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Potential of *Alnus acuminata* based agroforestry for carbon sequestration and other ecosystem services in Rwanda

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Abstract *Alnus acuminata* Kunth. (alnus) is widely used in agroforestry systems across the globe and is believed to provide multiple ecosystem services; however, evidence is lacking in agroforestry literature to support the perceived benefits, particularly in Rwanda. To understand carbon sequestration potential and other benefits of alnus, a household survey, tree inventory and destructive sampling were conducted in north-western Rwanda. Over 75% of the respondents had alnus trees in their farms. The trees provide stakes for climbing beans, firewood and timber. They also improve soil fertility and control soil erosion. Farmers had between 130 and 161 alnus trees per hectare with an average height of 7.7 ± 0.59 m and diameter at breast height of 16.3 ± 1.39 cm. The largest biomass proportion was found in stems (70.5%) while branches and leaves stock about 16.5 and 13% of the total biomass, respectively. At farm level, aboveground biomass of alnus trees was estimated to be 27.2 ± 0.7 Mg ha^{-1} representing 13.6 Mg of carbon (C) per hectare. Biomass carbon increased with tree size, from 7.1 ± 0.2 Mg C ha^{-1} in 3 years old trees to 34.4 ± 2.2 Mg C ha^{-1} in 10 years old trees. The converse was observed with elevation; biomass carbon decreased with increasing elevation from 21.4 ± 1.29 Mg C ha^{-1} at low (2011–2110 m) to 9.6 ± 0.75 Mg C ha^{-1} in the high elevation (> 2510 m). In conclusion, alnus agroforestry significantly contributes to carbon sequestration, although the magnitude of these benefits varies with tree age and elevation. Planting alnus trees on farms can meet local needs for stakes for climbing beans, wood and soil fertility improvement, as well as the global need for regulation of climate change.

Keywords Aboveground biomass · Agroforestry · Carbon stock · Firewood · Stakes · Soil fertility

Introduction

Concerns about increasing atmospheric greenhouse gases have encouraged efforts to determine the contribution of different land uses to climate change mitigation through carbon storage. Most of the studies have evaluated the amount of carbon stored in forests

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or that can be released to the atmosphere when forests are cleared, and only few studies have so far considered the role of trees in agricultural landscapes. Constraints cited include limited information regarding the extent of agricultural landscapes with trees (Zomer et al. 2016) and inadequate methods for quantifying biomass in these landscapes (Kuyah et al. 2012). In the latter, the main constraints are lack of standardized methods and heterogeneity of smallholder farms that limit the application of well-established forest-based methods (Kuyah et al. 2013). Allometric equations developed for tree species and perennial crops found in agroforestry systems has allowed estimation of biomass and carbon stored in various agroforestry systems, such as scattered trees on farmland (Gebrewahid et al. 2018), rangelands (Feyisa et al. 2018), miombo woodlands (Kuyah et al. 2014) and coffee agroforestry systems (Negash et al. 2013; Tumwebaze et al. 2013). However, there are no allometric equations developed specifically for estimating biomass of trees in agricultural landscapes in Rwanda, making it difficult to determine the contribution of Rwandan agroforestry systems to climate change mitigation.

Agroforestry practices mitigate climate change while contributing to livelihoods of smallholder farmers (Reppin et al. 2019). Reviews estimate that smallholder agroforestry systems in Africa could potentially sequester between 1 and 18 Mg C ha^{-1} in aboveground biomass (Montagnini and Nair 2004). Even though these estimates do not consider potential emissions associated with management of agroforestry systems or disturbance, they are within ranges (4.07 and 17 Mg C ha^{-1}) reported by studies evaluating carbon storage of farms in east Africa (Henry et al. 2009; Reppin et al. 2019). The potential of agroforestry to sequester carbon, however, varies depending on climatic conditions, age and management of trees in the landscape and the method used to quantify biomass (Montagnini and Nair 2004). The type of tree species has been shown to have the most impact on carbon storage as it limits the maximum amount of carbon that can be stored under favorable conditions (Kuyah et al. 2014).

