Restoration of degraded forest reserves in Ghana

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Abstract

Deforestation in Ghana has led to a forest loss of almost 20% from 9,924,000 ha in 1990 to 7,986,000 ha today. To restore degraded lands, Forest Landscape Restoration has become a critical approach globally. This study was conducted in Ghana focusing on the examples of two forest landscape restoration projects in the Pamu Berekum Forest Reserve: 10-year-old mixed-stands of two to four native tree species and an exotic species stands, including *Triplochiton scleroxylon*, *Terminalia ivorensis*, *Ceiba pentandra*, *Nauclea diderrichii* and *Cedrela odorata* at Pamu Berekum 1 and 4-year-old *Tectona grandis* and 2-year-old *Gmelina arborea* monoculture stands at Pamu Berekum 2. Estimates of productivity in the restored forests are described, as well as the effects of the restoration on provision of ecosystem service and benefits obtained by local communities. Stand productivity was assessed as mean annual increment of diameter and height, biomass production, and standing volume. For ecosystem services, carbon stocks were calculated for the restored forests; other ecological benefits, as well as financial benefits, were obtained through interviews with fringe communities. The results indicate that FLR can be implemented successfully using different models provided that local communities are involved during the planning and implementation of interventions. When all stands were projected to 10 years, results show higher productivity in *T. grandis* (331.77 m^3 ha^{-1}) and *G. arborea* stands (1,785.99 $m^3 ha^{-1}$) compared to mixed stand (160.41 m^3 ha^{-1}). The *Gmelina arborea* stand was more productive and had higher carbon stocks (1,350.10 Mg ha^{-1}) relative to the *T. grandis* stand (159.89 Mg ha^{-1}). Both restoration projects were found to deliver important benefits and ecosystem services at the local and national levels, including direct and indirect benefits. The results provide an example for forest/environmental managers on how FLR might be implemented to create multiple benefits at different levels from local communities to the national level. Thus, these results may be useful for guiding successful restoration activities within the context of the ongoing global Forest Landscape Restoration efforts.

Keywords

Forest restoration; Degraded forests; Productivity; Ecosystem services; Ghana

Contents

1 Introduction

Forest cover in Ghana declined almost 20%, from 9,924,000 ha in 1990 to 7,986,000 ha today. Plantations account for 297,000 ha, an almost six-fold increase since 1990 (FAO 2020). Forests in Ghana are divided into on-reserve and off-reserve areas, where on-reserve forests are legally demarcated areas vested in the traditional land-owning communities but set aside to be managed in trust by the national Forestry Commission (Osafo 2005), effectively making them “government” lands. Forest Reserves are divided into production, protection, conversion, and research areas. Timber production areas constitute almost 45% of the total area within the Forest Reserves (Oduro et al. 2012). There are 204 reserves occupying 1.6 million ha in the high forest zone. In 1995, 84% of the forests in reserves were deemed to be degraded(Hawthorne & Abu-Juam 1995). In response to the high level of degradation, both the government and private sector have over the years embarked on programs to restore degraded forests. Key among them was the government-led National Plantation Development Program (NPDP), which was launched in 2001 to develop a sustainable forest resource base to satisfy future demands for industrial timber and enhance environmental quality. The NPDP was reviewed and expanded in 2009 to introduce the National Forest Plantation Development Program (NFPDP) with additional objectives to restore degraded forest areas and to create livelihood opportunities for forest fringe communities, effectively rendering it a forest landscape restoration (FLR) program.

The NFPDP introduced the Expanded Plantation Program that expanded efforts to include private lands located outside forest reserves. It consisted of several components including the Government Plantation Development Project (GPDP), Community Forest Management Project (CFMP), Private Commercial Plantation Development, and Model Plantation (Foli 2018; Foli et al. 2009). The NFPDP uses three strategies to increase the timber resource: (1) partnering with farmers to establish plantations using the Modified Taungya System (MTS); (2) directly establishing industrial plantations using contractors; and (3) releasing degraded forest reserve lands to private entities (Forest Services Division 2017). As demonstrated elsewhere, funding sources can drive the implementation of activities by choice of species (native versus non-native, monoculture vs. mixed stands, etc.) (Coppus et al., 2019).

Ghana committed 2 million ha to the Bonn Challenge, to be under restoration by 2030 (IUCN 2018). The stage for making this commitment was spurred by the attention to needed policy reforms undertaken in Ghana's REDD+ Readiness effort (Andoh and Lee 2018; Tegegne et al. 2018). Ghana joined the international REDD+ Readiness Programme through the World Bank's Forest Carbon Partnership Facility in 2008 and its REDD+ Readiness Preparation Proposal was approved in 2010 (Forestry Commission Ghana, 2015). This set the stage for the Forest Landscape Restoration (FLR) process that underpins the Bonn Challenge (Stanturf et al., 2019) and there are multiple pathways for FLR that provide productivity (i.e., timber) and other ecosystem services. Here we report on two forest landscape restoration efforts in the Bono region in Ghana that mirror the NFPDP strategies. The two projects are (1) a partnership between local communities and the CSIR-Forestry Research Institute of Ghana (CSIR-FORIG) funded by the International Tropical Timber Organization (ITTO); and (2) a plantation development project under the Forestry Commission/Industry Plantation Development Fund. Our objectives are to illustrate that different options are available to restore degraded forests, estimate the productivity of the restored degraded forests, and describe the effects on ecosystem services by following the different strategies. Although the livelihoods aspect of FLR was not the focus of the present study, we present some information gathered from interviews with members of forest fringe communities.

