International Journal of Research Publication and Reviews, Vol 4, no 2, pp 908-918, February 2023

International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Carbon Sequestration Potential of Open-Grown Red Alder (*Alnus rubra* Bong) in a Silvopastoral Agroforestry System in North Wales, United Kingdom

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ABSTRACT:

This study was conducted to determine and compare the carbon sequestration potentials of two forms of open-grown red alder (*Alnus rubra* Bong) trees through destructive sampling, in a lowland Silvopastoral agroforestry system in North Wales, United Kingdom. Determination of carbon and carbon dioxide contents was based on dry biomass and universal conversion factors. Results showed that 20 years after field planting, the mean aboveground carbon stock and sequestrated carbon dioxide of red alder was significantly greater in good form trees than in poor form trees as well as between their components. Mean aboveground carbon stock was found to vary from 65 kg C tree^{-1} (13 Mg C ha^{-1}) in poor form to 123 kg C tree^{-1} (25 Mg C ha^{-1}) in good form red alder trees, based on a stocking density of 200 stems ha^{-1}, which translates to a mean annual carbon stock increment rate of 1.23 Mg C ha^{-1} yr^{-1} and 0.65 Mg C ha^{-1} yr^{-1}, respectively, over the past 20 years. Correspondingly, sequestered carbon dioxide varied from 237 kg CO_2 tree^{-1} (48 Mg CO_2 ha^{-1}) in poor form trees to 450 kg CO_2 tree^{-1} (90 Mg CO_2 ha^{-1}) in good form trees, which translates to a mean annual carbon dioxide increment rate of 4.50 Mg CO_2 ha^{-1} yr^{-1} and 2.38 Mg CO_2 ha^{-1} yr^{-1}, respectively. Carbon and sequestrated carbon dioxide were largest in stems (69.97%), intermediate in branches (23.02%), and lowest in twigs (7.00%) for the two forms of red alder. This disparity was attributed to the morphological differences between the two forms of red alder trees, among others. These findings imply that open-grown multi-formed trees planted in Silvopastoral agroforestry ecosystem in the United Kingdom are potentially useful in storing additional carbon.

Keywords: agroforestry, silvopasture, biomass, carbon sequestration, open-grown tree, good form red alder, poor form red alder.

1. Introduction

The steady rise in atmospheric carbon dioxide (CO_2), the main greenhouse gas (GHG), to the atmosphere in recent times is causing a serious global concern. It is generally recognised that the emission of carbon dioxide is mainly as a result of worldwide burning of fossil fuels. Disturbances such as indiscriminate exploitation of forest resources, wildfire, pest and disease occurrences, and conversion to non-forest use, particularly infrastructure, agriculture and pastures, are the sources of carbon dioxide because total respiration or oxidation of plants, soil, and dead organic matter have surpassed net primary productivity (Houghton *et al*., 2001).

The mitigation of carbon dioxide emissions is also a global concern and has underscored the need to develop the skills for accurate measurement of carbon stored and sequestered in forests (Brown *et al.*, 1996; Kauppi and Sedjo, 2001). The United Nations Framework Convention on Climate Change and in particular the Kyoto Protocol (Breidenich *et al*., 1998) highlights the need to monitor, regulate and maintain forest carbon stock.

The process of photosynthesis in plants sequesters and stores Carbon (C) as biomass in different components of the tree. The absorption of CO_2 from the atmosphere and the sequestration and storage of C in different plant tissues as biomass result in the development of different tree components (Ali *et al*., 2014). Tree increases in growth as more CO_2 is absorbed and excess C is stored in different plant organs. Trees therefore act as a sink for CO_2 by fixing C and sequestering excess C as biomass in different tree sections. In a forest setting, the rate of C sequestration is a function of forest type, dominant species, density and age, along with the edaphoclimatic conditions, management, fertilization, and land preparation (Quinkenstein *et al*., 2009; Mosquera-Losada *et al*., 2011). The higher the quantity of tree biomass the higher the C sequestered in the whole tree as well as in the tree components (Huy and Anh 2008; Ali *et al*., 2014).

The importance of trees in the global C cycling is well recognised as the amount of C stored in plant biomass globally surpasses that of atmospheric CO_2. It has been reported that almost 90% of the plant biomass C is stockpiled in tree biomass (Ali *et al*., 2014), and that forest biomass represents about 44% of the globe forest C pool (Pan *et al*., 2011). Hence, trees play significant role in climate change mitigation. This stresses the imperative need to accurately regulate the amount of C stored and CO_2 sequestrated in specific forest ecosystems of which Silvopastoral agroforestry system is a part.

In an analysis report by the International Panel on Climate Change (IPCC) on Land-Use Change and Forestry, re-/afforestation, the conversion of agricultural land into agroforestry systems has been recommended as one of the measures to mitigate increasing CO_2 emissions (Godal, 2003; Jose and

Bardhan, 2012). Agroforestry, the integration of trees on farms or pastures is known to increase the amount of C sequestered compared to a monoculture field of crop plants or pasture (Sharrow and Ismail 2004; Kirby and Potvin 2007). Agroforestry systems (including silvopasture) can also sequester significant amount of C stored in both aboveground and belowground biomass and have therefore emerged as land use with the greatest potential for carbon sink because the integration of trees results in greater CO_2 sequestration from the atmosphere and thus enhance carbon storage in permanent tree components (Dixon 1995; Sampson 2001; Montagnini and Nair 2004).

