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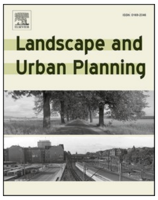

Research Paper

Afforestation of a pasture in Norway did not result in higher soil carbon, 50 years after planting

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HIGHLIGHTS

- Afforestation of marginal agricultural land did not increase soil carbon stocks.
- Only minimal build-up of organic horizon 50 years after planting Norway spruce.
- 50 years after afforestation, soil still shows legacy from former cultivation.

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ABSTRACT

Afforestation of marginal cultivated land is an internationally approved climate mitigation strategy, however, with uncertain implications for soil organic carbon (SOC) storage. We examined the effect of forest planting by measuring SOC at two adjacent sites: one with a Norway spruce forest planted in 1968 and one actively grazed pasture. Both sites had similar land-use history before forest planting, and they were as similar as possible in all other edaphic factors. There were no significant differences in SOC stocks down to 30 cm mineral soil, 7.15 and 8.51 kg C m^{-2} in the forest plantation and pasture respectively. Only a minimal build-up of an O horizon, less than 2 cm, was observed in the plantation. The SOC stocks of the plantation and pasture were not significantly different from that of a nearby old forest, 7.17 kg C m^{-2}. When comparing these three land-uses we found that there were significant differences in the upper 10 cm of the soil with regard to other soil properties. Nitrogen (N) stock and pH were significantly lower in the old forest compared to the plantation, which again was significantly lower than that of the pasture. The opposite was the case for the C/N ratio. We conclude that there were no significant differences in SOC stocks in the upper 30 cm 50 years after afforestation with Norway spruce, but that there is still a legacy from the former cultivation that may influence both productivity and organic matter dynamics.

1. Introduction

Afforestation of marginal cultivated land in order to sequester atmospheric CO_2 is an approved climate mitigation strategy (Smith et al., 2014) and is encouraged by many countries all over the world. Since Norway has very little cultivated land, only 3% of the total land area, it is usually strongly protected. However, recently the Norwegian Government has permitted afforestation on marginal agricultural land for climate mitigation purposes, provided certain environmental criteria are met (Haugland et al., 2013). A publication by Griscom et al. (2017) based on the IPCC Working Group III (Smith et al., 2014) investigated the mitigation potential for natural climate solutions to increase C storage and/or avoid greenhouse gas emissions across global terrestrial ecosystems. Their country-wise account suggested a maximum mitigation potential for reforestation in Norway of 0.43 Tg CO_2-eq yr^{-1}, which represents 4% of the maximum mitigation potential estimated for Norway (supporting information appendix in (Griscom et al., 2017)). Marginal agricultural land provides a range of important ecosystem services,

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such as biodiversity (including habitat for pollinators and genetic resources for farming), cultural heritage, open landscapes, tourism and space for everyday recreation activities (MacDonald et al., 2000; van Zanten et al., 2014). Such areas may be species-rich, frequently housing endangered species requiring traditional land-management in order to be preserved (Dahlberg et al., 2013; Panzacchi et al., 2010). Therefore, the combined value of various ecosystem services needs to be assessed before forest planting on marginal agricultural land can be approved in Norway (Haugland et al., 2013).

The background for employing afforestation as a climate mitigation strategy is its expected positive impact on long-term ecosystem C storage compared to non-forested areas as well as promoting the potential use of the biomass for products and bioenergy. While increased aboveground C stocks following afforestation are well documented e.g. Lal (2005), the effects on below ground C stocks are less certain, varying from sink to source depending on climate, land-use, time since conversion, soil depth considered, soil properties and tree species (DeGryze et al., 2004; Guo and Gifford, 2002; Paul et al., 2002). Most of these studies conclude that the amounts of soil organic carbon (SOC) lost or gained by soil are generally small compared to the accumulation in tree biomass (e.g. Paul et al., 2002, 2003). However, these studies are mainly aggregated on a global scale and can overlook regional climate variation and the time needed to identify cause, rates and persistence of changes in SOC, all of which are important for recommending national climate mitigation strategies (Vesterdal et al., 2011). Particular attention should be given to boreal ecosystems as they typically store large amounts of C in soils (Deluca and Boisvenue, 2012; Lal, 2005; Strand et al., 2016). In boreal climates, even small losses of SOC may offset the increased storage of C in slow growing coniferous trees.

