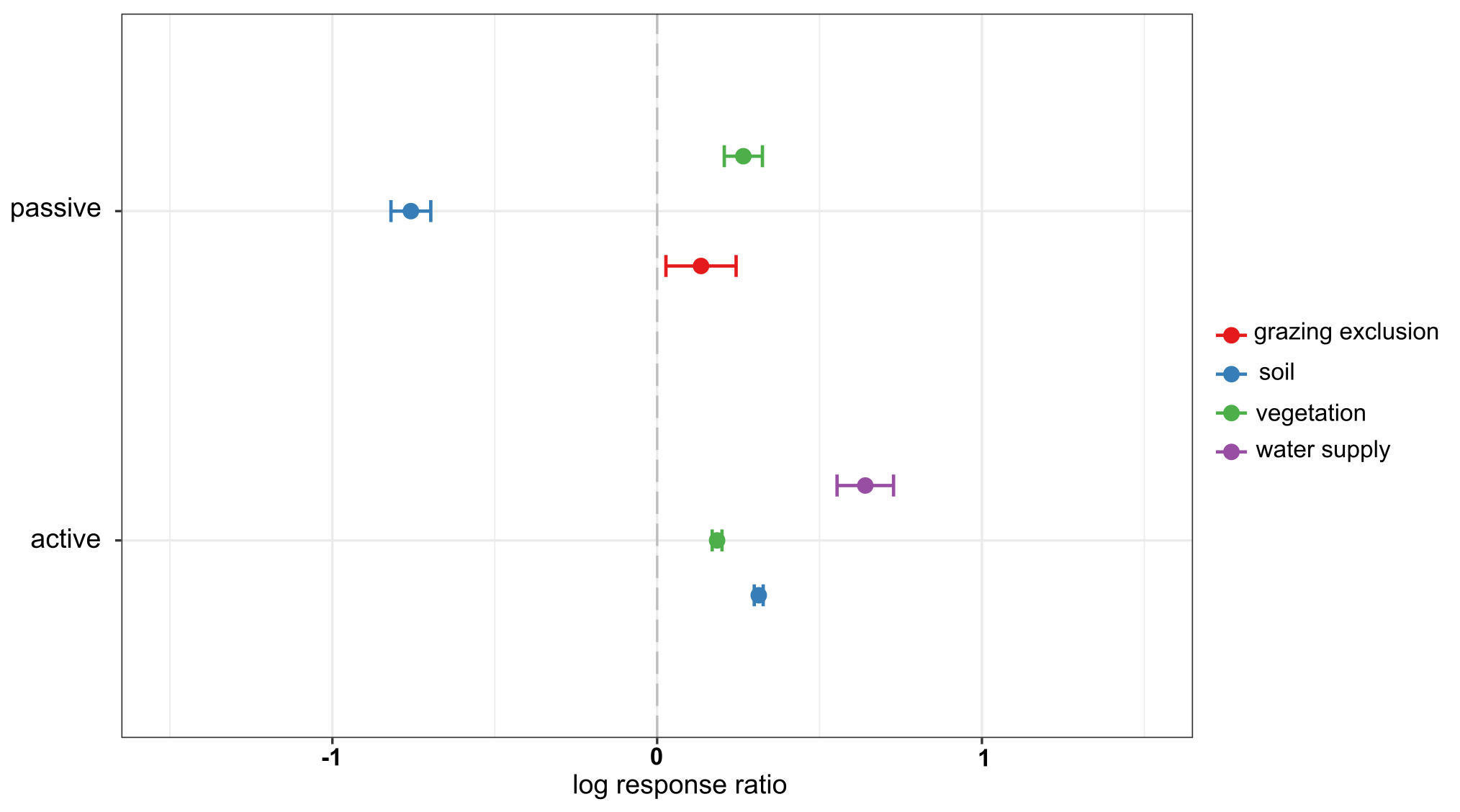
Table S1

References (1-33)