2 Materials and methods

The two study areas are in the Bono Region, a landscape mosaic of forest and grassland that lies within the forest-savanna transition in the dry semi-deciduous forest zone (Figure 1). The landscape contains three forest reserves that support diverse tree species such as *Entandrophragma utile*, *Chlamydocarya thomsoniana*, *Guibourtia ehie*, *Pericopsis elata* and *Khaya anthotheca.* The extent of forest coverin these reserves has declined dramatically over the course of the twentieth century (Blay et al. 2008; FORIG 2003). Annual bushfires since the early 1980s, logging, and slash and burn agriculture have contributed to degrading the landscape, turning closed forest into savanna woodland and grassland (Agyeman et al. 2010; Appiah et al. 2009; Blay et al. 2008). A growing human population supported by shifting cultivation, firewood collection, charcoal production, over-exploitation of timber, and illegal logging has all contributed to reducing the extent of forests. The majority of the population (56%) are smallholders practicing subsistence agriculture (maize, rice, cocoyam, cassava, and plantain) using slash and burn techniques. Some also cultivate cash crops (cocoa, cashew, coffee, oil palm, citrus, and cola). The result is scattered forest remnants in degraded reserves, with isolated trees that dot the landscape and in some areas invasion by non-native grasses and the shrub *Chromolaena odorata* (also known as devil weed, Siam weed, or bitter bush).

2.1 Sites

Active forest restoration activities took place at two sites in the dry semi-deciduous forest zone (DSFZ) of the Bono Region of Ghana, within the Pamu Berekum

Forest Reserve in the Dormaa Central Municipality (Figure 1). The study area is located in the western part of the Bono Region; within latitude 7°30' N and longitude 3°30' W. The terrain is relatively flat with elevation ranging from approximately 180 m to 665 m above sea level (Appiah et al. 2009). The climate is characterised by an average annual rainfall between 1,250 mm and 1,500 mm with a bi-modal pattern; major rainfall occurs between April and August and a minor rainfall season from September to October, separated by a pronounced dry season. Average monthly temperatures range between 26.1 °C and 30 °C.

Soils are dominated by Forest Ochrosols (equivalent to Acrisols in the FAO soil classification) which are generally deeply weathered, well drained and fertile (Hall and Swaine 1981). They developed on Precambrian Birimian and Tarkwain rocks. The soils are grouped into the Bekwai-Nzema Compound and Nkrankwanta associations (Adjei-Gyapong and Asiamah 2002). In addition, large parts of the area are mapped as the Kokofu, Oda, and Wenchi soil series. The perennial Pamu and Tain Rivers drain the area.

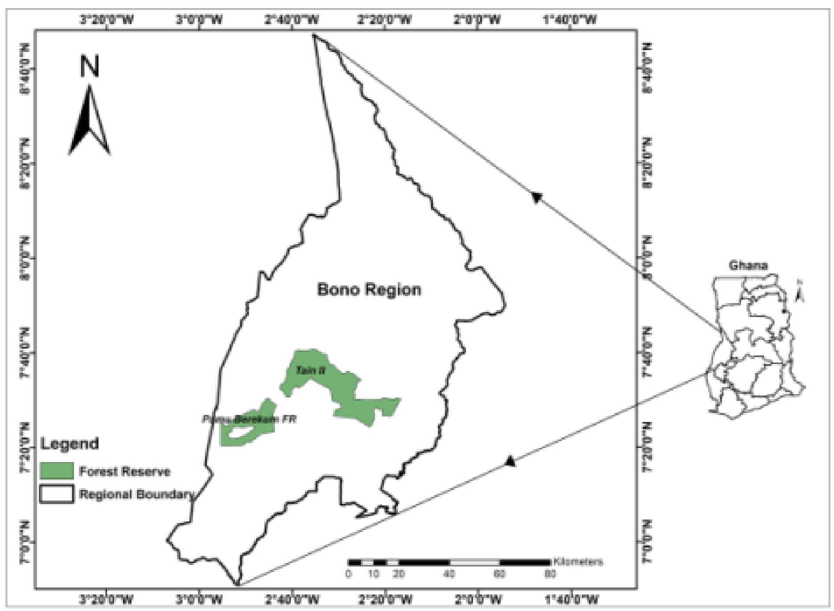

Figure 1. Map of the Bono Region of Ghana, showing the locations of Forest Landscape Restoration Projects in the Pamu-Berekum Forest Reserve.

2.2 Experimental design and data acquisition

2.2.1 Pamu Berekum 1 (PB 1) - Community-based project partnering with farmers

The vision (goals) for this project was to reduce the decline and degradation of forests, as well as improve livelihood of local communities by restoring secondary forests that integrate both indigenous and exotic tree species. The reserve was severely disturbed after years of shifting cultivation, heavy timber exploitation, and rampant bushfires (Appiah et al. 2009; 2010). In addition, local communities had encroached into the reserve for land for farming (Appiah et al. 2009). A baseline assessment was carried out to determine the underlying causes of deforestation and degradation and impacts on communities. Socio-economic indicators (e.g., household incomes) and biophysical indicators (e.g., survival and growth rate, extent of forest cover, compositional and structural diversity, and soil properties) were assessed. An early survey(Blay et al. 2008)of beneficiary households in four communities (N=143, 72% response) was repeated in 2019 by interviewing farmers (*N*=10, 100% response) from five local communities and focus group discussions were conducted to identify the major causes of forest loss and degradation in the area.

The project concept was to identify priority native tree species suitable for plantations and acceptable to the local people. The species chosen by the communities were *Albizia zygia, Alstonia boonei, Aningeriarobusta, Entandrophragma angolense, E. utile, Khaya antotheca, K. ivorensis,Nauclea diderrichii, Pericopsis elata, Terminalia superba, T. ivorensis, Ceiba pentandra,* and the non-native *Cedrela odorata.* Seedlings were raised in local nurseries established by the communities. Local people were trained to manage the nurseries, with technical support from extension services.

The Pamu Berekum 1 (PB 1) was modelled as a community-based project which was initiated in 2000 with a second phase starting in 2012. The project achieved restoration by adopting direct plantation development and agroforestry integrating both indigenous and exotic tree species using MTS. The use of the MTS is important as many of the local farmers, especially the migrants, lack adequate land for cultivating food crops. Actions taken to realize the concept were manually clearing degraded sites and encroached farmlands and preparing them for planting; care was taken to retain naturally regenerated seedlings. Seedlings were planted at wide spacing of 6 m x 6 m and wider (8 m x 3 m) under the MTS (plantain, cocoyam, maize, and pepper were cultivated for 3 years). The farmers maintained the plantations through regular weeding to reduce competition, but naturally regenerated seedlings were protected. Since the sites were in high fire risk zones, the farmers and other community groups were trained in the prevention and suppression of bushfires. A total area of 250 ha was planted under this initiative.

