**Title:** Opposite net effects of active and passive restoration in drylands globally

Global comparison of active and passive restoration in drylands

**Money for nothing and your restoration for free: a synthesis of active versus passive restoration in drylands globally.**

Or

**Something for nothing: a synthesis of active versus passive restoration in drylands globally.**

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**Abstract:**

Dryland ecosystems cover more than 40% of the Earth’s surface and are some of the most biodiversity rich places in the world, but also face an increasing threat from land degradation and climate change. One means to lessen those impacts is through restoration. Restoration often requires a significant investment in resources and can require many years to assess its effectiveness. For restoration to be the most successful across degraded dryland ecosystems globally, we need to know what types of restoration are most successful and the level of investment that may be necessary to see positive results. We conducted a global meta-analysis of to address these questions, reviewing 66 studies and 1400 individual restoration practices. We found that passive restoration practices overall led to negative outcomes, whereas active restoration practices, especially for soil and vegetation, led to positive outcomes. Removal of livestock grazing and addition of water promoted significant positive habitat outcomes. Armed with this information, restoration practitioners can focus limited resources on those practices that are likely to provide the greatest positive impact.

**One Sentence Summary:**

A global meta-analysis of restoration in dryland ecosystems revealed that passive restoration practices were ineffective, and that active restoration of soils and vegetation led to the largest most positive impacts.

**Main Text:**

The world is facing an ongoing rapid environmental degradation and biodiversity reduction due to land-use changes, climate change and species invasions as the main drivers (*1*, *2*). Ecological restoration is attempted to mitigate the degradation of ecosystems (*3*). General efforts to restore ecosystem services and biodiversity have focused on active and passive (i.e. natural recovery) types of intervention, which differ in the amount of resources invested (e.g. time, money and human assistance) (*4*). Although different restoration interventions have been implemented throughout the world (*5*, *6*), it is crucial to evaluate the current state of restored ecosystems to guide future management decisions.

Dryland ecosystems, which include grasslands, shrublands, deserts, and converted lands (e.g. farmlands), have historically contained some of the highest concentrations of biodiversity globally (citation). These ecosystems cover more than 40% of the global land surface (*7*), provide key ecosystem services such as food provision and carbon sequestration (citations), and also increasingly provide for sustainable energy development (*7*–*9*). Dryland ecosystems are under serious threat from land degradation and climate change (*10*). These ecosystems would benefit from increased protection (e.g. easements) (citation) and better land management practices (citation), but increasingly there is a real opportunity to mitigate past impacts through restoration, both of degraded natural lands (citation) and also more intensively farmed agroecosystems (citation) (*11*). Restoration is a complicated endeavor, one that often requires significant resources (time, money) and whose impact on soils, vegetation, and wildlife can take many years to evaluate (citation). To effectively and efficiently restore degraded dryland ecosystems and to take advantage of the current glocal opportunity, we need to know what restoration practices work best.

We performed a meta-analysis of 66 peer-reviewed publications that evaluated different restoration practices and outcomes (*12*, *13*). We focused the analysis on the most frequent land degradation/disturbance type, “agriculture”, which included both farm land (i.e. crops) and grazing land (fig. S1). To determine the effect of the restoration treatment on the degraded land, we classified each study into active or passive restoration. We assigned a restoration practice to “active” if XX, and to “passive” if XX. We then assessed the magnitude and direction of the restoration effect using the log response ratio (lrr) (*14*), a common approach for meta-analyses. We chose to group restoration practices in to four categories: soil, vegetation, water addition and grazing exclusion ( fig. S2 and table S1). We grouped restoration outcomes in to four categories as well: soil, plants, animals and “habitat” (fig. S3). We used random effects models to account for the variability within the 66 peer-reviewed studies (*13*), and then applied meta-regressions to test the potential influence of two additional covariates, aridity (*15*), and the time scale of experiments(*16*).

We reviewed studies from XX countries (Fig.1). We found that the average effect sizes calculated for both types of restoration in drylands were statistically different from zero and between them (p < 0.001 for t-tests of lrr). Active and passive restoration practices differed in their magnitude and direction (Table XX). Overall, active restoration led to positive outcomes (Table XX) (lrr estimate = 0.22, 95% CI= 0.21 to 0.23) while passive restoration practices were negative (Table XX). (lrr estimate= -0.34, 95% CI= -0.37 to -0.31). The three categories of active interventions (soil, vegetation and water addition) were net positive and significantly different from zero and among them (lrr estimatesoil= 0.31, 95% CI= 0.30 to 0.33; lrr estimatevegetation= 0.18, 95% CI= 0.17 to 0.20; lrr estimatewater addition= 0.64, 95% CI= 0.55 to 0.73; p < 0.0001; Fig. 2). On the other hand, the passive recovery of soil in drylands was net negative (lrr estimatesoil= -0.76, 95% CI= -0.82 to -0.70) while the other two passive interventions had a positive effect on restoration (lrr estimatevegetation= 0.26, 95% CI= 0.21 to 0.32; lrr estimategrazing exclusion= 0.13, 95% CI= 0.03 to 0.24; p < 0.0001; Fig. 2). Aridity and time since the restoration intervention both significantly influenced the effectiveness of active interventions (lrr estimatearidity= -0.01, 95% CI= -0.02 to -0.01; lrr estimatedexp.time= 0.003, 95% CI= 0.003 to 0.0035), while for passive interventions just the time scale of experiments was significant (lrr estimatedexp.time= 0.01, 95% CI= 0.008 to 0.01).

