

Carbon content of below-ground biomass of young Scots pines in Latvia

Ā. Jansons, A. Bārdulis, L. Kēniņa*, D. Lazdiņa, E. Džeriņš and R. Kāpostiņš

Latvia State Forest Research Institute ‘Silava’, Rigas street 111, LV–2169, Salaspils, Latvia

*Correspondence: laura.kenina@silava.lv

Abstract. Forest ecosystems play crucial role in global carbon cycling, therefore, increasing afforestation of agricultural land in Europe has been recognized as important contribution of carbon sequestration. In carbon reporting systems, root carbon content (CC) default value has been set to 50%. The study aimed to estimate CC in below-ground biomass and in relation to tree age in young Scots pine stands on forest and former agricultural land. The below-ground CC of young (8 to 40 years) managed Scots pine (*Pinus sylvestris* L.) stands growing on nutrient poor mineral soils in Latvia was carried out. In total 62 sample trees (43 in forest land, 19 in former agricultural land) were randomly selected for destructive sampling to estimate the CC within below-ground biomass. Below-ground biomass weighted mean CC was $49.7 \pm 0.4\%$, being slightly lower than the default CC value used to calculate carbon budgets. Root fractions stump, small roots (diameter 2–20 mm), coarse roots (diameter > 20 mm) differed ($p < 0.001$) in their CC. Stumps ($50.6 \pm 0.6\%$) had highest ($p < 0.001$) CC in the below-ground biomass, followed by coarse ($49.5 \pm 0.4\%$) and small ($49.1 \pm 0.4\%$) roots, which did not differ from each other in their CC. Results demonstrated age-dependent increase of CC ($p < 0.001$) from $48.2 \pm 0.3\%$ to $51.7 \pm 0.5\%$, indicating overestimation of the default value during the first two decades, but underestimation for older trees (24 to 40 years).

Key words: root biomass, coarse roots, stump, abandoned agricultural land.

INTRODUCTION

Forest ecosystems contain the majority of the carbon (C) pool on the Earth and play crucial role in global C cycling both as C sink and source (Dixon et al., 1994; Uri et al., 2012). Increasing afforestation of former agricultural land in Europe also has been seen as important contribution for C sequestration in future (Paul et al., 2002; Vesterdal et al., 2002). Both above- and below-ground biomass is an essential C pool of forest ecosystems (Helmisaari et al., 2002; Karsenty et al., 2003; Tang et al., 2015), however, the uncertainties in below-ground biomass C estimation remains (Varik et al., 2013; Addo-Danso et al., 2016). The importance of below-ground C pool inclusion in total C estimation is recognised through the Kyoto protocol and Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC) (Petersson et al., 2012; Merilä et al., 2014). In accordance to both international agreements, member states are required to monitor, report, and reduce greenhouse gas

(GHG) emissions (Frederici et al., 2008) to achieve ambitious climate goals worldwide (Rogelj et al., 2016).

In national and international GHG reporting systems for C stock estimates, the mean carbon content (CC) of tree roots is set 50% of the dry biomass (Lamloom & Savidge, 2003; Martin & Thomas, 2011). This default value is widely used for CC calculations in different forest zones (Saatchi et al., 2011) and in various forest management systems as managed forests, plantations and agro-forestry. However, this approach can lead to an accounting error of approximately 5% (Martin & Thomas, 2011). Partly due to methodological challenges (Finér et al., 2011), the accurate C estimation in forest below-ground biomass and its potential to mitigate global climate change in Europe are not always clearly defined (Addo-Danso et al., 2016; Sochacki et al., 2017). Efforts reducing uncertainty in the below-ground biomass studies on GHG attraction and C turnover cycle in the forest ecosystem recently have grown (Liski et al., 2003; Thomas & Martin, 2012; Sochacki et al., 2017).