In the light of the argument for the imperative need to monitor, regulate and maintain forest carbon stock, the Kyoto Protocol has led to greater worldwide attention being given to agroforestry as a strategy to sequester carbon. Amount of carbon sequestered in agroforestry has been estimated to range from 0.29 to 15.21 Mg C ha^{-1} yr^{-1} above ground, and 30–300 Mg Mg C ha^{-1} yr^{-1} up to 1 m depth in the soil (Pandey, 2002; Nair *et al*., 2010; Jose and Bardhan, 2012; Montagnini and Nair, 2004). Carbon sequestration potential in agroforestry systems in the tropical zone has been estimated to range between 21 and 240 t C ha^{-1}, achieved within a cutting cycle of ten or twenty years (Dixon 1995; Adesina *et al*., 1999; Montagnini and Nair 2004). while the estimates for Carbon sequestration potential in temperate climate agroforestry has been placed between 10 and 208 t C ha^{-1} over a longer cutting cycle of twenty to fifty years (Schroeder 1994; Dixon 1995; Turnock 2001; Montagnini and Nair 2004). Trees growing in agroforestry systems can therefore be crucial in national carbon budgets and the climatic regulation system.

Carbon sequestration is an important ecosystem service provided by Silvopastoral systems. Despite the recognition of these potentials and the paucity of data on carbon stored in open-grown trees on farms, there is a limited understanding of biomass and carbon sequestration in specific agroforestry practices from around the world (Jose and Bardhan, 2012; Kuyah *et al*., 2012). Furthermore, there is limited research investigating the C sequestration potential of Silvopastoral systems in temperate Europe. However, with increasing interest on farm forestry, agroforestry and extension of agricultural boundary in many countries, the interest in developing the potentials of such open-grown trees for carbon sequestration is on the rise (Kuyah *et al*., 2015). At present, there is increasing recognition of the value of such ecosystem service in the United Kingdom, in the context of increasing concerns about global climate change, provided by sustainable land management systems such as silvopasture. Silvopastoral systems are, therefore, believed to offer a low-cost method to sequester carbon because of their perceived ability for greater capture and utilization of growth resources (light, nutrients, and water) than single-species crop or pasture systems (Pandey, 2002; Montagnini and Nair, 2004).

Regardless of widespread recognition of agroforestry for carbon storage and more than 20 years of agroforestry research at the UK's Silvopastoral National Network Experiment (SNNE) there are still no actual baseline measurements of carbon storage capacities of the Silvopastoral agroforestry system. This study was conducted to determine and compare the carbon sequestration potentials of two forms of open-grown red alder (*Alnus rubra* Bong) trees in a lowland Silvopastoral system in North Wales, UK.

Since there is a dearth of information on carbon sequestration potential for red alder grown in agroforestry configurations in the UK, this study partially fills that deficiency and falls into site-specific studies as it is focused on the determination of carbon storage in a Silvopastoral National Network Experiment setting. The results of this study are expected to not only add to the body of knowledge on the potential of Silvopastoral agroforestry systems to sequester carbon but also serve as tool for policy makers for the formulation of appropriate environmental policy decisions.

It is hypothesised that the carbon stocks of the good form and poor form red alder samples do not differ significantly from each other.

2. Materials and methods

2.1. Study area description

The study was conducted in the years 2012 to 2014 at the United Kingdom's Silvopastoral National Network Experiment (SNNE), Henfaes in North Wales (Nworji, 2019), which is one of six National Network Experiments established across the country with trees planted at different arrangements and densities to investigate the potential of Silvopastoral agroforestry on UK farms (Sibbald and Sinclair, 1990). The site was established in 1992 on 14.47 ha of agricultural land at the Bangor University's Henfaes Silvopastoral Systems Experimental Farm (SSEF) (53°14′N 4°01′W), Abergwyngregyn, Gwynedd, North Wales (Figure 1).

