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Biomass, Carbon Stock and Economic Value of Carbon Sequestration Resulting from Forest and Landscape Restoration Actions in Semi-arid Ecosystems of Burkina Faso

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Original Research Article

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ABSTRACT

Plants contribute to mitigate global warming by capturing CO_2 from the atmosphere to produce biomass. This study aims to quantify the carbon stock sequestered in woody biomass of managed ecosystems in the semi-arid part of Burkina Faso (West Africa), and assess the economic value of additional carbon sequestered. Study sites include one managed forest and three agricultural lands restored from degraded soil. Forest and landscape restoration activities have been implemented over several decades and include zaï, stone barriers, natural regeneration and tree planting. Woody plant biomass is estimated using allometric equations which have been adapted to the case study site species and ecological conditions. The managed forest of the case study has an estimated 19.3-40.8 t/ha of woody biomass after 45 years. This corresponds to 0.7-1.5 tonne of CO_2 per hectare per year stored on average, i.e. a value of $575-7,243 per hectare per year at current carbon prices. Payments to land users for carbon storage services may help provide alternative livelihoods and incentives for reforestation effort.

Keywords: Forest and landscape restoration; agroforestry; assisted natural regeneration; carbon sequestration; carbon payments.

1. INTRODUCTION

Emissions of greenhouse gases (GHG) cause climate change such as global warming and changes in precipitation patterns (Omotoso & Omotayo 2024). Different studies show that unsustainable energy use, land use and land use change, and modern ways of life have led to a global temperature increase of 1.1°C in 2011-2020 compared to 1850-1900 (IPCC 2023). Vulnerable communities, who have historically borne the least responsibility for GHG emissions, are disproportionately at risk (IPCC 2023). In West Africa, average precipitations declined between 1950 and 1990 by 180 mm/year (Le Barbé et al. 2002). In this region, temperatures are expected to be +2.8 °C higher in 2031-2060 compared to 1961-1990 (Sultan et al. 2014). The combustion of fossil energies, deforestation and land degradation are the main sources of anthropic release of CO_2 in the atmosphere (421 ppm presently versus 500–600 ppm by 2050) (Omotoso & Omotayo 2024).

Rising temperatures lead to reduced production of cereals such as sorghum (Sultan et al. 2014), wheat and maize (Farooq et al. 2023). Reduced rainfall has led to lower food crop yields (Farooq et al. 2023, Kang et al. 2009, Rezaei et al. 2023) and accelerated loss of vegetation cover (Hailu 2023 and Lemenkova & Debeir 2023). Likely direct impact of changes in rainfall seasonality in the Sahel is a reduction in sorghum yields of around 16-20% (Sultan et al. 2014). In short, predictions from current models all seem to converge toward a significant reduction of food production.

At the same time, the population of the Sahel has more than tripled, from 40 million in 1970 to 135 million in 2020, and is projected to reach 330 million by 2050 (Bouquet 2021). This means increased demand for food in a context of decreasing food production. As a result, pressure on forest ecosystems, already weakened by natural phenomena, has increased. The social consequences are food insecurity (Gitz et al. 2016) and population migration (Alessandrini et al. 2021). In this context, the West African countries have set up the Permanent Interstate Committee for Drought Control in the Sahel (CILSS), a political and operational instrument for taking action to halt desertification, with a view to achieving food security through the restoration of landscapes and the sustainable management of agricultural and forestry systems.

In Sub-Saharan Africa, the main greenhouse gases released are CO_2 (80% of all anthropic GHG emissions), CH_4 (15%) and N_2O (17%) (Omotoso & Omotayo 2024). A number of studies have shown that the excess CO_2 produced by burning fossil fuels can be partially absorbed and sequested by woody plants (Toochi 2018, Sierra et al. 2021). To this end, one of the best strategies is plant formation conservation (maintaining the integrity of forest areas) and restoration of degraded forests and landscapes (Domke et al. 2020). Across Africa, tens of millions of US dollars have been mobilised for forest and landscape restoration (FLR) activities (Mansourian & Berrahmouni 2024). In the Sahel, FLR techniques include the use of local techniques and technologies to transform barren land into forest ecosystems. The technique of zaï and stone barriers has been used to reforest the site of Gourga. The landowner is Yacouba Sawadogo, an environmentally conscious farmer who has dedicated his life to the restoration of barre soils (Sawadogo et al.2014, Belmin et al. 2023 Pédarros et al. 2024). On arable lands, agroforestry and assisted natural regeneration (ANA) are the main techniques used to allow woody plants to develop while crops are being produced (Mansourian & Berrahmouni 2024).