Alternative income generating activities were introduced including rearing of the food delicacy cane rat (grass-cutter; *Thyonomyss winderianus*) to improve the living conditions of the local people. Cultivation of non-timber forest products (NTFPs) including *Piper guineense*, *Xylopia aethiopica*, *Myristica fragrans* and *Nephelium lappaceum*, were integrated into the established plantations (FORIG 2016). Other benefits included a share in the financial return from the final tree harvest.

Growth measurements were taken in 2012 from two communities, namely Twumkrom and Ntabene where mixed planting was done in 2002, at a spacing of 8 m x 3 m, using both indigenous and exotic species while retaining existing trees on the plots. Eighteen (18) randomly located circular plots of 500 m^2 (radius of 12.62 m) were used for the data collection; nine plots each from Twumkrom and Ntabene. All trees (both planted and naturally regenerated) within the plots were measured for diameter at breast height (DBH; at 1.3 m above the ground) and total height. The DBH was measured using a diameter tape while total height was measured with a clinometer. Only trees with DBH ≥ 5 cm were measured in each sample plot.

2.2.2 Pamu Berekum2 (PB 2) - Industry-based project

The vision and concept (goals and objectives) at PB 2 were to supplement raw material supply to the timber industry by establishing timber plantations of both indigenous and exotic species. In addition to establishing plantations, this project was to serve as an outstation center for research, training, and job creation. The background for this was the engagement in 2010 of CSIR-FORIG by the Forestry Commission/Industry Plantations Fund Board to establish plantations of fast growing indigenous and exotic commercial species at various locations in the country using best practices. Accordingly, CSIR-FORIG has been establishing forest plantations funded through the FC/Industry Fund at six locations in different ecological zones.

Actions under this arrangement included planting indigenous and exotic tree species in monocultures of especially teak (*Tectona grandis)* or mixed stands of two to four native tree species. The planting distances depended on the species and the site; *Tectona grandis* and gmelina (*Gmelina arborea*) were planted at 3 m x 3 m. Mixtures of indigenous species were planted at 6 m x 6 m (including *Triplochiton scleroxylon, Terminalia superba, T. ivorensis, Ceiba pentandra,Nauclea diderrichii* and the non-native *Cedrela odorata*).

At PB 2, restoration planting has mainly used *Tectona grandis* and *Gmelina arborea* with a total of 15 compartments so far planted.*Tectona grandis*was planted each year from 2016 to 2020, represented on all compartments, while *Gmelina arborea*was planted only in 2020. The *Gmelina arborea* seedlings were planted as monoculture stands on some portions of compartments 95 and 96 that had a larger portion planted with*Tectona grandis*. Local people from forest fringe communities were directly involved in the land preparation and tree planting, using some form of the MTS for the first three years. Here, the farmers were allowed to integrate some food crops with the planted tree seedlings but they did not hold any share in the final tree harvest as is usually practiced in the MTS. Seedlings raised from seeds collected from trusted provenances were supplied by the CSIR-FORIG nursery and augmented by commercial nurseries. A well-planned maintenance scheme was pursued involving weeding, pruning and thinning. Local people were hired to perform all maintenance activities. At the end of the 2020 major rainfall season (August), a total of 2006.35 ha of degraded land, covering fifteen (15) compartments, in the Pamu Berekum Forest Reserve were successfully replanted mainly with *Tectona grandis* but also some *Gmelina arborea.*

Survival data were recorded from three (3) 30 m x 30 m plots established randomly in each compartment (total of 15 compartments) from the onset of the restoration in 2016 until 2020. The survival data were recorded a year after planting,once for each compartment, by counting the number of surviving seedlings in each sample plot. To assess the growth performance of the species, three plots of 30 m x 30 m each were randomly established within each stand of *Tectona grandis* and *Gmelina arborea*. For the *Tectona grandis* stand, the three plots were located in compartments planted in 2016 (122 and 134) while for the *Gmelina arborea*stand, three study plots were located in compartments planted in 2020 (95 and 96). For comparison to other sites with comparable environmental conditions, a similar design was used at Mankrang Forest Reserve to collect data from a 2013 *Tectona grandis* stand and a 2018 *Gmelina arborea*stand. The Mankrang Forest Reserve is also located in the Bono region and within the same ecological zone as the Pamu Berekum Reserve. Data were obtained from each plot by measuring the total height and DBH of each seedlingusing a hypsometer and DBH was measured using a diameter tape.

2.2.3 Benefits and ecosystem services data acquisition

The benefits obtained from the landscape restoration projects were assessed broadly, taking into consideration the direct and indirect benefits as well as local and the national benefits. To get information about the benefits/ecosystem services obtained by the communities, semi-structured interviews were conducted with 26 farmers (100% response) in each of the two project areas. The questionnaire captured aspects of local livelihood and ecological benefits, as well as national benefits obtained from the restoration activities. For local livelihood benefits, the questions focused on issues such as possible economic benefits, if any, from the projects; possible improved food security; other non-timber forest products that might have been obtained; and if any new value chains were introduced for marketable products and services. Questions about ecological benefits focused on issues such as occurrence of changes in tree cover in the areas; changes in population of threatened species; changes in habitat cover/quality; and how such issues were measured. Questions on national benefits sought to elucidate from respondents their perceptions of any possible national benefits, whether economic, ecological, or otherwise.

Additionally, in 2006, a survey was conducted in ten farming communities around PB 1, using a semi-structured questionnaire, comprised of 431 farmers (representing about 14% of the farmers in the project area). Data were obtained through participatory rapid appraisal (PRA), using personal interviews, focus group discussion, and preference ranking.

