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Parisa Mazinanian

Supervisors: Professor Dr. Achim Dohrenbusch, University of Göttingen
Per-Magnus Ekö, SLU Southern Swedish Forest Research Centre

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Abstract

The development of secondary forest on abandoned agricultural lands has proven significant to land cover changes, especially in marginal areas across Europe. It is therefore important to quantify secondary forest succession in order to sustainably manage forest and agricultural resources, and also for modelling climate change. This study aimed to access secondary forest succession on abandoned agricultural land and its carbon stock compared to a nearby agricultural field and old-growth forest. The study was conducted at three sites (secondary forest, old-growth forest and an agricultural field) in Göttingen, Germany, where field inventory of the vegetation was carried out in the secondary forest alone. The top litter and soil were also sampled to a depth of 30cm to estimate the soil carbon stocks of all three land uses. To estimate the total carbon of the secondary forest, the aboveground biomass (ABG) was estimated from tree volume and wood density, and the estimated values converted to C stock estimates (C = AGB * 0.47).

A total of 304 trees belonging to 11 tree species were identified in the secondary forest, with Populus tremula and Fraxinus excelsior been the most abundant species. The total basal area per ha and volume per ha were 20 (m2/ha) and 129 (m3/ha), respectively. From the high proportion of pioneer species and relatively small average stand DBH (15.8 cm) of the secondary forest, an intermediate successional stage can be implied. Cornus sanguinea was found to be the most frequent understorey vegetation. A ring width analysis of the understorey vegetation showed an average decline in growth rate of the understorey trees, which may be a result of competition for available resources. The largest total carbon stock for this study was recorded in the old-growth forest, followed by the secondary forest and the agricultural field. However, the largest soil carbon stock was recorded in the secondary forest. This study has shown the potential of abandoned agricultural land in supporting tree diversity as well as contributing to the global carbon budget, alongside other ecosystem services. However, the reported soil carbon stocks for the three land uses may have been overestimated, due to the low sampling density. It is therefore recommended that future studies on the study sites increase the sampling density.

Keywords: Forest succession; Agricultural land abandonment; Biomass; Secondary forest; Old-growth forest; Soil carbon; Carbon sequestration; Carbon stock; Tree species; Understorey vegetation.

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1. Introduction

1.1 Agricultural land abandonment and driving forces

The phenomenon of agricultural land abandonment is increasing worldwide due to social, ecological and economic reasons (Cramer et al., 2008). The abandonment of agricultural land often starts with “marginalization”, which is characterized by a gradual reduction in the use of certain areas of the farmland because it is no longer viable under an existing land-use system (Brouwer et al., 1997). Marginalization may range from one small patch of land to sizeable regions, and is often a result of location-specific conditions (Baldock et al., 1996; MacDonald et al., 2000).

Ecological factors such as soil depth, soil erosion, fertility, slope and climate often affect agricultural production. However, the major driving force behind agricultural land abandonment, especially in Europe, is socioeconomic marginality (Brouwer, 2004). These social and economic factors include loss of labour to industrial and service divisions, loss in productivity of farmland, reduction in subsidies and incentives for certain crops or regions, and poor market of agricultural products and technology (Benayas et al., 2007).

While agricultural land abandonment poses serious threat to biodiversity and landscape features, the development of secondary forest may be seen as positive effects in the long term. This secondary succession also have some positive effects on preventing further soil erosion, and may consequently improve nutrient cycling and water retention (Benayas et al., 2007).

1.1.1 Agricultural land abandonment in Europe

There has been a long standing debate on the issue of land abandonment in Europe (see for example Brouwer et al., 1997; Pointereau et al., 2008). This is in part due to the difficulty in defining and measuring land abandonment (Keenleyside and Tucker, 2010), with different literature giving different interpretations of the term (Moravec and Zemeckis, 2007). As noted by Terres et al., (2013) and Pointereau et al., (2008), the current extent of abandoned agricultural land across Europe remains unknown, due to inconsistent methods used to measure the phenomenon.

Yet, during the last few decades, there has been a general consensus among the scientific community of the extensive increase in abandoned agricultural land in Europe, however defined (for example Terres et al., 2013). This is due to less productive agricultural land especially in the mountainous areas with harsh climate and poor soil conditions (Keenleyside et al., 2010).

Agricultural land abandonment has garnered attention in policy discussions across Europe because of the associated negative consequences. For instance, while fire risk is the major environmental concern associated with land abandonment in southern Europe, loss of biodiversity is of more concern in northern and central Europe (Terres et al., 2013).

The European Commission Joint Research Centre defines farmland abandonment as "*a cessation of management which leads to undesirable changes in biodiversity and ecosystem services*" (Terres et al., 2013).

In Germany, terminologies have been developed for land abandonment resulting predominantly from structural, social or natural factors (Bühnemann et al., 1979). Probably most dominant is "Grenzertragsbrache", which refers to the marginalization of land due to physical conditions such as poor soils, steep slopes, climate, and altitude. Other studies have also documented the effect of EU policy reforms as a driver for agricultural land abandonment (for example, Strijker, 2005).

1.2 Secondary forest succession on abandoned agricultural land

Forest succession refers to changes in species composition and vegetation type of an area with a constant climate over a period of time (Finegan, 1984). Natural reforestation on abandoned agricultural land has great importance due to ecological and economic consequences (Tasser et al., 2007). Tree species composition, biomass, diversity and productivity are often considered factors in a forest succession (Connell and Slatyer, 1977). While forest succession is easy to observe, it has proven difficult to quantify (Blatt, 2005). Basically, all plant community studies on succession take one of two forms:

- An aggregate measure where tree species are grouped using either their functional or botanical characteristics
- All tree species are included in one single measure or count (except for very rare species) (Blatt et al., 2003). This strategy was used to quantify the forest succession in this study.

The development of forest on abandoned agricultural land is caused by several natural and anthropogenic factors. Natural explanatory variables include soil and vegetation characteristics, seed bank and the process of seed dispersal (Mayer, 1976, as cited in Tasser et al., 2007), and climatic conditions (Rochefort and Peterson, 1996), whereas the type of former land-use and the intensity of use have also been noted to be significant (for example Wickham et al., 1999). Tasser et al., (2007) found that two important variables influencing natural reforestation on an abandoned area are seed dispersal and the type of former agricultural land-use. This indicates that abandoned agricultural lands that lie in close proximity to old trees are more likely to have a higher reforestation rate.

Presently, several measures are used to describe forest succession, making it difficult to both compare and discuss succession between different sites. Some of the most common used measures of succession include spatial rank consistency (Wickham et al., 1999), turnover rate, texture convergence and character values, among others. Blatt et al., (2003) discusses the shortcomings of some of these measures, including limited use due to large data requirements.

The most common used taxonomy of succession stages are an “initial stage” characterized by the presence of pioneer species on the abandoned land; a “sprouting stage” evidenced by an increase in wood layer cover; a “thickening stage” characterized by the dominance of trees on the land (approximately 80% of area is covered by trees); and a stage of “connected forests”, where the forest is completely dominated by competitive trees which create connected tree layer cover (80-100% of area is covered by trees), completing the successional cycle (Špulerová, 2008).

A gradual recovery of a unique tree understorey community accompanies the development of the tree thickening stage of the successional cycle (Tullus et al., 2013). Several studies have pointed to a difference in forest understorey community between new formed forests on abandoned agricultural lands and old-growth forests (for example

Flinn and Vellend, 2005; Flinn and Marks, 2007). The former agricultural land-use also affects the recovery and characteristics of the understorey vegetation (Koerner et al., 1997; Wulf, 2004), with understorey recovery quicker in former grasslands and pasture than in crop fields (Wulf, 2004).

