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Perspective

# Past and future carbon sequestration benefits of China's grain for green program

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ABSTRACT

Carbon sequestration through ecological restoration programs is an increasingly important option to reduce the rise of atmospheric carbon dioxide concentration. China's Grain for Green Program (GGP) is likely the largest centrally organized land-use change program in human history and yet its carbon sequestration benefit has yet to be systematically assessed. Here we used seven empirical/statistical equations of forest biomass carbon sequestration and five soil carbon change models to estimate the total and decadal carbon sequestration potentials of the GGP during 1999–2050, including changes in four carbon pools: aboveground biomass, roots, forest floor and soil organic carbon. The results showed that the total carbon stock in the GGP-affected areas was 682 Tg C in 2010 and the accumulative carbon sink estimates induced by the GGP would be 1697, 2635, 3438 and 4115 Tg C for 2020, 2030, 2040 and 2050, respectively. Overall, the carbon sequestration capacity of the GGP can offset about 3%–5% of China's annual carbon emissions (calculated using 2010 emissions) and about 1% of the global carbon emissions. Afforestation by the GGP contributed about 25% of biomass carbon sinks in global carbon sequestration in 2000–2010. The results suggest that large-scale ecological restoration programs such as afforestation and reforestation could help to enhance global carbon sinks, which may shed new light on the carbon sequestration benefits of such programs in China and also in other regions.

## 1. Introduction

Land use and cover change (LUCC) has important effects on regional ecological processes and global climate change (Ficetola et al., 2010). The conversion of natural vegetation to cropland during the past two centuries has contributed greatly to increased atmospheric carbon dioxide ($CO_2$) concentrations; in contrast, afforestation in cropland and wasteland may lead to carbon (C) sinks (Pan et al., 2011; Deng et al., 2014; Deng and Shangguan, 2017). Thus, afforestation and reforestation have often been proposed as effective strategies for mitigating climate change (UNFCCC, 2005; IPCC, 2007; Heimann and Reichstein, 2008).

Intentional and large-scale afforestation and reforestation projects are considered earth climate engineering works, and actual implementations are rare. China's Grain for Green Program (GGP), started in 1999 and completed in 2010, was a large-scale ecological restoration program with all-embracing purposes ranging from ameliorating regional climate to improving environmental conditions such as by reducing soil erosion (State Forestry Administration (SFA), 2000). The GGP is the largest ecological restoration program in China to date, mainly implemented through LUCC. The GGP involved the conversion of sloped (> 15°) and degraded cropland and barren land into forest and grassland with the intent of reducing soil erosion, enhancing biodiversity and conserving natural resources (State Forestry Administration (SFA), 2000). This program was implemented in 25 provinces, municipalities and autonomous regions located in central and western China, accounting for 82% of China's land area (State Forestry Administration (SFA), 2012). At its completion in 2010, the GGP had converted 34.4 million ha of degraded cropland and barren land into forestland or grassland. About 9.2 million ha of cropland

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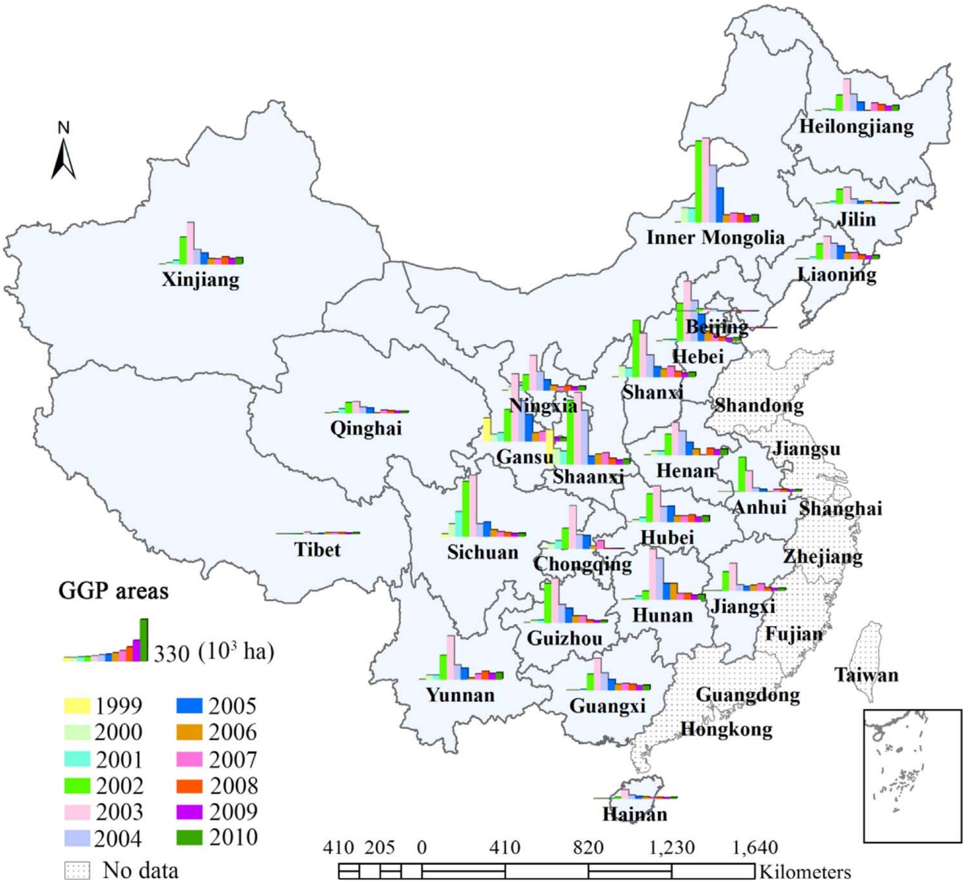