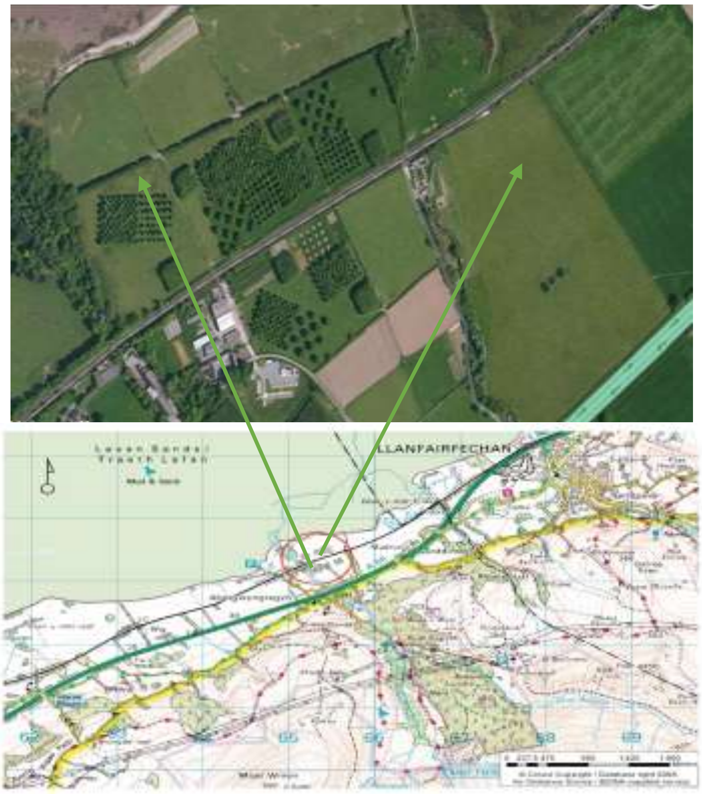

Figure 1. Location and aerial photograph of the Henfaes study site

The local climate in Henfaes is hyperoceanic, cool and temperate. Mean monthly temperature over the course of this study period was 10.6 oC, and temperatures of the warmest and coldest month was 20.0 ^{o}C in July and 3.4 ^{o}C in January, respectively. Average monthly precipitation ranged from a minimum of 25 mm in April to a maximum of 114 mm in December (Nworji, 2019). Soil is a fine loamy brown earth over gravel (Rheidol series) classified as a Dystric Cambisol (Teklehaimanot and Mmolotsi, 2007). The parent material consists of postglacial alluvial deposits from the Aber River with a water table that is between 1 and 6 metres deep (Teklehaimanot and Sinclair, 1993). Further details of the site topography, climatic conditions, soil geology and hydrology etc. can be found in Teklehaimanot *et al*., 2002 and Sibbald & Sinclair, 1990.

Red alder (*Alnus rubra*) and sycamore (*Acer pseudoplatanus*) were planted on the site at establishment in 1992 at different configurations to investigate their use in agroforestry systems (Sibbald *et al*., 2001). Both species were chosen because they are fast growing broadleaf, medium strength with potential to grow well over the wide range of sites represented in the Network. The blocks were 4,225 m2 (0.42 ha) each and sown to a mixture of perennial ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.) at establishment of the farm. All treatments and controls are replicated three times in a complete randomised block design. The experimental area was rotationally grazed by sheep through the period of the study at average stocking rate of 0.5 to 1.0 AU per ha (Teklehaimanot *et al.*, 2002).

For the purpose of this study, due to limited time and resources, only the three-red alder (*Alnus rubra*) blocks were studied. Red alder (*Alnus rubra* Bong) was introduced to investigate the use of biological nitrogen fixation as an alternative to chemical fertilizer as well as for its rapid early growth rate, tolerance of wet sites and wide range of quality wood products. The red alder that was originally planted at 400 stems ha-1 across three blocks were selectively thinned to 200 stems ha-1 in 2000 and subsequently to 100 stems ha-1 in the winter of 2012, respectively, primarily to improve the health and productivity of both the trees and the understory pasture as well as to provide data for the construction of biomass allometric equations for open-grown red alder trees (Nworji, 2017, 2019). A detailed description of the experimental design and site characteristics is given on the Henfaes agroforestry website, which can be found in the reference (Henfaes, 2009).

2.2. Data collection

2.2.1. Selection and measurement of 'good' and 'poor' forms of trees

The destructive sampling method was adopted in order to determine the aboveground biomass (AGB), carbon stock (C) and carbon dioxide (CO_2) mitigation potential of the good and poor forms of red alder.

During summer (full leaf) season in 2012, the three blocks of red alder 200 stem ha-1 (400 stems ha-1 at the start of the experiment in 1992) at Henfaes research farm were inventoried. Then in the winter of 2012, the three 200 stem ha-1 blocks were thinned to 100 stem ha-1 during which ten good form and ten poor form of the red alder trees were randomly selected. The thinned trees were selected on the following criteria (Nworji, 2017, 2019):

- Good form trees generally free of defects, showing good health and expected to reach their full age and size potential, and chosen arbitrarily on the basis of their location.
- Poor form trees with moderate to high risk of failure: trees in obvious decline, or with significant health and/or irremediable structural defects, including advanced decay and crack, root problems, weak branch union, canker, poor architecture, stunted growth, and dead wood.
- Out-of-line trees irrespective of form.

2.2.2. Measurement of fresh weight

Before harvest, the 20 individual alder trees were measured for diameter at breast height (DBH) over-bark in cm using a diameter tape at 1.3 m above ground level while total height (HT) was measured in metres using a clinometer (Nworji, 2017, 2019). After felling, the fresh weight of each tree was determined on-site. The trees were segmented into their individual components: stems, branches, and twigs. To facilitate the weighing process, the stem and branches of each tree were cut into logs of varying sizes which could be lifted by hand while the twigs were chipped straight into a 1 m^3 bag. Fresh weights of the segmented logs and the chipped twigs were then obtained using the tractor-based weighing scales. The tractor-based weighing scales were accurate to 0.1 kg (Dietz and Kuyah, 2011).