Within the active restoration practices that we evaluated, we found that there was a positive effect on soil, plant and habitat restoration, but a negative effect on the restoration of animal communities (lrr estimatesoil= 0.22, 95% CI= 0.15 to 0.28; lrr estimateplants= 0.51, 95% CI= 0.49 to 0.52; lrr estimatehabitat= 0.06, 95% CI= 0.04 to 0.08; lrr estimateanimals= -0.11, 95% CI= -0.115 to -0.114; p < 0.0001). For the passive restoration practices, we found that soils will not recover on their own (lrr estimatesoil= -0.76, 95% CI= -0.82 to -0.70), but plants and habitat can recover (lrr estimateplants= 0.44, 95% CI= 0.03 to 0.85; lrr estimatehabitat= 0.16, 95% CI= 0.09 to 0.22; p < 0.0001).

Active restoration interventions require more significant investments in resources (time, money) (citation), so it was important that this meta-analysis evaluated the potential characteristics of active restoration interventions within drylands globally. We found that water addition had the largest and most positive impact on active restoration interventions (Table XX), followed by nutrient addition and re-seeding/re-planting of vegetation (Table XX)..

The conclusion from this meta-analysis that active restoration interventions are often required to see positive outcomes in dryland ecosystems differs from recent studies in tropical forests that found that passive natural succession is the most effective strategy to restore degraded forests (*17*). These differences are likely driven by rainfall, soil fertility, and vegetation productivity differences (*18*), all of which are severely constrained in dryland ecosystems globally (citation). We found that the positive impacts from active restoration outcomes decreased increasing aridity (Table XX).

Agricultural practices have high impacts on soil health, affecting key processes such as nutrient cycles (*19*). Moreover, the addition of synthetic inputs such us fertilizer and pesticide in conventional agriculture (*20*) state a challenge for soil and vegetation restoration after agriculture abandonment. Our results showed the restoration of soil in drylands requires the implementation of active management, whereas plants communities can regenerate naturally. On the other hand, restoration of animal communities represents another challenge; we found that active interventions performed to date did not have a positive effect on invertebrate and vertebrate community’s restoration. According to restoration from grazing, the exclusion of livestock is one of the most common and cost-efficient passive regeneration strategies implemented (*4*) (see another citation). Our results showed this intervention has a positive effect in drylands restoration.

Resources are and will always be limiting for restoration and we cannot ignore minimal intervention strategies to manage drylands globally. This point may be one of the most limiting factors in restoration plans for developing countries (*7*). This meta clearly identifies that depending on the specific outcome for stakeholders, some strategies can sustain limited investments. However, active strategies are critical for more rapid, less variable, and more consistently positive efficacious interventions in drylands. Aridity and drought will continue to present challenges to recovery and if longer and more sustained timeframes are possible, i.e. at least 2 years, interventions will be more viable. In summary, drylands are critical to sustaining both human and other resident populations of species globally and restoration in some form is major path forward.

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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

To conduct this meta-analysis, we followed the PRISMA guidelines (Preferred Reporting Items for Systematic reviews and Meta-Analyses; fig. S1) (*21*). To identified different restoration techniques implemented in drylands globally and to compare the effectiveness of active and passive restoration, we systematically searched in the databases Scopus and Web of Science the following terms combination: [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 conducted in September 2018 and returned 1504 published articles.

For this meta-analysis, we collected data from studies that met the following inclusion criteria: (1) research articles including results, no review articles; (2) agriculture as the main disturbance reported (crops and grazing); (3) studies with treatment (restoration intervention) and control (no intervention) groups; (3) reported statistical analysis and significance of treatments. After the application of the above inclusion criteria, a total of 66 studies were included in the meta-analysis (fig. S1).

Data extraction

We extracted data of the restoration technique implemented in each study and classified them as active or passive restoration. Active restoration implies human interventions in degraded lands while passive restoration refers to the natural recovery of systems, with minimal or no interventions (*5*). As a high variety of restoration techniques were implemented globally, we grouped different techniques that addressed a similar restoration goal into four main categories of interventions: soil, i.e. including those techniques with intervention in soils; vegetation; water addition and grazing exclusion. “Soil” and “vegetation” interventions included both active and passive restoration techniques, while “water addition” was classified as an active intervention and “grazing exclusion” as a passive intervention (fig. S1 and table S1). Moreover, for each study we extracted data of the restoration outcome used to measure the intervention effect (*13*). We grouped the different outcomes into four general categories: soil, plants, animals and habitat. These four outcomes categories were measured by studies with an active restoration approach, while passive restoration studies have not evaluated the “animals” category (fig. S3).

We collected data of all the response variables reported in each article. For each response variable, we extracted data of mean, standard deviation and *p*-value. When these data were showed in figures, we used WebPlotDigitizer (*22*) to extract them. 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 (*15*) and, of the length of experiments expressed in months. The aridity index and the time scale of experiments were used as covariates in statistical models (see below).

Data analysis

We performed random effect models due to the high heterogeneity of studies included in our meta-analysis. To determine the effect of restoration treatments (restoration intervention) over the control groups, we calculated the log response ratio (lrr). This effect size is calculated as the natural logarithm of the response ratio (ratio between the treatment and control groups). A negative value of 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 response evaluated compared with the control.

We examined whether the aridity (measured as the aridity index, deMartonne 1927) and the extent of experiments can explain the very large between-study heterogeneity.

All figures and analyses were performed using the packages tidyverse and meta in R (R Core Team 2018).

Figures S1-S3

Table S1

References (1-*##*)

**Fig. 1.** The figure caption should begin with a short descriptive statement of the entire figure followed by additional text. Captions should be immediately after each figure. Figure parts are indicated with capital letters (A). If you prefer, you can place both figures and captions logically throughout the text near where they are cited rather than at the end of the file (but not both). If a paragraph in the main text begins with the name of a figure, write out “Figure” in full (e.g., <para>“Figure 1 shows….”)

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