Alnus is among trees that have been recommended for agroforestry in the tropics (Russo 1990; Okorio et al. 1994). In Rwanda, alnus has been widely promoted under climate change mitigation and adaptation programs (Byamukama et al. 2011; Mukuralinda et al. 2016). The tree is found in most household farms in northern and western Rwanda, where it is planted on terraces, as contour hedgerows and in small farm woodlots (Mukuralinda et al. 2016). It also occurs as plantations on degraded landscapes, as trees scattered on crop fields and in homegardens around the homestead (Ndayambaje et al. 2012, 2013).

The potential of alnus for carbon sequestration is high, owing to its fast-growing nature (Rytter and Rytter 2016). However, no study has specifically assessed carbon sequestration potential of alnus under agroforestry management in Rwanda or East Africa. Available studies on the species focused on standing volume for purposes of estimating wood fuel in Rwanda (Ndayambaje et al. 2013), growth and leafing phenology in semiarid (Thika and Naro Moru) areas in Kenya (Muthuri et al. 2004, 2005) and firewood production in Uganda (Siriri et al. 2013). The influence of management on carbon storage potential of alnus is also not known. Generally, agroforestry management influences biomass of trees due to competition with crops and management practices aimed at increasing crop productivity (Nicodemo et al. 2016). Practices such as pollarding and pruning are used to regulate the degree of competition with adjacent crops, and to provide firewood and stakes. Pruning changes the allometry of trees and the partitioning of biomass among components of the tree (Kuyah et al. 2012). In addition, changes in leafing phenology (being semi-deciduous to deciduous in some areas) affects assimilation and water use efficiency in these trees (Muthuri et al. 2009) and hence growth and biomass. It is therefore important to estimate the distribution and biomass carbon of alnus in smallholder systems in Rwanda.

Agroforestry features prominently in Rwanda's national policies on land use, climate change, agriculture and forestry (Ministry of Environment 2018) having been identified as one of the key approaches for increasing agricultural productivity while harnessing ecosystem services provided by trees (Mukuralinda et al. 2016). These policies embed agroforestry as part of land management on hills, given its contribution to soil protection and encourage farmers to grow and manage trees on farms in order to meet the increasing demands of tree products (Iiyama et al. 2018). Planting trees on farms is also encouraged by government agencies, community-based and international organizations working on food security, land restoration and climate change. However, lack of reliable estimates of the distribution and carbon density of dominant tree species on farmland limits our ability to project agroforestry's potential for climate change mitigation. This study aims at assessing the potential of *alnus*-based agroforestry for carbon sequestration and other ecosystem services in Rwanda. The study addressed following research questions: (1) how is biomass carbon distributed along elevation gradient? (2) How is alnus carbon stock influenced by the size and age of alnus trees in the region? (3) What are the benefits that motivated farmers to plant alnus trees in their farmlands?

Materials and methods

Study site

The study was conducted in Bugeshi sector located in Rubavu district and Karago sector in Nyabihu district (Fig. 1). Bugeshi sector is located at 1° 31′ 52″ S; 29° 21′ 39″ E with an elevation of 2319 m while Karago sector is located at 1° 38′ 49″ S and 29° 30′ 16“ E with an elevation of 2415 m. The two sectors receive 900 to 1500 mm rainfall per annum, with annual temperature varying from 10 to 15 °C in Bugeshi sector and 16–20 °C in Karago sector. Although Bugeshi sector is at lower elevation compared to Karago, it has lower temperatures because of its location in the vicinity of Karisimbi volcano (elevation: 4750 m) which is known for its cold wind and low temperatures. Soils in Karago and Bugeshi sectors are classified as Alisols and Andosols, respectively (Verdoodt and Van Ranst 2006). In both sectors, the vegetation is dominated by many small plantation forests of *Markhamia lutea*, *Grevillea robusta* and *Eucalyptus* spp. (Habiyaremye et al. 2015). Agriculture is the main economic mainstay in the region, practiced for both subsistence and income generation. Tea, coffee, pyrethrum, vegetables, fruits and flowers are grown for export while potato, beans, maize and wheat are grown for subsistence and local market.