Forest sector has high importance in Baltic States. Nearly half of the territory of Baltic States are covered by forests (Eurostat, 2016). According to the Latvian State Forest Service, forests cover 52% of the total land area. The forest area has almost doubled from 1935 till 2015, mostly due overgrowth of agricultural land (Nikodemus et al., 2005). Scots pine (*Pinus sylvestris* L.) is the most common and economically important in Latvia, occupying 34% of the total forest area, of which nearly half are located on dry mineral soils (Baumanis et al., 2014). Despite the intensive forest management practices in region, studies of C accumulation in tree root biomass and their role in C budgets of forests in this region have been scarce.

Carbon sequestration and amount of root biomass in forest are dependent on tree species, site types, soil properties, environmental factors and forest management practices (Haynes & Gower, 1995; Gill & Jackson, 2000; Pregitzer et al., 2000; Brassard et al., 2011). Moreover, previous studies suggest that CC in below-ground biomass has been strongly influenced by the stand age (Peichl et al., 2006; Jain et al., 2010; Uri et al., 2012; Bijak et al., 2013). With the increase of forest harvesting in Europe for the substitution of fossil fuels in energy production (Levers et al., 2014; Merilä et al., 2014), due to slow decomposition and life-cycle features, roots and stump may play essential role for long term C input in soil (Bardgett et al., 2014; Kaarakka et al., 2016). Therefore, due to changes in forest age-structure, it is crucial to understand the contribution of young tree root biomass growth to C fluxes in forest and woodland (Pajtik et al., 2008; Finér et al., 2011; Fonseca et al., 2011).

The aim of this study was to estimate CC in below-ground biomass and in relation to tree age in young Scots pine stands on forest and former agricultural land (FAL).

MATERIALS AND METHODS

Site characteristics

The study was carried out in young Scots pine stands in Latvia (Table 1). Latvia is located in the north-western edge of the East European Plain within hemiboreal forest zone with mixed broad-leaved and coniferous forests (Ahti et al., 1968; Hytteborn, 2005). The climate of Latvia is moderate. According to data from the Latvia Environment, Geology and Meteorology Agency, mean annual temperature is around 6 °C. January is the coldest month with mean temperature -5.3 °C, but warmest month

is July when mean temperature is 17.2 °C. The mean annual precipitation is 645 mm, though half of annual precipitation is recorded during summer period May-September.

Table 1. Characteristics of Scots pine experimental stands

Land type	Stand location	N	Stand age	Tree height (m)	dbh (cm)	Tree below-ground dry-mass (kg)	Basal area (m ² ha ⁻¹)	Stand density (trees ha ⁻¹)
	56°50 N 24°38 E	5	8	2.7	2.4	0.7	2.3	3,600
	56°50 N 24°38 E	7	8	2.4	2.2	1.0	4.6	8,800
	56°34 N 25°01 E	3	12	4.0	6.6	7.5	7.3	2,145
	56°24 N 25°01 E	6	13	4.6	5.2	4.1	4.8	2,215
	56°51 N 24°35 E	6	14	4.8	5.3	4.8	7.2	3,200
	56°41 N 24°27 E	10	24	10.0	11.0	17.4	13.2	1,385
	56°43 N 24°34 E	3	40	17.7	18.8	38.9	18.0	583
	56°43 N 24°34 E	3	40	17.1	18.6	41.6	16.2	570
	56°34 N 24°08 E	5	12	7.7	11.2	14.7	21.1	2,145
	56°32 N 24°04 E	5	14	8.2	10.3	21.8	24.3	2,925
	56°41 N 26°01 E	3	38	17.3	14.4	19.6	28.9	1,680
	56°41 N 26°09 E	6	38	17.0	14.4	19.3	18.6	1,260

FAL – former agricultural land; N – number of sampled trees; dbh – tree diameter at breast height.

All sampled stands were on dry sandy nutrient poor mineral soils, representing typical Scots pine forest growth conditions in Latvia. The study material was collected in 8 Scots pine stands on forest land and 4 stands on FAL at the age of 8 to 40 years. Except one naturally regenerated 8 years old Scots pine stand, all studied stands was planted after soil preparation with 2 years–old bare–rooted or containerised seedlings.