Changes in SOC following afforestation may be divided into three different stages before reaching a new equilibrium (Covington, 1981; Lal, 2005). Given a land-use change, in this study from pasture to plantation forest, there will be an initial stage (SOC loss) (i) where forest plantation net primary production (NPP) is small and most C goes to building biomass. At this stage the changes in SOC will mainly reflect the severity of disturbance and the waning influence of the previous land-use (Paul et al., 2002). Disturbances caused by afforestation (e.g. site preparation) may, in this stage, accelerate decomposition of residues from the previous land-use, leading to net loss of SOC (Lal, 2005; Yanai et al., 2003). In the second (SOC recovery) stage (ii) at first much of the plantation NPP is allocated to long-lived woody components (stems, branches, and coarse roots), giving only minor additions of litter and root input to SOC. As the forest plantation biomass increases the litter and root input gradually increases and subsequently replaces the soil organic matter (SOM) from the former land-use. The third (new SOC equilibrium) stage (iii) develops as the forest stand matures, and inputs from the more lignified, recalcitrant material increase. This causes changes in soil conditions, reallocation and change in the quantity and quality of the SOM and, in many instances, also formation of an O horizon. The change in SOC following afforestation will therefore be dependent on progress in the stand development. The effect and duration of these three stages will vary with many regulating factors such as disturbance regime, climate, soil moisture regime, tree species, geological parent material and soil type see e.g. (Barcena et al., 2014b; Laganiere et al., 2010; Paul et al., 2002; Poeplau et al., 2011; Rahman et al., 2017).

The IPCC '*Good practice guidelines for greenhouse gas inventories*' (IPCC, 2006) uses a default timeframe of 20 years for SOC to reach a new equilibrium after a land-use change, whilst the European Union allows the use of 30 years (Regulation (EU) 2018/841, article 6:2). Several studies point out that this transition period should be much longer (more than 40 years) particularly for soils in cold climates (Barcena et al., 2014a; Hiltbrunner et al., 2013; Laganiere et al., 2010; Rahman et al., 2017; Vesterdal et al., 2011). Vesterdal et al. (2011) showed that rates of SOC change, upon land-use change, increase with increasing temperature and precipitation. This implies that input of SOC is more climate sensitive than the SOC decomposition rate. The SOC changes following afforestation in colder climates are therefore expected to be smaller and slower due to low productivity.

In the present study, we investigate a typical case of afforestation in Mid-Norway, i.e. a 50-year-old plantation of Norway spruce (*Picea abies* L.) on former agricultural land. Our hypothesis is that the afforested site has within this timespan reached a higher SOC stock than the adjacent pasture site and that this increase is mostly connected to a build-up in the upper mineral soil and in an O horizon. We tested this by i) comparing SOC stocks at four depths of mineral soil down to 30 cm; ii) observing forest O horizon build-up and iii) comparing a wide range of soil properties that may help explain the SOC changes due to afforestation. To assess the effects of land-use change on SOC stocks against other factors we also compare the effects of plantation versus continuous forest and landscape position on SOC stocks.

2. Methods

2.1. Site description and site history

Ideally, to measure the effects of afforestation on soil carbon, one would take measurements before planting the trees, then measure at the same location 50 years later. However, since no soil measurements were taken 50 years ago, instead we use a "space-for-time" approach (Pickett, 1989). We aimed to find an area (space) that could provide a surrogate for the historic situation (time). This involved finding a study area where i) part of the area was converted from agricultural use to plantation forest, whilst an adjacent area remained as agriculture, ii) climate and edaphic factors were the same across the whole study area, iii) land-use history differed only in that one area was planted and the other not, and iv) there were no other disturbing influences in close vicinity.

To find a suitable study area, we used information from the Norwegian monitoring programme for agricultural landscapes (Dramstad et al., 2002). This Programme involves detailed mapping of sample monitoring squares and includes a land class "plantation". This enabled us to find a number of examples of plantation forest adjacent to agricultural land in Mid-Norway. This region was chosen because it is one of the regions where the Norwegian Government has permitted afforestation on marginal agricultural land for climate mitigation purposes (Haugland et al., 2013). We looked for pasture next to plantation, since pasture is a more marginal land-use and therefore more likely to be used for planting for climate mitigation. Having found potential study areas, we checked the land-use history by examining time-series of aerial photographs (available at https://kilden.nibio.no).

The chosen study area was located at Haugset, in Verdal municipality, Trøndelag County, Mid-Norway (11°51′ E, 63°48′N) (Fig. 1). The study area was divided between two owners, one owning the pasture and the other owning the forest plantation. The altitude is 110–120 m above sea level. The study area falls into the middle boreal vegetation zone, and 'slightly oceanic' climate section, a vegetation ecological region covering approximately 20 000 km^2 (ca. 5%) of Norway's land area (Moen, 1998). The mean annual precipitation in the area is 900 mm and the mean annual temperature is 4.7 °C. The underlying bedrock is a complex of amphibolite and mica schist. The soils around the Haugset farms are all on marine deposits, the area having become dry land some 8–9000 years ago due to land uplift following deglaciation. Classified according to World Reference Base for Soil Resources version 2006 (WRB, 2007) the soils in the study area are Albeluvisols (Endostagnic Albeluvisol (Siltic)), with a small patch of Fluvisols (Gleyic Fluvisol (Humic)) in the lower southeastern part.