2.2.3. Measurement of oven dry weight

Sampling for dry mass analysis was taken immediately after completion of measurement of fresh weight of each tree components. Representative subsamples of wood and twig were randomly collected from different sections of the stem, branches and twigs to take into account variations in moisture content. For stem sample, three discs of about 2 – 3 cm thick were cut from the lower, middle and upper portions of the stems, and for branch sample, four small discs were taken from different parts of the branches. About 500 g of twig sub-sample was collected from each tree in tared sample bags (Kuyah *et al*, 2012). The sub-samples from the segmented trees were collected in duplicates and stored in sealed polythene bags to prevent evaporation, and then taken immediately to the Henfaes research laboratory to determine gravimetric moisture content and dry weight, and to estimate the carbon storage capacity per tree and components (Nworji, 2017, 2019).

In the laboratory, the subsamples were weighed in situ using a 0.1 g precision scale. The volume of a disc was calculated as the cross-sectional area of the disc times the thickness (measured at four points, 90° to each other). The subsamples were oven-dried at a temperature of 105 °C for 48 hours and re-weighed daily until constant weight (measured to the nearest 0.1 g) was achieved for each sample (Ketterings *et al*., 2001; Nworji, 2017, 2019). The oven dry weights (biomass) of the subsamples obtained were then used to convert fresh weight into total oven dry weight for each tree using the following formula:

$$TDW = TFW * SDW / SFW \qquad (1)$$

Where: TDW is total dry weight; TFW is total fresh weight; SDW is absolute dry sample weight and SFW is fresh sample weight.

2.2.4. Estimation of carbon and carbon dioxide sequestered

Carbon (C) stocks of the sampled trees and their component parts were estimated based on their respective oven dry weights (biomass) (Nworji, 2017). The amount of carbon stored in the trees were determined by multiplying the oven dry biomass obtained from the sub-samples by an international standard conversion coefficient of 0.5 to determine tree component biomass C. This conversion factor indicates that 50% of the total tree biomass consists of elemental Carbon (Dixon *et al*., 1994; FAO 2004). The general formula for calculation of carbon stock is as follows:

$$CSi = TDWi * CFi \qquad (2)$$

Where: CSi is carbon stock of each component in kg; TDWi is total oven dry weight of each component in kg; and CFi is default carbon conversion coefficient in percent.

The amount of carbon dioxide that would be emitted to the atmosphere if the 20 sampled trees were cut down and burned completely was calculated by multiplying the weight of carbon by the ratio of CO_2 to C (44/12 = 3.6663) as follows:

$$\text{Weight Of Sequestered } CO_2 \text{ (Kg)} = \text{Weight Of Carbon In Tree (Kg)} * 3.6663 \qquad \textbf{(3)}$$

where 3.6663 is the universal conversion factor of C content values to CO_2 values. The factor 3.6663 is derived from a calculation measuring the atomic weights of Carbon, Oxygen and Carbon Dioxide and then calculating the ratio of the atomic weight of CO_2 (44) to the atomic weight of C (12) (Walker *et al*., 2011; Ali *et al*., 2014).

Separate biomass, C stock and sequestered CO_2 estimates were computed for the various tree components (stem, branches and twigs). The mean annual increments were computed by multiplying the aboveground biomass, carbon and carbon dioxide contents per tree by the tree density of 200 trees ha^{-1} and dividing the product by 20 years, the age of the trees at the time of study (Nworji, 2017).

2.3. Statistical Analyses

Statistical significance (*p<0.05*) was tested by applying independent sample *t*-tests. All statistical analyses were conducted using the SPSS version 22 software.

3. Results

3.1. Descriptive statistics of tree variables

The general properties of the variables, diameter at breast height (DBH), tree height (HT), basal area (BA), volume (V), crown area (CA), wood density (WD), and bifurcation ratio (BR) measured for each of the destructively sampled good form and poor form red alder trees, respectively are summarised in Table 1 and Appendix A.

Results of the dendrometric measurements show that stem diameter at breast height measurements ranged from 21 cm to 38 cm for the good form trees and from 13 cm to 29 cm for the poor form trees with coefficient of variation of 17.70% and 18.44%, respectively, whereas height varied from 11 m to 13.50 m for good form trees and from 9 m to 13 m for poor form trees with coefficient of variation (CV) of 6.39% and 11.32%, respectively. Tree basal area in the red alder blocks varied from 0.01 m^2 in poor form trees to 0.11 m^2 in good form trees, while tree volume ranged from 0.03 m^3 in poor form trees to 0.47 m^3 in good form trees. The mean value of the measured variables is greater in the good form trees than in the poor form trees. Again, among all the variables measured, tree height had the smallest CV (6.39% for good form trees and 11.32% for poor form trees) compared to other variables (Table 1) (Nworji, 2017, 2019).