If Burkina Faso is to achieve the objectives associated with its international commitments, FLR activities will have to be rolled out on a large scale. Scaling up in this way means convincing potential investors of the benefits of financing this type of intervention. However, while the costs associated with FLR activities in the Sahel are relatively well known depending on the type of intervention implemented (Sawadogo et al. 2014) the same cannot be said for the ecosystem benefits (market or non-market) expected from this type of intervention.

At the international level, the Paris Climate Agreement, with its goal of limiting global warming to 2°C, is a powerful tool for negotiating the carbon market. The Kyoto Protocol and the voluntary carbon markets can finance the storage of carbon dioxide through biomass, but also through other approaches such as biochar (Michaelowa et al. 2023). Carbon markets use empirical credits, commercial insurance and buffer reserves (Michaelowa et al. 2023). In Burkina Faso, the implementation of REDD+ mechanisms is directly funding forest restoration and management projects by the national Ministry of the Environment. The direct payment for carbon sequestration to small users is not well implemented in Burkina Faso.

For several decades, numerous initiatives have been undertaken in the arid and semi-arid zones of the Sahel to restore forests and landscapes and to promote sustainable land management (SLM) techniques (Vinceti et al. 2020). However, these actions remain poorly capitalised and/or replicated. The aim of this study is to quantify the carbon stock sequestered in woody biomass and to assess the economic value of additional carbon sequestered in different managed ecosystems in the semi-arid part of Burkina Faso. This work contributes to the scientific knowledge and national awareness of the capacity of FLR actions to improve carbon storage, which can help mitigate climate change.

2. MATERIALS AND METHODS

2.1. Study Area

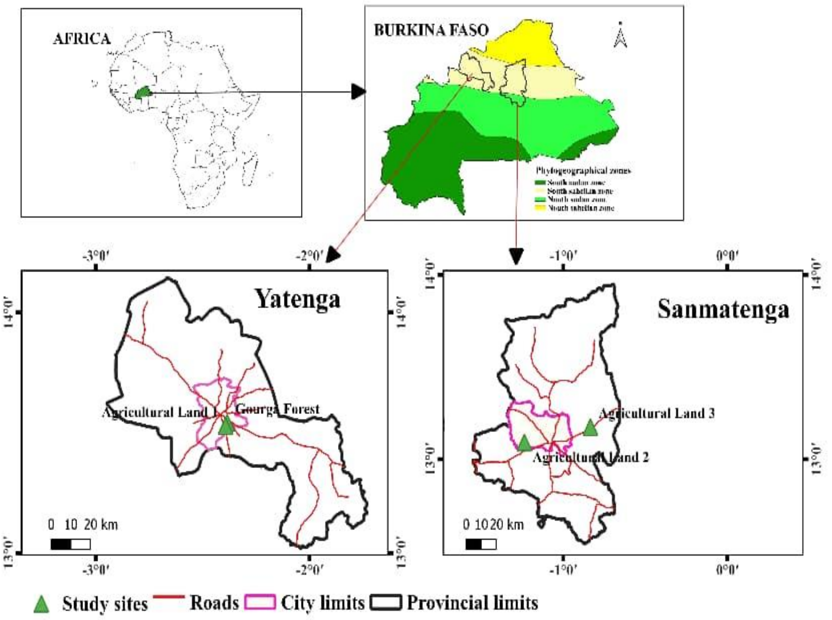
Four sites were selected on the basis of the restoration activities undertaken and their location in the semi-arid area of Burkina Faso (Fig. 1). The first two sites are the Gourga Managed Forest (GMF) and the Agricultural Land number 1 (AL1), both located in Ouahigouya in the province of Yatenga (180 km north of Ouagadougou). The soil types are lithosols on cuirass and ferruginous soils. Shrub savannah is the predominant vegetation. Average annual rainfall is around 679 ± 172 mm (Yameogo et al. 2023). The other two sites are the agricultural land number 2 and 3 (AL3 and AL4), located in Kougrinsin and Pissila respectively in the province of Sanmatenga. These two sites are located about 30 km from Kaya (100 km north-east of Ouagadougou). The Kaya region belongs to the northern Sudanese phytogeographical zone. The average annual rainfall is 655±133 mm (Yameogo et al. 2023).