1.3 Forest carbon sequestration in secondary forest

The succession of abandoned agricultural lands by trees leads to subsequent accumulation of tree carbon, alongside the carbon already stored in the soils. Typical reported rates of soil carbon accumulation on afforested farmlands ranges from 0.15 to 0.66 t C/ha/yr (Post and Kwon, 2000). A review of 74 studies on the effects of land use change on soil carbon stocks concluded that a change in land-use from cropland to secondary forest leads to a 53% increase in soil carbon stocks (Guo and Gifford, 2002). However, Vesterdal et al., (2002) did not find an increase in soil carbon stocks after 30 years of conversion from farmland to forest. Likewise in another review, Deng et al., (2016) did not find any significant increase in soil carbon stocks after conversion from farmland to forest land.

Interestingly, some studies have documented an initial decrease in soil carbon stocks after conversion of farmland to forest (for example Post and Kwon, 2000; Deng et al., 2014). The decrease in soil carbon stocks has been reported to last between 3 to 30 years, followed by a gradual increase in C stocks, which often results in net gains (Paul et al., 2002).

Tree succession on abandoned agricultural lands has been reported to accumulate an average 5.9 t C/ha/yr in the aboveground biomass (Karberg et al., 2008). The amount of carbon sequestered is dependent on a combination of factors such as site conditions (intensity of previous land use, and the tree species growing on the site.

1.4 Study aim and objectives

The main aim of the study is to quantify the development of secondary forest succession on abandoned agricultural land, and to assess its carbon sequestration potential compared to a nearby agricultural land and an old-growth forest.

The specific objectives are to:

- Establishing the pattern of forest succession by assessing tree species richness and composition.
- Assess the development of understorey vegetation.
- Assess the above- and below-ground biomass and carbon stock of the secondary forest.
- Compare the soil carbon content in the secondary forest with the content in agricultural land and in old-growth forest.

2. Materials and methods

2.1 Study area

The study was conducted in a secondary forest in close proximity to an old-growth forest and an agricultural land. The study sites are located in Göttingen in Lower Saxony at latitude 51.54128 N and longitude 9.9158 E, Germany, at about 215 m asl, exposition west (Fig. 1).

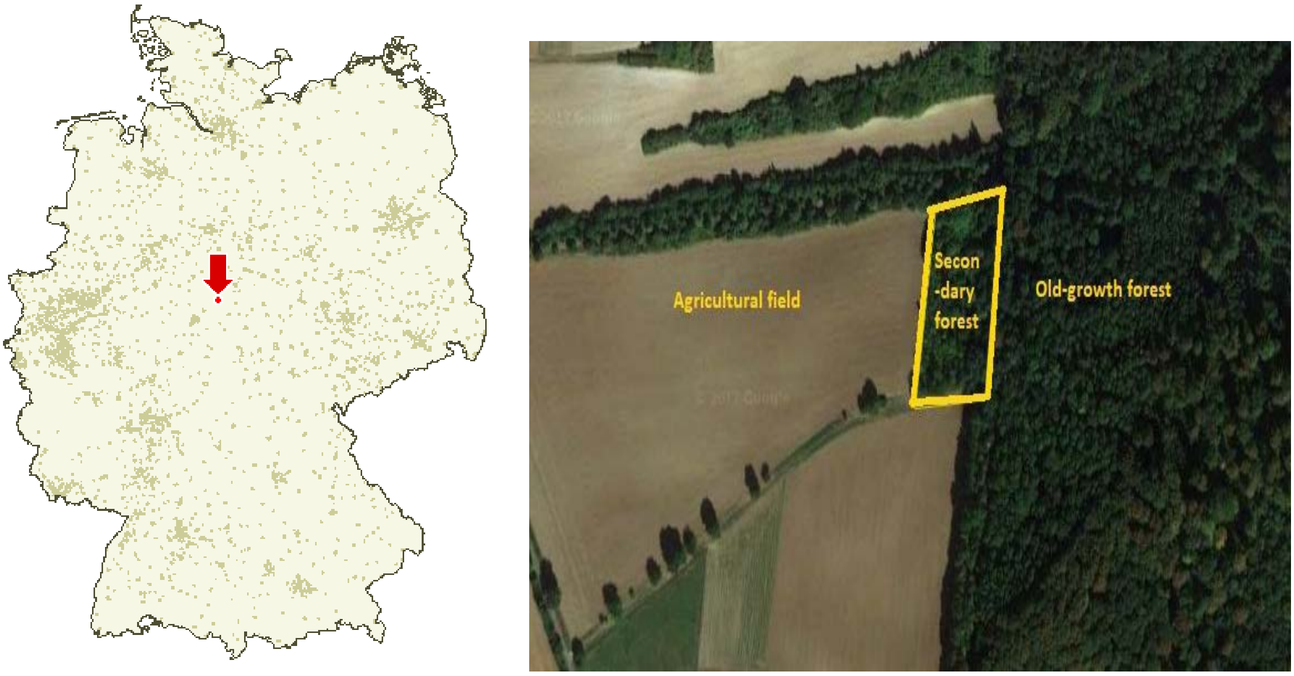

Figure 1. Map of the study area and research sites. The red arrow points to the location of Göttingen in Germany; the secondary forest site is demarcated by the yellow rectangle. The north-east corner has the coordinates 51.572534 N and 9.946548 E.

Göttingen experiences a temperate oceanic climate characterized by significant rainfall throughout the year (Fig. 2). Mean annual precipitation is ~650 mm, with the highest (79 mm) and lowest (38 mm) average rainfall occurring in June and March respectively; mean annual temperature is 8.5 °C.

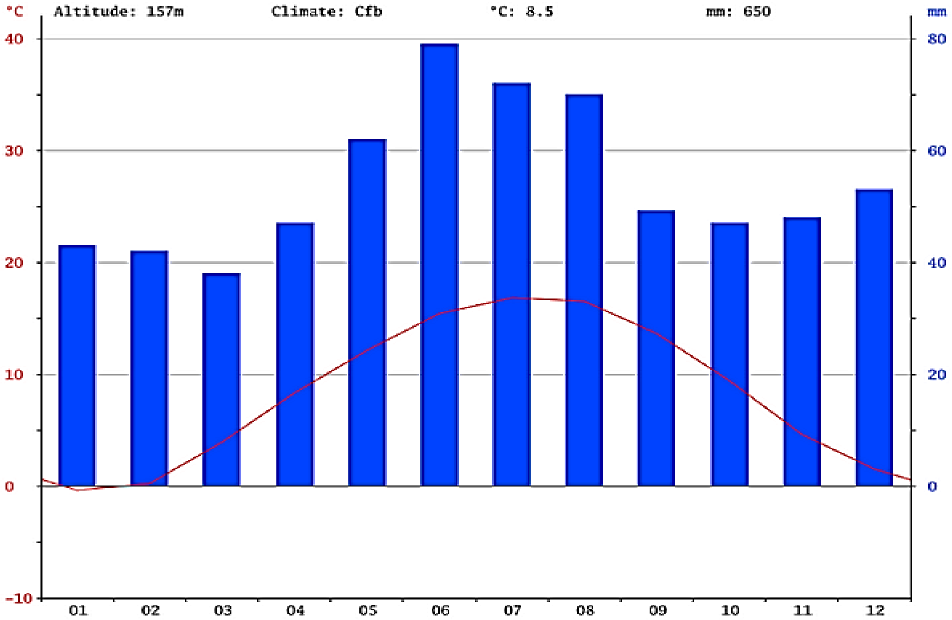

Figure 2. Mean monthly precipitation and mean monthly temperature for Göttingen (Data source: WorldClim).