The north-western of the two small farms at Haugset was abandoned in the late 1960 s, farming ceased, and the fields were planted with Norway spruce (*Picea abies* (L.) H. Karst) in 1968. According to the information from the Norwegian forest resource map (available at https://kilden.nibio.no) the average tree height in present plantation is 17 m, the standing timber is estimated to 350 m^3 ha^{-1} and the forest

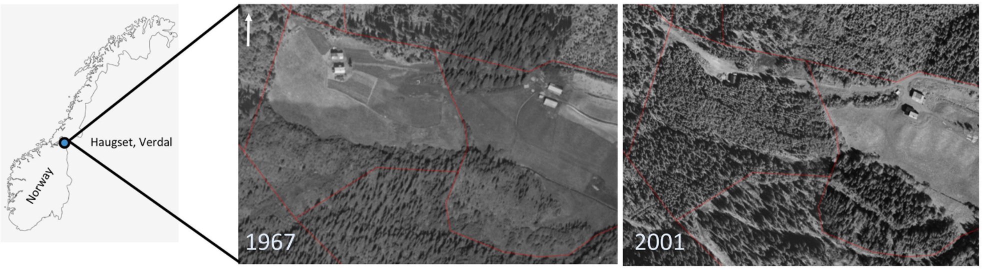

Fig. 1. The study area of Haugset in Verdal municipality in Trøndelag, Mid- Norway. Aerial photos of the Haugset farm in 1967 show connected fields, before the Norway spruce was planted. Photos from 2001 show that the field on the left has become mature plantation forest. The eastern Haugset farm is still actively farmed. The fields are used as pasture for cattle and sheep. Aerial photo © Norway Digital.

productivity is considered medium to high according to Norwegian standards. The south-eastern farm is still actively farmed. The fields are used as pasture for cattle and sheep in the summer season. No other fertilizer has been added than manure from grazing animals since 2000 (pers. comm. landowner). The plantation area is approximately 1.6 ha and the pasture area is 1.7 ha. Both areas are on south–south-eastward slopes down towards a creek running eastward. A nearby forested area (~80-year-old Norway spruce stand), from here on referred to as the old forest, and an abandoned poorly drained meadow on the opposite side of the creek, from here on referred to as the meadow (see Fig. 2) were sampled for comparison with the plantation and the pasture. The meadow was physically separated from the pasture in 1997 when the creek was restored. After 1997, vegetation from the meadow was removed mechanically, not regularly, until approximately 2010 to avoid regrowth of forest and shrubs (landowner, pers. comm.).

2.2. *Soil sampling and analysis*

Sampling points were selected to give area-representative samples for each land-use type, 12 points for the plantation and 9 points for the pasture (Fig. 2). Six additional sampling points were taken from the nearby old forest (3 points) and the meadow (3 points) (Fig. 2). For all sampling points, slope, aspect, landscape position and surface properties (vegetation and litter cover, stones and boulders) were registered. The soil was sampled with a split-tube sampler, a corer with an inner diameter of 4.8 cm and a full length of 45 cm. Four cores were taken at each sampling point, the corer was pressed or carefully hammered into the soil as deep as possible to ensure a sampling depth of at least 30 cm, if the depth was less than 30 cm this was recorded. The mineral soil in each soil core was divided into four layers by depth; 0–5 cm, 5–10 cm, 10–20 cm, 20–30 cm. For each depth, the entire soil material from all four cores was pooled into one composite sample. If an O horizon was present (in the core), the thickness was registered, and the horizon was sampled separately. Sample soil volume was calculated based on the inner diameter of the sampling cylinder and the total length of the soil sample (cm). Each composite sample was dried and weighed. The dried soil samples were sieved through a 2 mm sieve. The soil volume and weights before and after sieving were used to calculate natural bulk density (weight before sieving) and fine-earth bulk density (weight after sieving). Total carbon (Tot-C), total nitrogen (Tot-N) and pH were measured in all soil samples. Tot-C and Tot-N were measured by dry combustion using a LECO TruSpec® CNH analyser. Ten percent hydrochloric acid was added to the soil samples to check whether any inorganic carbon was present, no effervescence was registered, this together with a pH lower than 6,5 suggest that Tot-C could be interpreted organic carbon (SOC) in all samples. Soil pH was measured in a 1:2.5 v/v ratio of soil to distilled water using a glass membrane combination electrode (ORION SA 720 pH/ISE meter). Cation exchange capacity (CEC) and soil texture were analysed only in the third layer (10–20 cm). The CEC was measured by extraction with 1 M ammonium acetate ($NH_4CH_3CO_2$) buffered at pH = 7.00 and calculated as the sum of cations Calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), sodium (Na^+) and total acidity (H^+). The concentrations of Ca, Mg, K and Na were analysed using inductively coupled plasma optical emission spectrometry (ICP-OES; Perkin Elmer Optima 3000 DV). Determination of total acidity was done by titrating the percolate back to pH 7.00 by use of NaOH. Particle size distribution was measured by the pipette method as described in (Van Reeuwijk, 2002). Texture classes were determined according to FAO (FAO, 2006)