Table 1: Summary of descriptive statistics for good form and poor form alder tree variables (n=20)

Variables	Form	No.	Minimum	Maximum	Mean	Stdev	CV (%)
DBH (cm)	Good	10	21.00	38.00	29.66	5.25	17.70
	Poor	10	13.00	29.00	23.00	4.24	18.44
HT (m)	Good	10	11.00	13.50	12.20	0.78	6.39
	Poor	10	9.00	13.00	11.13	1.26	11.32
BA (m^2)	Good	10	0.03	0.11	0.07	0.02	28.57
	Poor	10	0.01	0.07	0.04	0.01	25.00
V (m^3)	Good	10	0.13	0.47	0.29	0.11	37.93
	Poor	10	0.03	0.27	0.16	0.06	37.50
CA (m^2)	Good	10	21.21	62.84	53.45	12.23	22.88
	Poor	10	12.19	40.14	31.97	8.56	26.77
WD (kg/m^3)	Good	10	0.26	0.75	0.44	0.18	40.90
	Poor	10	0.15	0.62	0.39	0.15	38.46
BR	Good	10	2.00	5.00	3.22	0.94	29.19
	Poor	10	1.82	3.20	2.35	0.40	17.02

3.2. Aboveground biomass, carbon and carbon dioxide content

The results of the estimated aboveground biomass (AGB), carbon stock (C) and carbon dioxide (CO_2) mitigation potential of the good and poor forms of red alder (expressed in kg) are presented in Table 2 while the Mean biomass, carbon stock, carbon dioxide sequestration, and the annual increment of the aboveground components (expressed in Mg) are presented in Tables 3 and 4, respectively.

The estimated mean aboveground biomass per tree was 245.43 kg/tree (49.09 Mg ha^{-1}) for the good form trees, and 129.52 kg/tree (25.91 Mg ha^{-1}) for the poor form trees (Tables 2 and 3), which translates to a mean annual biomass increment rate of 2.46 Mg ha^{-1} yr^{-1} and 1.30 Mg ha^{-1} yr^{-1}, respectively, over the past 20 years (Table 4) (Nworji, 2017, 2019).

Using the default coefficient of 0.50 for the conversion of biomass to carbon (FAO 2004), the estimated mean aboveground carbon stocks per tree was 122.73 kg C/tree (24.55 Mg C ha^{-1}) for good form trees, and 64.76 kg C/tree (12.95 Mg C ha^{-1}) for poor form trees (Tables 2 and 3), which translates to a mean annual carbon stock increment rate of 1.23 Mg C ha^{-1} yr^{-1} and 0.65 Mg C ha^{-1} yr^{-1}, respectively, over the past 20 years (Table 4) (Nworji, 2017).

Mean stem, branch and twig carbon stock per tree were 85.86 kg C/tree, 28.26 kg C/tree and 8.59 kg C/tree, respectively, for good form trees, and 45 kg C/tree, 15.51 kg C/tree and 4.24 kg C/tree, respectively, for poor form trees (Table 2).

Using the universal conversion factor of 3.6663 for the conversion of carbon stock values to carbon dioxide values, the estimated mean aboveground sequestered carbon dioxide was 449.90 kg CO_2/tree (89.98 Mg CO_2 ha^{-1}) for good form trees, and 237.43 kg CO_2/tree (47.50 Mg CO_2 ha^{-1}) for poor form trees (Tables 2 and 3), which translates to a mean annual carbon dioxide increment rate of 4.50 Mg CO_2 ha^{-1} yr^{-1} and 2.38 Mg CO_2 ha^{-1} yr^{-1}, respectively, over the past 20 years (Table 4). Correspondingly, mean stem, branch and twig sequestered CO_2 per tree were 314.81 kg CO_2/tree, 103.59 kg CO_2/tree and 31.51 kg CO_2/tree, respectively, for good form trees, and 164.99 kg CO_2/tree, 56.88 kg CO_2/tree and 15.57 kg CO_2/tree, respectively, for poor form trees (Table 2) (Nworji, 2017).

Result of the independent-sample t-test for the comparison of the biomass, sequestered Carbon or Carbon dioxide of the two forms of red alder tree show significant difference between good form trees ($\bar{x}$ = 245.43, □ = 51.23, n = 10) and poor form trees ($\bar{x}$ = 129.52, □ = 42.19, n = 10), t (18) = 5.52, p < 0.05 (Tables 2, 3 and 4). Standard deviations were comparatively largest in stems, and least in twigs. Furthermore, component-wise, biomass and sequestrated carbon were largest in stems (69.97%), intermediate in branches (23.02%), and lowest in twigs (7.00%) for the two forms of red alder (Figure 2) (Nworji, 2017, 2019).

Table 2. Estimates of biomass dry weight, carbon content and carbon dioxide sequestration (mean ± standard deviation) of the aboveground components of the two forms of 20-year old red alder trees at the Henfaes SNNE (n = 20).