2.3 Data analyses

2.3.1 Survival, growth, and productivity

Survival data for the species were computed as average percentages of survived planted seedlings in each sample plot. To estimate growth rates of planted species at the restoration sites, mean annual increments (MAI) and standard deviations in DBH and total height were computed by dividing mean diameter at breast height and total height, respectively, by the plantation age (subtracting year of planting from year of measurement). A paired t-test was applied to compare growth rates of *Tectona grandis* and *Gmelina arborea* with in PB 2. From the study of (Danquah et al. 2011), the mean diameter and height as well as the species diversity were also calculated in mixed mahogany (*Khaya* spp.) plantation and a nearby natural regeneration site.

Aboveground biomass (AGB) was calculated for the various stands using different suitable allometric equations. In the case of PB 1, AGB (dry weight) was estimated using the R package BIOMASS (Rejou-Mechain et al. 2017). The package is designed to compute AGB estimates using a Bayesian inference procedure that builds upon previous work on pantropical and regional biomass allometric equations. In this case the AGB was calculated using the equation – $AGB = 0.0673 * (WD * H * D^2) * 0.976$ – proposed by Ounban et al. (2014). Here, the AGB of all individual trees (both planted and naturally occurring) in each 500 m^2 plot were calculated and summed up to obtain a plot total. The plot totals were averaged over the eighteen (18) plots studied and scaled up to hectare basis. In PB 2, the AGB (dry weight) of *Tectona grandis* was calculated using the allometric equation, $AGB = 0.077 * DBH^{2.546}$. The equation was developed by Ounban et al. (2016) based on data from a *Tectona* *grandis* plantation in Thailand with climatic conditions (mean annual precipitation 1200 – 1500 mm and temperature of 27^{0}C) similar to those of the Pamu Berekum site. Also, the AGB for *Gmelina arborea* was calculated using the allometric equation, AGB = 0.190*DBH$^{2.391}$ developed by Ige (2018). The belowground biomass (BGB) for all species was calculated using the default formula 0.25*AGB as per the guidelines of the Intergovernmental Panel on Climate Change (IPCC). The carbon content of trees was calculated as 0.5*total dry biomass where total dry biomass is a sum of AGB and BGB. Carbon content per tree was summed up to obtain carbon content per plot. The plot totals were averaged over the three (3) plots studied and finally was up-scaled to hectare basis.

Tree standing volume was also calculated for the various stands using different suitable allometric equations. For the mixed stand at PB 1, the standing volume was estimated using the volume equation – 0.0004634*D$^{2.201}$ – proposed by Wong (1989) and successfully used in the estimation of standing volumes for commercial species in Ghana (e.g. Foli 1995; Wong 1990). For the *Tectona grandis*stand at PB 2, the volume over bark (V_{ob}) equation – V_{ob} = 0.000046∗D$^{2.136615}$∗H$^{0.785557}$ – proposed by Tewari et. al.(2013) – was used. Finally, the standing volumes for *Gmelina arborea* was calculated using the equation – V = 0.0206 + 0.00004D^{2}H – proposed by Akinnifesi and Akinsanmi (1995).The tree volumes per plot and hectare were calculated following similar protocol explained above for biomass and carbon.

In order to compare biomass, volume, and carbon accumulation across the two sites and stands (i.e., mixed stand at PB 1, *Tectona grandis* stand at PB 2 and *Gmelina arborea* stand at PB 2), we projected the DBH values of *Tectona grandis* and *Gmelina arborea* (based on DBH mean annual increment values) to 10 years, similar to the age of the mixed stand. Using these projected DBH values, biomass production and carbon sequestration was calculated for the *Tectona grandis* and *Gmelina arborea* stands applying the allometric equations described above. Although this assumption is rather simplistic and may under- or over-estimate projected values, it was nevertheless applied here to obtain estimates for comparison due to lack of better data.

3 Results

Surveys in fringe communities around the project sites identified the proximate degradation factors as bushfire, unsustainable agriculture, and uncontrolled logging. Access to land was also mentioned as a critical factor that has contributed to the loss of vegetation within the reserve as landless, mostly migrant, farmers encroached into reserves.

Degraded natural forests can be restored to planted secondary forests (plantations) and restore key tree species that dominated the original forest (PB 1) or converted to plantations of exotic species (PB 2). Survival of the native species (Table 1) planted in the Pamu Berekum forest reserve was 85% or greater and the non-native species averaged from 73% (*Tectona grandis*) to 92% (*Cedrela odorata*).

3.1 Pamu Berekum 1 (PB 1)

Survival after planting depended upon species and local site conditions and ranged between 85 and 92% (Table 1). Results from a 2012 growth assessment study revealed mean annual increments (MAI) in height ranging between 1.15 m/yr – 2.04 m/yr for the different species across the two planting sites while MAI in diameter ranged between 1.47 cm/yr – 3.44 cm/yr (Table 2). At both planting sites, the exotic species *Cedrela odorata* was the fastest growing species in both diameter and height (Table 2). Total biomass production (i.e., aboveground + belowground biomass) was estimated as 7.15 Mg/plot (Table 4) based on the average of 18 plots, summing up all trees including naturally occurring trees that were retained during planting.

Table 1. Species planted at Pamu Berekum 1 (PB 1) and at Pamu Berekum 2 (PB 2) project sites and their percentage survival (species vary at the different sites hence the data gaps).

	Survival PB 1 (%)	Survival PB 2 (%)
Native Species		
Alstonia boonei	88	
Ceiba pentandra	90	
Khaya ivorensis	87	
Pericopsis elata	85	
Terminalia superba	92	
Terminalia ivorensis	88	
Pericopsis elata	90	
Entandrophragma angolense	92	
Non-Native Species		
Cedrela odorata	92	
Tectona grandis		73
Gmelina arborea		82

Table 2. Mean annual increments (MAI) in diameter and height of six species planted at Twumkrom and Ntabene at Pamu Berekum 1.