One circular sample plot was established in each stand: in stands younger than 15 years the area of sample plot was 100 m² (R = 5.64 m), in older – 500 m² (R = 12.62 m). In each plot tree diameter at breast height (dbh) (± 0.1 cm), tree height (h) (± 0.1 m) and age was measured.

Sampling

In total 62 sample trees (43 in forest land, 19 in FAL) were randomly selected for destructive sampling of the root biomass to estimate the CC allocation in root fractions (Table 1). The sample trees, 3–10 trees per plot, were selected based on quality criteria (health, vitality, single tree top) from different size classes. Samples were collected during the vegetation period from June to August. The dbh and h of sample trees ranged

from 1.2 to 26.5 cm and 1.9 to 20.8 m, respectively on forest land. In FAL at age of 12 to 38 years the dbh and h corresponding figures were 3.7 to 26.0 cm and 5.9 to 20.8 m (Fig. 1).

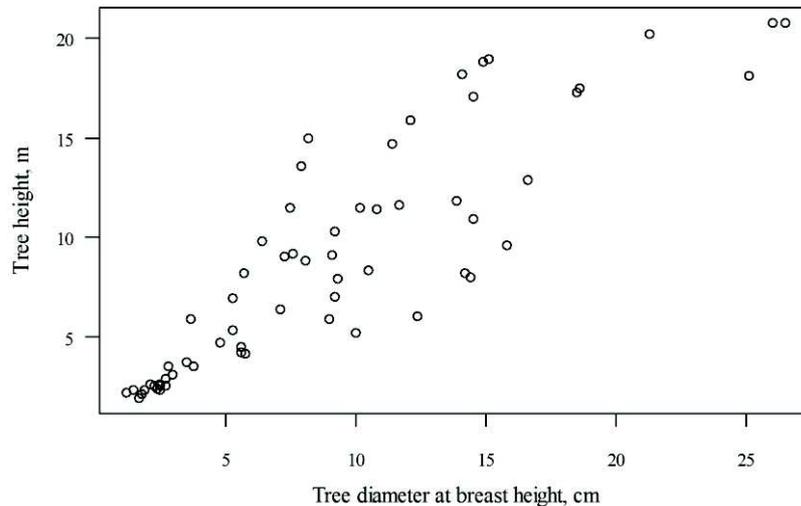


Figure 1. Tree diameter at breast height and height of the sample trees.

For CC analysis, the sample tree root biomass was divided into fractions: small roots (diameter 2–20 mm), coarse roots (diameter > 20 mm) (Fujii & Kasuya, 2008; Finér et al., 2011) and stump. Stump biomass included both the above-ground (5–8 cm above the root collar) and below-ground monolithic part.

The stumps and roots were excavated and washed using high pressure water jet. The entire root system was weighted (± 0.02 kg), divided into fractions and each root fraction was weighted (± 0.02 kg). CC analysis were performed for small roots, coarse roots and stump samples. For 16 sample trees (12 trees at age of 8 years and 4 trees at the age of 14 years) coarse roots were not detected, suggesting that coarse roots are developed later. All root components were dried to constant mass at 105 °C temperature and weighted. The mean total below-ground biomass of the sampled trees varied between 0.1 and 155.3 kg with an average of 17.1 kg on forest land. The mean total below-ground biomass of the sampled trees on FAL was 27.3 kg and ranged from 1.3 to 104.2 kg. For CC analysis of individual tree, small roots and coarse roots were divided on 3 diameter classes. In each diameter class, from randomly selected roots on average 2 cm long cuts of both ends and centre of the root were collected in one homogenised sample (150–200 g) for each root fraction. Whole stump (if it was less than 200 g) or two 2 cm samples from the radial cut zone were obtained. Air-dried samples were milled and 0.25–0.50 g samples for carbon determination were taken.