The development of the Gourga managed forest began in 1973. The site was a *zippelé*, i.e. bare soil without vegetation. The site has been restored using the zaï technique, which involves digging small areas of soil to allow rainwater to seep through. This allows the seeds of woody and herbaceous plants to germinate. The farmer, Yacouba Sawadogo, has chosen restoration techniques based on helping vegetation to reclaim the site (for more details please see (Rodrigues et al. 2019 and Kaboré et al. 2024). In addition to zaï, he has mobilised stone barriers, organic fertiliser, crop-fallow succession, assisted natural regeneration (ANR), woody species plantations, techniques to encourage the return of termites, and the installation of water troughs and seeds to attract and settle birds and small mammals on the site. The site was first used to grow cereals (millet, sorghum) and then abandoned to allow the regenerating woody vegetation to develop into a wooded savannah. For the three agricultural sites, restoration activities do not consist of reforestation. They consist of water and soil conservation/soil restoration and preservation activities to restore degraded land for agriculture. Agricultural land number 1 (AL1) covers 31 hectares. It was initially devoid of vegetation and had crusted soil. Management of the site began in 1991 and consisted of the use of zaï, stone barriers, RNA, fallow and crop rotation. Millet, cowpeas and peanuts are the main crops grown on the site.

Agricultural land number 2 (AL2) covers four hectares. It was initially a degraded and unproductive land, with a crusted surface. Soil restoration work began in 2007 with zaï, organic fertiliser amendments and stone barriers. The farmer currently has a good production of millet and cowpeas on the site. Agricultural land number 3 covers 2.7 hectares. Soil restoration activities were initiated on bare, degraded soil in 2000. The techniques used are zaï, stone barriers, organic fertiliser and RNA. The farmer uses crop rotation with sorghum, cowpea and millet.

2.2 Data Collection and Allometric Equations

Control sites, identical to the restored sites prior to their development, were identified by the farmers carrying out the restoration works. A floristic inventory was carried out on all these restored and control sites in 2018 (Table 1). Oriented sampling was used to cover all the heterogeneities of the sites. The inventory was carried out on 36 plots of 900 m^2 each. The scientific names and dendrometric parameters (diameter at breast height -dbh-, height, crown diameter) of each woody species were recorded.



Sources: BNDT/2012 Author : DAGNON Moussa Year : September 2024

Fig. 1. Location of study sites

Table 1. Site characteristics and number of survey plots

Sites	Area (ha)	Number of plots	
		Restored sites	Controls
Gourga Managed Forest	27	9	6
Agricultural land 1	31	3	3
Agricultural land 2	4	4	3
Agricultural land 3	2,7	4	4
Total	64,5	20	16

Table 2. Allometric equations used to calculate plant biomass

Species	Location	Allometric equations	Sources
Acacia nilotica (L.) Willd. ex Delile	Senegal	$Y=5.066Dbh -0.696dbh^2 +0.05dbh^3$	Mbow et al. (2014)
Acacia senegal (L.) Willd.	Senegal	$Y = 0.032dbh3 - 1.016dbh^{2} + 10.87dbh + 7.430$	Thiam et al. (2014)
Acacia seyal Delile	Senegal	$Y=5.066dbh -0.696dbh^2 +0.05dbh^3$	(Mbow et al. 2014)
Anogessus leiocarpa Guill. & Perr.)	Benin	Ln(Y)=-2.4996 + 1.5133ln (dbh) +1.1256 ln(h)	Guendehou et al. (2012)
Combretum micranthum G.Don	Tiogo, Burkina	Y= 0.827+0.184db+0.0337dbh-0.001db×dbh+0.0004dbh×h	Sawadogo et al. (2010)
Guira senegalensis Lam.	Tongomayel, Burkina	Log10Y(g)= (0.55+(1.89×log(X))) ×10^ (–3)	Henry et al. (2011)
Piliostigma reticulatum (DC.) Hochst.	Kollo, Niger	Y = 5.485Dbh + 15.717	Larwanou et al. (2010)
Pterocarpus lucens Lepr. ex Guill. & Perr.	Senegal	Log10 y (g MS) = 0.6156 + 1.862 Log 10 C	Ngom et al. (2014)
Other species		Y = EXP ((-1,996) + 2,32*Ln (dbh))	FAO1, (Brown 1997)
Other species		$Y = 42,69-12,8*dbh +1,24*dbh^2$	FAO2 (Brown 1997)
Other species		Y = EXP ((-2,134) +2,53*Ln (dbh))	FAO3 (Brown 1997)

Y: Aboveground biomass; DBH: Diameter at Breast Height; FAO: Food and Agriculture Organisation.