Species	Twumkrom			Ntabene		
	N	Diameter MAI (cm/yr)	Height MAI (m/yr)	N	Diameter MAI (cm/yr)	Height MAI (m/yr)
Albizia adianthifolia				4	2.12±0.64	1.71±0.41
Alstonia boonei	2	2.88±0.67	1.15±0.09			
Cedrela odorata	16	3.06±1.09	1.55±0.56	46	3.44±0.64	2.04±0.55
Ceiba pentandra	5	2.96±1.11	1.40±0.62			
Terminalia superba	23	2.68±0.95	1.48±0.44	17	2.29±0.71	1.40±0.41
Khaya ivorensis				8	1.47±0.37	1.30±0.17

Table 3. Mean annual increments (MAI) in diameter and height of six species planted at Twumkrom and Ntabene at Pamu Berekum 1.

Index	Mixed mahogany plantation	Natural regenerated site
Diversity Indices		
Species richness	10.10 ± 0.57	7.90 ± 0.37
Shannon-Wiener diversity	1.91 ± 0.07	1.60 ± 0.06
Pielou's evenness	0.82 ± 0.02	0.80 ± 0.02
Structural variables		
Tree DBH (cm)	9.63 ± 0.83	4.82 ± 0.53
Height (m)	11.17 ± 0.24	9.82 ± 0.20

3.2 Pamu Berekum 2 (PB 2)

Survival one year after planting was higher for *Gmelina arborea* than *Tectona grandis*; average of 82% for *Gmelina arborea* and 73% for *Tectona grandis*. Results from a study assessing early growth rates revealed that *Gmelina arborea* grew faster than *Tectona grandis* in height; 7.32 m and 8.68 m after 2 years and 4 years respectively (mean annual increments of 3.66 for *Gmelina arborea* vs. 2.17 m yr^{-1} for *Tectona grandis*). Similarly, diameter growth was 9.0 cm for *Gmelina arborea* and 10.58 cm for *Tectona grandis* (mean annual increments of 4.50 cm/yr for *Gmelina arborea* vs. 2.60 cm yr^{-1} for *Tectona grandis*). A t-test analysis showed significant differences in the growth of *Gmelina arborea* and *Tectona grandis* for both diameter (df = 4.86, t = 7.95, p = 0.001) and height (df = 4.76, t = 13.31, p = <0.001).

The total aboveground + belowground biomass production of *Tectona grandis* stands was estimated as 4.21 Mg 900 m^{-2} plot equivalent to 46.78 Mg/ha (Table 4). For *Gmelina arborea*, estimated total biomass was 5.18 Mg 900 m^{-2} plot equivalent to 57.56 Mg ha^{-1} (Table 4). When the biomass and carbon accumulation was projected to 10 years for *Tectona grandis* and *Gmelina arborea* at PB 2, the results show that both stands have higher values than the mixed stand at PB 1. The total standing volume per hectare for trees at current ages was highest for the mixed stand at PB 1 (160.41 m^3 ha^{-1}) followed by the *Gmelina arborea* stand (48.68 m^3 ha^{-1}) while the lowest volume was recorded in the *Tectona grandis* stand (41.54 m^3 ha^{-1}). Also, the projected volumes at 10 years, considering a short rotation cycle, reveal the highest in the *Gmelina arborea* (1785.99 m^3 ha^{-1}) stand followed by the *Tectona grandis* stand (331.77 m^3 ha^{-1}) while the mixed stand has the lowest (160.41 m^3 ha^{-1}) (Table 4).

Table 4. Estimated biomass production and carbon storage per plot and hectare at Pamu Berekum 1 and Pamu Berekum 2 sites.

Species	N ha^{-1}	Age	AGB (Mg $plot^{-1}$)	BGB (Mg $plot^{-1}$)	Total biomass (Mg ha^{-1})	Volume (m3 ha^{-1})	C $plot^{-1}$ (Mg $plot^{-1}$)	C (Mg ha^{-1})
Pamu Berekum 1								
Mixed species	450	10	5.72	1.43	143.0	160.41	3.58	71.6
Pamu Berekum 2 (Current values i.e., 4-yr old *T. grandis* and 2-yr old *G. arborea*)								
Tectona grandis	911	4	3.37	0.82	46.78	41.54	2.11	23.44
Gmelina arborea	1100	2	4.14	1.04	57.56	48.68	2.59	28.78
Pamu Berekum 2 (values projected to 10-yr old *T. grandis* and *G. arborea*)								
Tectona grandis	911	10	23.03	5.76	319.89	331.77	14.39	159.89
Gmelina arborea	1100	10	194.42	48.61	2700.31	1785.99	121.51	1350.10

3.3 Benefits and ecosystem services from the restored forest

From an earlier survey of 143 beneficiary households in four communities under the PB 1 project, most respondents (72%) mentioned access to land for farming as the most significant benefit of the project (Blay et al. 2008). This is because many of the local farmers, especially the migrants, lack adequate land for cultivating food crops. Increasing population, commercial tree farming (e.g., cashew and cocoa), among others have led to reduction in lands for agriculture in the area. Even if farmers obtain alternative lands outside the MTS under the FLR projects, they are mostly rented or leased lands for which farmers have to pay. For example, farmers can access land for agricultural purposes through share-cropping arrangements locally referred to as "abunu" or "abusa" for tree crops or food crops respectively. With "abunu", a farmer is required to divide farm yield into two equal parts; shared between landowner and farmer, while "abusa" entails dividing the farm produce into three parts with one part to the landowner and two parts to the farmer. From our interviews with 26 farmers in 2019, all respondents (100%) reported access to fertile lands as a benefit of the project which improved crop yield and enabled them to feed their families, thereby improving food security. Respondents also reported an improvement in their household incomes through the sale of food crops, NTFPs such as medicinal plants, bush meat, firewood, and others that enabled them to pay for cost of health services, school fees and agricultural inputs.