Component Variables	**Tree form**	**Biomass dry weight (kg)**	**C content (kg C)**	**CO_2 (kg CO_2)**
Stem	Good	171.73^a ± 35.66	85.86^a ± 17.83	314.81^a ± 65.38
	Poor	90.00^b ± 20.36	45.00^b ± 14.68	164.99^b ± 53.82
Branch	Good	56.50^a ± 11.89	28.26^a ± 5.94	103.59^a ± 21.79
	Poor	31.02^b ± 10.25	15.51^b ± 5.12	56.88^b ± 18.80
Twig	Good	17.19^a ± 3.70	8.59^a ± 1.85	31.51^a ± 6.79
	Poor	8.49^b ± 2.59	4.24^b ± 1.29	15.57^b ± 4.74
Total aboveground	Good	245.43^a ± 51.25	122.71^a ± 25.63	449.90^a ± 93.95
	Poor	129.52^b ± 42.19	64.76^b ± 21.10	237.43^b ± 77.35

^{ab} Means within a column followed by different letters vary significantly (*P < 0.05*)

Table 3. Mean biomass (Mg ha^{-1}), carbon stock (Mg C ha^{-1}), and carbon dioxide sequestration (Mg CO_2 ha^{-1}) of the aboveground components of the two forms of 20-year old red alder trees at the Henfaes SNNE.

Component Variables	**Tree form**	**Biomass (Mg ha^{-1})**	**Carbon (Mg C ha^{-1})**	**Carbon dioxide (Mg CO_2 ha^{-1})**
Stem	Good	34.35^a	17.17^a	62.96^a
	Poor	18.00^b	9.00^b	33.00^b
Branch	Good	11.30^a	5.65^a	20.72^a
	Poor	6.21^b	3.10^b	11.38^b
Twig	Good	3.44^a	1.72^a	6.30^a
	Poor	1.70^b	0.85^b	3.12^b
Total aboveground	Good	49.09^a	24.55^a	89.98^a
	Poor	25.91^b	12.95^b	47.50^b

^{ab} Means within a column followed by different letters vary significantly (*P < 0.05*)

Table 4. Mean annual biomass, carbon and carbon dioxide sequestration of the aboveground components of the two forms of red alder trees at the Henfaes SNNE

Form	**No of Tree/ha**	**Annual increase in Biomass (Mg ha^{-1} yr^{-1})**	**Annual increase in Carbon (Mg C ha^{-1} yr^{-1})**	**Annual increase in Carbon dioxide (Mg CO_2 ha^{-1} yr^{-1})**
Good	200	2.46^a	1.23^a	4.50^a
Poor	200	1.30^b	0.65^b	2.38^b

^{ab} Means within a column followed by different letters vary significantly (*P < 0.05*)

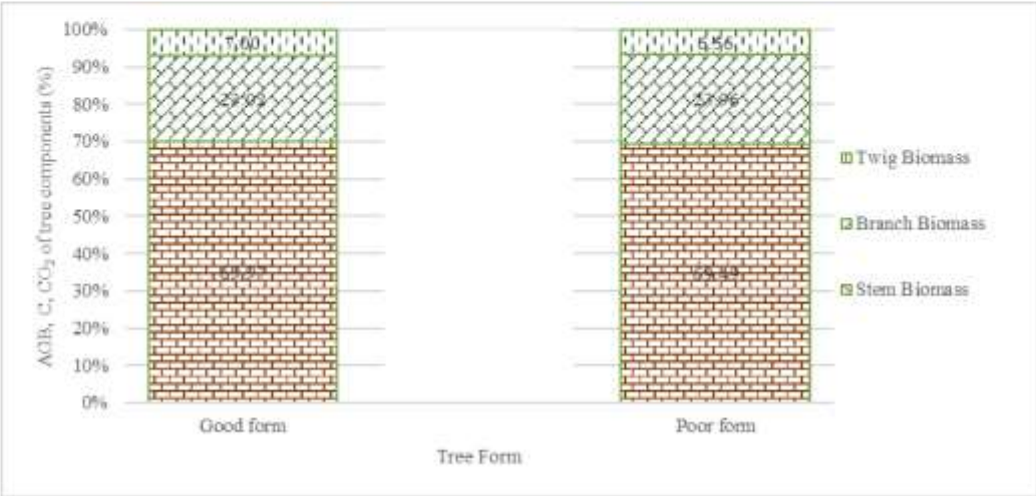

Figure 2: Percentage distribution of biomass (AGB), carbon (C) and carbon dioxide (CO_2) stock of aboveground tree components of the two forms of 20-year old red alder trees at the Henfaes SNNE.

4. Discussion

Generally, results of this study showed that biomass, carbon stock and sequestered carbon dioxide differed significantly ($p < 0.05$) between the two forms of red alder trees as well as between their components (Tables 2 and 3). On the average, aboveground carbon content varied from 12.95 Mg C ha-1 to 24.55 Mg C ha-1 between the two forms of trees, resulting in carbon dioxide mitigation potential of 47.50 Mg CO_2 ha^{-1} to 89.98 Mg CO_2 ha^{-1} (Tables 2 and 3). Aboveground carbon stock and sequestered carbon dioxide were found to be greater in good form trees than in poor form trees. Thus, the hypothesis of no significant difference between the carbon stocks of the two forms of red alder trees was therefore rejected in this study (Nworji, 2017).