**Fig. 1.** Converted area ($10^3$ ha) under the GGP in each province per year during 1999–2010. The vertical axis in the bar graphs indicates the converted area per year, and the value (330) on the right of the bar graph in the legend represents the scale of the Y-axis in the bar graphs within the figure.

unsuitable for cropping was converted to forestland or grassland, and trees planted on 25.2 million ha of barren land deemed suitable for afforestation (State Forestry Administration (SFA), 2011; Fig. 1, Appendix Excel S1).

As China continues its rapid development, dealing with its massive and growing greenhouse gas emissions (representing 25.5% of the global total in 2011) will be vital in the context of global climate change (Dai, 2014). Consequently, the international community pays close attention to the C sequestration capacity of forests in China. The large-scale LUCC under China's GGP resulted in a large amount of new forestland, contributing to its first rank in plantation area in the world with growing forest cover (The World Bank, 2010) and its C sequestration capacity (Deng et al., 2014). Although hundreds of papers have been published reporting field observations of soil C stock change (Chang et al., 2011; Deng et al., 2014) or forest stand C stock change (Chen et al., 2009; Cheng et al., 2015; Deng et al., 2017) after afforestation or reforestation at the local scale, to our knowledge, few studies have attempted to assess the overall C sequestration benefits of China's GGP (Persson et al., 2013; Liu et al., 2014).

Given the large area affected by the GGP and lack of information on similar projects elsewhere, a comprehensive investigation of GGP effects on C sequestration would be very valuable. The results could shed light on the C sequestration benefits of large-scale ecological restoration programs, a critical knowledge gap not only for China but also for other regions. In this study, we used seven forest biomass C sequestration models and five soil C change models to estimate the trajectories of C stock change in biomass and soil in areas affected by the GGP. The study seeks to answer two fundamental questions: how much C can be sequestrated under the GGP during 1999–2050 and is the C sequestration potential significant compared to national total C emissions?

## 2. Materials and methods

### 2.1. Delimitations

Estimating the C sequestration under the GGP required several delimitations:

(i) No rotation. Because the GGP goal of preventing soil erosion on marginal lands was accomplished by increasing vegetation cover, we assumed that the trees were allowed to grow for more than 50 years without harvesting, which would yield a measurable stock of C in standing trees.

(ii) Grassland not included. The total area of land converted into grassland during 2002–2009 was 638,761 ha; in relation to the area converted into forestland this is about 3% (State Forestry Administration (SFA), 2011). Because the converted areas in 1999, 2000 and 2001 were not available and the area converted to grassland was marginal compared to conversion to forestland, grassland was not included in this study.

(iii) Survival rate. The GGP mainly afforested barren hills and croplands with a slope gradient > 15°, of which the soil was relatively poor and soil moisture was low, meaning the afforestation survival rates were unlikely to reach 100%. Thus, a correction factor of the actual afforestation survival rate was introduced. China's State Forestry Administration (SFA) survey showed that the afforestation survival rate was only 90.2% (State Forestry Administration (SFA), 2005). Thus, the actual planted areas are the cited afforestation areas multiplied by a correction factor of 0.902.

(iv) Time frame. Because the GGP came to an end in 2010, the study estimates the future potential of GGP forests as C sinks assuming that the forest areas remain unchanged and the Chinese Government does not fell the forests during the study timeframe of