In PB 1, farmers were also trained in alternative livelihood schemes including rearing of cane rat and cultivation of different NTFPs (e.g. *Piper guineense, Xylopia aethiopica, Myristica fragrans* and *Nephelium lappaceum*) which were integrated into the established plantations (FORIG 2016). Also, the project provided indirect jobs to local communities through activities such as seedling production, tree planting and plantation maintenance (FORIG 2016). These jobs were temporary during the lifespan of the project, but they also equipped the local people with skills for the future. Additionally, the project ensured improved tree tenure rights for farmers and local communities through a benefit-sharing arrangement. Similarly, from PB 2, about 97% of 26 respondents interviewed mentioned that access to fertile land through the MTS had increased their food production thus improving their livelihoods. Some indicated that the monthly allowance they received from being employed as casual workers (33%) on the project and selling of food crops (75%) improved their cash income and enabled them to meet their financial commitments such as payment for health services and children's school fees. The project has also constructed two ponds that serve as source of water for fringe communities for various farming activities as well as roads from fringe communities to the plantation site.

Another benefit of the restoration project is the improvement on provision of ecosystem services. An important ecosystem service is climate regulation through carbon sequestration, which is made possible by the restoration projects. The results of the current study reveal that the mixed species stand at PB 1 stored the highest amount of carbon (71.6 Mg ha^{-1}) compared with the stands at PB 2. At PB 2, the *Gmelina arborea*st and stored more carbon (28.78 Mg ha^{-1}) than the *Tectona grandis* stand (23.44 Mg ha^{-1}) despite the fact that the *Tectona grandis* stand is twice older than the *Gmelina arborea* stand.

Another ecosystem service made possible through the FLR projects is the contribution to reduced soil erosion/degradation, while improving soil fertility. For instance (Danquah et al. 2012) studied the effect of a mixed mahogany plantation on the soil chemical properties 10 years after establishment in PB 1 and reported that with the exception of available soil P, all the properties, including pH, cation exchange capacity, organic carbon and nitrogen were significantly higher in soils sampled from the mixed mahogany stands compared to an adjacent degraded site (Table 5).

Although, a wildlife survey is yet to be conducted in the landscape, interviews with farmers indicated there has been an increase in the presence of wildlife in the restoration areas of both project sites. Common wildlife species that have been spotted by farmers include various bird species, striped ground squirrel (*Xerus erythropus*), African brush-tailed porcupine (*Atherurus africanus*), rabbit (*Poelagus* *marjorita*), bushbuck (*Tragelaphus scriptus*), cane rat (*Thryonomys swinderianus*), and African bush fowl (*Francolinus bicalcaratus*) among others.

Table 5. Soil characteristics of a degraded forest site and a 10-year-old mixed mahogany plantation in the Pamu-Berekum Forest Reserve in Bono region, Ghana. Soils were sampled to 30 cm depth (separated into 3 layers; 0–10, 10–20 and 20–30 cm); each value is the mean of 40, 20 m x 20 m subplots from four 1 ha plots. (Data adapted from (Danquah et al. 2012). CEC is Cation Exchange Capacity).

Soil parameter	Degraded site	Mixed-mahogany plantation
pH (water)	4.96 ± 0.11	6.23 ± 0.12
Organic matter (%)	1.78 ± 0.13	5.07 ± 0.54
Organic Carbon (%)	1.03 ± 0.07	2.94 ± 0.32
Total Nitrogen (%)	0.19 ± 0.01	0.25 ± 0.03
Available phosphorus (ppm)	0.33 ± 0.08	0.17 ± 0.07
CEC (meq $100g^{-1}$)	7.97 ± 0.55	26.69 ± 2.57

4 Discussion

The FLR projects presented here illustrate two pathways toward restoration of degraded secondary tropical forests. They were initiated at different times, both within the Pamu Berekum Forest Reserve, progressively incorporating broader goals and objectives. The first effort (PB 1) was a community-based project in two phases (2000 and 2012), undertaken by the CSIR-FORIG and supported financially by the ITTO and the Government of Ghana. The other project (PB 2) was an industry-based initiative also managed by CSIR-FORIG under the auspices of the FC/Industry Plantations Fund Board. Since 2010, CSIR-FORIG has been establishing timber plantations of both indigenous and exotic species to supplement raw material supply to the timber industry.

4.1 Productivity of restored forests

Generally, survival of seedlings was high in both projects for both indigenous and exotic tree species. At PB 1, growth assessments showed that *Cedrela odorata* was the fastest growing species in comparison to the other five species. *Cedrela odorata* was the only exotic species grown at PB1. In PB 2, survival and growth of *Gmelina arborea* was better than *Tectona grandis*; both are exotic species in Ghana although *Tectona grandis* is widely planted. *Gmelina arborea* is known to be a fast growing species (Dvorak 2004; Sanon et al. 2006) and thrives well in diverse environmental conditions. The superior growth of *Gmelina arborea* to *Tectona grandis* was also observed at Mankrang Forest Reserve (DBH – 10.58 cm; MAI in DBH – 5.29 cm yr^{-1} and height – 10.23 m; MAI in height - 5.11 m yr^{-1} of *Gmelina arborea* compared to DBH – 7.61 cm; MAI in DBH – 1.9 cm yr^{-1} of *Tectona grandis*) that has similar conditions as Pamu Berekum Forest Reserve. Similar to our findings, Adekunle (2000) and Adekunle et al. (2011), reported that *Gmelina arborea* grew faster than *Tectona grandis* when they compared trees of the same age. In an experimental trial evaluating the potential of *Senna siamea*, *Terminalia superba*, *Nauclea diderrichii* and *Gmelina arborea* for restoring degraded mined lands in Ghana, Guuroh et al. (2020), also reported superior survival and growth (diameter and height) of *Gmelina arborea* than the other three species on both the unmined and mined soils. In the severely degraded mined soils, *Gmelina arborea* was the only species that maintained a survival greater than 80% after ten months. Similarly, *Gmelina arborea* recorded the highest diameter and height relative growth rates in the mined soils and was significantly different from all the other species.

The growth of both *Gmelina arborea* and *Tectona grandis* at PB 2 were comparable to the same species of the same age at Mankrang Forest Reserve. While *Tectona grandis* growth was faster in PB 2 (diameter – 2.64 cm yr^{-1}) than Mankrang (1.9 cm yr^{-1}), growth of *Gmelina arborea* was slower at PB 2 (diameter – 4.57 cm yr^{-1} and height – 3.68 cm yr^{-1}) than Mankrang (diameter – 5.29 cm yr^{-1} and height – 5.11 m yr^{-1}).