Farm selection, household survey and tree inventory

A household survey was conducted between June and July 2019 from all the seven cells of Bugeshi sector (Buringo, Hehu, Butaka, Mutovu, Kabumba, Rusiza and Nsherima) and three cells in Karago sectors (Kadahenda, Gihirwa and Cyamabuye). The selection

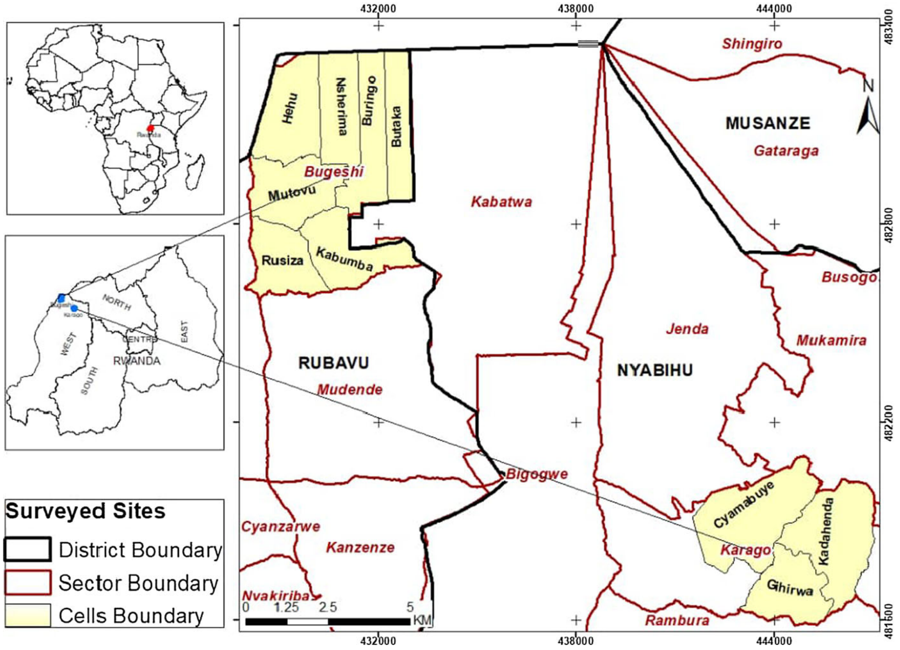

Fig. 1 Location of study sites in north-western Rwanda

of these cells was purposively done because of the predominance of alnus trees in the farmlands. Farmers were randomly selected for the interview from the list obtained from community leaders in the two sectors. Eighty four farmers from Bugeshi sector and 57 in Karago sector, which ensured at least 10% of the farmer households were sampled in each sector. The total number of farmers interviewed was 141. The selected households were interviewed using structured survey questionnaires to elicit information relevant to the study objectives. However, prior to the field interviews, a test survey was conducted with 10 farmers to evaluate the questionnaire, and based on these responses, some minor modifications were made prior to conducting the full survey. The test survey period also permitted standardization of the interview technique for all interviewers.

Tree inventory was only conducted in Rubavu district in the cells of Bugeshi sector. A two-step process was used to collect inventory data. First, all alnus trees within the farm were identified and their diameter at breast height (DBH in cm) and height (m) measured using calipers and calibrated pole. DBH was measured over-bark at a height of 1.3 m above the ground level, with the caliper held tight and horizontal to the stem axis. The diameter was measured twice (crosswise) to account for irregular stems. Tree height was measured from the base of the tree to the tip using a 50 m-measuring tape. In the case of tall trees, height measurement was determined with the help of professional climbers. A professional climber held a calibrated stick so that the zero mark reaches highest tip of the tree. Measurements are then taken from the tip of the tree downward, and summed up to obtain the total height of the tree. This method is recommended where tools such as laser rangefinders or optical dendrometers are not available to make readings at ground level (MacFarlane et al. 2014). Methods outlined by Dietz and Kuyah (2011) were used to maintain consistence in obtaining diameter and height measurements for irregular trees in agricultural landscapes. Crown area was not determined for inventory trees as most of the trees are heavily managed by pruning to provide firewood, stakes for climbing beans and to reduce competition with crops. The niche of the trees within the farm (i.e. whether the tree was planted on boundary, contour hedges, terraces, scattered in crop field or homestead) was documented. The age of the tree was recorded as reported by farmers and varied between 1 and 10 years. Second, the inventory team walked around the farm to identify and document the names of all other tree species found in the farm. The Global Positioning System (GPS) coordinates of each tree measured were recorded and the size of the farm determined by walking around the farm with a handheld GPS device.