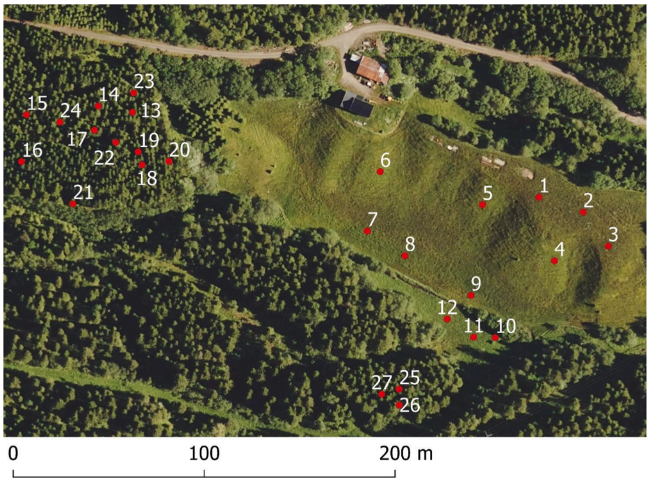

Fig. 2. Aerial photos showing the sampling points; Pasture sampling points 1–9, Abandoned meadow sampling points 10–12, Plantation forest sampling points 13–23 and Old forest sampling points 25–27. Aerial photo © Norway Digital.

2.3. *Carbon and nitrogen stock calculations*

As afforestation and grazing both may affect bulk density and presence of an O horizon, they also may affect SOC stock calculations. Ellert and Bettany (1995) suggest that it is more correct to compare SOC stock in similar soil masses rather than down to similar depths when investigating the effects of land-use and management changes. We therefore calculated SOC and N stocks in two different ways, 1) down to a depth of 30 cm (ESD = equivalent soil depth) and 2) by comparable mineral soil mass (ESM = equivalent soil mass). The soils were all on marine deposits devoid of stones and coarse gravel, so no volumetric correction was needed for the fraction greater than 4.8 cm (the core diameter). However, we used fine-earth bulk densities in our SOC and N stock calculations, which corrects for the coarse fragments (0.2–4.8 cm) that may be present in some samples. The following equations were used to calculate the SOC stocks.

For each layer the SOC stock was calculated using the following equation:

1) SOC-stock (kg m^{-2}) = BD (kg m^{-3}) × Thick (m) × C concentration (kg kg^{-1})

- BD is bulk density of the fine earth (kg m^{-3})
- Thick is the thickness of the soil layer (m)
- C concentration is the elemental concentration of C by mass (kg C kg^{-1}).

The ESD (30 cm) SOC stock was thereafter calculated by summing the SOC stocks calculated for the individual layers Σ O horizon, 0–5 cm, 5–10 cm, 10–20 cm. 20–30 cm.

The ESM calculations were done as suggested by Poeplau and Don (2013). To find the ESM we summed the mass of the mineral soil of each layer down to 30 cm at each sampling point. The sampling point with the lowest mass determined the nominal mineral soil mass for the ESM estimation. To calculate the cumulative SOC stock by ESM the SOC stocks for each layer were calculated using equation 1). The SOC stocks of the sampled layers were accumulated from the upper to the lower part of the soil profile until equivalent mass was reached. Nitrogen stocks were calculated using the same procedure, substituting C concentrations with N concentrations (Tot N kg kg^{-1}).

2.4. *Statistical analysis*

All statistical analyses were performed with SAS statistical analyses program (SAS Institute, 2012). Statistical differences between the land-use types were assessed using an analysis of variance, performed using standard general linear model (GLM procedure) with a Student Newman Koule (SNK) range test for multiple comparisons between the land-uses. When nothing else is stated, statistical tests are considered significant when P less than 0.05.

3. Results

Soil properties of the plantation and the pasture showed that the pasture had significantly higher clay and silt content compared to the plantation (Table 1) though the differences were not great enough to affect the texture classes. The volume percentage of coarse material was low, but a couple of samples in the plantation had a volume of 15 to 25%. Though there were no significant differences in slope (Table 1) there was a slight difference in topography between the two sites, the plantation being generally inclining, while the pasture had a complex relief with pronounced summit, slope and depression.

The difference in land-use caused a significant difference in soil bulk density. Differences in moisture, root activity, and trampling of grazing animals all influenced the bulk density particularly of the surface horizon. Fine-earth bulk-density was significantly higher in the 0–5 cm and 5–10 cm depths of the pasture compared to the plantation. There was a systematic difference between soil samples from the plantation and the pasture with regard to Tot-C concentrations and fine earth bulk density (Fig. 3).