The secondary forest was previously an agricultural land and it was abandoned approximately 45 years ago. Since the abandonment of the agricultural practice, there has been no intervention in the successional development of the forest. The size of the secondary forest is about 0.58 ha and is characterized by different tree species with a dense understory in one half of the plot.

Similarly, the old-growth forest is comprised of different tree species, but mainly dominated by beech and ash. It is about 100 years old, with an estimated growing stock of 400 m^3/ha. The understorey vegetation is less dense compared to the secondary forest.

2.2 Plot selection and data collection

Following the small size (0.58 ha) of the secondary forest, the whole plot was considered as the study area. Data on soil carbon were collected from the secondary forest, old-growth forest and agricultural land to compare their carbon stock. In addition, tree species composition data was also sampled from the secondary forest only.

2.2.1 DBH and height measurement

For this study, field data collection was carried out in March, 2017. The primary information of the forest was collected using a field map system (Fig. 6). Within the secondary forest plot, all trees with diameter at breast height (DBH) equal or larger than 7 cm were identified and measured for DBH using an electronic calliper at a stem height of 1.3 m. When using the electronic calliper, two DBH measurements were taken at right angles on the same tree and the final DBH calculated from the mean of the two measurements. At the same time, the trees were mapped based on their locations in the field by means of a field map system (Fig. 3).

Figure 3. A field map system (Source: http://www.fieldmap.cz/?page=keywords)

Among the mapped trees, some individuals were selected for height measurement using a Vertex IV Ultrasonic Hypsometer. Trees were selected to reflect the range of DBH recorded in the plot.

2.2.2 Height-diameter curves

Height measurement was done in the field separately for different tree species except *Corylus avellana* and *Viburnum opulus* due to the low number of observed individual trees for these two species. Using measured data on tree DBH and height, height-diameter curves were produced separately for each tree species and logarithmic equations were derived from the curves to estimate the height of those trees for which only DBH was measured in the field (Table 1). Finally, a single height-diameter curve for all species combined was constructed and the logarithmic equation for this curve was used to estimate the height of trees for *Corylus avenella* and *Viburnum opulus*.

Table 1. Derived linear equations from height-diameter relationships for the different tree species in the study plot. In the equations, x is the DBH of the tree (cm).

Species	Equation	R^2
European aspen (*Populus tremula*)	12.562ln(x)-20.316	0.87
Norway maple (Acer platanoides)	3.8639ln(x)+1.7168	0.40
Field maple (*Acer campestre*)	4.4704ln(x)-2.235	0.79
Ash (Fraxinus excelsior)	5.4068ln(x)-1.1395	0.59
Oak (Quercus robur)	7.4992ln(x)-8.8538	0.91
Hornbeam (Carpinus betulus)	1.8113ln(x)+6.4961	0.41
Silver birch (*Betula pendula*)	6.5362ln(x)-6.4807	0.95
Beech (Fagus sylvatica)	2.3222ln(x)+8.1085	0.67
Sweet cherry (*Prunus avium*)	4.9045ln(x)-2.1451	0.66
Hazel (Corylus avenella)	7.8679ln(x)-8.6376	0.67
Snowball (Viburnum opulus)	7.8679ln(x)-8.6376	0.67

2.2.3 Tree species identification

Tree species were identified in the field by observing a combination of tree characteristics such as bark, leaves and branch shape. The tree identification was done with the help of the supervisor and Göttingen university staff.

2.2.4 Soil sampling

Soil samples were subjectively taken at six different locations in each of the old-growth forest and the secondary forest, and at one location in the agricultural field. For all the land uses, the size of the soil sampling plot was 20 cm x 20 cm. The top litter was collected by hand in secondary forest and old-growth forest in order to calculate the amount of carbon in it. Soil samples were then collected at two different depths (0-10 cm and 10-30 cm) in all the 13 replicate plots to compare their carbon content.

2.2.5 Understorey vegetation sampling

To understand the growth pattern of the understorey vegetation in the secondary forest, 6 replicate plots (5 m x 5 m each) were placed subjectively in different parts of the forest. The plots were purposefully laid out across the secondary forest to capture the difference in density of the understorey vegetation. In each of the replicate plot, the density, average DBH and height of the understorey trees which was mainly frequented by *Cornus sanguinea* were estimated. Stem discs were also sampled from 7 randomly selected understorey trees of *Cornus saguinea* tree species to analyse the ring width and average understorey age.

2.3 Compilation and analyses of data

2.3.1 Forest succession on abandoned land

2.3.1.1 Tree species composition

The total number of tree species in the secondary forest and the number of trees in the understorey subplots were counted, here referred to as “observed” species richness (Bobo et al., 2006). From the DBH and height data, the basal area per hectare and volume per hectare were calculated.

Using data on DBH and height of the measured trees, volume was calculated separately for each tree species. For this study, tree volume was calculated using the formula:

$$V = \pi * \frac{D^2}{4} * H * F_h$$

Where V is the volume of the tree (m^3), D is the mean DBH (m), H is height of the tree (m), and F_h is the form factor of the tree species.

The form factors of the trees were taken from yield tables (Schober, 1975) according to the DBH and height of the tree species. The total volume of the secondary forest was calculated by summing up the volume of the individual tree species.

2.3.1.2 Understorey vegetation and growth pattern

Stem disk samples were collected from 7 different understorey trees of *Cornus sanguinea* at a height of 10 cm to analyze their ring width. The surfaces of the wood core samples were polished to enhance the boundaries of the annual rings. The samples were then scanned and imported into LignoVision software (RINNTECH), a dendrological software for automatic determination of tree ring width. The mean ring widths for all the stem discs were then graphed to show the annual growth rhythm.

2.3.2 Estimation of tree biomass and carbon stocks

Biomass and carbon stocks for the land uses were calculated through the following steps:

2.3.2.1 Aboveground and belowground biomass

Living biomass was calculated separately for aboveground- and belowground biomass. The estimation of aboveground biomass was also done separately for trees with diameter ≥ 7 cm, and for leaves, twigs and branches smaller than 7 cm diameter. The results of the different biomass components were then summed to obtain the total living biomass. The biomass of the forest was calculated as follows:

1- Aboveground biomass ≥ 7 cm (including branches ≥ 7 cm) was calculated by using the volume and wood density of each tree species. Wood density of the tree species was taken from IPCC (Nabuurs et al., 2003). Following Reyes (1992) and IPCC (2003, 2006), commercial AGB is given by:

$AGB_1 = V * WD$

Where AGB is the biomass of tree trunk and the branches with diameter larger than 7 cm, V is the volume (m^3), and WD is the wood density (g/m^3). The estimated AGB is given in hectares.

2- Following the guidelines by (Burger 1951 and 1953, as cited in Mitscherlich, 1970), a relationship was established between AGB_1 and the percentage of AGB_1 in the twigs, leaves and branches smaller than 7 cm diameter, using the tree DBH as reference and beech (*Fagus sylvatica*) as the model tree species (Fig. 4). Then an exponential equation was derived to calculate the percentage of AGB in the branches smaller than 7cm, and in the twigs and leaves.