Biomass sampling

A total of 172 trees were harvested from volunteer farms in Karago sector, Nyabihu district. Prior to felling trees, DBH and canopy dimensions were measured. DBH was measured using a caliper while the crown diameter was measured twice using a 50 m measuring tape: the largest diameter (l) and the diameter perpendicular to it (w). Crown area (m^2) was calculated using the formula for an ellipse: $ca = \pi(l/2) \times (w/2)$. Trees were cut at the lowest point and the total height determined using 50 m measuring tape. Felled trees were separated into stem, branches and twigs; larger stem and branches were cut into weighable sections. The stem and branches were bundled separately, and the twigs put in a sack and each weighed using a spring balance. Discs measuring 2.5 cm thick were taken from the base, middle and top of the stem and their fresh weight determined on a 3 ± 0.01 kg scale. Subsamples from branches and twigs including leaves were also taken and weighed in the field. Subsamples were oven-dried in the laboratory at 105 °C (stem discs and branches) and 70 °C (twigs) to constant weight. Subsample dry weights of the stem, branches and twigs were determined, and the ratio of dry-to-fresh weights used to convert the fresh weights of the components to dry weights (biomass). Aboveground biomass (AGB) of harvested trees was obtained by adding up the biomass of stem, branches and twigs.

Estimation of biomass carbon

Data was screened to clean up and to determine outliers and test for normality. Descriptive statistics (means and standard error, SE) for dendrometric variables, biomass and carbon stock were calculated for trees inventoried on farms and harvested trees. Stem diameter was converted to cross-sectional area at breast height to obtain basal area of trees (Torres and Lovett 2013):

$$BA\,(\mathrm{m}^2) = \pi * \frac{DBH\,(\mathrm{cm})^2}{4} \qquad (1)$$

where BA is the basal area usually expressed in m^2; $\pi = 3.14$; DBH = diameter at breast height and is measured in cm. By converting the cm^2 to m^2 the formula of the basal area becomes:

$$BA = \pi * \frac{DBH^2}{40000}\ \mathrm{m}^2\mathrm{ha}^{-1} \qquad (2)$$

Allometric equations developed for tropical moist forest (Brown 1997) was used to estimate aboveground biomass (AGB) of inventory trees:

$$\mathrm{AGB} = \exp[(-2.134 + 2.530 * \mathrm{LN(DBH)}] \qquad (3)$$

where LN is natural logarithm. This equation was selected since there were no suitable species-specific allometric equations for alnus in literature. The equation (power-law model) was considered most appropriate as it includes DBH alone as the predictor variable. Belowground biomass was calculated as a fraction (26%) of aboveground biomass (Mokany et al. 2006). Total biomass was obtained as the sum of above- and below-ground biomass. Carbon stored in the trees was calculated by multiplying the sum of the total biomass with a carbon fraction of 0.5 (Smith et al. 2014). The amount of CO_2 sequestered in aboveground biomass was estimated by multiplying the weight of carbon in the trees by the ratio of CO_2 to C (44/12 = 3.67). The mean annual carbon increment was estimated by dividing the amount of carbon sequestered by the age of the tree. Significant difference means were separated using Fishers protected Least of significant test (LSD) at $p = 0.05$. All statistical analyses were done in R software version 3.5.1 (Team 2018).

Results

Uses and benefits of alnus in Rwanda

The results revealed a limited variety of tree species on farms in the study sites. More than 78% of the respondents reported alnus as the most abundant tree species on their farms, followed by *Acacia angustissima* (6%), *Erythrina abyssinica* (4.9%) and *Vernonia amygdalina* (2.7%). Other tree and shrub species occasionally mentioned were *Discopodium penninervium*, *Calliandra calothyrsus*, *Tetradenia riparia*, *G. robusta*, *Eucalyptus* spp. and *Persea americana* (avocado).

The majority of farmers (81.5%) practiced tree-crop integration while a few of them (16.4%) practiced tree-crop-livestock integration. Only 1.4% of the farmers planted trees alone as woodlots. Trees in the farms surveyed were mainly planted as contour hedgerow (45%) or scattered within the farm (32.4%). Majority of the households (82%) own small pieces of lands of about 0.3 ha. Farmers listed 11 major benefits derived from agroforestry trees (Fig. 2). When asked about the purpose of trees on their farms, respondents mentioned provision of stake for climbing beans, soil erosion control, soil fertility improvement, provision of timber, firewood, poles and fodder (Fig. 2).

