Forest Ecology and Management 373 (2016) 44–55

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Carbon sequestration and biodiversity following 18 years of active tropical forest restoration

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ARTICLE INFO

Article history:
Received 23 December 2015
Received in revised form 11 April 2016
Accepted 12 April 2016
Available online 22 April 2016

Keywords:
Forest degradation
Natural regeneration
Arrested succession
Biodiversity co-benefits
Replanting
Biomass accumulation

ABSTRACT

Vast areas of degraded tropical forest, combined with increasing interest in mitigating climate change and conserving biodiversity, demonstrate the potential value of restoring tropical forest. However, there is a lack of long-term studies assessing active management for restoration. Here we investigate Above-Ground Biomass (AGB), forest structure, and biodiversity, before degradation (in old-growth forest), after degradation (in abandoned agricultural savanna grassland), and within a forest that is actively being restored in Kibale National Park, Uganda. In 1995 degraded land in Kibale was protected from fire and replanted with native seedlings (39 species) at a density of 400 seedlings ha^{-1}. Sixty-five plots (50 m × 10 m) were established in restoration areas in 2005 and 50 of these were re-measured in 2013, allowing changes to be assessed over 18 years. Degraded plots have an Above Ground Biomass (AGB) of 5.1 Mg dry mass ha^{-1}, of which 80% is grass. By 2005 AGB of trees ⩾10 cm DBH was 9.5 Mg ha^{-1}, increasing to 40.6 Mg ha^{-1} by 2013, accumulating at a rate of 3.9 Mg ha^{-1} year^{-1}. A total of 153 planted individuals ha^{-1} (38%) remained by 2013, contributing 28.9 Mg ha^{-1} (70%) of total AGB. Eighteen years after restoration, AGB in the plots was 12% of old-growth (419 Mg ha^{-1}). If current accumulation rates continue restoration forest would reach old-growth AGB in a further 96 years. Biodiversity of degraded plots prior to restoration was low with no tree species and 2 seedling species per sample plot (0.05 ha). By 2005 restoration areas had an average of 3 tree and 3 seedling species per sample plot, increasing to 5 tree and 9 seedling species per plot in 2013. However, biodiversity was still significantly lower than old-growth forest, at 8 tree and 16 seedling species in an equivalent area. The results suggest that forest restoration is beneficial for AGB accumulation with planted stems storing the majority of AGB. Changes in biodiversity appear slower; possibly due to low stem turnover. Overall this restoration treatment is an effective means of restoring degraded land in the area, as can be seen from the lack of regeneration in degraded plots, which remain low-AGB and diversity, largely due to the impacts of fire and competition with grasses.

1. Introduction

Large areas of forest lands have been converted to other land uses, and large areas of degraded tropical forest exists, covering some 550 million ha by some estimates (Pan et al., 2011). Degraded forests and abandoned agricultural lands have the potential to recover back to higher carbon and biodiversity value forest if left to regenerate naturally. However, natural regeneration is often arrested in very heavily degraded lands (Lawes and Chapman,

Abbreviations: UWA-FACE, Uganda Wildlife Authority and FACE (Forest absorbing carbon emissions) the future foundation forest rehabilitation project; KNP, Kibale National Park; AGB, Above Ground Biomass; DBH, diameter at breast height; NMDS, non-metric multi-dimensional scaling; AGWP, above-ground wood production.

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http://dx.doi.org/10.1016/j.foreco.2016.04.025
0378-1127/

2006; Paul et al., 2004). One of the major factors leading to arrested succession is the increased susceptibility of degraded forest to wildfires (Cochrane, 2003). In addition, other factors can exacerbate arrested succession in degraded areas. Seed banks are often poor following logging or agricultural cultivation, due to topsoil removal (Dupuy and Chazdon, 1998). Seed rain from surrounding forest into degraded land can also be limited, with wind dispersed seeds often not travelling large distances (Cubiña and Aide, 2001) and animal dispersed seeds rarely found, as few forest animals pass through such areas (Holl, 1999). Thus, the distance to the nearest primary forest can determine the success of regeneration (Cubiña and Aide, 2001). This is problematic in highly fragmented habitats where only small patches of forest remain, particularly if the species composition of such fragments is not representative of old-growth forest.

Thus, large areas of abandoned degraded land, and their propensity for arrested succession, mean that forest restoration could play a vital role in mitigating climate change. Not only could restored forest sequester carbon, they also have the potential to aid the recovery of biodiversity and ecosystem function. Collectively these factors have increased the desirability of forest restoration, often termed Forest Landscape Restoration (Chazdon et al., 2016).

Despite active management to restore forests being suggested as a potentially important method to increase terrestrial carbon storage and improve ecosystem function of tropical forests, research is sparse. In particular, very little is known about the long-term effects of forest restoration in terms of forest structure, carbon sequestration, and changes in biodiversity. This evidence is necessary as, the costs associated with forest restoration can be considerable (Lamb et al., 2005). For example, a study by Parrotta and Knowles (1999) estimated that restoration of a bauxite mine in the Amazon cost is $2500 per ha. Thus, it is important to quantify the benefits of active forest restoration to ensure restoration projects are successful enough in terms of the long-term recovery of ecosystem services to warrant the costs.