The scientific names of the plants and their diameter at breast height, were used to calculate the woody biomass. The research focused on allometric equations expressing the dry biomass of each species. The analysis included individuals with dbh ≥ 5 cm. Data on carbon stock estimates are patchy or non-existent for some species and for some countries such as Burkina Faso (Gibbs et al. 2007). Allometric equations for aboveground biomass (AGB) of the main species were determined from a literature review (Table 2). The allometric equations of Brown (1997) (FAO1, FAO2, FAO3) were applied to other species that do not have allometric equations (after unsuccessful literature search). Below-ground woody biomass (BGB) was calculated by multiplying the coefficient 0.27 by aboveground biomass (Mokany et al. 2007). Total woody biomass (DM) is the sum of AGB and BGB. Carbon stock was calculated by multiplying total woody biomass by 0.47 (IPCC 2006). The conversion rate from carbon stock to metric tonne equivalent of CO_2 is 44/12 (Mass of CO_2/Mass of Carbon). The monetary value of a tonne of CO_2 has been estimated on the basis of two sources in order to see how this value varies from a minimum value to a maximum value. These sources are REDD+, which estimates a tonne of CO_2 at $30 (United Nations Environment Programme 2023 and Rennert et al. 2022) which estimates a tonne of CO_2 at $185.

3. RESULTS

3.1 Diversity of Woody Species

3.1.1 Gourga managed forest

The soil restoration activities had an impact on the change in phytodiversity. In the Gourga managed forest, 31 adult woody species (dbh ≥ 5 cm) were recorded. *Combretum micranthum* (30.2%) was the most abundant species in terms of number of trees. It was followed by *Guiera senegalensis* (19.6%), *Sclerocarya birrea* (8.1%), *Cassia sieberiana* (6.5%) and *Balanites aegyptiaca* (6.0%) (Table 2). The average density of woody plants is 594 plants/ha, with a maximum of 1210 plants/ha in the woody savannah and a minimum of 178 plants/ha in the shrub savannah.

In contrast to the forest, the diversity of woody species in the controls is very low, with only 11 species. All of these species were recorded in the forest. Management therefore had the effect of conserving 11 species and regenerating 20 other woody species. The average density in the control was 22 plants/ha, with a maximum density of 44 plants/ha and a minimum density of 0 plants/ha in the bare soil (Table 3).

3.1.2 Agricultural lands

Five woody species were recorded in AL1 compared to none in the control. Average tree density is 93 plants/ha. AL2 has two woody species. The density of these woody species is 11 plants/ha. Seven species were inventoried on the controls. Four woody species were inventoried on AL3 (Table 4). The density of the woody plants is 19 plants per hectare. On the control plots, the same density is 14 plants per hectare for a woody species diversity of three species.

3.2 Woody Biomass and Stock of Carbon

The results show that the estimation of biomass differs according to the type of allometric equation that is used (Table 5). The results are often similar between the use of specific equations and FAO1. In all cases, the highest values are obtained with FAO2. The Gourga managed forest has a potential of 19.3 (40.8) tonnes of woody biomass (AGB + BGB) per hectare, compared to 1.2 (2.9) tonnes per hectare in the control area.

The difference between the biomass per hectare in the FMG and that in the control gives 18.1(37.8) t/ha, representing the effort of more than four decades of management with FLR activities. Woody biomass calculated for AL1 was 0.7 (4.3) t/ha versus 0.0 t/ha for control. In the Kaya region the results were 11.8 (24.6) and 1.3 (3.4) t/ha for AL2 and the control respectively.