Data analysis

Carbon content was analysed with an LECO CR–12 Carbon analyser set at 900 °C and the CC was assessed directly by measurement of the CO₂ using infrared radiation (LECO Corporation, 1987). The instrument was calibrated using calibration substance – carbon powder containing 64.8% C and an empty test without a sample was

performed. The mean CC of sample tree below-ground biomass was calculated as weighted average of total CC.

All statistical analyses were performed using R v.3.3.1 statistical environment (R Core Team, 2016). Analysis of covariance ANCOVA was used for estimating the effect of the land type and different root fractions on the root CC. Stand age was added as a numeric covariate in analyses (Peichl & Arain, 2006; Seedre et al., 2015). The Turkey Honest Significant difference (HSD) test was employed to perform multiple post hoc comparisons between CC for different root fractions.

RESULTS AND DISCUSSION

Below-ground biomass CC was compared in each root fraction among and within forest land and FAL (Fig. 2). Mean CC of below-ground parts of young Scots pine trees was $49.7 \pm 0.4\%$. In forest land and FAL the mean below-ground CC was $49.4 \pm 0.4\%$ and $50.4 \pm 0.7\%$, respectively. The observed mean root CC of young Scots pine showed slight differences (0.3%) from generally accepted CC of 50%, as shown for other conifers (Ritson & Sochacki 2003, Thomas & Martin, 2012). Such differences have been related to ecological factors (e.g. stand density, tree dimensions, forest type) effecting the assimilation of C as well as sampling methodology of studies (Vucetich et al., 2000; Lamtom & Savidge, 2003; Jain et al., 2010, Thomas & Martin, 2012).

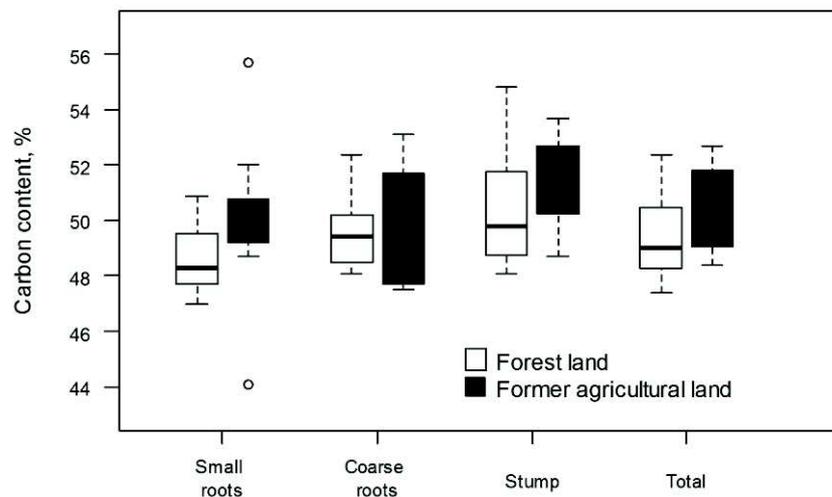


Figure 2. Carbon content in different root fractions in afforested former agricultural land and forest land. Total is carbon content of weighted means based on the weights of different components (stumps, small roots, coarse roots). Line shows the median of dataset, box represents 1st and 3rd quartile, whiskers mark range (not exceeding 150% of interquartile distance) and circles indicate outliers of the datasets.

The observed difference in the mean CC between land types was non-significant ($p > 0.05$) (Table 2), however, higher variations of CC at the individual tree level were observed in FAL (Fig. 2) likely due to physical and biological features, such as content of lignin, different age and composition of root fraction (Lamtom & Savidge, 2003; Peichl & Arain, 2006; Bennett et al., 2014; Seedre et al., 2015).