To begin to address this gap in current knowledge, we undertook research in the UWA-FACE (Uganda Wildlife Authority and FACE the future foundation) rehabilitation project, in Kibale National Park, Uganda (hereafter Kibale). Since 1995 this project has been restoring abandoned agricultural land that had become dominated by invasive elephant grass (*Pennisetum purpureum*), due to repeated wildfires (UWA-FACE, 2011). Restoration activities involved protection from fire and replanting with native tree species to restore forest ecosystem functions, and enhancing biodiversity conservation (UWA-FACE, 2007, 2011). In 2005 a study was conducted by Omeja et al. (2011a) to assess AGB and biodiversity of the project 10 years after planting.

Our aims in this study are twofold. Firstly, to quantify the effect of tree planting and fire management on AGB accumulation and plant species diversity over 18 years by remeasuring the study plots established in 2005. It is likely that the rate of AGB accumulation will change with increasing time after planting, as has been demonstrated in an Australian tropical forest restoration project (Paul et al., 2015). Specifically, we predict that initial AGB accumulation will be slow as planted seedlings have few photosynthesizing leaves, limiting growth, which will increase as the size of trees in the stand increases. Thus, we expect more recent AGB accumulation rates to be greater, and be more representative of rates over the coming decades.

Secondly, we estimate woody plant species diversity after 18 years of restoration. We expect that restoration activities will result in an increase in tree species diversity. Initially tree diversity will be dominated by planted tree species. However, the presence of planted trees is expected to assist natural regeneration and the shade created once a canopy develops will create more favourable conditions for seedlings of old-growth forest species to become established. Furthermore, the presence of planted trees will also encourage the movement of animals through the area and they will bring with them seeds of animal-dispersed species. Therefore, restoration will help increase tree diversity from pre-restoration levels, yet, it is likely to take longer for species composition to become similar to old-growth forest that forest structure of AGB due to the time delay in pioneer planted tree species being superseded by old-growth forest species.

Here, we calculate changes in forest structure, AGB and biodiversity at two periods following forest restoration, 10 years post planting in 2005 and 18 years post planting in 2013, in Kibale National Park and compare these to nearby grassland areas that have not been restored and old-growth forest that has not been degraded.

2. Methods

2.1. Study site

This study was conducted in the southern part of Kibale National Park, Uganda (E 30.31–30.36, N 0.31–0.56, Fig. 1). Kibale is a moist evergreen forest covering 795 km^2. It received on average 1672 mm y^{-1} of rainfall between 1992 and 2013 (the project duration). Rainfall distribution is bi-modal with two pronounced rainy seasons, the short rains March–May and the long rains August–November. The park elevation is 1100–1500 m.a.s.l., decreasing from north to south, which accompanies a decrease in rainfall and increase in temperature (Struhsaker, 1997).

Kibale has had some form of protection since 1932 (Baranga, 1991; Osmaston, 1959; Struhsaker, 1997), however, during the 1970s and 1980s illegal agricultural encroachment and deforestation took place in the southern part of the park (Chapman and Lambert, 2000), with ~90% of this area having undergone some form of encroachment by the 1990s (Baranga, 1991; Van Orsdol, 1986), predominantly for growing subsistence crops including banana (*Musa* sp.), cassava (*Manihot esculenta*) and maize (*Zea mays*) and the removal of timber for fuel wood (Chapman and Lambert, 2000). In 1993, the area that now forms Kibale was given national park status. An estimated 10,000–40,000 people living in the southern part of the park at this time were resettled outside the park boundary (Baranga, 1991; Chapman and Lambert, 2000; Van Orsdol, 1986).

The southern part of Kibale quickly became dominated by elephant grass (*Pennisetum purpureum*), due to repeated fires spreading from nearby subsistence farms or being set by poachers. Elephant grass can grow up to 5 m tall, severely inhibiting natural regeneration of native forest (UWA-FACE, 2011). In 1995 the UWA-FACE Natural High Forest Rehabilitation Project was initiated, a joint forest restoration project between the Uganda Wildlife Authority and FACE the future, an independent Dutch organization that aims to mitigate climate change via sustainable forest management.

The project aimed to replant of 10,000 ha of degraded habitat with native tree species, to improve biodiversity and ecological functions, whilst also producing carbon credits established via monitoring and verification of the replanted areas. By mid-2014 some 3500 ha have been replanted.

2.2. Forest restoration

Restoration consisted of protection from fire (creation and maintenance of 10 m fire breaks; staffed fire towers for monitoring) and planting areas with native seedlings (400 ha^{-1}). Seedlings were collected from surrounding forest and raised in a nursery, under partial shade, using local forest soil, without the addition