The amount of biomass among the tree components for the two forms of red alder was found to be largest in stems, intermediate in branches, and lowest in twigs (Nworji, 2017, 2019). As expected, this result indicated that the component which constituted a maximum portion of biomass stored the maximum amount of carbon. Since the stem contributed more biomass as compared to other components hence it stored and sequestrated more carbon in its biomass compared to the branch and twig (Nworji, 2019). This disparity could be explained by the morphological differences between the two forms of trees. It is pertinent to recall that the tree forms were chosen on the basis of their conditions: Good form trees are generally free of defects, showing good health and expected to reach their full age and size potential while poor form trees are trees in obvious decline, or with significant health and/or structural impairments, and showing very little signs of life or remaining vitality, or with severe, irremediable structural defects, including advanced decay and crack, root problems, weak branch union, canker, poor architecture, stunted growth, and dead wood. It is evident that both forms of trees do not share comparable trunk shape and crown architecture. Consequently, good form trees are expected to have greater biomass, and hence carbon stock and carbon dioxide mitigation potential, than poor form trees.

The figures of biomass and carbon stock estimates in the present study compared with estimates reported in other studies. For example, the estimated carbon sequestration potential of 12.95 Mg C ha^{-1} to 24.55 Mg C ha^{-1} in the present study is within the range of 10 Mg C ha^{-1} to 208 Mg C ha^{-1} reported for temperate latitude, and 21 Mg C ha^{-1} to 240 Mg C ha^{-1} reported for tropical climate (Dixon 1995; Adesina *et al*., 1999; Kort and Turnock 1999; Turnock 2001; Montagnini and Nair 2004; Zianis *et al*., 2005; Peichl *et al*., 2006). Again, this study demonstrates that the use of fast-growing broadleaf tree species such as Red alder on UK's Silvopastoral agroforestry farms may result in significant short-term C storage. This finding is in agreement with earlier studies that suggested that significant short-term biomass carbon storage and sequestered carbon dioxide can best be achieved with fast growing tree species (Peichl *et al*., 2006).

The high variability of mean tree biomass C contents and sequestered CO_2 as illustrated by the relatively high standard deviations in this study implies that at the end of rotation, there may be considerable variations between the C storage capacity of individual red alder trees. Peichl *et al*. (2006) reported similar findings after destructively harvesting 13-year-old trees and attributed variation to management practices, such as pruning, and the length of cutting cycles. As tree biomass C content and sequestered CO_2 can differ considerably between individual tree components and among different tree species in a system, it is important to take cognizance of this factor by including all above- and belowground tree components when determining tree carbon pools in order to obtain realistic values that will provide accurate estimates over the wide range of sites represented in the Silvopastoral National Network Experiment.

Factors that could influence the carbon storage and mitigation capacity of these aboveground tree components include tree density, growth habit of red alder, crown size, average number of branches on the trees, tree age, site condition, soil, moisture conservation, and management interventions, among others (Quinkenstein *et al*., 2009; Mosquera-Losada *et al*., 2011). Again, the difference between carbon stocks of tree components in this study may be related to the fibre composition of plant tissues. Research studies have reported higher content of cellulose, hemicellulose and lignin in woody materials compared to herbaceous components. Ververis *et al*. (2004) have observed that lignin and cellulose content is contingent upon tissue maturity, but does not change significantly within each species. Lamlom and Savige (2006) reported cellulose has a mean carbon percentage of 42.1%, and that the carbon content varies between 40-44% and 63-72% in hemicelluloses and lignin, respectively.

These results imply that the Silvopastoral agroforestry ecosystem in the United Kingdom represents a significant carbon sink. Open-grown trees planted in agroforestry landscapes are potentially useful in storing additional carbon and can be harvested and used as a fuel in place of non-renewable energy sources (e.g. coal, oil, gas…) in addition to their primary function as wind breaks, microclimate amelioration, conservation of soil and water, and wildlife habitat (Zhou *et al*., 2011). Variations in the carbon stock from these systems modifies the amount of CO_2 in the atmosphere significantly.

This study was the first to assess the carbon sequestration potential of different forms of open-grown red alder trees in a Silvopastoral agroforestry system in the United Kingdom. Although not inherently carbon dense compared to systems such as forests or pure woodlands, agroforestry systems provide opportunities to increase carbon storage in silvopasture through the incorporation of fast-growing and deep-rooted trees. Higher density Silvopastoral systems (400 stems ha^{-1}) will have a potential to sequester more C than open pasture and lower density Silvopastoral systems (100 stems ha^{-1}) (Nworji 2020) This is expected because as planting density increases, aboveground biomass increases, and consequently the amount of C sequestered increases. Tree stands that have denser canopy cover continuously add organic matter to the soil resulting in higher soil organic matter content (Patenaude *et al*., 2003).

Even though the methods in this study were developed specifically for open-grown red alder trees in Silvopasture, the procedure has valuable applications to other open-grown tree species and can provide a reference to estimation of carbon sequestration potential for other open-grown tree species in Silvopastoral settings. Complimentary studies of similar nature should be conducted on all tree species grown in silvopasture across the wide range of sites represented in the UK's Silvopastoral National Network Experiment using the procedure laid out for open-grown red alder trees in the present study (Nworji, 2017, 2019). Further research is also required to accurately estimate the C pool in red alder trees in silvopasture. This can be achieved by quantifying the above- and belowground components and including the estimates in the total C budget.