Table 2. The effect of root component and growing conditions on CC in roots according to the results of ANCOVA; the age of the stand have been added as covariate in analysis

Model Anova (Type II test)				
Variable	Sum of Square	Degree of freedom	F value	<i>p</i> -value
Root fraction	93.91	2	45.389	< 0.001
Land type	1.85	1	1.789	0.183
Age	269.55	1	260.549	< 0.001
$R^2 = 0.69$ (Adjusted $R^2 = 0.68$)				
Multiple Comparisons of Means of Tukey HSD Test				
Root fraction	Difference	Standard Error	<i>t</i> -value	<i>p</i> -value
Coarse roots – Stump	-1.51	0.20	-7.566	< 0.001
Small roots – Stump	-1.57	0.18	-8.608	< 0.001
Small roots – Coarse roots	-0.06	0.20	-0.302	0.951

Root fraction differed in their CC (Table 2). The CC were estimated to be $49.5 \pm 0.4\%$ and $49.1 \pm 0.4\%$ in the coarse roots and small roots, but there were not statistically significant ($p > 0.05$) difference observed between both root fractions. The CC of both root fractions is also comparable to earlier study (cf. Janssens et al., 1999; Bert & Danjon, 2006). Stumps had significantly ($p < 0.001$) higher CC ($50.6 \pm 0.6\%$), that might be explained by the differences in length of the life cycle of different root fractions (Palviainen et al., 2010; Uri et al., 2012), hence lignification of tissues (Bert & Danjon, 2006).

At the age from 8 to 40 years, mean below-ground biomass CC increased significantly ($p < 0.001$) from $48.2 \pm 0.3\%$ to $51.7 \pm 0.5\%$, approving our hypothesis that CC is age dependent, as it has been previously observed for other *Pinus* species by Ritson & Sochacki (2003), Peichl & Arain (2006,) Jain et al. (2010). Steeper increase of mean below-ground CC was observed for younger trees, reaching $50.6 \pm 0.3\%$ at the age of 24 years (Fig. 3).

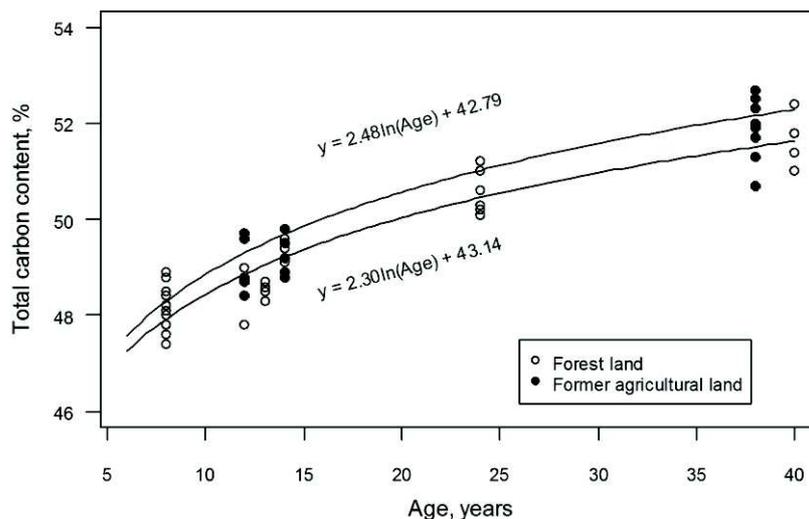


Figure 3. Effect of stand age on the total root CC on forest land and former agricultural land.

The age-dependent increase of root CC followed logarithmic curve (Fig. 3), indicating overestimation of the default value during the first two decades of tree life, but underestimated CC at older age 24 years). Considering that, the below-ground biomass CC could be determined as a function of stand age to improve C estimation within reporting systems for climate change mitigation (Bert & Danjon, 2003; Lamtom & Savidge, 2003). Further studies shall address older trees and other tree species in order to improve overall accuracy of below-ground C assessment.

CONCLUSIONS

Below-ground CC was age dependent, but was not affected by land type. More accurate below-ground biomass CC values for young trees had been established.