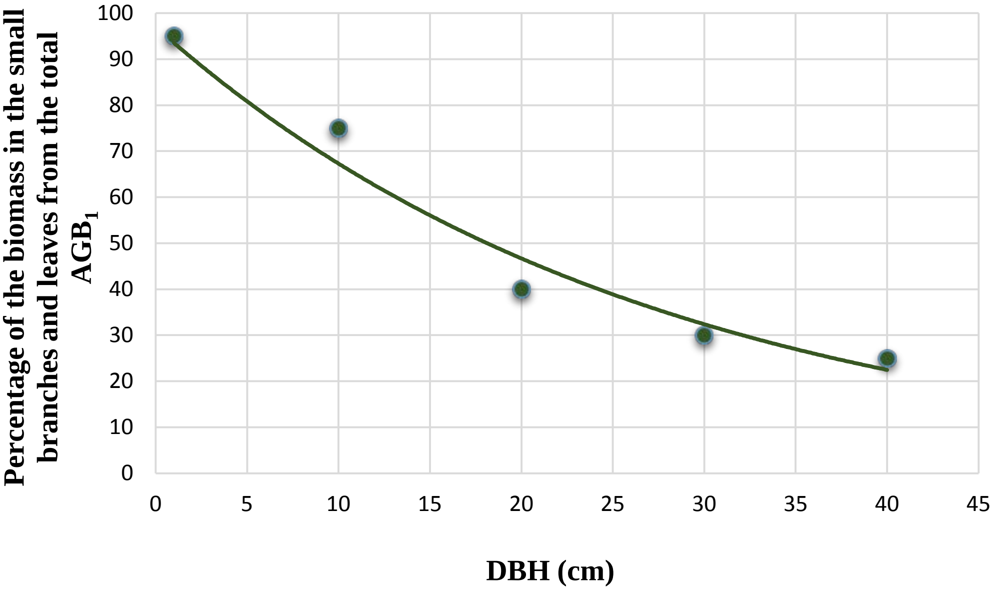

Figure 4. Relationship between DBH and tree biomass of small branches (<7 cm) and leaves.

The exponential equation used to calculate the percentage of biomass in leaves, twigs and branches < 7 cm is given by:

$$P_1 = 97.024\, \boldsymbol{e^{-0.037x}} \qquad (R^2=0.9603)$$

Where P_1 is percentage of the biomass in branches smaller than 7cm, twigs and leaves in relation to the $AGB_{1;}$ and x is DBH (cm).

. Therefore:

$AGB_2 = AGB_1 * P_1$

Where AGB_2 is the amount of biomass in the branches smaller than 7cm, twigs and leaves (t/ha); AGB_1 is the amount of biomass in the trunk and branches ≥7 cm (t/ha); and P_1 is the percentage of the biomass in branches smaller than 7cm, twigs and leaves in relation to the AGB_1.

3- For estimating the belowground biomass, the percentage of the root biomass in different DBH classes was calculated for beech (Mitscherlich, 1970). Then, the graph of this relationship was drawn (Fig. 5) and a logarithmic equation was derived to calculate the percentage of belowground biomass in the AGB_1. Thus:

$P_2 = -10.44 * \ln(x) + 60.87$ $(R^2=0.9882)$

Where P_2 is the percentage of the biomass in the root in relation to the AGB_1; and x is the DBH (cm)

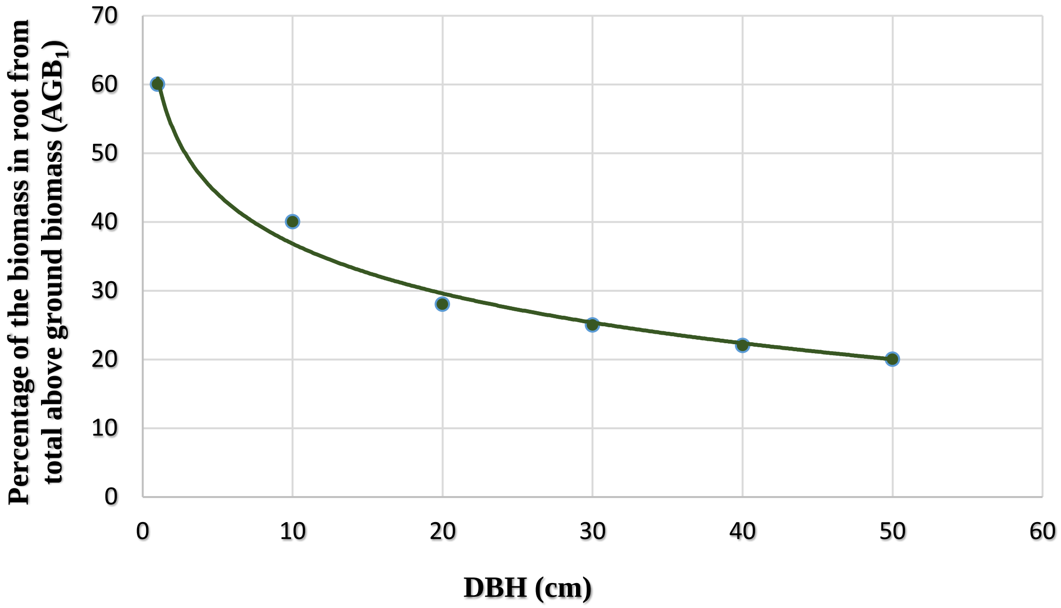

Figure 5. Relationship between DBH and tree biomass of the root.

Thus:

$BGB = AGB_1 * P_2$

Where BGB is the amount of biomass in the root (t/ha); AGB_1 is the amount of biomass in the trunk and branches bigger than 7 cm (t/ha); and P_2 is the percentage of the biomass in root in relation to the $AGB_{1.}$

The total living biomass in the tree was calculated by:

Total biomass (t/ha) = $AGB_1 + AGB_2 + BGB$

Recent findings suggest that generic approximation of C to represent 50% of total tree biomass overestimates actual forest C stocks by approximately 3-5% (for e.g., Martin and Thomas, 2011). Hence, following the recommendation of IPCC (see Gibbs et al., 2007), total AGB was converted to C stocks estimates using a 0.47 conversion factor. Carbon stock in living biomass (t/ha) = Total biomass * 0.47

2.3.2.2 Calculating biomass of the litters and forest floor

The forest floor was sampled to calculate both the biomass and carbon stock in the litter and soil. First, the wet weight of the litter samples collected within the 20 cm x 20 cm plot was measured. Then, the samples were dried in an oven at a temperature of 45 ºC for 48 hours until they reached a constant weight. Dried samples were weighted after removing from oven.t. The amount of biomass in the litter was calculated following the equation given in the USDA guideline (Pearson et al., 2007) for carbon measurement:

$$\text{Litter biomass} = \frac{\textbf{Forest floor oven dry weight (g)}}{\textbf{Sampling frame area (cm}^{\mathbf{2}}\textbf{)}} * \mathbf{100}$$

The result is multiplied by 100 to convert from (g/cm^2) to (t/ha). Litter biomass results were converted to carbon stock estimates values by multiplying with a 0.5 conversion factor, assuming a 50% C content as suggested by (Pearson et al., 2007).

2.3.2.3 Soil carbon calculation

Following the USDA guidelines (Pearson et al., 2007), three variables were used to estimate the soil carbon: Soil depth, soil bulk density and percentage of the soil carbon in the samples. The soil samples taken from the three land uses were taken to the lab and after sieving, they were dried in an oven at a temperature of 45 ºC for 48 hours until it had reached a constant weight. The dried soil samples were then crushed to a fine powder and 30 mg of the soil was sent to the laboratory to measure the percentage of carbon in it.