Soil organic carbon stock by horizon showed that the land-use had greatest influence on the upper 10 to 20 cm of the soil (Table 2). However, there were no significant differences in SOC stocks at any depth. A thin O horizon had developed in most, but not all, of the plantation sampling points. The mean O horizon was 1.2 cm (standard deviation 1.2 cm), and consisted of a mix of easily recognizable litter, mostly spruce needles, (Oi) and poorly decomposed organic material (Oe). There were no significant differences in SOC stock between the land-uses, either when compared by ESD or by ESM (Table 2). The pasture stored 16% more compared to the plantation forest by ESD and 13% more when comparing by ESM.

Table 1
Soil and site properties for the plantation and pasture, standard deviation in brackets. The CEC and texture analysis are all from the 10–20 cm soil depth. Lower case letters indicate significant differences between the sites (α = 0.05).

	unit	Plantation (n = 12)	Pasture (n = 9)
CEC*	$cmol_c\ kg^{-1}$	16.9(3.38)	19.5(4.5)
Base saturation	%	6.9(6.0)	12.6(9.0)
Clay	%	9.6(4.1)b	15.8(4.2)a
Silt	%	56.2(9.5)b	67.9(7.5)a
Sand	%	34.2(13.3)a	16.4(11.2)b
Coarse fragmentsSlope	Volume%%	5.6(9.2)17(11)	0.3(0.1)11(15)

* CEC = cation exchange capacity by ammonium acetate in pH 7.

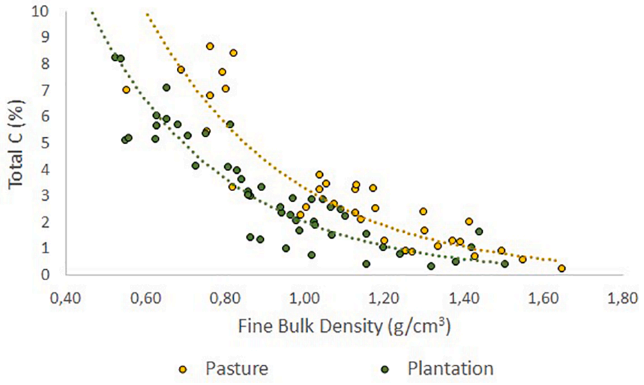

Fig. 3. Relationship between carbon concentrations and fine earth bulk density for the plantation and the pasture.

Table 2
Comparisons of SOC and N stocks between plantation and pasture by different soil depths, equivalent soil depth of 30 cm (ESD) and equivalent soil mass (ESM). Standard deviation given in brackets. Lower case letters indicate significant differences (α = 0.05).

	SOC stocks (kg C m^{-2})		N stocks (kg N m^{-2})	
	Plantation	Pasture	Plantation	Pasture
O horizon	0.35 (0.37)	–	0.014(0.05)	
0–5 cm	1.91(0.31)	2.20(0.50)	0.117(0.022)b	0.177(0.037)a
5–10 cm	1.34(0.32)	1.70(0.78)	0.094(0.022)b	0.138(0.057)a
10–20 cm	2.16(0.86)	2.70(1.52)	0.146(0.055)	0.210(0.110)
20–30 cm	1.46(0.88)	1.92(1.90)	0.092(0.053)	0.154(0.143)
ESD	7.15(2.36)	8.51(4.39)	0.460(0.138)b	0.680(0.320)a
ESM	6.30(2.17)	7.23(4.68)	0.401(0.116)	0.572(0.351)

There were larger differences in soil nitrogen (N) stocks (Table 2). Comparisons by ESD showed significantly, by 32%, higher N stock in the upper 30 cm soil depth of the pasture compared to the plantation. Comparing soil N stock by ESM showed the same pattern but gave a smaller (30%) and not significant difference between the two land-uses (Table 2). Comparing the different depth layers of the mineral soil revealed that the differences in N stock were related to the upper 10 cm of the mineral soil. No significant differences in N stocks were found for the deeper layers 10–20 cm and 20–30 cm (Table 2).

We compared the SOC stock in the plantation and pasture with the adjacent old forest (Norway spruce) and the abandoned poorly drained meadow (Fig. 4). The soil type on the meadow, Gleyic Fluvisol (Humic), differed from the Endostagnic Albeluvisol (Siltic) dominating the three other land-uses by having a Histic surface horizon. The humus form in the old forest was moder. There was a significantly larger SOC stock in the meadow compared to the other land-use categories, irrespective of method for calculating stocks.

For the land-uses plantation, old forest and pasture, on the same soil type Endostagnic Albeluvisol (Siltic), there were no significant differences in SOC stocks. However, there were significant differences at greater depth when comparing the pH and the C/N ratios of these three sites (Fig. 5).