Basing on the data at time of measurement, biomass accumulation was higher in the mixed stand at PB 1 (143.0 Mg ha^{-1}) than PB 2 (57.56 Mg ha^{-1} for *Gmelina arborea* and 46.78 Mg ha^{-1} for *Tectona grandis*). Similarly, carbon sequestration followed the same trend with 71.6 Mg ha^{-1} for the mixed stand in PB 1 compared to 28.78 Mg ha^{-1} for *Gmelina arborea* at PB 2 and 23.44 Mg ha^{-1} for *Tectona grandis* at PB 2. However, when the data from the 4-year-old *Tectona grandis* and 2-year-old *Gmelina arborea* stands were projected to 10 years (comparable to the mixed stand at PB 1), the mixed stand recorded the least biomass (143 Mg ha^{-1}) and carbon content (71.6 Mg ha^{-1}) compared to the *Tectona grandis* stand (AGB = 319.89 Mg/ha; C = 159.89 Mg ha^{-1}), while the *Gmelina arborea* stand recorded the highest biomass (2700.31 Mg ha^{-1}) and carbon content (1350.1 Mg ha^{-1}) (Table 4). The observed trends for biomass and carbon accumulation are similar to standing volumes of trees where the mixed stand at PB1 recorded (160.41 m^3 ha^{-1}) followed by the *Gmelina arborea*stand (48.68 m^3 ha^{-1}) and *Tectona grandis* (41.54 m^3 ha^{-1}). In terms of timber value, assuming a 10-year rotation for the three stands, the projected volumes at 10 years, reveal that the mixed stand had the lowest (160.41 m^3 ha^{-1}) compared to the *Tectona grandis* (331.77 m^3 ha^{-1}) and *Gmelina arborea* stands (1785.99 m^3 ha^{-1}) (Table 4).Using a prevailing round logs sale price of GH₵ 220 (37.40 USD) per cubic meter for *Tectona grandis* and GH₵ 120 (20.40 USD) per cubic meter for *Gmelina arborea*, it is estimated that the current total value of the *Tectona grandis* and *Gmelina arborea* stands per hectare is respectively GH₵ 9,138.80 (1,553.69 USD) and GH₵ 5,841.60 (993.13 USD). The 10-year projected financial value per hectare, using the current market prices, is GH₵ 72,989.40 (12,409.00 USD) for *Tectona grandis* and GH₵ 214,318.80 (36,436.50 USD) for *Gmelina arborea.*

Projected growth to 10 years was achieved by assuming a constant annual increment in diameter until age 10-yrs for the *Tectona grandis* and *Gmelina arborea* stands and that the same stand density would be maintained. This assumption is rather simplistic but due to lack of better data, this was used to provide estimates. Generally, differences in biomass production and carbon stocks might be attributed to several factors, including species composition, stand density, age, and site conditions. Different species have different growth, biomass accumulation, and carbon storage rates. Also, site conditions and age influence growth of all plants, which ultimately affects biomass and carbon accumulation. Additionally, the number of stems per unit area directly affects the biomass values. From the results of the 10-yr-old projections, it appears that species and stand density are responsible for the observed differences in biomass and carbon accumulation. This is in conformity with findings by (Adeyemi and Adeleke 2020) who found that species differences and stand density significantly influence carbon sequestration as well as findings of (Guo et al. 2010) who noted that plant density highly influences accumulation of carbon in any forest. The *Gmelina arborea* stand had the highest stand density of 1100 stems ha^{-1} followed by the *Tectona grandis* stand (911 stems ha^{-1}) while the mixed stand has the lowest (450 stems ha^{-1}).

It was not surprising that *Gmelina arborea* recorded the highest biomass and carbon accumulation because *Gmelina arborea* is known for fast growth and high biomass production. This is consistent with findings by (Ige 2018) who also reported that *Gmelina arborea* produces high biomass even at young ages. Even if we compare the biomass production based on data at the time of measurement, the 2-year-old *Gmelina arborea* stand still produced higher biomass (57.56 Mg/ha) and stored more carbon (28.78 Mg ha^{-1}) than the 4-year-old *Tectona grandis* stand (AGB = 46.78 Mg/ha; carbon = 23.44 Mg ha^{-1}). From this result, it may be argued that tree age might be a less important determinant of biomass and carbon accumulation than species composition and stand density. In a study by (Adeyemi and Adeleke 2020), a 23-year-old *Pinus caribaea* stand produced the highest biomass and stored the most carbon followed by a 35-year old *Gmelina arborea* stand while 43-year old *Tectona grandis* and *Nauclea diderrichii* stands recorded the lowest biomass and carbon storage.

Planted forests served as nurse crops that facilitated natural regeneration, and enhanced tree species composition and diversity. Results from PB 1 showed that species composition and diversity were significantly higher in mixed mahogany plantation than nearby naturally regenerated stand after 10 years (Table 3). This suggests that the planted forests played a role in improving natural regeneration thereby enhancing tree species composition, a common observation (Parrotta *et al.*, 1997; Brockerhoff *et al.*, 2008). Another study, conducted in the Dormaa area in same region, which assessed understory plant diversity of an 8-year-old mixed species plantation, reported that species richness increased by 24% and the number of families by 48% per 1,000 m^2 between 2001 and 2008 (Appiah 2012). They recorded 92 plant species after 8 years compared to the 22 plant species that were recorded prior to the establishment of the plantation. Indeed, some of the native tree species that were recorded (e.g. *Daniellia ogea*, *Entandrophragma angolense, Milicia excelsa, and Pericopsis elata*) are considered to be locally and globally vulnerable or near threatened due to their declining population in the natural forest (Hawthorne and Gyakari 2006).