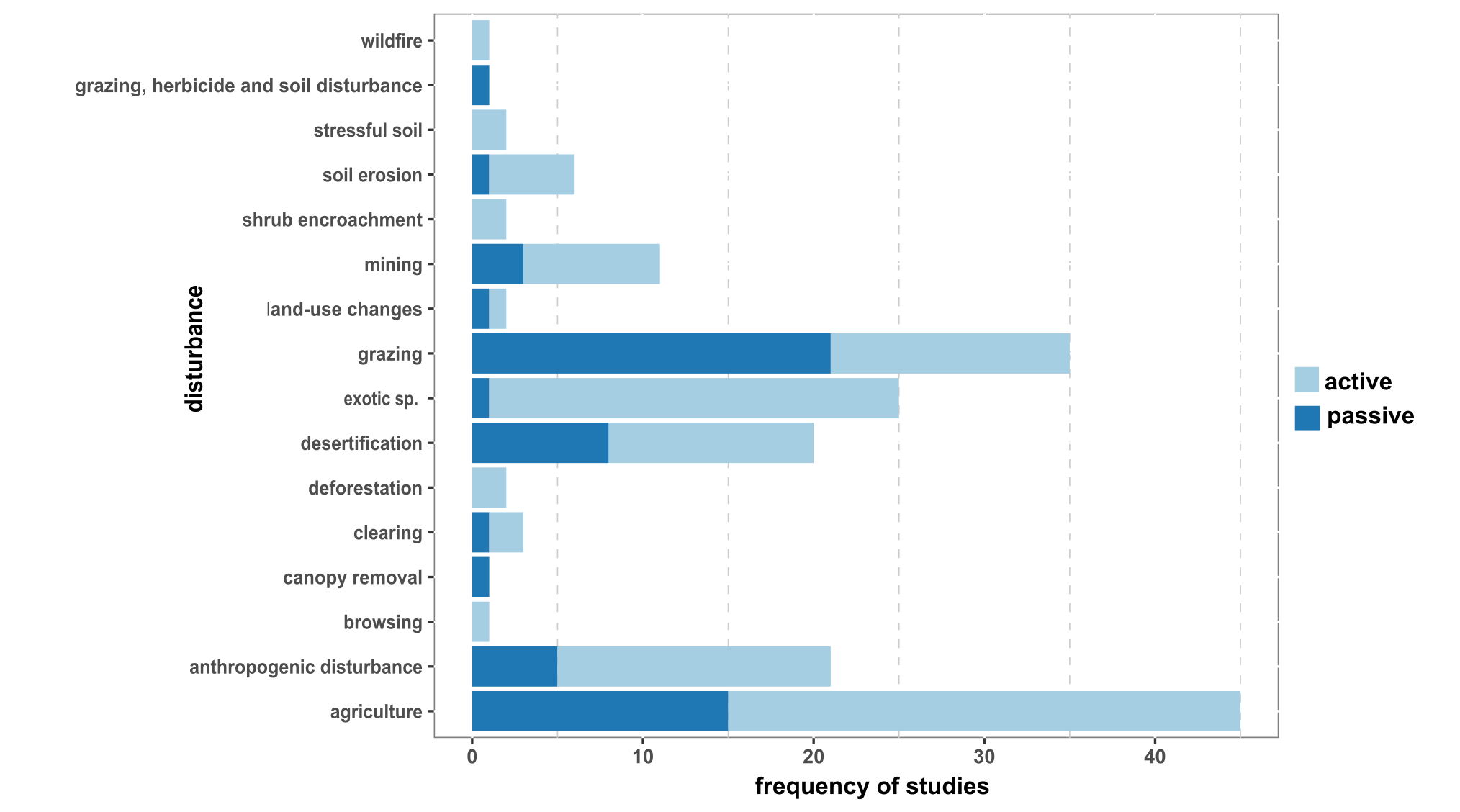
**Fig. 1.** Global distribution of studies included in a meta-analysis comparing categories of restoration (active versus passive) and individual restoration practices in dryland ecosystems. Articles included in the meta-analysis reported agriculture (crop and grazing natural lands) as the main disturbance and included treatment and control groups. In light blue is represented the location of studies applying active restoration practices, while in dark blue the location of studies evaluating passive restoration practices.



**Fig. 2.** Overall effect sizes (log response ratio) for the effect of active and passive restoration practices in drylands globally, based on a meta-analysis of published studies. The *x* - axis shows the natural log of the response ratio (mean and 95% confidence interval), whereas the *y* - axis describes passive (vegetation, soil and grazing exclusion) and active (water supply, vegetation and soil) restoration practices. A value of zero of the log response ratio represents there was no difference among both groups compared (treatment and control), while a positive log response ratio value indicates the mean of the treatment group was higher than that of the control group and a negative value indicates the mean of the control group was higher than that of the treatment group. Active and passive restoration practices are represented by different colors, color references are at the right of the plot.



**Fig. S1.** Disturbances reported in drylands globally and the category of restoration implemented (active or passive). The *y*- axis represents the frequency of studies that reported each disturbance. Light blue represents the frequency of studies that implemented active restoration interventions, while dark blue represents passive restoration studies.



**Fig. S2** PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) report of a meta-analysis comparing categories of restoration (active versus passive) and individual restoration practices in dryland ecosystems globally.

**Table S1.** List of restoration practices and outcomes included in a meta-analysis comparing categories of restoration (active versus passive) and individual techniques for restoration in drylands globally. Number of entries indicates the number of independent variables and data entries obtained for each restoration technique from the studies included in the meta-analysis.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Categories of restoration** | **Restoration practices** | **Outcomes** | **Restoration techniques** | **No. of entries** |
| Active | soil | habitat | carbon addition, top soil removal, seeding | 45 |
| habitat | carbon amendment | 27 |
| soil | fertilization, biostimulants, seeding | 48 |
| vegetation | mycorrhizal inoculation | 128 |
| vegetation | habitat | burning, mowing | 24 |
| vegetation | mechanical disturbance, seeding | 4 |
| habitat | mowing | 3 |
| habitat | planting | 369 |
| vegetation | planting | 26 |
| soil | planting | 84 |
| animals | planting | 24 |
| vegetation | seeding | 44 |
| soil | seeding | 117 |
| vegetation | seeding and ripping | 12 |
| habitat | seeding, cutting, grazing treatments | 2 |
| habitat | seeding, gypsum and organic mulch | 9 |
| vegetation | seeding, irrigation | 7 |
| habitat | seeding, mowing and herbicide, mulching | 18 |
| vegetation | seeding, mulching, weeding | 6 |
| habitat | seeding, planting | 15 |
| vegetation | seeding, safe sites for seeds, fencing | 8 |
| vegetation | seeding, soil tilling, fertilization | 7 |
| water supply | vegetation | seeding, irrigation | 63 |
| habitat | water supply | 12 |
| Passive | grazing exclusion | vegetation | fencing | 21 |
| vegetation | grazing exclusion | 8 |
| soil | soil | mycorrhizal recovery | 6 |
| soil | natural recovery | 198 |
| vegetation | habitat | facilitation | 59 |
| habitat | natural recovery | 30 |
| vegetation | natural recovery | 4 |
| habitat | fencing | 15 |
| vegetation | grazing exclusion | 17 |