For the pasture the sampling points easily could be grouped into summit (sampling point 1,2,3), slope (sampling point 4,5,6) and

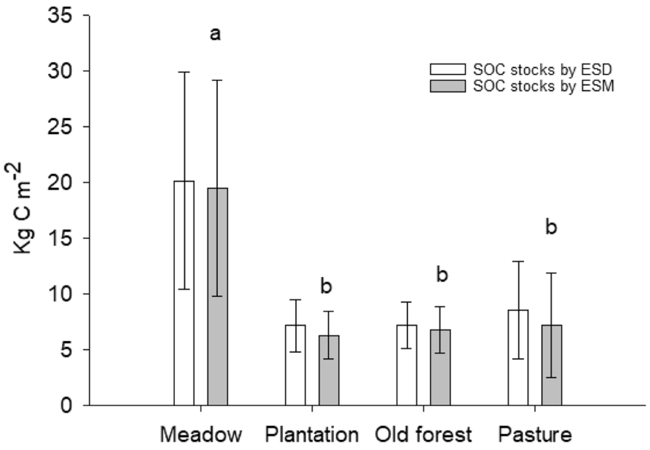

Fig. 4. Carbon stocks in soil down to 30 cm (ESD) and by equivalent mass (ESM) in four adjacent land-use types, meadow (n = 3), plantation (n = 12), old forest (n = 3) and pasture (n = 9). Lower case letters indicate significant differences (α = 0.05).

depression (sampling points 7,8,9) (Fig. 2). By stratifying the samples in this way, we could clearly see the effects of drainage and soil moisture. The largest SOC stocks were found in the moister depression and lowest on the steep slopes (Fig. 6). The differences between the SOC stocks down to 30 cm mineral soil at the summit and the depression was 4.1 kg C m^{-2}. When comparing with the SOC stocks on the steep slopes of the pasture, the differences compared with the depression were even larger (7.8 kg C m^{-2}).

4. Discussion

In agreement with studies from comparable climate zones (Alberti et al., 2011; Berthrong et al., 2009; Guidi et al., 2014; Poeplau et al., 2011; Risch et al., 2008), we found little effect on SOC stocks of afforestation of marginal agricultural land. Our study suggests that within a timeframe of 50 years after conversion of pasture to Norway spruce plantation, there are no significant changes in SOC stocks, neither when compared by ESD nor EMS (Table 2). This is in line with (Laganiere et al., 2010) and (Vesterdal et al., 2011) who both suggest that afforestation carried out in colder, boreal climate zones could result in small SOC losses compared with other warmer climate zones in similar time-spans. They explained this with slow-growing trees and little litter input coupled with slow decomposition, implying that soils in cold regions need longer time to reach a new equilibrium following land-use change. Also studies of afforestation of subalpine pastures in Switzerland, Italy and in Northern European grasslands (Barcena et al., 2014a; Guidi et al., 2014; Hiltbrunner et al., 2013; Poeplau et al., 2013) have shown a reduction in SOC stock for the first 40–45 years before gradually increasing. From this we expect that the SOC stock of the plantation has not reached an equilibrium and thus it is still uncertain whether the new equilibrium will stabilize at a higher, lower or similar level compared with the previous land-use. When we compare the plantation SOC stocks with information from the Norwegian forest soil database (Strand et al., 2016) we find that forest soils in the same region and site index have considerably larger SOC stock: on average 13.4 kg C m^{-2}, down to 30 cm mineral soil depth. 4.8 kg C m^{-2} of this is stored in the O horizon (Strand et al., 2016). This suggests that there may be potential for sequestering more SOC in the plantation given enough time. However, when we compare with the nearby old forest it only stores slightly more SOC than the plantation (Fig. 4), suggesting that the potential for further increasing SOC stocks in the upper 30 cm of the soil by afforestation, at this location, is not large. The SOC stocks of the pasture were lower than the national averages of 9.32 kg C m^{-2} for Norwegian pastures on mineral soil calculated for the upper 25 cm by Klakegg and Fjellstad (2013). They had few observations (n = 49) and their data did not discriminate between soil types, climate and management making comparisons difficult.

Afforestation may cause a change in quality and depth distribution of SOM not necessarily reflected in the ESD and ESM SOC stocks. Several studies of afforestation on pastures and grasslands found that the most pronounced effect was the formation of an O horizon (Barcena et al., 2014a; Guidi et al., 2014; Hiltbrunner et al., 2013; Poeplau et al., 2013; Thuille and Schulze, 2006). In our study the O horizons of the plantation and old forest were thin, 1.20 cm and 2–3 cm respectively, compared to the 8 cm average found for the O horizons in forests the same region and site index (Strand et al., 2016). The SOC stock in these O horizons represent 5%, 15% and 35% of the SOC stock down to 30 cm mineral soil

