Science of the Total Environment 650 (2019) 1–9

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

# How is biodiversity changing in response to ecological restoration in terrestrial ecosystems? A meta-analysis in China

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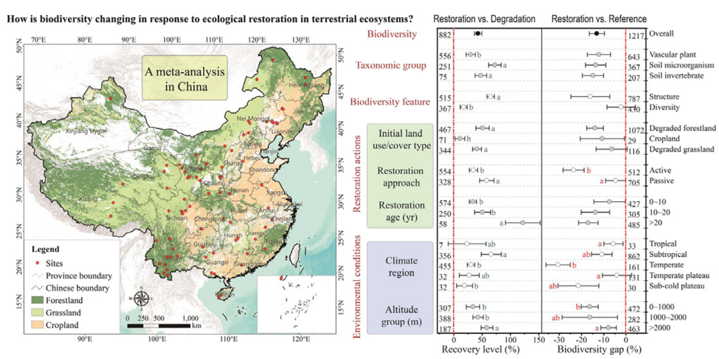
## HIGHLIGHTS

- Restoration enhanced biodiversity in degraded ecosystems but couldn't recover to natural level.
- Restoration improves habitat condition more than vegetation coverage.
- Impacts of restoration on biodiversity depended on restoration actions and climate conditions.

## GRAPHICAL ABSTRACT




## ARTICLE INFO

*Article history:*
Received 20 May 2018
Received in revised form 23 August 2018
Accepted 23 August 2018
Available online 25 August 2018

Editor: Sergi Sabater

*Keywords:*
Biodiversity
Ecological restoration
Land use
Climate
Restoration age

## ABSTRACT

Biodiversity is an important ecosystem characteristic, and is vital for maintaining ecosystem health and stability. However, biodiversity was often ignored in previous Chinese restoration planning and design due to its complex roles and the unclear mechanisms in providing human well-being. In order to evaluate the response of biodiversity to ecological restoration in terrestrial ecosystems, we assembled biodiversity in different metrics and different organisms and generated a large dataset comprised 2099 observations from 103 published studies to conduct a meta-analysis in China. Our results revealed that the biodiversity of restored ecosystem increased by 43% compared with degraded state, but it was difficult to recover to the natural level across the whole China. The gap between restored and natural ecosystems was about 13%. Ecological restorations have contributed not only to increasing vegetation coverage but also to improving soil environment and habitat quality. The recovery levels of vascular plant, soil microorganism and soil invertebrate were 30%, 73% and 48%, respectively. Biodiversity recovery would be better reflected in enhancing the structure feature (65%) such as plant height and density rather than the diversity feature (18%) such as diversity indices of Shannon and Simpson. Moreover, the response of biodiversity to ecological restoration varied with restoration actions (i.e., initial land use/cover type, restoration approach and restoration age), and the interaction effects among restoration actions significantly impacted biodiversity recovery. Passive approach performed better than active approach for biodiversity recovery. Meanwhile, the magnitude and direction of the impact of ecological restoration on biodiversity greatly altered with environmental conditions (i.e., climate condition and altitude). Our findings could facilitate priority setting and selection of treatment methods for biodiversity recovery during ecological restoration planning and assessment to ensure high effectiveness and sustainability.



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https://doi.org/10.1016/j.scitotenv.2018.08.320
0048-9697/

## 1. Introduction

Due to intensive human activities and dramatic climate changes, natural ecosystems have been severely degraded or damaged, leading to habitat fragmentation, ecosystem function degradation and ecosystem service loss (Benayas et al., 2009; Jackson and Hobbs, 2009; Allan et al., 2015). Ecological restoration, which aims to enhance ecosystem characteristics such as carbon sequestration, hydrologic regulation and species and landscape diversity enhancement (Stanturf et al., 2014; Kollmann et al., 2016; Deng and Shangguan, 2017), has been performed in degraded ecosystems at different spatial scales by implementing ecological restoration projects such as the Grain-to-Green Program (GGP) in China (Lamers et al., 2015; Deng et al., 2017a). Meanwhile, restoration actions are increasingly being supported by political decision makers and global policy commitments such as the Convention on Biological Diversity, which proposes a goal to protect at least 17% of terrestrial and 10% of marine areas in 2020 (Kullberg and Moilanen, 2014; Suding et al., 2015). Currently, improvements of ecosystem services are receiving more attention in restoration planning and design (Kollmann et al., 2016), however, biodiversity is often ignored because of its complex roles and the unclear mechanisms in providing human well-being, especially in previous Chinese restoration projects.

Biodiversity is perceived with varying connotations by different people (Maclaurin and Sterelny, 2008; Gaston, 2010). The definition proposed by the Convention on Biological Diversity, which is "the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part, including diversity within species, between species and of ecosystems", is more commonly used to describe the term biodiversity in ecological restoration (Purvis and Hector, 2000; Mayer, 2006; Odenbaugh, 2009). According to this definition, the term biodiversity is a general concept, and is the sum total of all biotic variations from the level of genes to ecosystems (Purvis and Hector, 2000; Feest et al., 2010). Biodiversity could be measured in many different ways, and biodiversity metrics depended on the investigated organisms and purposes (Mayer, 2006; Mooers, 2007). Although biodiversity has a multitude of facets that can be quantified, it is still difficult to be fully explained by a single measuring feature such as diversity indices, which is held by scientists as well as non-scientists (Mooers, 2007; Gaston, 2010; Jax and Heink, 2015).