4.2 Benefits and ecosystem services from the restored forests

Improved livelihoods are a defining component of FLR. Both restoration projects have greatly contributed to increasing forest cover and the provision of critical ecosystem services as well as enhancing livelihoods and well-being of the local communities. The benefits reported here cut across livelihood, ecological, environmental, and national benefits (Foli 2019). In both projects, farmers gained access to fertile land for the period of the MTS; usually about three years from the year of planting tree seedlings. This improved food security through increased production and diversified income sources (sale of food crops, medicinal plants, bush meat, and firewood). Farmers were trained in climate-smart agricultural and agroforestry practices and were introduced to new marketable cash crops, thereby helping to diversity their income.

Other benefits included employment including women and youth from fringing communities for seedling production, tree planting, and maintenance of plantations. Additionally, two ponds in the PB 2 project were constructed and serve as a water source for fringe communities, reducing the distance women must carry water from home to their farms. Roads that were constructed to the restoration sites also increased access to markets in urban centers for farm produce, which helped reduce farm waste and thus increased earnings of farmers.

Local communities benefited from the FLR projects in multiple ways, including capacity building that enhanced their leadership capacity and technical capacity in managing forests (Foli 2019). A benefit-sharing arrangement in the PB 1 project improved tree tenure rights for farmers and local communities; they gained a 40% share of the revenue from future timber products. A document that recognized the rights of farmers and local communities to a share in the future timber products was produced but has yet to be signed and distributed to participating farmers. When implemented, the money farmers will receive from the timber harvest would serve as a form of long-term investment for the beneficiaries. For instance, using the current market values above, a farmer will receive GH₵ 88.00 (14.96 USD) and GH₵ 48.00 (8.16 USD) for each cubic meter of *Tectona grandis* and *Gmelina arborea* sold, respectively.

Interviews with community members indicated that the projects have contributed to improved ecosystem service provision. One important benefit is the return and or increase in abundance of wildlife (birds and mammals) in the area. Some of the species are a protein source to local people and in some instances contribute to income generation. Other ecosystem services reported from the PB1 project were reduced soil erosion and improved soil fertility (Table 5). The positive impact of trees on soil is well known and documented (Habumugisha et al. 2019; Montagnini 2000; Rhoades and Binkley 1996).

Apart from livelihood and ecological benefits, there are also important national benefits from these restoration projects. The Forestry Commission receives 20% of future timber revenues. The projects contribute to meeting Ghana’s Intended Nationally Determined Contributions (INDC) as party to the United Nations Framework Convention on Climate Change (UNFCCC) and the 2 million ha commitment under the Bonn Challenge. The FLR projects also help to meet national goals and objectives of Ghana’s restoration and climate change mitigation strategies adopted in the 2012 National Climate Change Policy and the National Forest and Wildlife Policy as well as Ghana’s Poverty Reduction Strategy. Additionally, the FLR projects contribute to providing C-sinks that sequester high amounts of atmospheric carbon dioxide due to increased tree cover. This will contribute to reducing the adverse effect of climate change in the country.

The use of afforestation and reforestation to reduce atmospheric C by building up terrestrial C-stocks was adopted by the UNFCCC in July 2001 at the seventh Conference of Parties (CoP 7). Although young trees store less C than mature trees, in the long-term, plantations are a critical carbon sink. For instance *Tectona grandis* grown in plantations have ten times higher growth than naturally regenerated *Tectona grandis* (Mohdar and Zuhaidi 2005). *Tectona grandis* wood is also known to store C longer than other timber species (Eliyani et al. 2005). Estimates of C-storage in the two restoration projects showed that the mixed species stand in PB 1 stored about 71.6 Mg ha^{-1} while the *Tectona grandis* and *Gmelina arborea* stands at PB 2 stored about

23.44 Mg ha^{-1} and 28.78 Mg ha^{-1} of C respectively. The C-sequestration is expected to continue to increase as the plantations grow older. For example, an assessment of carbon stocks by Jah (2015) in young (1, 5, 11 years old) *Tectona grandis* plantations with stand densities of 1183, 1728 and 376 trees per hectare respectively, growing under similar environmental conditions as the present study showed that 1.6, 15.8, and 35.4 Mg ha^{-1} was stored in the 1-year, 5-year, 11-year-old *Tectona grandis* standsrespectively. By comparison, it is evident that the 4-year-old *Tectona grandis* stand in our study stores more carbon than the 5-year-old *Tectona grandis* stand studied by Jha (2015), notwithstanding that the stand density in the Jha (2015) study was almost twice higher (1728 trees per ha) than in the current study (911 tree per ha). This suggests that the trees at the project sites potentially can sequester significant quantities of carbon and gain carbon credits in the future.

To further enhance ecological benefits, several patches of near-natural remnant vegetation were retained at the project site (see examples in Figure 2 and 3). In addition, naturally occurring individual stems within the landscape were deliberately retained during land preparation (see examples in Figure 4 and 5). These remnant individuals and patches are critical for providing suitable habitats for various wildlife species especially during the initial stages of restoration when the planted trees are still too young. Additionally, streams and water courses were identified within the landscape and planting was done along the boundaries as a way of conserving them.

Figure 2. An example of remnant forest patch retained in compartment 97 of Pamu Berekum 2 site.

Figure 3. An example of remnant forest patch retained in compartment 94 of Pamu Berekum 2 site.

Figure 4. An example of individual trees retained in compartment 107 of Pamu Berekum 2 site.

Figure 5. An example of individual trees retained in compartment 108 of Pamu Berekum 2 site.

5 Conclusions

This assessment of two FLR projects in the Pamu Berekum Forest Reserve of Ghana demonstrated that different options are available to restore degraded forests. Estimates of productivity in the restored forests were described, as well as the effects of the restoration on ecosystem service provision. The two FLR projects showed that FLR delivers important benefits and ecosystem services both at the local and national levels. The results provide an example for forest/environmental managers on how FLR might be implemented to create multiple benefits at different levels from local communities to the national level. The results indicated that FLR can be done successfully through different strategies but that it is important to work closely with local communities around the restoration areas. Whether we consider direct benefits such as income from being employed to work on a FLR project or indirect benefits such as provision of access roads, farmers and other community people can be positively impacted by restoration activities. Additionally, farmers are also motivated by the improving tree tenure and expected income from future tree sales.

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