For calculating soil bulk density, 4 soil samples were taken from secondary forest and 2 soil samples from each of old-growth forest and agricultural field using bulk density rings of sizes 251.3 cm^3 and 502.6 cm^3. The soil samples were then put in the oven at a temperature of 105ºC for 48 hours until they had reached a constant weight. The dried soil samples were sieved with a 2mm sieve to separate stones from the soil. Then, core soil and stones were weighted separately to calculate the bulk density. Bulk density was calculated from the following formula:

$$\text{Bulk density} = \frac{\textbf{soil dry weight in a core (g)}}{\textbf{volume of cylinder } (\boldsymbol{cm^3})}$$

In the above equation, volume of cylinder refers to volume of the bulk density rings. The final bulk density of each land use was calculated as the average bulk density of the samples from that site.

Soil carbon stocks were calculated from the following equation as given in Pearson et al., (2007):

$$C\ (t / ha) = [(\text{soil bulk density, } (g / cm^3) \times \text{soil depth (cm)} \times \%\ C)] \times 100$$

In this equation, the percentage of the carbon is used in a decimal fraction. Differences in soil carbon stock for the secondary forest and old-growth forest was assessed using an Independent t-test. Statistical significance was set at $p \leq .05$.

2.3.2.4 Calculation of total carbon stock

Carbon sequestration potential was calculated as the summation of aboveground biomass, below ground biomass, litter carbon and soil carbon stock.

Total carbon stock (t C/ha) = aboveground biomass carbon (t C/ha) + belowground biomass carbon (t C/ha) + carbon stock in litter (t C/ha) + soil carbon stock (t C/ha)

3. Results

3.1 Forest succession on the abandoned land

3.1.1 Tree species composition

A total of 304 trees belonging to 11 tree species were identified in the secondary forest (547 trees per ha) (Fig. 6). The total basal area per ha and volume per ha were 20 (m^2/ha) and 129 (m^3/ha) respectively (Table 2). *Populus tremula* and *Fraxinus excelsior* were the most abundant tree species, accounting for 23% of the total tree species found in the plot, while *Corylus avellana* was the least abundant species, constituting only 1% of the total tree population. Moreover, *Populus tremula* recorded the largest mean DBH and the highest mean height, making it the primary tree species in the study plot. Accordingly, it had the largest basal area compared to the rest of the tree species.

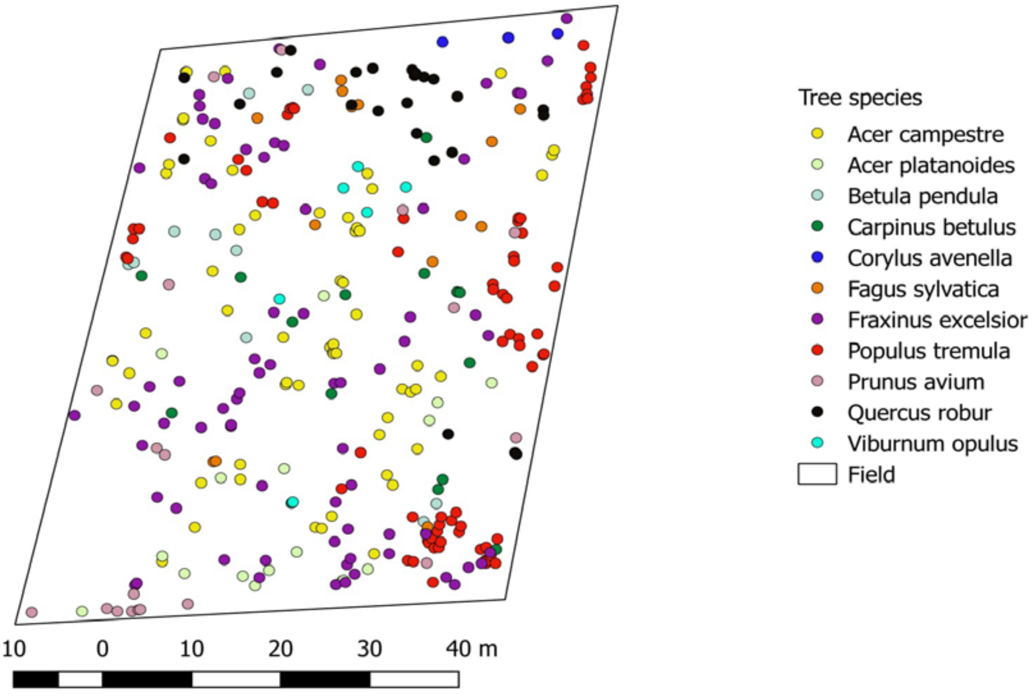

Figure 6. Spatial distribution of field measured individual trees in the secondary forest. Different tree species are represented by different colours in the map.

Table 2. Summary of vegetation characteristics in the secondary forest plot.

Tree species		Number of trees in plot (0.58 ha)	Volume (m^3/ha)	Mean DBH (cm)	Mean height (m)	Basal area (m^2/ha)
Common name	Scientific name					
European aspen	Populus tremula	71	74.5	25.6	19.3	7.6
Norway maple	Acer platanoides	17	5.6	18.1	12.6	0.9
Field maple	Acer campestre	55	2.3	9.8	7.7	0.9
Ash	Fraxinus excelsior	71	16.5	14.4	12.8	2.6
Oak	Quercus robur	23	9.5	15.4	10.2	4.7
Hornbeam	Carpinus betulus	14	3.5	16.5	11.4	0.6
Birch	Betula pendula	11	5.7	23.2	13.7	0.8
Beech	Fagus sylvatica	14	6.0	18.4	14.6	0.8
Sweet cherry	Prunus avium	18	4.5	14.0	10.1	0.7
Hazel	Corylus avellana	4	0.32	10.1	9.3	0.1
Snowball	Viburnum opulus	6	0.22	8.0	7.6	0.1
Total		304	129			20

3.1.2 Understorey vegetation structure

The understorey plots were grouped into three different groups (A, B and C) based on density. Group A plots (Plots 5 and 6) had the lowest density of with less than 50 trees in plot (less than 20,000 trees per ha); group B (Plots 1 and 4) had medium density with between 50-70 trees per plot (between 20000 to 28000 trees per ha); and group C plots (Plots 2 and 3) had the highest density with between 70-100 trees in each plot (between 28000 to 40000 trees per ha) (Fig. 7).