Alnus tree inventory for biomass estimates

A total of 1767 trees were measured over an area of 13 ha covering 84 farms with an elevation gradient of 2011 to 2634 m above sea level. Descriptive statistics of the variables from the inventory are summarized in Table 1. The number of alnus trees per farm ranged from 10 to 40 while tree density was between 130 and 161 individuals per hectare. Majority of the trees were of medium age, planted between 2009 and 2018. Across the landscape, the DBH of the trees inventoried ranged between 3.5 to 30.7 cm, while the tree height ranged between 3.3 and 15.2 m. When the locations were compared, Kabumba cell had significantly larger (22.2 ± 0.4 cm) and taller trees (9.9 ± 0.22 m) compared to other cells ($p < 0.001$). However, higher tree density was found in Rusiza cell. Basal area varied across the locations, ranging from 1.9 to 6.4 $\mathrm{m}^2\ \mathrm{ha}^{-1}$ with a landscape level mean of 3.6 $\mathrm{m}^2\ \mathrm{ha}^{-1}$. Aboveground biomass of alnus trees found in farms ranged between 11.8 and 53.6 $\mathrm{Mg\ ha}^{-1}$ (mean of 27.2 $\mathrm{Mg\ ha}^{-1}$). This represents a mean annual increment in aboveground biomass carbon stock of 2.9 Mg C $\mathrm{ha}^{-1}\ \mathrm{year}^{-1}$and belowground biomass of 7.1 $\mathrm{Mg\ ha}^{-1}$. The total biomass (above- and belowground) on farms with alnus was estimated at 34.3 $\mathrm{Mg\ ha}^{-1}$ representing the carbon stock of 17.1 Mg C ha^{-1} or 62.9 Mg CO_2 eq ha^{-1}.

The mean annual increment (MAI) in carbon stock was lower in young trees and increased with the age of trees. For example, the MAI in carbon stock averaged

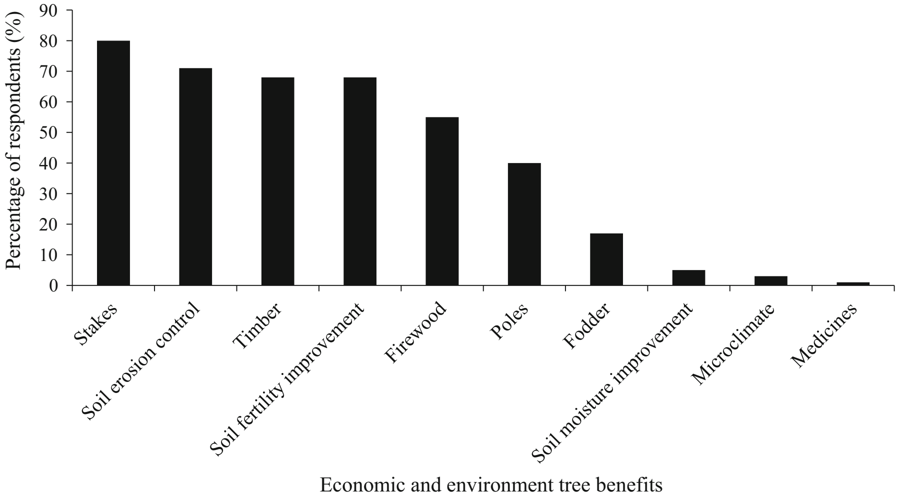

Fig. 2 Uses and benefits that farmers derive from agroforestry trees in Rwanda

Table 1 Descriptive statistics of the variables from alnus tree inventory. Errors are given as standard errors (± SE) of means