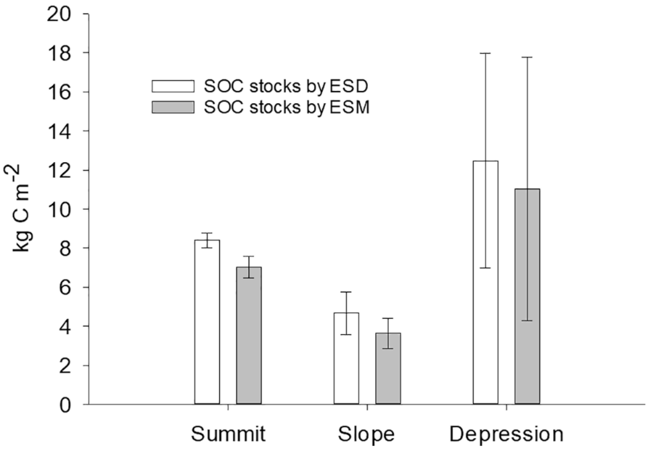

Fig. 6. Carbon stocks in soil down to 30 cm (ESD) and by equivalent mass (ESM) in the pasture, error bars show standard deviations. Each landscape position is represented by three sampling points.

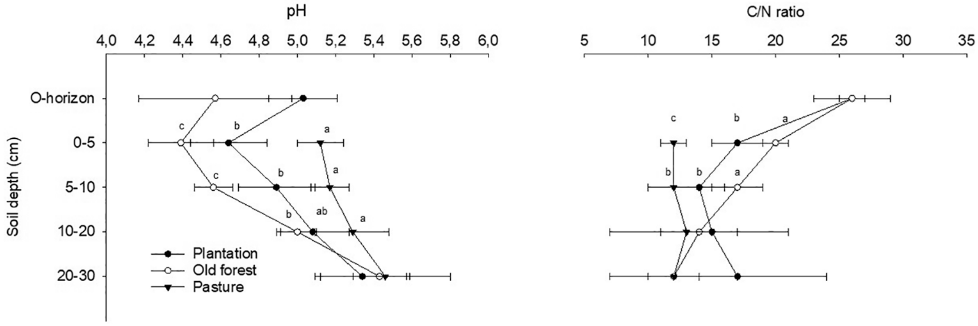

Fig. 5. pH and C/N ratio by depth in old forest (n = 3), plantation (n = 12) and pasture (n = 9) all on same soil type Endostagnic Albeluvisol (Siltic). Lower case letters indicate significant differences (α = 0.05).

depth for the plantation, old forest and the regional forest respectively. The thin O horizons in our study may be due to the fine textured soil. Fine textured soils in general have thinner, less developed O horizons than coarser textured soils (Callesen et al., 2003; Vesterdal et al., 2007). There was no sign of bioturbation that may have reduced the O horizon formation. Given the SOC stock in the O horizon accumulated over the 50 years since afforestation we can assume a yearly accumulation rate in the plantation O horizon of on average 8 g C m^{-2} yr^{-1}. This is, as expected, lower than the 36–38 g C m^{-2} yr^{-1} found for afforestation of grasslands in temperate regions (Poeplau et al., 2011; Thuille et al., 2000) and the 20–24 g C m^{-2} yr^{-1} found for afforestation in alpine grasslands (Guidi et al., 2014; Thuille and Schulze, 2006). The rate we found is, however, similar to the mean annual accumulation rates 8.8 g C m^{-2} yr^{-1} found for Norwegian forest soils in general and 7.2 g m^{-2} yr^{-1} for the Trøndelag region more specifically (de Wit et al., 2015).