ACKNOWLEDGEMENTS. This study was funded by the European Regional Development Fund project Development of decision support tool for prognosis of storm damages in forest stands on peat soils (No. 1.1.1.1/16/A/260).

REFERENCES

- Addo-Danso, S.D., Prescott, C.E. & Smith, A.R. 2016. Methods for estimating root biomass and production in forest and woodland ecosystem carbon studies: A review. *For. Ecol. Manage* **359**, 332–351.
- Ahti, T., Hämet-Ahti, L. & Jalas, J. 1968. Vegetation zones and their sections in northwestern Europe. *Ann. Bot. Fenn.* **5**, 169–211.
- Bardgett, R.D., Mommer, L. & De Vries, F.T. 2014. Going underground: Root traits as drivers of ecosystem processes. *Trends Ecol. Evol.* **29**(12), 692–699.
- Baumanis, I., Jansons, A. & Neimane, U. 2014. *Scots pine: breeding, genetics and seed orchard management*. SIA 'Latgales druka', Rēzekne, 325 pp. (in Latvian).
- Bennett, A.E., Grussu, D., Kam, J., Caul, S. & Halpin, C. 2014. Plant lignin content altered by soil microbial community. *New Phytol.* **206**, 166–174.
- Bert, D. & Danjon, F. 2006. Carbon concentration variations in the roots stem and crown of mature *Pinus pinaster* (Ait.). *For. Ecol. Manage* **222**, 279–295.
- Bijak, S., Zasada, M., Bronisz, A., Brinisz, K., Czajkowski, M., Ludwisiak, Ł., Tomusiak, R. & Wojtan, R. 2013. Estimating coarse roots biomass in young silver birch stands on post-agricultural lands in central Poland. *Silva Fenn.* **47**, N2, id. 962.
- Brassard, B.W., Chen, H.Y.H., Bergeron, Y. & Paré, D. 2011. Coarse root biomass allometric equations for *Abies balsamea*, *Picea mariana*, *Pinus banksiana*, and *Populus tremuloides* in the boreal forest of Ontario, Canada. *Biomass Bioenergy* **35**(10), 4189–4196.
- Dixon, R.K., Brown, S., Houghton, R.A., Solomon, A.M., Trexler, M.C. & Wisniewski, J. 1994. Carbon pools and flux of global forest ecosystems. *Science* **263**, 185–190.
- EUROSTAT 2016. <http://ec.europa.eu/eurostat/en/web/products-statistical-books/-/KS-FK-16-001>. Accessed 14.03.2017.
- Federici, S., Vitullo, M., Tulipano, S., De Lauretis, R. & Seufert, R. 2008. An approach to estimate carbon stocks change in forest carbon pools under the UNFCCC: The Italian case. *iForest* **1**, 86–95.
- Finér, L., Ohashi, M., Niguchi, K. & Hirano, Y. 2011. Factors causing variation in fine root biomass in forest ecosystems. *For. Ecol. Manage* **261**, 265–277.
- Fonseca, W., Benayas, J.M.B. & Alice, F.E. 2011. Carbon accumulation in the biomass and soil of different aged secondary forests in the humid tropics of Costa Rica. *For. Ecol. Manage* **262**, 1400–1408.