Location	Number of farms	Farm size (ha)	Stems (ha^{-1})	Age of tree (years)	Tree height (m)	DBH (cm)	BA (m^2 ha^{-1})	AGB (Mg ha^{-1})
Buringo	12	0.17 ± 0.002	133.9 ± 0.9	3 ± 0	7.3 ± 0.12	12.9 ± 0.3	2 ± 0.12	13.4 ± 1.1
Butaka	11	0.17 ± 0.002	140.9 ± 1.4	3.2 ± 0.03	7 ± 0.13	14.1 ± 0.3	2.4 ± 0.08	15.5 ± 0.7
Hehu	12	0.2 ± 0.002	131.5 ± 1.6	3.7 ± 0.05	6.9 ± 0.09	14.2 ± 0.2	2.2 ± 0.07	14.2 ± 0.5
Kabumba	14	0.17 ± 0.001	151.5 ± 2.6	7 ± 0.15	9.9 ± 0.22	22.2 ± 0.4	6.4 ± 0.24	53.6 ± 2.4
Mutovu	13	0.12 ± 0.002	159.4 ± 1.5	4.5 ± 0.13	8.3 ± 0.22	18 ± 0.5	5 ± 0.27	40.1 ± 2.7
Nsherima	10	0.16 ± 0.003	130.4 ± 2.0	3.5 ± 0.06	6.3 ± 0.11	13.2 ± 0.3	1.9 ± 0.07	11.8 ± 0.5
Rusiza	13	0.13 ± 0.003	161 ± 2.9	4.7 ± 0.16	7.6 ± 0.17	18.5 ± 0.5	4.8 ± 0.19	37.0 ± 1.7

2.4 Mg C ha^{-1} $year^{-1}$ in trees aged between 1 and 5 years, and 4.03 Mg C ha^{-1} $year^{-1}$ in trees aged between 5 and 10 years old. The amount of biomass carbon in young trees (1 to 5 years) was 9.6 ± 0.21 Mg C ha^{-1}, and increased to 33.8 ± 0.06 Mg C ha^{-1} in trees between 5 and 10 years (Fig. 3). Majority of the trees in the landscape were 3 to 5 years old. There was a negative relationship between aboveground biomass and elevation. Aboveground biomass carbon decreased with increasing elevation from 21.4 ± 1.29 Mg C ha^{-1} at low (2011–2110 m) to 9.6 ± 0.75 Mg C ha^{-1} in the high elevations (> 2510 m) (Fig. 4). Similarly, the number of trees per farm increased from 188 trees per farm at low elevations to 444 trees per farm at middle elevations; then decreased (76 trees per farm) at high elevations.

Tree growth and productivity

A total of 172 alnus trees were harvested on farms for evaluation of growth and productivity in the study area (Table 2). The age of the trees was 3 years (39), 4 years (89) and 5 years (44). Trees were generally small to medium size (DBH > 23 cm) because most of Alnus were planted between 2009 and 2014. Basal diameter ranged between 10 and 25 cm (mean: 17.9 cm) while DBH varied between 7.3 and 22.7 cm (mean: 14.5 cm). The average height of the trees was 10.8 m with minimum and maximum values

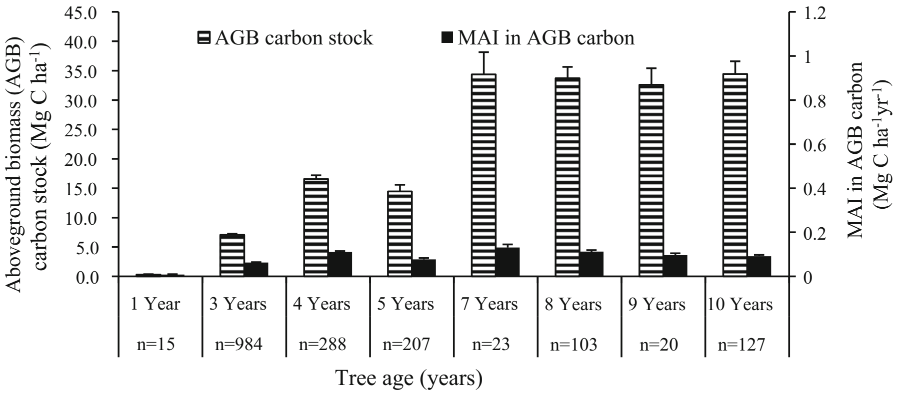

Fig. 3 Aboveground biomass (AGB) carbon stock and mean annual increment (MAI) in carbon for alnus trees of different ages in study sites. n represents the number of trees in each age group