3.3 CO_2 Sequestration and Economic Value

In the Gourga forest, the amount of carbon dioxide sequestered varies between 33.27 and 70.32 t CO_2/ha over a 45 years period, depending on the allometric equations used to calculate aboveground biomass. Assuming that the forest would follow the same trajectory as the controls, we can extract the contribution of soil restoration to carbon sequestration. The analyses therefore show that the efforts to restore the soil lead to a gain of 31.2 (65.3) tonnes of CO_2 per hectare over 45 years. This amounts to about 0.7 (1.5) tonne of CO_2 per hectare per year on average. If this rate is

Table 3. Woody plant diversity in the Gourga managed forest and in the control sites

Species	**Frequency (%)**	
	Site	**Control**
Vachellia nilotica (L.) P.J.H.Hurter & Mabb. (syn. *Acacia nilotica* (L.) Willd. ex Delile)	1.0	-
Senegalia senegal (Brenan) Kyal. & Boatwr. (syn. *Acacia senegal* (L.) Willd.)	1.3	6.7
Vachellia seyal (Delile) P.J.H.Hurter (syn. *Acacia seyal* Delile)	2.1	-
Adansonia digitata L.	4.4	-
Albizia chevalieri Harms	0.6	-
Terminalia leiocarpa (DC.) Baill. (syn. *Anogeissus leiocarpa* Guill. & Perr.)	0.2	-
Azadirachta indica A.Juss.	3.3	6.7
*Balanites aegyptiaca (*L.*)* Delile	6.0	6.7
Combretum aculeatum Vent.	0.4	-
Combretum collinum Fresen.	0.2	-
Combretum glutinosum Guill. & Perr.	1.0	6.7
Combretum molle R.Br. ex G.Don	0.2	-
Cassia sieberiana DC.	6.5	13.3
Combretum micranthum G.Don	30.2	6.7
Dichrostachys cinera (L.) Wight & Arn.	1.5	-
Diospyros mespiliformis Hochst. *ex* A.DC.	0.8	6.7
Gardenia erubescens Stapf *&* Hutch.	0.2	-
Guiera senegalensis Lam.	19.6	6.7
Holarrhena floribunda (G. Don) T. Durand. & Schinz	0.2	
Khaya senegalensis (Desr.) A.Juss.	0.2	-
Lannea microcarpa Engl. & K.Krause	1.9	20.5
Piliostigma reticulatum (DC.) Hochst.	3.5	13.3
Pterocarpus lucens Lepr. ex Guill. & Perr.	2.7	-
Bauhinia rufescens Lam.	0.2	-
Sclerocarya birrea Hochst.	8.1	-
Stereospermum kunthianum Cham.	0.2	-
Tamarindus indica L.	0.2	-
Terminalia avicenioides Guill. & Perr	-	6.7
Vitellaria paradoxa C. F. Gaertn.	0.2	-
Ximenia americana L*.*	0.2	-
Ziziphus mauritiana Lam.	2.7	-

applied to the area of the forest (27 ha) and CO_2 prices, the minimum real value of carbon sequestration through restoration is $575 and the maximum is $7,243 per year. The same analysis gives $46-$1,588 for AL1, $185-$2,466 for AL2 and $0,32-$11,92 for AL2 as the value of carbon sequestration attributable to forest and land restoration actions per year (Table 6).

4. DISCUSSION

4.1 Woody Species and Carbon Stock

The most abundant species in the Gourga managed forest (*Combretum micranthum* and *Guiera senegalensis*), the agricultural land 1 (*Vachellia seyal* and *Combretum micranthum*) and the agricultural land 3 (*Vachellia seyal* and *Cassia sieberiana*) are schrub species. *Combretum micranthum* and *Guiera senegalensis* are typical species of semi-aride sahelian zones (Becker & Müller 2007). The Gourga managed forest has more woody species diversity than outside the forest, as found by Bognini et al. (2023). The present study records 31 species versus 55 species recorded in the same forest by Bognini et al. (2023). They recorded all woody species whereas the present study recorded only woody species with dbh ≥ 5 cm. The owner of the Gourga managed forest, Yacouba Sawadogo, was called the "man who stopped the desert" for his exploit to restore a bare soil to a forest (Rodrigues 2019 and Codur et al. 2022). Other plantation initiaves exist in the Sahel region of Burkina Faso but the case of Gourga remains the oldest and most successful experience (Vinceti et al. 2020). On the agricultural lands, farmers grown more diverse woody species compared to the control. The land can therefore be used to farm, while helping to preserve plant diversity.