5. Conclusion

This study was the first to quantify C sequestration potential of two forms of 20-year old open-grown red alder trees in a lowland silvopastoral agroforestry configurations at the UK's Silvopastoral National Network Experiment in North Wales. Generally, aboveground biomass, carbon stock and sequestered carbon dioxide differ significantly between the two forms of red alder trees, and were found to be significantly greater in good form trees than in poor form trees. Component-wise, biomass and sequestrated carbon were largest in stems, intermediate in branches, and lowest in twigs, which was attributed to the morphological differences between the two forms of trees, among others.

These findings suggest that the agroforestry ecosystem in the United Kingdom represents a significant carbon sink and that the use of open-grown fast-growing broadleaf tree species such as red alder in Silvopastoral agroforestry farms may be potentially useful in storing additional carbon.

This initial study of C sequestration potential of open-grown red alder trees in agroforestry setting in the United Kingdom should be viewed as part of a continuing process. Further research is needed to provide adequate data for a wider range of fast-growing open-grown and multi-formed broadleaf species for proper estimation of aboveground biomass carbon in Silvopastoral systems, which will not only add to the body of knowledge on the potential of Silvopastoral agroforestry systems to sequester carbon but also serve as important tool for making informed environmental policy decisions associated with greenhouse gas mitigation strategies in the forestry and agricultural sectors.

The procedure employed in this study, provides a reference for quick estimation of above-ground carbon sequestration potential of other open-grown, multiple-formed tree species in agro-forestry settings.

Acknowledgement

The completion of this research study was made possible with the assistance, encouragement and guidance of the following people and organisations to whom I owe my sincerest gratitude:

Foremost, I owe my deepest gratitude to my supervisors, Dr. James Walmsley and Dr. Mark Rayment, at Bangor University, Bangor, United Kingdom for their sustained guidance, wisdom, thoroughness, support, patience and commitment over the many years of my field research and during the writing up process despite their many other academic commitments.

I am equally grateful to other staff at the Bangor University research farm at Henfaes (the site of the UK's Silvopastoral National Network Experiment) for their support, assistance and patience during my data collection process and laboratory works.

For financial support, I am deeply indebted to the Nigerian Tertiary Education Trust Fund (TETFUND) for sponsoring my PhD research programme in agroforestry under its Academic Staff Training and Development Programme as well as to the Management of Chukwuemeka Odumegwu Ojukwu University (COOU) (Former Anambra State University), Anambra State, Nigeria for granting me the leave to undertake this research programme.

A big thanks to the Farm Woodland Forum for awarding me the Lynton Incoll Memorial Scholarship that enabled me to present some of my research chapters at the 2014 Farm Woodland Forum annual meeting in Devon, UK.

Appendix

Appendix A: Descriptive statistics of harvested good form and poor form red alder trees

Block	Tree ID	Form*	Diameter at Breast Height	Height	Basal Area	Volume	Crown Area	Wood Density	Bifurcation Ratio
			(cm)	(m)	(m^2)	(m^3)	(m^2)	(g/m^3)	
1	P1 F5	1	33.6	12.00	0.09	0.35	56.71	260.50	3.00
1	P1 F11	1	38.0	12.50	0.11	0.47	62.84	359.90	3.07
1	P1 K8	1	26.0	12.00	0.05	0.21	60.09	333.50	3.10
1	P1 L3	1	29.0	11.50	0.07	0.25	53.92	334.30	2.91
2	P2 E9	1	26.0	13.00	0.05	0.23	62.21	751.90	2.74
2	P2 G3	1	25.0	11.00	0.05	0.18	53.41	742.00	2.38
2	P2 L7	1	21.0	11.50	0.03	0.13	21.21	507.40	2.00
3	P3 B12	1	35.0	13.00	0.10	0.42	61.86	323.20	4.71
3	P3 C15	1	33.0	13.50	0.09	0.38	52.92	514.10	3.38
3	P3 J8	1	30.0	12.00	0.07	0.28	49.41	319.80	5.00
1	P1 D11	2	29.0	12.50	0.07	0.28	32.99	491.00	2.35
1	P1 E8	2	25.0	13.00	0.05	0.21	31.67	236.30	2.44
1	P1 K10	2	23.0	12.50	0.04	0.17	40.14	265.30	2.48
2	P2 D13	2	21.0	10.00	0.03	0.12	27.34	455.00	2.38
2	P2 E13	2	23.0	11.00	0.04	0.15	25.06	518.40	1.82
2	P2 L11	2	25.0	10.75	0.05	0.18	35.94	485.70	1.88
2	P2 M9	2	24.0	10.50	0.05	0.16	37.39	624.30	2.13
3	P3 B2	2	26.0	11.60	0.05	0.21	37.78	244.40	3.20
3	P3 C11	2	21.0	10.50	0.03	0.12	39.21	443.60	2.18
3	P3 F6	2	13.0	9.00	0.01	0.04	12.19	152.10	2.67

*Form 1 represents Good Form trees while Form 2 stands for Poor Form trees.

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