- Gill, R.A. & Jackson, R.B. 2000. Global patterns of root turnover for terrestrial ecosystems. *New Phytol.* **147**, 13–31.
- Haynes, B. & Gower, S.T. 1995. Belowground carbon allocation in unfertilized and fertilized red pine plantations in northern Wisconsin. *Tree Physiol.* **15**, 317–325.
- Helmisaari, H.S., Makkonen, K., Kellomäki, S., Valtonen, E. & Mälkönen, E. 2002. Below- and above-ground biomass, production and nitrogen use in Scots pine stands in eastern Finland. *For. Ecol. Manage* **165**, 317–326.
- Hytteborn, H., Maslov, A.A., Nazimova, D.I. & Rysin, L.P. 2005. Boreal Forests of Eurasia. In A.F. (ed.): *Coniferous forests, ecosystems of the world*, Elsevier, Amsterdam, pp. 23–99.
- Jain, T.B., Graham, R.T. & Adams, D. 2010. Carbon Concentrations and Carbon Pool Distributions in Dry, Moist, and Cold Mid-Aged Forests of the Rocky Mountains. In Jaun, T.B., Graham, R.T., Sandquist, J. (eds): *Proceedings of the 2009 National Silviculture Workshop. Proceedings RMRS-P-61*. Fort Collins, CO, Rocky Mountain Research Station, U.S. pp. 39–59.
- Janssens, I.A., Sampson, D.A., Cermak, J., Meiresonne, L., Riguzzi, F., Overloop, S. & Ceulemans, R. 1999. Above- and belowground phytomass and carbon storage in a Belgian Scots pine stands. *Ann. For. Sci.* **56**, 81–90.
- Kaarakka, L., Hyvonen, R., Stromgren, M., Palviainen, M., Persson, T., Olsson, B.A., Launonen, E., Vegerfors, B. & Helmisaari, H.S. 2016. Carbon and nitrogen pools and mineralization rates in boreal forest soil after stump harvesting. *For. Ecol. Manage* **377**, 61–70.
- Karsenty, A., Blanco, C. & Dufour, T. 2003. *Forest and climate change. Instruments related to the United Nations Framework Convention on Climate Change and their potential for sustainable forest management in Africa*. FAO, Rome, 82 pp.
- Lamlom, S.H. & Savidge, R.A. 2003. A reassessment of carbon content in wood: Variation within and between 41 North American species. *Biomass Bioenergy* **25**, 381–388.
- Latvian State Forest service 2015. <http://www.vmd.gov.lv/valsts-meza-dienests/statiskas-lapas/publikacijas-un-statistika/meza-statistikas-cd?nid=1809#jump>. Accessed 14.3.2017.
- Levers, C., Verkerk, P.J., Müller, D., Verburg, P.H., Butsic, V., Leitão, P.J., Lindner, M. & Kuemmerle, T. 2014. Drivers of forest harvesting intensity patterns in Europe. *For. Ecol. Manage* **315**, 160–172.
- Liski, J., Korotkov, A., Prins, C., Karjalainen, T., Victor, D. & Kauppi, P. 2003. Increased Carbon Sink in Temperate and Boreal Forests. *Climate Change* **61**(19), 89–99.
- Martin, A.R. & Thomas, S.C. 2011. A Reassessment of Carbon Content in Tropical Trees. *PLOS ONE* **6**:N8.
- Merilä, P., Mustajärvi, K., Helmisaari, H.S., Hilli, S., Lindroos, A.J., Nieminen, T.M., Nöjd, P., Rautio, P., Salemaa, M. & Ukonmaanaho, L. 2014. Above- and below-ground N stocks in coniferous boreal forests in Finland: Implications for sustainability of more intensive biomass utilization. *For. Ecol. Manage* **311**, 17–28.
- Neumann, M., Moreno, A., Mues, V., Härkönen, S., Mura, M., Bouriaud, O., Lang, M., Achten, W.M.J., Thivolle-Cazat, A., Bronisz, K., Merganič, J., Decuyper, M., Alberdi, I., Astrup, R., Mohren, F. & Hasenauer, H. 2016. Comparison of carbon estimation methods in European forests. *For. Ecol. Manage* **361**, 397–420.
- Pajtik, J., Konôpka, B. & Lukac, M. 2008. Biomass functions and expansion factors in young Norway spruce (*Picea abies* [L.] Karst) trees. *For. Ecol. Manage* **256**, 1096–1103.
- Palviainen, M., Finér, L., Laiho, R., Shorohova, E., Kapitsa, E. & Vanhu-Majamaa, I. 2010. Carbon and nitrogen release from decomposing Scots pine, Norway spruce and silver birch stumps. *For. Ecol. Manage* **259**, 390–398.
- Paul, K.I., Polglase, P.J., Nyakuengama, J.G. & Khanna, P.K. 2002. Change in soil carbon following afforestation. *For. Ecol. Manage* **168**(1–3), 241–257.