Despite the minor effects of afforestation on SOC stocks there were clear effects of land-use change on other soil properties related to SOM quality and dynamics. The N stocks calculated by ESD were statistically significantly higher in the pasture compared to the plantation, but this was not significant when calculated as ESM. The differences were mainly linked to the O horizon and the upper 10 cm of the mineral soil (Table 2). When including the old forest in the comparison differences in soil properties reflecting land-use became more pronounced (Fig. 5). The C/N-ratio of the O horizons of the old forest and plantation were virtually identical, suggesting similarities in litter quality of the Norway spruce forest in this locality (Fig. 5). This is a fairly low C/N ratio for spruce forest, but not unusual in stands with high site index and fine textured soil (Callesen et al., 2007). The old forest had the highest C/N ratios and the lowest pH while the plantation was in between the old forest and the pasture (Fig. 5). This suggests that the plantation is still affected by its history as former agricultural land. This is supported by Kacalek et al. (2011) they found a legacy of higher pH and Ca in the soil of a 50-year old Norway spruce plantation on former agricultural land compared with a 100 year old Norway spruce stand in a continuously forested area in the Czech Republic. Also Brudvig et al. (2013) observed differences in both above ground vegetation and soil properties nearly 60 years after agricultural abandonment particularly in N and P content of organic matter and soil water holding capacity. Former cultivation clearly has a long legacy in forest plantation. The most dynamic soil properties are related to the SOM and they change gradually following the development in the plantation stand. Boreal forests are generally N deprived (e.g. Sogn et al., 1999). The growing trees immobilise N in their biomass, extracting N from the soil mostly through decomposition of legacy SOM from the former agricultural practice. The closed, dense canopy of the 50-year old plantation may intensify the change in quality of the SOM as it provides an increasing input of ligneous litter with a high C/N ratio whilst blocking out light and intercepting rain. The water demand of the trees also dries the ground and these dark, dry conditions support little or no ground vegetation. The drier surface layer may also increase soil respiration and decomposition in otherwise often wet soils, thereby leading to lower SOC stock (Upson et al., 2016). Kirschbaum et al. (2008) pointed out that a decrease in SOC stocks, after afforestation, is more common in regions with high rainfall and explained this with greater amounts of N being leached from systems where water supply exceeds plant requirements. Precipitation surplus is certainly the case in this location, but we have no measurements to confirm any N-leaching. The grass vegetation in the pasture, though only maintained through grazing, provides more root-litter and higher amounts of easily decomposable litter and N additions through manure from grazing animals giving lower C/N ratios, all suggesting a more rapid turnover of the litter added to the pasture. Low-intensity grazing by domestic herbivores, as the case is in this study, may enhance soil N cycling and net primary production (NPP) leading to increased C sequestration (Soussana and Lemaire, 2014). Soil organic matter added through root litter also has a longer residence time, particularly in fine textured soils this organic matter will be protected both physically and chemically (Rasse et al., 2005; von Lutzow et al., 2006). Stabilisation efficiency of root-derived carbon in soil is two to three times greater than that derived from above ground vegetation (Katterer et al., 2011; Rasse et al., 2005). The soil in this study was relatively fine textured (Table 1), a property that we were particularly interested in as we expected these soils to be more efficient in C sequestration. Clay-rich soils are expected to sequester more C than sandy soils due to higher NPP and more stabilizing processes through aggregation, occlusion, complexation and mineral surface interactions (von Lutzow et al., 2006). However, according to a meta-study by (Barcena et al., 2014b) afforestation on fine textured soils may have a slight negative effect on SOC stocks. They explained this as a confounding effect caused by the fact that afforestation of grassland nearly always is on fine textured soils (Barcena et al., 2014b). In our study the texture of the pasture was significantly higher in clay content, a difference we expect was there prior to the afforestation of the neighbouring area (Table 1). This may suggest that there was also an initial difference in SOC between the areas prior to the conversion to plantation thereby dampening the results we achieved through our space-for-time approach.

The largest SOC stock was found in the poorly drained abandoned meadow. Here the poor drainage caused development of a Histic horizon (20–40 cm deep organic surface horizon) which explains the high C stocks at this location (Fig. 4). However, even within soil types of similar classification, Endostagnic Albeluvisol (Siltic), SOC stocks differ significantly with landscape position and soil moisture conditions (Fig. 6). This was also found in a study of Norwegian agricultural soils by Klakegg and Fjellstad (2013). They showed that differences in drainage could cause more than 15–20% difference in SOC stock in the upper 25 cm of mineral soil with meadow as land-use ($n = 699$), less in well drained and more in poorly drained soils. They also found the largest differences were in strongly oceanic climatic zones and the smallest in weak continental climatic zones. For the pasture in this study, the difference between the drier summit and more moist depression was 33% (Fig. 6). The high SOC stocks in the lower landscape positions may be due to several factors i) reduced decomposition (loss) following water saturation 2) high productivity (input) due to nutrient rich runoff from abovelying areas 3) higher production (input) due to no draught stress.

5. Conclusions

Fifty years after afforestation of agricultural land with Norway spruce in the mid-boreal, slightly oceanic region of Norway, there were no significant differences in SOC stocks in the upper 30 cm of the soil compared with an adjoining actively grazed pasture. We still find a legacy from the former land-use, influencing both quantity, quality and distribution of soil organic matter. This shows how slowly soil properties change in fine textured soils in cold climates. Though there is little doubt that forest sequesters more carbon in the aboveground vegetation compared to pasture, it is highly unlikely that forest planting on fine-textured soils will lead to any significant increase in stable carbon storage within the normal rotation length of a plantation forest in this region. This should be taken into account in the ongoing discussions of benefits and trade-offs of afforestation in a climate perspective, where carbon sequestration must be balanced against values of other ecosystem services such as biodiversity, the aesthetic appeal of open landscapes, and food and livelihoods from smallholder farming.

CRediT authorship contribution statement

Line Tau Strand: Writing - original draft, Methodology, Formal analysis. **Wendy Fjellstad:** Visualization, Writing - review & editing. **Leah Jackson-Blake:** Methodology, Visualization, Writing - review & editing. **Heleen A. De Wit:** Conceptualization, Funding acquisition, Project administration, Writing - review & editing.

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