**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.**

**Authors:** M. Florencia Miguel1\*, Scott H. Butterfield2 and Christopher J. Lortie3

**Affiliations:**

1Instituto Argentino de Investigaciones de las Zonas Áridas (UNCuyo-Gobierno de Mendoza-CONICET), Mendoza, Argentina.

2The Nature Conservancy, San Francisco, CA, United States of America.

3Department of Biology, YorkU, and NCEAS, UCSB.

\*Correspondence to: fmiguel@conicet-mendoza.gob.ar

**Abstract:**

Ecological restoration proposes strategies to mitigate land degradation. Whether active and passive interventions in drylands globally are successful, is unclear. Here, a global meta-analysis of restoration in drylands was completed describing over 1400 instances of reported restoration from 66 studies that met inclusion criteria. Active and passive interventions examined the efficacy of soil, grazing, vegetation, and water as general mechanisms to restore drylands. The net efficacy of passive interventions was negative and active was net positive. Soils do not recover passively in the time horizons tested to date whilst vegetation and to a lesser extent exclusion of grazing can promote significant positive outcomes with minimal to no interventions. This evidence suggests that something for nothing is possible for only some contexts but that investment in ecological restoration in drylands yields greater returns.

**One Sentence Summary:**

By performing a global meta-analysis of drylands restoration, we found the net efficacy of passive interventions was negative and active was net positive; vegetation can recover passively but soil requires active interventions to be restored.

**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.

Drylands such as semi-arid grasslands, shrublands and deserts are critical ecosystems for people and for natural processes. They are one of the most extended and populated ecosystems on Earth, covering about 41% of the global land surface (*7*). Drylands provide key ecosystem services such as food provision, carbon sequestration, biodiversity and ecological interactions support and sustainable energy development (*7*–*9*). Despite the positive aspects supported by drylands, these ecosystems are suffering an increasing degradation resulting from human activities and climatic variations (*10*). This trend encourages restoration practices and management efforts to mitigate land degradation (*11*). Yet a global synthesis is needed to provide a roadmap for major mechanisms that focus on the building blocks of drylands, such as soil and vegetation.

We performed a meta-analysis of 66 scientific publications undertaken in drylands globally that evaluated different restoration interventions and outcomes (*12*, *13*). We included data of the most frequent disturbance reported in the literature, agriculture (including crops and grazing; fig. S1). To determine the effect of the restoration treatment (i.e. experimental group), we classified each study into active or passive restoration according to the intervention implemented and extracted data of every variable measured. The difference (i.e. magnitude and direction) between the experimental and control groups was assessed by calculating the log response ratio (lrr) (*14*). Due to a low replication of the individual techniques implemented in the studies, we grouped them into four general categories of interventions: soil, vegetation, water addition and grazing exclusion. Some of the interventions belong to the active (water addition), passive (grazing exclusion) or both types of restoration (soil and vegetation; fig. S2 and table S1). On the other hand, we grouped the outcomes evaluated into four general categories: soil, plants, animals and habitat. The “animals” category was included into the active restoration while the other three categories belong to both types of restoration (fig. S3). We performed random effects models which allow us to account for the variability of studies (*13*). In addition, we applied meta-regressions to test the potential influence of two covariates, aridity (*15*) and the time scale of experiments, on the effectiveness of interventions examined (*16*).

Data of drylands from all continents are represented in our study (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). Furthermore, active and passive restoration differed in their magnitude and direction; thus, active restoration was net positive (lrr estimate = 0.22, 95% CI= 0.21 to 0.23) while passive restoration was net negative (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). Both covariates examined 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).

According to the outcomes evaluated in active restoration studies, we found net positive effects of interventions on soil, plants and habitat restoration but a negative effect on animal communities restoration (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 outcomes evaluated in passive restoration studies, we found a negative effect of no intervention on soil restoration (lrr estimatesoil= -0.76, 95% CI= -0.82 to -0.70); however, plants and habitat can regenerate unaided (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 interventions implemented until now in drylands globally have positive effects on the restoration of degraded ecosystems by agriculture. The addition of water seems to be the most effective strategy, followed by interventions on soil (e.g. nutrients addition) and vegetation (e.g. planting). However, the net negative result of passive restoration shows the difficulty of these harsh ecosystems to recover by themselves. Our results differ to that of recent studies in tropical forest that found natural succession to be the most effective strategy to restore degraded forests (*17*). Nonetheless, the abiotic limitations that characterize drylands such us scarce rainfall and low soil fertility (*18*) might impose constraints to the natural recovery of disturbed lands. The effect of aridity on the efficacy of active interventions was negative, -0.01, which translates in a reduction of positive restoration outcomes with increasing aridity. Furthermore, our results showed that the time invested for experimentation in active and passive interventions in drylands is a significant aspect to consider in future restoration projects.

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).

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) (*23*, *24*). To determine the effect of restoration treatments (restoration intervention) over the control group, we calculated the log response ratio (lrr)(*14*). This effect size quantifies the log-proportional change between the means of the treatment and control group (*25*). 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) (*15*) 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 (*16*). All figures and analyses were performed using the packages tidyverse and meta in R (*26*).

Figures S1-S3

Table S1

References (1-26)

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