- Peichl, M. & Arain, M.A. 2006. Above- and belowground ecosystem biomass and carbon pools in an age-sequence of temperate pine plantation forests. *Agric. For. Meteorol.* **140**, 51–63.
- Petersson, H., Holm, S., Ståhl, G., Alger, D., Fridman, J., Lehtonen, A., Lundström, A. & Mäkipää, R. 2012. Individual tree biomass equations or biomass expansion factors for assessment of carbon stock changes in living biomass – A comparative study. *For. Ecol. Manage* **270**, 78–84.
- Pregitzer, K.S., King, J.S., Burton, A.J. & Brown, S.E. 2000. Responses of tree fine roots to temperature. *New Phytol.* **147**(1), 105–115.
- R Core Team 2016. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. <https://www.R-project.org/>.
- Ritson, P. & Spachacki, S. 2003. Measurement and prediction of biomass and carbon content of *Pinus pinaster* trees in farm forestry plantations, south-western Australia. *For. Ecol. Manage* **175**, 103–117.
- Rogelj, J., Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., Schaeffer, R., Sha, F., Riahi, K. & Meinshausen, M. 2016. Perspective: Paris Agreement climate proposals need boost to keep warming well below 2 °C. *Nat. Clim. Chang.* **534**, 631–639.
- Saatchi, S.S., Harris, N.L., Brown, S., Lefsky, M., Mitchard, E.T.A., Salas, W., Zutta, B.R., Buermann, W., Lewis, S.L., Hagen, S., Petrova, S., White, L., Silman, M. & Morel, A. 2011. Benchmark map of forest carbon stocks in tropical regions across three continents. *Proc. Natl. Acad. Sci. USA* **108**(24), 9899–9904.
- Seedre, M., Kopáček, J., Janda, P., Bače, R. & Svoboda, M. 2015. Carbon pools in a montane old-growth Norway spruce ecosystem in Bohemian Forest: Effects of stand age and elevation. *For. Ecol. Manage* **346**, 106–113.
- Sochacki, S.J., Ritson, P., Brand, B., Harper, R.J. & Dell, B. 2017. Accuracy of tree biomass sampling methodologies for carbon mitigation projects. *Ecol. Eng.* **98**, 264–274.
- Tang, X., Fan, S., Qi, L., Guan, F., Lui, G. & Du, M. 2015. Effects of understory removal on root production, turnover and total belowground carbon allocation in Moso bamboo forests. *iForest* **9**, 187–197.
- Thomas, S.C. & Martin, A.R. 2012. Carbon content of tree tissues: a synthesis. *Forests* **3**, 332–352.
- Uri, V., Varik, M., Aossar, J., Kanal, A., Kukumägi, M. & Lõhmus, K. 2012. Biomass production and carbon sequestration in a fertile silver birch (*Betula pendula* Roth) forest chronosequence. *For. Ecol. Manage* **267**, 117–126.
- Varik, M., Aosaar, J., Ostonen, I., Lõhmus, K. & Uri, V. 2013. Carbon and nitrogen accumulation in belowground tree biomass in a chronosequence of silver birch stands. *For. Ecol. Manage* **302**, 62–70.
- Vesterdal, L., Ritter, E. & Gundersen, P. 2002. Change in soil organic carbon following afforestation of former arable land. *For. Ecol. Manage* **169**(1–2), 137–174.
- Vucetich, J.A., Reed, D.D., Breymeyer, A., Degórski, M., Mroz, G.D., Solon, J., Roo-Zielinska, E. & Noble, R. 2000. *For. Ecol. Manage* **136**, 135–145.