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Review

Balancing the environmental benefits of reforestation in agricultural regions

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ABSTRACT

Reforestation is an important tool for reducing or reversing biodiversity loss and mitigating climate change. However, there are many potential compromises between the structural (biodiversity) and functional (carbon sequestration and water yield) effects of reforestation, which can be affected by decisions on spatial design and establishment of plantings. We review the environmental responses to reforestation and show that manipulating the configuration of plantings (location, size, species mix and tree density) increases a range of environmental benefits. More extensive tree plantings (>10 ha) provide more habitat, and greater improvements to carbon and water cycling. Planting a mixture of native trees and shrubs is best for biodiversity, while traditional plantation species, generally non-native species, sequester C faster. Tree density can be manipulated at planting or during early development to accelerate structural maturity and to manage water yields. A diversity of habitats will be created by planting in a variety of landscape positions and by emulating the patchy distribution of forest types, which characterized many regions prior to extensive landscape transformation. Areas with shallow aquifers can be planted to reduce water pollution or avoided to maintain water yields. Reforestation should be used to build forest networks that are surrounded by low-intensity land use and that provide links within regions and between biomes. While there are adequate models for C sequestration and changes in water yields after reforestation, the quantitative understanding of changes in habitat resources and species composition is more limited. Development of spatial and temporal modelling platforms based on empirical models of structural and functional outcomes of reforestation is essential for deciding how to reconfigure agricultural regions. To build such platforms, we must quantify: (a) the influence of previous land uses, establishment methods, species mixes and interactions with adjacent land uses on environmental (particularly biodiversity) outcomes of reforestation and (b) the ways in which responses measured at the level of individual plantings scale up to watersheds and regions. Models based on this information will help widespread reforestation for carbon sequestration to improve native biodiversity, nutrient cycling and water balance at regional scales.

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1. Introduction

Extensive areas of native forest ecosystems have been cleared and converted to other land uses, such as agriculture, plantation forestry and cities, a trend that will continue with increasing human populations. Forest area is estimated to have decreased by a third over the past three centuries in China, the Middle East, North Africa, the eastern United States of America and Southeast Asia (Ramankutty and Foley, 1999). Deforestation has substantial and widespread negative impacts on climate, hydrology, soils and biodiversity, with consequent impacts on societies and economies (Meyfroidt and Lambin, 2011). A considerable proportion of the remaining native forests has been severely degraded to produce primary resources. In their current restricted and degraded state, the remaining native forests face the potentially rapid and extreme stress of climate change and increased climate variability (Dale et al., 2001). In recent years, there have been several important agreements that suggest there will be extensive reforestation to address this issue (CBD, 2010; GPFLR, 2013; UN, 2014; UNEP, 2014).

It is imperative that the environmental impacts of global deforestation are mitigated by a combination of active (i.e. tree planting) and passive (i.e. regrowth following land abandonment) reforestation. Here, we focus on active reforestation, which we define as the planting of forests on lands that historically had forests but that have since been converted to other land uses (IPCC, 2007). This excludes afforestation of areas that were formerly native grasslands or shrublands, which generally is detrimental to biodiversity (Bremer and Farley, 2010; Gerstner et al., 2014). Land has been reforested actively for many reasons including for plantations for timber, riparian plantings to reduce stream pollution, upland plantings to reduce soil erosion and salinity, and to increase habitat for native species (Jackson et al., 2005). Reforestation may improve links among existing remnant forest patches, increasing movement, gene flow and effective population sizes of native species (Gilbert-Norton et al., 2010). Re-establishing forests can restore biogeochemical cycling of carbon, oxygen and nutrients among the atmosphere, biomass, pedosphere and hydrosphere (Arneth et al., 2010). Reforestation of agricultural land can improve biodiversity, which can result in increased primary production, reduced susceptibility to invasion by exotic species and increased ecological resistance to pressures such as climate change (Hooper et al., 2005).

Restoration of forest ecosystems could directly mitigate climate change by sequestering atmospheric carbon, both above- and below-ground. Trees sequester and retain more atmospheric carbon in their biomass than do crops or pastures (Pan et al., 2011). Under carbon trading or carbon emission reduction schemes (e.g. United Nations REDD+ programme), it is possible that widespread reforestation will become economically viable (Bradshaw et al., 2013). Increasing uncertainties in crop yields with climate change may encourage landholders to diversify into other investments such as ‘carbon farming’. Reforestation could provide an important tool for mitigating climate change in the short-term while fostering a low-carbon economy and improving environmental conditions jointly in the long-term (Mackey et al., 2013).

How reforestation is approached has long-term consequences with compromises between the structure and function of the forest. The number of trees and the types of tree species planted (exotic vs native, mixed vs single species) and whether shrubs are included are key decisions. Plantations of fast-growing production species can sequester carbon faster than native mixed-species plantings but often have little biodiversity value (Lindenmayer et al., 2003). Reforestation of riparian zones can lead to larger increases in biodiversity but greater reductions in stream flow than reforestation in upslope areas (Scott, 1999; Palmer and Bennett, 2006). Permanent restoration plantings are likely to provide more environmental benefits than harvested plantations (Kanowski et al., 2005).

Issues associated with passive reforestation or land abandonment have been covered in depth by other reviews (e.g. Bowen et al., 2007; Rey-Benayas et al., 2007; Meyfroidt and Lambin, 2011). Here, we explore the range of potential responses of ecosystem structure and function to active reforestation of agricultural land. *Structure* includes the diversity of species in an area, including animals, plants, fungi and bacteria, and the spatial arrangement of these components from the planting (<0.1 km^2, e.g. canopy strata) to the regional scale (10^5–10^6 km^2, e.g. forest networks). *Function* includes the biogeochemical processes resulting from interactions between species and the physical environment, such as production, decomposition and nutrient dynamics. We outline how the benefits of reforestation may be maximized by practitioners in agricultural regions given the potential compromises between structure and function, and current spatial and temporal constraints. Extensive reforestation of agricultural land is limited by social, economic and political obstacles, which are covered elsewhere by a growing literature (e.g. Barr and Sayer, 2012; Knight et al., 2010). We finish by presenting a modelling framework, and the knowledge required, that would allow land managers to quantify the compromises among structure (biodiversity) and function (carbon and water) under different reforestation scenarios and hence balance the environmental benefits of widespread reforestation in agricultural regions.

2. Structural changes following reforestation

2.1. Development of forest structure

Mature native forests contain strata of different-sized trees, shrubs and a ground layer, which create a range of microhabitats and microclimates beneath the canopy (Oliver and Larson, 1996; Franklin et al., 2002). The structural complexity of a forest includes the density, spatial arrangement, size and height distribution, species richness (see following sections on diversity), canopy cover, canopy strata and debris of trees (McElhinny et al., 2005). Forest structure and the associated habitat resources take decades to centuries to develop following reforestation. The expected sequence