The biomass of a given ecosystem cannot be evaluated with certitude but can be well estimated when many methods are used. In this study, four methods with different allometric equations adapted for the semi-arid regions were used. The dry biomass of woody species found in the Gourga managed forest is between 15.2 t ha^{-1} and 32.2 t ha^{-1}. For comparison, two plantations of *Piliostigma reticulatum*, 5 and 15 years old, store a dry aboveground biomass of 3.65 t ha^{-1} and 30 t ha^{-1}, respectively, at a density of 1100 plants ha^{-1} in the Sudanese zone of Burkina Faso (Tyano et al, 2019). The carbon stocks in the GMF (9.075-19.178 t·ha^{-1}) is closed to those of woodland (10.2 ± 6.4 t·ha^{-1}) while the carbon stocks in the agricultural lands are closed to shrub savannas (0.9 ± 1.2 t·ha^{-1}) found by Dimobe et al. (2018) in Dano (sudanian zone of Burkina Faso). The aboveground carbon stock in the Gourga managed forest (9.1-16.3 t C/ha) is near the range found in a stand of *G. senegalensis* (15.45-20,80 t C/ha) by Awé et al. (2024) and in a shrub savannah (12.52 t C/ha) by Awé et al. (2019) in Cameroon.

4.2 CO_2 Sequestred and Economic Potential

In semi-arid areas, afforestation with resilient species such as *Acacia nilotica* increases carbon assimilation and sequestration (Kumar et al. 2022). The CO_2 flux of *Combretum micranthum* and *Guiera senegalensis* has been studied well by Levy & Jarvis (1998). Stem respiration per hour is estimated at 3.97 mol CO_2 m^{-2}. The efflux of CO_2 is an important part of the annual carbon balance of the ecosystem [47]. The amount of CO_2 sequestered in AL2 (20.26-42.46 tCO_2 ha^{-1}) and in the GMF (33.27-70.32 tCO_2 ha^{-1}) is close to that found by [48] (24.71 tCO_2 ha^{-1}) in the parklands of Ouahigouya.

Table 4. Diversity of woody plants in agricultural lands and its controls

Species	**Frequency (%)**					
	AL1		**AL2**		**AL3**	
	Site	**Control**	**Site**	**Control**	**Site**	**Control**
Azadirachta indica A.Juss.	-	-	-	7.7	-	-
Balanites aegyptiaca (L.) Delile	-	-	-	23.1	-	-
Vachellia nilotica (L.) P.J.H.Hurter & Mabb. (syn. *Acacia nilotica* (L.) Willd. ex Delile)	-	-	-		-	40.0
Vachellia seyal (Delile) P.J.H.Hurter (*Acacia seyal* Delile)	32.0	-	-	15.4	-	-
Balanites aegyptiaca (L.) Delile	-	-	-	-	-	20.0
Cassia sieberiana DC.	8.0	-		7.7	-	40.0
Combretum glutinosum Guill. & Perr.	20.0	-	-	15.4	-	-
Combretum micranthum G.Don	32.0	-	-	-	-	-
Faidherbia albida	-	-	25	-	-	-
Lannea microcarpa Engl. *&* K.Krause	-	-	-	-	28.0	-
Guiera senegalensis Lam.	-	-		7.7	-	-
Piliostigma reticulatum (DC.) Hochst.	8.0	-	-	23.1	43.0	-
Sclerocarya birrea Hochst.	-	-	-	-	14.0	-
Vitellaria paradoxa C. F. Gaertn.	-	-	75	-	-	-
Ziziphus mauritiana Lam.	-	-	-	-	14.0	-

AL1, AL2, AL3: Agricultural land number 1, 2 and 3.

Table 5. Woody biomass and its equivalent in tonnes of carbon in the different types of ecosystems

