**Title:**

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

**Authors:** M. Florencia Miguel1\*, H. Scott 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@mendoza-conicet.gob.ar

**Abstract:**

Restoration is a fundamental priority globally. Dryland ecosystems are biodiversity hotspots and ideal to explore different restoration strategies. These regions face serious threats due to land conversion and degradation. Using drylands as a case study, a formal synthesis including meta-analyses contrasted two general restoration strategies, 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 limited recovery of vegetation but not for soils. These findings suggest that direct interventions are critical in many ecosystems especially those experiencing severe anthropogenic pressures and environmental stress.

**One Sentence Summary:**

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

**Main Text:**

Restoration is a complex field of research and crucial in all ecosystems (*1*). Restoration of degraded ecosystems provides multiple benefits to people (*2*) including 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*). Active and passive restoration strategies typically differ in the resources invested such as time, money, and human assistance (*9*). These resources are likely to be scarce, and we need to identify interventions that generate consistent and positive outcomes that support enhanced ecosystem function and services. Dryland ecosystems are an exemplary case study to evaluate the effectiveness of restoration practices and encompass many habitats such as grasslands, shrublands, and deserts (*10*). Agricultural lands comprise almost 40% of the terrestrial surface on Earth and are present in all drylands with significant impacts (*11*, *12*). Drylands are hotspots of biodiversity supporting some of the most endangered species worldwide (e.g. large herbivores in Africa) (*13*). Furthermore, a wide variety of ecosystem services that contribute to the quality of life for people (*14*) such 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*), and continued land conversion (e.g. to agriculture), land degradation, and climate change (*17*) all threaten delivery of ecosystem services from these systems (*14*). While increased land protection such as conservation easements (*18*) and better land management practices (*19*) will benefit remaining habitat in drylands, changing conditions 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 the relative merit of restoration practices that have the greatest positive outcomes with most likely resource limitations.

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). The data were extensive at more than 1400 independent observations measured across all studies. Among the diverse disturbances reported in drylands globally (Fig. S1), we focused on restoration within agricultural lands on both farmland and grazed natural lands. Each restoration was broadly classified as either active defined as direct human assistance in the restoration process or passive whereby lands were left to natural recovery processes after removing human disturbances (*21*, *22*). We also extracted response data outcomes for each specific restoration practice (*23*). The success of these restoration practices and outcomes was assessed using the log response ratio (lrr) (*24*). We grouped active restoration practices into the following three categories based on their primary focus: soil, vegetation, and water supplementation (Table 1A; Table S1). Soil, vegetation, and grazing exclusion were tested passively. Soil, vegetation, animals, and habitat interventions were examined directly as active restoration practices (Table 1B). The habitat classification was used for studies that reported measures of both soil and vegetation recovery. We used random effects models to account for the variability within the studies evaluated (*25*), and then applied post hoc meta-regressions to test the potential influence of aridity (*26*) and time from onset of study.

Active restoration consistently led to positive responses providing evidence for a commitment to active restoration strategies in planning management for drylands (Table 1). All three specific categories of active restoration had net positive responses (Table 1A, Fig. 2); water supplementation was the most effective restoration practice followed by soil then vegetation remediations (Table 1A, Fig. 2). Passive recovery of vegetation and grazing exclusion (i.e. passive because grazing was removed and no other interventions were applied) also had positive effects on restoration outcomes (Table 1A, Fig. 2) such us vegetation and habitat (Table 1B). Nonetheless, passive recovery had lower and more variable effect sizes, and this strategy for soils such as fallowing typically led to negative responses (Table 1A, Fig. 2). Aridity had a weak negative impact on direct interventions suggesting that environmental limitations are critical drivers of change in these systems while increasing duration of study had a significant but minimal positive return suggesting longer studies and time-frames be considered (lrr aridity = -0.01, 95% CI = -0.02 to -0.01; lrr time = 0.003, 95% CI= 0.003 to 0.0035). Duration of recovery positively influenced passive strategies but variation in aridity was not generally relevant (lrr aridity= 0.004, 95% CI = -0.002 to 0.01; lrr time = 0.01, 95% CI = 0.008 to 0.01). Soils did not passively recover in drylands, but plants and habitat can to some extent recover (Table 1B). Several studies (active n =16 and passive n =14) were not included in this meta-analysis due to the absence of control groups. This highlights the likely difficulty in securing undisturbed reference sites and the further challenges we face in identifying general baselines for restoration (*27*). Restoration is a relatively new discipline, but its importance to inform ecosystem health cannot be overstated for drylands because of the need to redress global change and mitigate drought and species loss.

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 and that something for nothing is a risky strategy to adopt. In contrast, recent meta-analyses in tropical and temperate forests concluded that passive recovery through natural succession was the most effective strategy (*28*, *29*). This difference profoundly suggests that environmental limitation and anthropogenic pressures 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 the extent of land transformation and prior land use history further exacerbate these issues (*21*). This synthesis shows that croplands will need active restoration strategies to overcome the legacies of soil disturbances, nutrients, and pesticides (*30*).