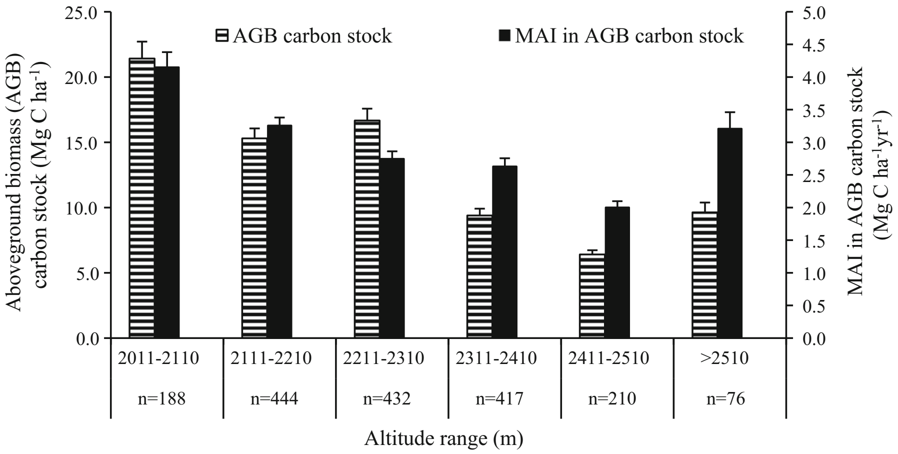

Fig. 4 Amount of carbon stored in alnus trees and mean annual increment (MAI) across elevation gradient (2011–2510 m) in the study sites. n represents the number of trees

Table 2 Summary statistics of the parameters of harvested alnus trees

Measured parameters	Min	Max	Mean ± SE
Basal diameter (m)	10	25	17.9 ± 0.4
Diameter at breast height (cm)	7.3	22.7	14.5 ± 0.3
Total height (m)	6.3	14.2	10.8 ± 0.1
Crown area (m^2)	5.4	35.2	20.4 ± 0.4
Stem biomass (kg tree^{-1})	15.0	93.7	54.9 ± 1.3
Branch biomass (kg tree^{-1})	2.5	25.9	12.9 ± 0.5
Leaf biomass (kg tree^{-1})	2.6	30.7	10.5 ± 0.4
Aboveground biomass (kg tree^{-1})	35.7	119.9	78.3 ± 1.5
Aboveground biomass carbon (kg tree^{-1})	17.8	59.9	39.2 ± 0.7
Aboveground CO_2 equivalent (kg tree^{-1})	65.4	219.9	143 ± 2.7
Carbon sequestration rate (kg tree^{-1} year^{-1})	13.1	73.3	36.6 ± 0.8

Numbers in the three columns represent mean (and standard error) of trees; Min represents the minimum values, Max the maximum values and SE the standard error of means

of 6.3 and 14.2 m respectively. Tree crowns were not large and ranged from 5.4 to 35.2 m^2 (mean: 20.4 m^2). The aboveground biomass per tree varied between 35.7 and 119.9 kg tree^{-1} (mean of 78.3 kg tree^{-1}). The largest biomass proportion was found in stems (70.5%) while branches and leaves held 16.5 and 13.0% of the aboveground biomass, respectively.

Discussion

Alnus is the dominant tree on farmland in the highlands of north-western Rwanda. This is because alnus is adapted to the climate of the region and attract many farmers due to its multiple benefits (Mukuralinda et al. 2016). Most farmers cited provision of stakes for climbing beans as the leading reason for planting alnus. This is consistent with findings by Uwineza et al. (2019) who reported the need for bean staking materials as a motivation for tree planting in the smallhoder farms in Rwanda. Planting of alnus for timber, poles and firewood is motivated by its fast growing nature compared to the majority of other tree species in the region. Farmers also plant alnus trees for environmental benefits such as soil erosion control and soil fertility improvement. These ecosystem services are linked to farmers' desire for improved crop yields via improvement of soil fertility (Ndoli et al. 2017), water regulation and control of soil erosion (Kuyah et al. 2019). Soil and water conservation benefits from alnus have previously been reported in Kenya (Muthuri et al. 2005) and Uganda (Okorio et al. 1994). The density of alnus trees as found during tree inventory (130–161 trees ha^{-1}) is in the range of densities of trees reported on croplands in southern Rwanda and depended largely on the size of the land owned by the farmer and other socioeconomic characteristics such as wealth category (Bucagu 2013).