Parameters	**Specific allometrics equations**	**FAO1 allometric equation**	**FAO2 allometric Equation**	**FAO3 allometric equation**
Gourga managed forest (GMF)				
AGB/ha	15,202.9	15,586.4	32,129.9	27,246.4
BGB/ha	4,104.8	4,208.3	8,675.1	7,356.5
DM/ha	19, 307.7	19,794.8	40,804.9	34,602.9
Total DM	521,308.3	534,459.3	1,101,732.6	934,277.7
t C/ha	9.075	9.304	19.178	16.3
GMF t C	245.0	251.2	517.8	439.1
Control of GMF				
AGB/ha	929.5	989.6	2 316.4	1 599.6
BGB/ha	251.0	267.2	625.4	431.9
DM/ha	1,180.5	1,256.8	2,941.8	2,031.4
t C/ha	0.555	0.591	1.383	0.955
Agricultural land 1 (AL1)				
AGB/ha	604.9	1,546.3	3,415.4	2,356.7
BGB/ha	163.3	417.5	922.2	636.3
DM/ha	768.2	1,963.8	4,337.6	2,993.0
Total DM	23,815.7	60,876.9	134,466.1	92,782.5
t C/ha	0.361	0.923	2.039	1.407
AL1 t C	11.2	28.6	63.2	43.6
Control of AL1				
AGB/ha	0.0	0.0	0.0	0.0
BGB/ha	0.0	0.0	0.0	0.0
DM/ha	0.0	0.0	0.0	0.0
t C/ha	0.0	0.0	0.0	0.0
Agricultural land 2 (AL2)				
AGB/ha	9,258.2	9,258.2	19,398.4	18,158.5
BGB/ha	2,499.7	2,499.7	5,237.6	4,902.8
DM/ha	11,758.0	11,758.0	24,635.9	23,061.3
Total DM	47,031.9	47,031.9	98,543.8	92,245.1
t C/ha	5.526	5.526	11.579	10.839
AL2 t C	22.1	22.1	46.3	43.4
Control of AL2				
AGB/ha	986.1	1,528.3	2,647.1	2,264.0
BGB/ha	266.3	412.6	714.7	611.3
DM/ha	1,252.4	1,941.0	3,361.8	2,875.3
t C/ha	0.589	0.912	1.580	1.351
Agricultural land 3 (AL3)				
AGB/ha	305.2	186.1	362.1	249.1
BGB/ha	82.4	50.2	97.8	67.3
DM/ha	387.6	236.3	459.9	316.3
Total DM	1,550.3	945.2	1,839.5	1,265.3
t C/ha	0.182	0.111	0.216	0.149
AL3 t C	0.4	0.3	0.5	0.3
Control of AL3				
AGB/ha	172.7	148.2	340.0	205.3
BGB/ha	46.6	40.0	91.8	55.4
DM/ha	219.3	188.2	431.8	260.7
t C/ha	0.103	0.088	0.203	0.123

AGB: Aboveground biomass in kg; BGB: Belowgroung biomass in kg, DM: dry matter in kg; t C/ha: metric tonne of carbon per hectare

Table 6. Carbon sequestration and associated economic values for the different study sites (in USD)

Parameters	Specific allometrics equations	FAO1 allometric equation	FAO2 allometric Equation	FAO3 allometric equation
Gourga managed forest (GMF)				
t CO_2/ha	33.27	34.11	70.32	59.63
Total t CO_2 sequestered	898.4	921.1	1 898.7	1 610.1
Average t CO_2 sequestered /year	20.0	20.5	42.2	35.8
Minimum value/year	599	614	1 266	1 073
Maximum value/year	3 693	3 787	7 806	6 619
Control t CO_2/ha	2.03	2.17	5.07	3.50
Difference between GMF and control t CO_2/ha/year	0.7	0.7	1.5	1.2
Minimum value for CO_2 sequestration due to restoration/year	562	575	1175	1010
Maximum value for CO_2 sequestration due to restoration/year	3468	3546	7243	6231
Agricultural land 1 (AL1)				
t CO_2/ha	1.32	3.38	7.48	5.16
Total t CO_2 in AL1	41.0	104.9	231.7	159.9
Average t CO_2 sequestered/year	1.5	3.9	8.6	5.9
Minimum value/year	46	117	257	178
Maximum value/year	281	719	1588	1096
Control t CO_2/ha	0.0	0.0	0.0	0.0
Difference between AL1 and control t CO_2/ha/year	0.05	0.13	0.28	0.19
Minimum value for CO_2 sequestration due to restoration/year	46	117	257	178
Maximum value for CO_2 sequestration due to restoration/year	281	719	1588	1096
Agricultural land 2 (AL2)				
t CO_2/ha	20.26	20.26	42.46	39.74
Average t CO_2 sequestered/year	7,4	7,4	15,4	14,5
Minimum value/year	221	221	463	434
Maximum value/year	1363	1363	2856	2674
Control t CO_2/ha	2.16	3.34	5.79	4.96
Difference between AL2 and control t CO_2/ha/year	1.6	1.5	3.3	3.2
Minimum value for CO_2 sequestration due to restoration/year	198	185	400	379
Maximum value for CO_2 sequestration due to restoration/year	1218	1138	2466	2340
Agricultural land 3 (AL3)				
t CO_2/ha	0.67	0.41	0.79	0.55
Average t CO_2 sequestered/year	0.15	0.09	0.18	0.12
Minimum value/year	4	3	5	4
Maximum value/year	27	17	33	22
Control t CO_2/ha	0.38	0.32	0.74	0.45
Difference between AL3 and control t CO_2/ha/year	0,02	0,00	0,00	0,01
Minimum value for CO_2 sequestration due to restoration/year	1,93	0,55	0,32	0,64
Maximum value for CO_2 sequestration due to restoration/year	11,92	3,41	1,99	3,94