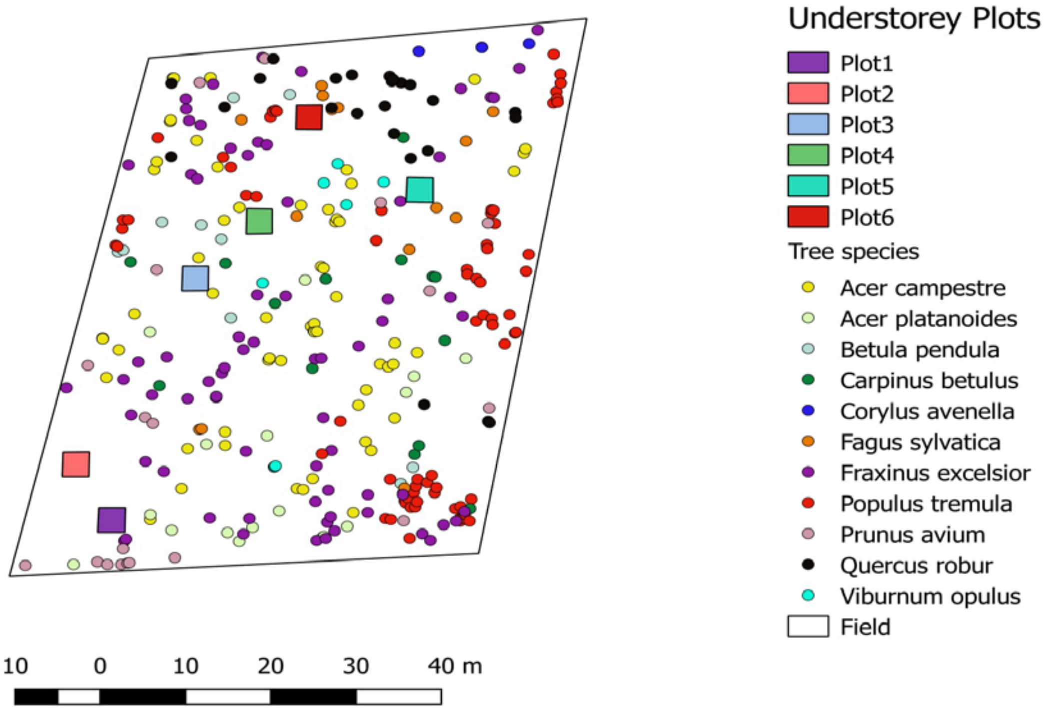

Figure 7. Spatial distribution of understorey plots in the secondary forest. Different plots are indicated with different coloured square boxes.

On average, 37% of the understorey trees in group A were single-rooted stems, compared to 51% and 44% in groups B and C respectively. In all the understorey plots, clustered trees occurred in groups of 2 to 4 trees, with less than 10% of trees occurring in clusters of 5 trees or more. The trees in group A had an average DBH of 3.5cm and height of

4.5m, while trees in group were estimated to be 2.3cm and 2.5m for DBH and height respectively. For group C, the average DBH and height was 2.4cm and 4m respectively.

The analyzed stem discs had between 12 to 27 rings, with the oldest disc dating back to the year 1990. The average width increment of the rings was 0.45 ± 0.16 mm per year. Narrow tree rings (< 0.5 mm) dated back to 1990 - 1993 and after 2004. Analysis of tree ring widths showed a similar growth rhythm for all the measured trees, with a general decrease in radial growth rate as the trees aged (Fig. 8). The average tree ring index curve showed two main increases from 1992 to 1997, followed by a progressive decrease in ring width, and then a short increase again from 2001 to 2002 (Fig.8). Afterwards, a decline in tree ring width was observed until 2016.

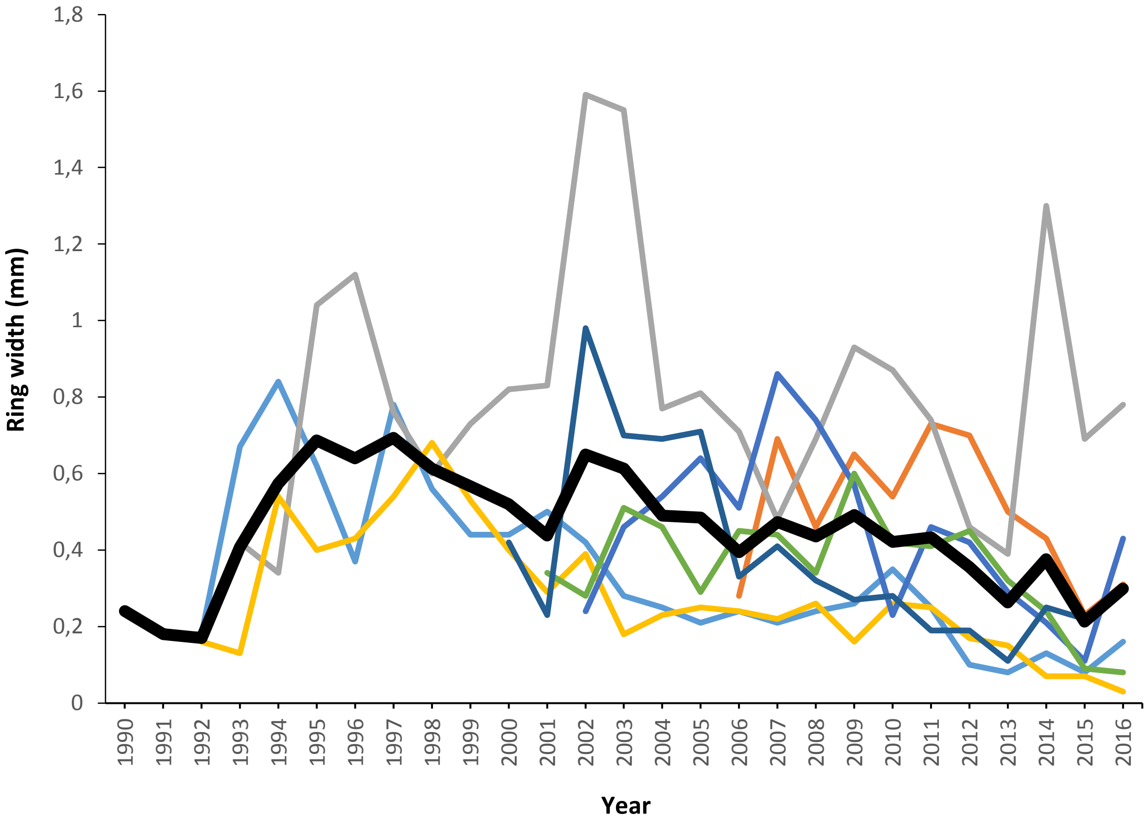

Figure 8. Tree ring width time-series (annual increment) of 7 sampled trees from the understorey of *Cornus sanguinea*. Different coloured lines represent different tree samples; black bold line represents average of all-time series.

3.2 Biomass and carbon stock

3.2.1 Living biomass and its carbon stock

The secondary forest stocked on average, a total of 90.3 t/ha of living aboveground and belowground biomass (Table 3). Woody AGB accumulation correlated strongly with basal area. Consequently, *Populus tremula* and *Fraxinus excelsior* accumulated about 62% of the total biomass stored in the secondary forest (Table3). The amount of carbon storage was relatively similar among 5 of the tree species, with *Corylus avellana* and *Viburnum opulus* sequestering the least carbon. The total carbon sequestered by the living biomass of the secondary forest was on the average, 42.4 t C/ha.

Table 3. Aboveground biomass, belowground biomass and carbon stock distribution for the tree species in the secondary forest.

Tree species	AGB_1 (t/ha)	AGB_2 (t/ha)	Total AGB (t/ha)	BGB (t/ha)	Carbon stocks (t C/ha)
Populus tremula	26.1	7.3	33.4	6.3	18.6
Acer platanoides	2.9	1.2	4.1	0.8	2.3
Acer campestre	1.2	0.7	1.9	0.4	1.1
Fraxinus excelsior	9.4	3.8	13.2	2.6	7.4
Quercus robur	5.5	1.6	7.1	1.4	4.0
Carpinus betulus	2.2	1.0	3.2	0.7	1.8
Betula pendula	2.9	1.0	3.9	0.8	2.2
Fagus sylvatica	3.5	1.3	4.8	0.9	2.7
Prunus avium	2.0	0.8	2.9	1.1	1.9
Corylus avellana	0.2	0.2	0.4	0.1	0.2
Viburnum opulus	0.1	0.1	0.3	0.1	0.2
Total	56.1	18.9	75.1	15.2	42.4

3.2.2 Litter biomass and soil carbon stocks

Litter biomass and carbon stock was calculated separately for each replicate plot (Fig. 9). The amount of carbon stored in the litter was an average 5.3 t C/ha in the secondary forest. This was higher than the average 5.0 t C/ha found in the top litter of the old-growth forest.