Resources to restore ecosystems will always be in short supply relative to need, particularly in developing countries and in those with limited political incentives to address environmental deterioration (*5*). Active investment in interventions will certainly lead to more consistent positive outcomes for soils, vegetation, and habitats - arguably the foundations of ecosystem functions. We face global challenges to biodiversity, natural resources, ecosystem services and supporting functions than are thus under serious threat. We show here that while humans are certainly part of the problem, we can also be the solution to some of the recovery of drylands.

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**Data and materials availability:**

Data collected to a meta-analysis comparing active and passive restoration strategies and individual techniques in drylands globally. All support code and data are published (Lortie, C.J. and Miguel M.F. 2019. A set of R code to test dryland restoration efficacy using meta-analysis. Zenodo. DOI: 10.5281/zenodo.2653943).

**Supplementary materials:**

Materials and Methods

Figures S1-S2

Table S1

References (1-36)

**Table 1.** The effect of active and passive restoration interventions on dryland ecosystems globally. The log response ratio (effect size) and 95% confidence interval (CI) were from random effects models (Lortie C.J. and Miguel M.F. 2019. R code, DOI: 10.5281/zenodo.2653943). Effect of active and passive restoration strategies was tested by t-tests with mu = 0, and restoration interventions and outcomes were considered significant if their estimated 95% confidence intervals did not overlap 0. (A) Random effects model results comparing restoration interventions. (B) Random effects model results comparing restoration outcomes. The outcomes listed describe target goals from each restoration intervention or practice.

|  |  |  |
| --- | --- | --- |
| **Restoration** | **log response ratio** | **95% CI** |
| *(A)* | | |
| **Active interventions** | 0.28 | 0.21, 0.35 |
| Water supplementation | 0.64 | 0.55, 0.73 |
| Soil | 0.31 | 0.30, 0.33 |
| Vegetation | 0.18 | 0.17, 0.20 |
| **Passive interventions** | -0.35 | -0.44, -0.26 |
| 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 |

**Fig. 1.** Global distribution of studies reporting different disturbances and implementing active or passive restoration strategies in dryland ecosystems (n = 178). Articles included in the meta-analysis reported agriculture (crop and grazing natural lands) as the main disturbance (n = 40). Red points represent the location of studies that used active restoration while blue points show those studies using passive recovery.

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**Fig. 2.** Assessment of overall effect sizes (log response ratio) and 95% confidence intervals for active and passive interventions included in a meta-analysis on restoration strategies in drylands globally. The dashed vertical line denotes no effect of interventions, or a mean of 0. A positive log response ratio value indicates the mean of the intervention 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 intervention.

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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) (*31*). 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 to no human interventions such as the cessation of disturbance by installing fences to terminate grazing locally (*9*, *22*). Active restoration strategies were always 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, vegetation, water supplementation and grazing exclusion. Soil and vegetation practices included both active and passive types of restoration, water supplementation was classified as an active restoration practice, and grazing exclusion as passive (Table 1A). Moreover, for each study we extracted data of the outcomes reported for each restoration practice in primary studies (*25*). We grouped the different outcomes into four general categories including soil, vegetation, animals, and habitat (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 for the restoration practice implemented, either active or passive, and control conditions. When these data were provided in figures within a publication, we used WebPlotDigitizer (*32*) 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 (*26*), and recorded the reported duration of study in months. When climatic data were not provided in studies, we used the latitude and longitude listed to look up the means 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, either active or passive, over the control group, we calculated the log response ratio (lrr) (*24*). This effect size quantifies the log-proportional change between the means of the two groups compared (*33*). 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. Statistical significance of active and passive restoration strategies was tested with t-tests with mu = 0. All analyses done in R version 3.5.5 (*34*), and both the packages meta (*35*) and metafor (*36*) were used for meta-analytical analyses. All support code is published (Lortie, C.J. and M.F. Miguel. 2019. A set of R code to test dryland restoration efficacy using meta-analysis. Zenodo. DOI: 10.5281/zenodo.2653943).

**Fig. S1.** Disturbances reported in drylands globally and the restoration strategy implemented, active or passive. The *y*- axis represents the frequency of studies that reported each disturbance. Red represents the frequency of studies that applied active restoration practices while blue represents the frequency of those studies using passive recovery practices.

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

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**Table S1.** List of restoration interventions and outcomes included in a meta-analysis comparing active versus passive restoration strategies, and individual techniques for restoration in drylands globally. Sample size indicates the number of observations and data entries obtained for each restoration technique from the studies included in the meta-analysis (n = 40).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Restoration strategies** | **Interventions** | **Outcomes** | **Techniques** | **Sample size** |
| 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 supplementation | 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 |