t CO_2/ha: metric tonne of carbon dioxyde per hectare; t C/ha: metric tonne of carbon per hectare

There are a number of ecosystem benefits, including carbon sequestration, from restoring plant cover. Plants, especially woody plants, store CO_2 in the atmosphere. This reduces greenhouse gas levels Rodríguez-Calcerrada et al. (2014). According to the IPCC (2023) the net anthropogenic greenhouse gas emissions of the world is estimated to be 59 ± 6.6 $GtCO_2$-eq in 2019, 54% (21 $GtCO_2$-eq) higher than in 1990. The IPCC scenarios show that there is a rapidly closing window of opportunity to secure a liveable and sustainable future for all with a very high level of confidence IPCC (2023). Emitting one tonne of carbon into the atmosphere has warming consequences that cannot be offset by sequestering one tonne of carbon (Sierra et al. 2021). Sequestering atmosphere carbon by planting and preserving trees can help mitigate climate change but the best strategy is to decrease fossil fuel combustion in the first place.

Carbon storage in woody biomass only counts if such biomass is not harvest for cooking or heating purposes, which would release the carbon stored back into the atmosphere. Net carbon stored every year in woody biomass could qualify for carbon payments. This is in line with economic theory that prescribes that only additional carbon stored is paid for in a given year.

The implementation of the REDD+ mechanism is based on the quantification of carbon stored in order to propose compensation schemes (Awé et al. 2019). Neya et al. (2020) showed that if the price of one tonne of additional CO_2 sequestered per hectare is around US$4.00, the carbon payment system of the REDD+ initiative can, in theory, compensate smallholders for their efforts in planting and maintaining trees. Thus, the use of $30 as the price of REDD+ (United Nations Environment Programme 2023) in this paper allows for an incentive price that could largely compensate smallholders' efforts if a project decides to finance a carbon project. It is important to note that REDD+ does not pay for carbon stocks, but for the enhancement of existing forest carbon stocks (SN-REDD+. Strategie 2022). It is this payment based on the performance of forest systems (additional carbon) that is presented in this article. Most articles on carbon sequestration only estimate the total value of carbon sequestered, without knowing how much additional carbon is sequestered per year. The payments based on the current carbon market are far from sufficient to provide the necessary incentives, since the land restorer makes a net loss compared to “business as usual” (Kaboré et al. 2024).

One problem also is who receives the payment for carbon storage: national governments or small land users? If national government claim payments on the international market, then land users do not have an incentive to store carbon (plus land tenure insecurity may be a disincentive to plant more trees on their land). Small land users do not typically have access to international carbon markets, so they would require some form of broker to help them out with cashing in carbon payments against a small fee.

The various methods used to remove CO_2 from the atmosphere are not of equal maturity, durability, co-benefits or cost. The capture of CO_2 by photosynthesis is greatly enhanced. It is possible to protect forests for many decades, but it is virtually impossible to guarantee protection for more than a thousand years (Michaelowa et al. 2023). This will be one of the shortcomings of carbon sequestration in plant biomass.

5. CONCLUSION

The study quantified the carbon stock sequestered in woody biomass and assessed the economic value of additional carbon sequestered each year in the semi-arid region of Burkina Faso. The various techniques of forest and landscape restoration (FLR), such as zaï and stone barriers, have made it possible to restore both forest and agricultural lands. The woody plants growing in these ecosystems stored between 0.02 tonne and 1.5 tonne of CO_2 per hectare per year. This study contributes to the scaling up of FLR activities needed to convince potential investors of the merits of funding this type of intervention. Based on the economic value of carbon stored in plant biomass, farmers restoring degraded land could be encouraged to keep trees on their farms. Future research should focus on rethinking financial incentives for restoring and growing woody plants on degraded lands in Burkina Faso.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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