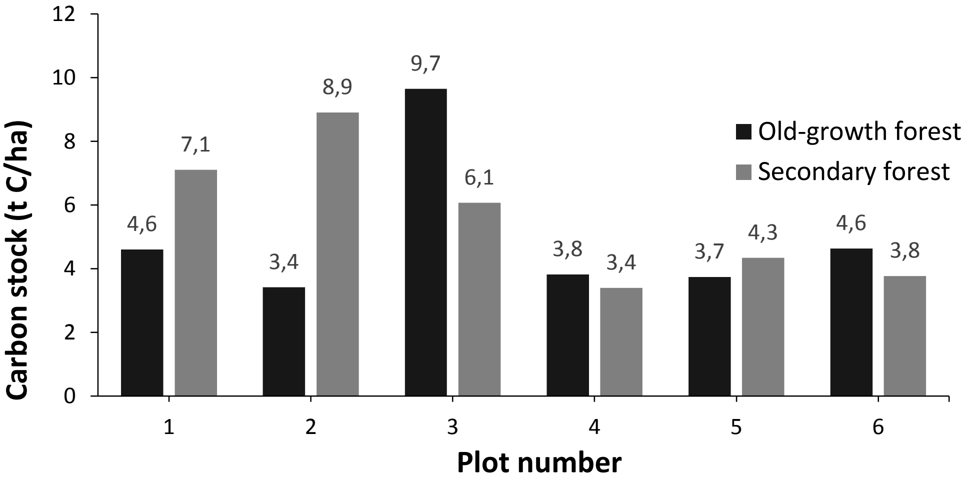

Figure 9. Carbon stock distribution in the surface litter of the secondary forest and old-growth forest.

Soil carbon was also calculated for all the land uses (Fig. 10). The secondary forest stored on average, 16% more carbon in the soil than the agricultural field (Fig. 10). The amount of soil carbon was relatively similar between the old-growth forest (156.9 ± 68.6 t C/ha) and the agricultural plot (151.6 t C/ha); while the difference in soil carbon between the secondary forest (207.5 ± 40.6 t C/ha) and the old-growth forest was not statistically significant (student t-test, t (10) = 1.55, *p* > .05)

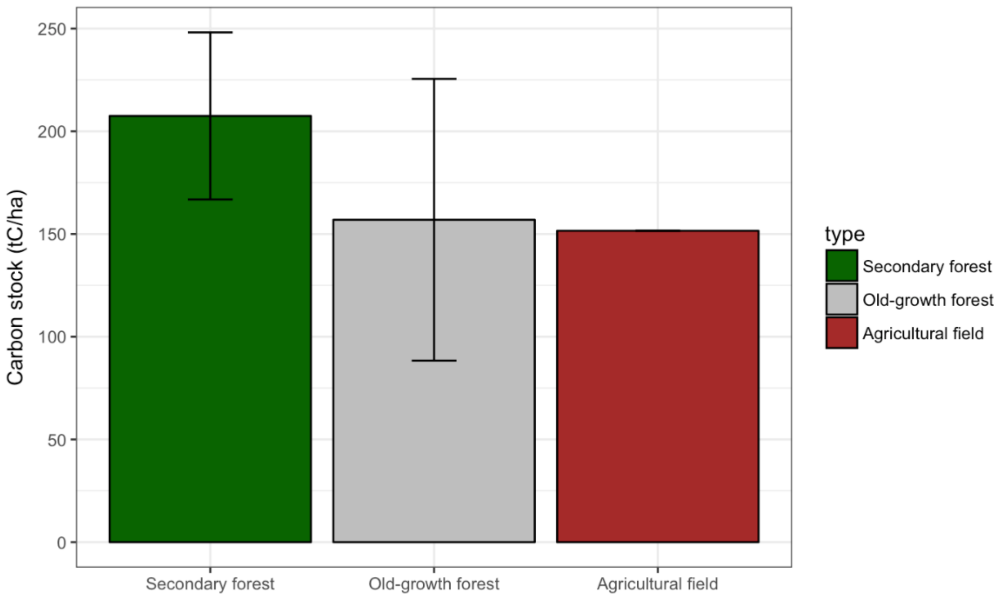

Figure 10. Soil carbon stock distribution in the top 30 cm of the three land uses. Error bars represent standard deviation.

3.2.3 Total carbon stock in the secondary forest

While no aboveground biomass measurement was done in the old-growth forest, the age of the forest was found to be about 100 years old, with an estimated growing stock of 400 m^3 (A. Dorenbusch, personal communication, July 24, 2017). Using the wood density of beech and yield tables, the aboveground and below ground biomass of the old-growth forest is estimated to be 240 t/ha (120 t C/ha). Consequently, the old-growth forest has the highest storage of total carbon, followed closely by the secondary forest. For all land uses, most of the carbon was stored in the soil (Table 4).

Table 4. Total soil carbon in the three land uses. All the values are reported in t C/ha.

Estimated parameters	Secondary forest	Old-growth forest	Agricultural land
Tree carbon (AGB and BGB)	42.4	120	-
Litter carbon	5.3	5.0	-
Soil carbon	207.5	156.9	151.6
Total	255.2	281.9	151.6

4. Discussion

4.1 Forest succession on the abandoned land

4.1.1 Tree species composition

German forests are among the most densely wooded forests in Europe, having an average growing stock of about 336 m^3/ha (Seintsch, 2013). As expected, this value is higher than the volume (129 m^3/ha) calculated for the secondary forest in this study which can be attributed to the young forest succession.

The number of tree species (11) found in this secondary forest is comparable to what has been reported in similar studies conducted in Europe. For example, 10 tree species were recorded on an abandoned arable land in Great Britain (Harmer et al., 2001), while Korzeniak (2005) found 13 tree species in abandoned meadows in the Eastern Carpathians. Although the number of tree species may not appear high, the comparable findings around Europe underscore the significance of abandoned agricultural land in conserving tree species diversity and the provision of other ecosystem services.

Populus tremula and *Fraxinus excelsior* were found to be the two most abundant tree species in this study. As pointed out by Latva-Karjanmaa et al., (2007), *Populus tremula* is a pioneer species that is especially abundant when there is a young successional stand. It is a long-term persistence tree species with high biodiversity value which has a wide distribution in Eurasia's boreal and temperate ecosystem (Myking et al., 2011). Its ability to quickly invade abandoned fields by means of root suckers makes aspen a successful species in most secondary successions (Frivold, 1998, as cited by Myking et al., 2011). European ash (*Fraxinus excelsior*) is also a fast growing tree species (Fraxigen, 2005) which is common in different forest types and can regenerate naturally through seed fall and also by planting (Dobrowolska et al., 2011). Although is a post-pioneer species (Bugala, 1995), it plays a role in both primary and secondary succession, but often occurs as an intermediate (Beck et al., 2016).

Other species such as field maple, oak and cherry all exhibited intermediate pioneering attributes. The low pioneering activity of the rest of the tree species may be due to the low frequency of the tree species in the adjacent old-growth forests as well as a quick establishment by other more persistent and competitive tree species. As a pioneer species, silver birch constituted only 3.6% of total tree species composition. This is probably because silver birch is a shade intolerant species that maintains vigorous growth only as a dominant species, and tend to perform poorly in a competitive environment (Hynynen et al., 2009). Hazel and hornbeam were also very poorly represented in the plot, which may be indicative of a poor or discontinuous regeneration pattern (Kacholi. 2015). Due to small sizes of these tree species, there is concern about their long-term survival in the secondary forest (Table 2).