The rate of biomass accumulation increased with tree size and age. These results are compatible with the metabolic scaling theory which predicts that mass growth rate of a tree should increase continuously with tree size and age (Enquist et al. 2000). Similar findings have been reported by various researchers who found that tree growth increased with increase in tree size, and that large trees fix large amounts of carbon compared to smaller trees (Stephenson et al. 2014; Sheil et al. 2017). However, maintaining alnus trees to an advanced age on farmland may not be an easy task considering farmers' pressure on planted trees to satisfy their needs in tree products such stakes for climbing beans, firewood for cooking, and timber for construction. Based on our informal discussion with farmers during tree inventory, tree products are obtained by branch pruning or tree coppicing. This may positively or negatively affect the amount of carbon sequestered by alnus trees depending on how the management practices are conducted (Yadav et al. 2016). Therefore, attention needs to be focused on improving farmers' knowledge on agroforestry tree management practices to enhance tree growth and biomass productivity. Moreover, alnus being the most abundant tree in the region, there is need to diversify tree species to reduce farmers' pressure on alnus trees and maintain them for long duration on farmlands.

Aboveground biomass carbon decreased with increase in elevation. Since the study area neighbors Karisimbi volcano situated at 4507 m above sea level, the cold temperatures that prevail as altitude increases may have slowed the growth of alnus trees and thus affecting the rate of biomass accumulation. Tree growth rates and biomass productivity may decline because of reduced air and soil temperatures, shorter growing seasons and the increased exposure to wind in high elevation regions (Coomes and Allen 2007). Similar results have been reported in Kilimanjaro, Tanzania, where tree biomass was higher at intermediate elevations and very lower at higher elevations (Ensslin et al. 2015).

Much of the biomass of alnus was held in the stem. The low biomass in branches and leaves can be attributed to farmer management such as pruning, coppicing and pollarding. Farmers remove branches to reduce light competition between trees and understory crops and as part of harvesting wood for firewood and stakes for climbing beans. In the study area, observations in the field indicated that farmers pruned trees leaving only 30% of the canopy. These results agree with the findings of Mensah et al. (2016) who reported that when trees grow larger, the contribution of wood biomass to the aboveground biomass increases at the expense of leaf biomass.

Alnus trees on farms in Rwanda hold substantial amount of carbon in aboveground biomass (13.6 Mg C ha^{-1}). This amount falls within the range of carbon stock of 7 to 28 Mg C ha^{-1} reported for agroforestry systems of Sub-Saharan Africa (Unruh et al. 1993). However, the values of carbon stock of alnus trees in our study were lower than those (29 to 53 Mg C ha^{-1}) observed in the humid tropical Africa agrosilvicutural system (Albrecht and Kandji 2003) and in traditional agroforestry systems in the tropics (145 Mg C ha^{-1}) (Kirby and Potvin 2007).

Comparing the amount of alnus biomass (78.3 kg tree^{-1} $\approx$ 12.6 Mg ha^{-1} for a density of about 161 tree ha^{-1}) estimated using destructive sampling approach and the biomass amount ($\approx$27.2 Mg ha^{-1}) estimated using inventory data (indirect method), the difference is high and reveals an important bias associated with the methods of biomass estimation (Sileshi 2014). Therefore, this pleads for the use of existing published equations when attempting to assess carbon sequestration potential of the target species in an agroforestry system (Walker et al. 2013).

Conclusion

This study investigated the potential of carbon sequestration and other benefits of alnus in the agricultural landscape of the highlands of northwestern Rwanda. Alnus dominates the landscape and is planted along contour hedges or scattered within the farms. The tree is mainly managed for provision of stakes for climbing beans, timber and firewood, soil erosion control and for improving soil fertility. Alnus in the agroforestry system contributed to carbon sequestration but the benefits vary with tree age and elevation. Although old trees sequestered higher amount of carbon than young trees, maintaining alnus trees to an advanced age on farmland may not be an easy task considering the farmers' pressure on planted trees to satisfy their needs in tree products. These are obtained through tree pruning and coppicing which may exert adverse effect on alnus trees depending on how the management practices are conducted. The amount of carbon sequestered was higher in lower elevations than that in higher elevation regions suggesting that variation in elevation can significantly affect alnus carbon stocks on farmland. Attention needs to be focused on improving farmers' knowledge on tree management practices to enhance alnus growth and biomass productivity. Beside, diversification of tree species on farmland may reduce farmers' pressure on alnus trees and at the same time fill the gap in high elevation regions where alnus is not well adapted.

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