There is a widespread assumption that ecological restoration will increase biodiversity in the degraded ecosystems (Benayas et al., 2009). Some field studies have used many diversity metrics to evaluate the alterations in biodiversity caused by restoration actions. However, field studies typically focus on such small spatial scales that these results are most likely to be affected by the site conditions and monotonous organisms, especially plants (Cardinale et al., 2012; Wardle, 2016). Due to the environmental backgrounds varying with sites, the results and interpretations obtained from these field studies are not consistent, and debates on the responses of biodiversity to ecosystem changes have been contentious and lively (Balvanera et al., 2006). Fortunately, the evidence provided by meta-analysis suggests that ecological restoration could enhance biodiversity, which could allow future restoration efforts for biodiversity to achieve high effectiveness and sustainability (Benayas et al., 2009; Vellend et al., 2013). The present meta-analysis studies focused on the alterations in some specific species groups caused by restoration actions in the long-term, and only collected several biodiversity metrics to quantify the effects (Worm et al., 2006; Mooers, 2007). However, biodiversity is a comprehensive variable and should not be captured by several biodiversity metrics, and its changes should not be represented by the responses of several species groups to ecological restorations at large spatial scales (Maclaurin and Sterelny, 2008; Feest et al., 2010). Since plants, soil microorganisms and invertebrates are the most monitored organisms in terrestrial ecosystems, some meta-analyses integrated them to evaluate the biodiversity level at a large spatial scale (Benayas et al., 2009; Barral et al., 2015; Ren et al., 2017). Therefore, it is necessary to integrate biodiversity in different metrics and different organisms for assessing restoration success at the regional scale in the meta-analysis, which would inform recovery decisions at large spatial scales.

Over the past two decades, the Chinese government has launched many ecological projects and land-use policies to improve environmental conditions and habitat qualities for terrestrial ecosystems (Liu et al., 2003; Li, 2004; Long, 2014; Deng et al., 2017b), especially vegetation restorations such as the GGP, Three North Shelterbelt Project (TNSP) and Natural Forest Protection Program (NFPP) (Li, 2004; Deng et al., 2017a). Although these ecological projects have been performed on a larger scale with a long duration, most of them are specifically targeted to recover a (or several) ecosystem characteristic(s), leading to relatively simple structure and composition for restored ecosystems (Tang et al., 2006; Cao et al., 2011). For instance, GGP is specifically targeted to prevent soil erosion by converting degraded croplands to forests, shrubs or grasslands (Deng et al., 2017a), but inflexible regulations of afforestation and subsequent poor management generate low diversity ecosystems such as monotonous tree plantation (Cao et al., 2011; Deng et al., 2016). Meanwhile, some studies documented that the effects of land use/cover type and restoration age are vital on ecological restoration (Liu et al., 2003; Deng et al., 2017a, 2017b). Some ecological restoration studies have revealed the changes in ecosystem characteristics following restoration actions and quantified the relationship between biodiversity and ecosystem services (Barral et al., 2015; Ren et al., 2017). China is a vast country with the complex physical environment, and these projects have directly provided raw materials and improved human living conditions by enhancing ecosystem services (Chazdon, 2008; Kollmann et al., 2016). However, the responses of biodiversity on ecological restorations and the biodiversity level of restored ecosystems in China remain uncertain and rarely quantified.

In this study, we used a standardized procedure to collect biodiversity observations from published ecological restoration studies in Chinese terrestrial ecosystems, and then quantified the recovery levels of biodiversity for overall and three taxonomic groups by a meta-analysis. To ensure suitable baselines for examination of restoration sequence, we separated observations into two comparisons of restoration vs. degradation and restoration vs. reference. The former would evaluate the actual recovery level of biodiversity, and the latter would assess the biodiversity gap between restored and natural ecosystems. Typical biodiversity metrics in published field studies included key biomass indicators (such as plant height and density) and diversity indices (such as Shannon and Simpson), and were reclassified into structure and diversity features. Also, we collected the potential influential factors of restoration actions and environmental conditions to analyze the effects of these factors on biodiversity recovery. We raise the following research questions: (1) What is the biodiversity level of restored ecosystem compared with degraded or natural state? (2) Which taxonomic group is most supported by restoration? (3) Which feature (structure or diversity) recovers more drastically? (4) How restoration actions and environmental conditions effected on the recovery level of biodiversity? This study can contribute to empowering ecological projects towards future biodiversity recovery by policy makers and researchers, and it could provide a sustainable solution of biodiversity recovery by combining restoration actions and environmental conditions.

## 2. Materials and methods

### 2.1. Literature search and data extraction

To identify quantitative studies evaluating the effects of ecological restoration on biodiversity in terrestrial ecosystems, we performed a systematic search of the peer-reviewed literature from the Web of Knowledge (www.isiwebofknowledge.com) and the China National Knowledge Infrastructure (CNKI, http://www.cnki.net/). We searched these databases on 26 October 2017 with no restriction on publication