4.1.2 Understorey vegetation structure

Studies have shown that the overall diversity of a forest is given by a combined assessment of both overstorey and understorey vegetation (for example Kacholi, 2015). Understorey vegetation was divided into three different groups: high density, medium density and low density. Lower densities of understorey vegetation can be caused by lower resource availability like nutrient or light (Oliver and Larson, 1996). Most of the lower density group of understorey vegetation were situated in the shaded (by the overstorey trees) areas of the secondary forest, where they had less access to sunlight and perhaps nutrients due to uptake by larger trees. This follows the classical self-thinning effect, where younger trees get overcrowded and suppressed, leaving them at a competitive disadvantage.

The more open spaces in the secondary forest had high densities of understorey vegetation, probably as a result of available sunlight and less competition for other resources. Given that the secondary forest is still at an intermediate successional stage, it is likely that pioneer species such as European aspen and European ash may become the future dominant canopy species in the more open areas of the forest.

Tree ring width provides valuable information on the history of tree growth (Hember et al., 2015), with variation in climatic conditions considered as a main influential factor of ring width growth (Oberhuber et al., 2014). However, other factors may also be at play, such as competition for resources, and disturbances such pest/insect outbreak (Krause and Morin, 1995; Prévosto et al., 1999). The observed pattern of understorey tree ring growth may be a consequence of varying climatic conditions during the life of the tree. The small size of the mean ring width for the trees may stem from their young age, as some of the trees may have been younger than 15years old. As reported by Worbes et al., (2003), understorey trees tend to grow slower compared to overstorey trees, due to low light availability at the bottom of the forest.

4.2 Biomass and carbon stock

4.2.1 Living biomass and its carbon stock

The aboveground biomass and belowground biomass for the secondary forest in this study averaged an estimated 75.1 t/ha (35.3 t C/ha) and 15.2 t/ha (7.1 t C/ha) respectively. This is expectedly lower than the 240 t/ha (120 t C/ha) estimated for the old-growth forest. As highlighted by Peichl and Arain (2006), aboveground and belowground biomass increases with increasing age of the forest due to aboveground and root biomass increment. This justifies the higher living biomass carbon found in the old-growth forest compared to the secondary forest. Given the intermediate successional stage of the secondary forest as implied from the average stand DBH of 15.8 cm and the high proportion of pioneer tree species, the carbon stock of the site can be expected to increase as the secondary forest ages.

The total carbon stock of the living biomass of the secondary forest was 42.4 t C/ha, which is at the lower end of the range reported for most temperate forests in different parts of the world (see Keith et al., 2009). Generally, moist temperate forests have a high potential in sequestering carbon due to moderately high precipitation and cool temperatures which results in rapid forest development. Nevertheless, the living biomass carbon storage potential of the secondary forest in this study is still growing, and is most likely to increase as the forest continues to age. This result is relevant to on-going climate change negotiations in Europe, given the extent of abandoned agricultural land in the region. With minimal human disturbance, abandoned fields can develop to mimic nearby forest ecosystems, as well as make an important contribution to the global C budget.

4.2.2 Litter biomass and soil carbon stock

The total average litter carbon for the secondary forest and old-growth forest were 5.3 t C/ha and 5.0 t C/ha, respectively. These are similar to the 5.3 t C/ha value calculated for mixed deciduous forest in the “Hainich National park” in central Germany (Knohl et al., 2003), and higher than the average values of between 1.8 and 3.5 t C/ha calculated for a beech forest in “Hainich-Dün”, Germany (Mund, 2004). The moderately high amount of litter carbon in the secondary and old-growth forests may be due to the dense population of the tree species and a perhaps a slower decomposition rate of the litter (Prescott, 2010).

The largest total carbon stock for this study was recorded in the old-growth forest, followed by the secondary forest and the agricultural field (Table 4). This is similar to findings in other studies where the highest carbon stocks were found in the oldest stands (usually old-growth forests). For example, a study in northern Belgium found a total carbon stock of 232 t ha^{-1} under 69-year-old stand, 173 t ha^{-1} for a 29-year-old forest and 128 t ha^{-1} under pasture (Schauvlieghe and Lust, 1999).

Soil forms the largest carbon pool in the terrestrial ecosystem, storing between 1500 to 2000 Gt C globally (Watson et al., 2000). The amount of soil carbon (207.46 t C/ha) in the secondary forest was well within the range (80 to 250 t C/ha) reported for most temperate forest soils (Lal and Lorenz, 2012). Reforestation of abandoned agricultural fields has been found to have a strong impact on the sequestration of soil organic carbon by enhancing carbon storage (Johnson et al., 1996; Schauvlieghe and Lust, 1999). However, the total carbon stock of the secondary forest (255 t C/ha) was higher than the average (190 t C/ha) reported by Dieter and Elsasser (2002) for Germany’s forests. This is mainly because of the high C content of the soil in the secondary forest.

Soil carbon was also compared between the old-growth forest, secondary forest and agricultural field. The secondary forest accumulated the highest percentage of soil carbon, followed by the old-growth forest and agricultural land. The high amount of soil carbon in the secondary forest may result from the decomposition of organic input after years of land abandonment (Davis et al., 2004). Increasing soil carbon sequestration as a result of less soil tillage, soil mass increment and continuous plant cover throughout the year results in a higher amount of carbon in secondary and old-growth forests compared to agricultural lands (Kane and Solutions, 2015).

On average, considerably lower soil carbon stocks have been reported in the top 30 cm for most European pasture fields (83 ± 8 t C/ha) and forests (88 ± 29 t C/ha) (Wiesmeier et al., 2012) compared to the values of 151.6 t C/ha and 156.9 ± 68 t C/ha found for the pasture field and old-growth forest in this study, respectively. Due to the small sample size of soil collected samples in this study, the results may be inconclusive and perhaps overestimated.

5. Conclusion

This study was carried out to assess forest tree succession on abandoned agricultural land and its potential for carbon sequestration in comparison with an old-growth forest and agricultural fields. A total of 11 deciduous tree species were identified in the secondary forest, which is comparable to other studies conducted across Europe. *Populus tremula* and *Fraxinus excelsior* were found to be the two most abundant species in the secondary forest. Together with an average stand DBH of 15.8 cm and high proportion of pioneer species, an intermediate successional stage can be implied.

There was a high abundance of understorey trees in the open areas of the secondary forest compared to the shaded part of the forest. The low number of understorey vegetation in the shaded areas may be due to less availability of resources, such as nutrient and water. A ring width analysis of the understorey vegetation showed an average decline in growth rate of the understorey trees, which can be a result of competition for available resources.

Aboveground and belowground biomass for this study was in the lower range of values reported for most temperate forests of the world. The comparably low carbon storage of the trees in this study may be due to the young age of the forest. This implies that there is more potential for tree carbon sequestration as the stand continues developing.

The results also showed that reforestation of abandoned agricultural land in this case resulted in higher soil carbon storage, probably due to new management procedures such as abandoned tillage. This study has shown the potential of abandoned agricultural land in supporting tree diversity as well as contributing to the global carbon budget, alongside other ecosystem services. However, the reported soil carbon stocks for the three land uses may have been overestimated, due to the low sampling density. It is therefore recommended that future studies on the study sites increase the sampling density. It may also prove beneficial in the future to sample the soil down to the parent material in order to improve the accuracy of soil carbon calculations.

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