**Reports** (up to ~2500 words including references, notes and captions–corresponds to ~3 printed pages in the journal)

**Title:** (96 character maximum for Research Articles and Reports)

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.**

**Short title:** (40 character maximum)

Restoration in drylands globally

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**Abstract:** The abstract should be 100-125 words, and organized in this structure: An opening sentence that sets the question that you address and is comprehensible to the general reader, background content specific to this study, results, and a concluding sentence. It should be a single paragraph.

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.

**Keywords:** agriculture, deserts, drylands, intervention, restoration, outcomes, vegetation, and water limitation.

**One Sentence Summary:** A brief teaser statement highlighting main result of the paper, understandable by a scientist not in your field, without jargon or abbreviations. This will appear online adjacent to the title and should not repeat phrases already present there. Please keep to under 125 characters.

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:** In general, this should include a brief (1-2 paragraph) introduction, followed by a statement of the specific scope of the study, followed by results and then interpretations. Please avoid statements of future work or claims of priority, and avoid repeating the conclusions at the end.

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 of restoration interventions and outcomes undertaken in drylands globally. 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) (*12*). 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). 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 (*14*) and the time scale of experiments, on the effectiveness of interventions examined (*15*).

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 (*16*). Nonetheless, the abiotic limitations that characterize drylands such us scarce rainfall and low soil fertility (*17*) 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 (*18*). Moreover, the addition of synthetic inputs such us fertilizer and pesticide in conventional agriculture (*19*) 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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**Acknowledgments:**

Supplementary Materials:

Materials and Methods

Figures S1-S3

**Fig. 1.**

**Fig.2**