**Title:**

Global comparison of active and passive restoration in drylands

Restoration of ag-lands: a synthesis of active versus passive restoration in drylands globally.

**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:**

Drylands are one of the most extended and biodiverse ecosystems in the world, but also face threats from land degradation and climate change. One means to lessen those impacts is through restoration. The key issues are to identify the types of restoration and the level of investment that may be necessary to see positive results. Here, a global meta-analysis of restoration in drylands was completed. We found that passive restoration practices overall led to negative outcomes, whereas active practices led to positive outcomes. Soils do not recover passively in the time horizons tested to date whilst vegetation and to a lesser extent exclusion of grazing can promote positive outcomes. Active restoration practices were more effective and had low relative variances. 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:**

Active restoration practices evaluated in drylands led to the largest most positive impacts while some passive practices led to positive outcomes.

**Main Text:**

Drylands, which include natural (i.e. semi-arid grasslands, shrublands and deserts) and managed ecosystems (e.g. farmlands), are one of the most extended and populated ecosystems on Earth, covering over 40% of the global land surface (*1*). These lands provide key ecosystem services, such as food provision (crops and livestock), carbon sequestration, biodiversity support and increasingly provision of sustainable energy (e.g. solar energy) (*1*–*3*). Regarding their physical extent and the extremely heterogeneous biomes that include, drylands are highly unique and biodiverse rich ecosystems (*4*). However, one issue of increasing global concern that demanded concrete mitigation efforts (e.g. United Nations Convention to Combat Desertification) (*5*) is drylands degradation due to land-use and climate changes (*6*), which may have severe impacts on the provision of ecosystem services and biodiversity conservation (*7*). These degraded ecosystems would benefit from increased protection (e.g. easements) (*8*) and better land management practices (*9*), but increasingly there is a real opportunity to mitigate past impacts through restoration, both of degraded natural lands (*10*) and more intensively farmed agroecosystems (*11*).

Ecological restoration represents an alternative to mitigate the degradation of ecosystems (*12*). 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) (*13*). Restoration is a complicated endeavor whose impact on soils, vegetation, and wildlife can take many years to evaluate (*14*). Furthermore, the types of intervention adopted may imply different amount of money and timescales to evidence successful restoration of ecosystems (*13*). Although different restoration practices have been implemented in drylands throughout the world (*14*, *15*), it is crucial to evaluate the current state of these ecosystems to guide future management decisions. To effectively and efficiently restore degraded dryland ecosystems we need to know what restoration practices work best. Thereby, the retirement of agricultural (rangelands and croplands) drylands offers a global opportunity to evaluate the effectiveness of the restoration practices implemented (*11*).

We performed a meta-analysis of 66 peer-reviewed publications that evaluated different restoration practices and outcomes (*16*, *17*). We focused the analysis on the most frequent land degradation, “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 involves human activities to help the restoration process, and to “passive” if allows for the natural recovery of the system (*18*). We then assessed the magnitude and direction of the restoration effect using the log response ratio (lrr) (*19*), a common approach for meta-analyses. We chose to group restoration practices into four categories: soil, vegetation, water addition and grazing exclusion (fig. S2 and table S1). We grouped restoration outcomes into four categories as well: soil, plants, animals and “habitat” (fig. S3). The “habitat” category includes measures of plants and soil. We used random effects models to account for the variability within the 66 peer-reviewed studies (*17*), and then applied meta-regressions to test the potential influence of two additional covariates, aridity (*20*), and the time scale of experiments (*21*).

We reviewed studies from 19 countries throughout the World (Fig.1). Active and passive restoration practices differed in their magnitude and direction of effect sizes (Table 1). Overall, active restoration led to positive outcomes (Table 1) (lrr estimate = 0.22, 95% CI= 0.21 to 0.23) while passive restoration practices were negative (Table 1). (lrr estimate= -0.34, 95% CI= -0.37 to -0.31). All three categories of active restoration practices examined (soil, vegetation and water addition) were net positive and statistically significant (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), whereas passive soil recovery had significant negative outcomes (lrr estimatesoil= -0.76, 95% CI= -0.82 to -0.70). Vegetation and grazing exclusion passive restoration practices had positive effects 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 restoration practices (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 practices just the time scale of experiments was significant (lrr estimatedexp.time= 0.01, 95% CI= 0.008 to 0.01). The negative effect of aridity on the efficacy of active practices translates in a reduction of positive restoration outcomes with increasing aridity.

Within the active restoration practices 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 and passive restoration interventions require different investments in resources (time, money) (*13*) therefore, it was important to evaluate as a meta-analysis the potential characteristics of both types of restoration within drylands globally. Overall, active restoration practices were more effective, consistently positive and had low relative variances. We found that water addition had the largest and most positive impact on restoration (Table 1), followed by soil (e.g. nutrients addition) and vegetation practices (e.g. planting). The conclusion from this meta-analysis that active restoration interventions are often required to see positive outcomes in dryland ecosystems differs from a recent meta-analysis in tropical forests, that found passive natural succession is the most effective strategy to restore degraded forests (*22*). These differences are likely driven by rainfall, soil fertility and vegetation productivity which are severely constrained in dryland ecosystems globally (*1*).

Agricultural practices have high impacts on soil health, affecting key processes such as nutrient cycles (*23*). Moreover, the addition of synthetic inputs such us fertilizer and pesticide in conventional agriculture (*24*) 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 (*13*) (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 (*1*). The present study 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 (citation) and if longer and more sustained timeframes are possible, i.e. at least 2 years, restoration practices 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 a 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) (*26*). 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 (*14*). 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 (*17*). 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 (*27*) 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 (*20*) 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).

Statistical analysis

Our main objective was to estimate the intervention effects in different outcomes and to compare these effects among different interventions. To account for these estimations, we performed random-effect models due to the high between-study variability (e.g. different restoration techniques implemented, predictor variables evaluated) (*28*, *29*). To determine the effect of restoration treatments (restoration intervention) over the control group, we calculated the log response ratio (lrr)(*19*). This effect size quantifies the log-proportional change between the means of the treatment and control group (*30*). Therefore, 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.

We examined whether the effectiveness of the restoration interventions depend on the aridity (measured as the aridity index) (*20*) and on the extent of experiments (expressed in months). For doing this, we performed meta-regression models using aridity and extent of experiments as covariates (*21*). All figures and analyses were performed using the packages tidyverse and meta in R (*31*).

Figures S1-S3

Table S1

References (1-26)

**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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