J For Res (2013) 18:440–444
DOI 10.1007/s10310-012-0374-x

SHORT COMMUNICATION

Coarse woody debris of *Fagus sylvatica* produced a quantitative organic carbon imprint in an andic soil

**Viliam Pichler · Erika Gömöryová ·
Marián Homolák · Magdaléna Pichlerová ·
Wojciech Skierucha**

Received: 13 February 2012 / Accepted: 9 September 2012 / Published online: 16 October 2012

Abstract Coarse woody debris (CWD) is involved in important forest ecosystem functions and processes, e.g., habitat provision, water retention, and organic matter decomposition. However, a quantitative, CWD-produced soil organic carbon (SOC) imprint has not yet been detected, possibly due to lack of free adsorption sites on soil minerals. To circumvent this potential constraint, we selected plots with and without CWD in a beech (*Fagus sylvatica* L.) primeval forest in the West Carpathian volcanic range (Slovakia). Local andic soil contains abundant allophane and amorphous Fe-compounds as important SOC binding agents. The C concentration in the fine earth of sampled soils was determined by the dry combustion method. We established that organic carbon concentration decreased with depth from 0.20 kg kg^{-1} (0.0–0.3 m) to 0.11 kg kg^{-1} (0.3–0.5 m) in soil with CWD and from 0.13 kg kg^{-1} (0.0–0.3 m) to 0.07 kg kg^{-1} (0.3–0.5 m) in soil without CWD. The respective average differences in soil organic carbon concentration (0.07 kg kg^{-1}) and stock (15.84 kg m^{-2}) between the two series of plots within the upper 0.3 m were significant according to the *t* test ($P < 0.05$ or $P < 0.01$, respectively). Also, corresponding differences within the 0.3–0.5 m layer (0.04 kg kg^{-1} and 5.51 kg m^{-2}) were significant ($P < 0.05$, $P < 0.001$). Our results represent the first indication that CWD-produced SOC imprint may reach deeper than just a few centimeters in soils featuring high adsorption capacity, such as Andosols.

Keywords Andosol · Coarse woody debris · *Fagus sylvatica* L. · Soil organic carbon

Introduction

Dead trees are associated with many key functions in forest ecosystems (Harmon and Hua 1991). Because water soluble and nutrient-rich organic compounds are abundant in coarse woody debris (CWD), interstitial water and leachate (Yavitt and Fahey 1985), it has ben suggested that CWD decomposition and leaching may affect soil organic matter (e.g., Hafner et al. 2005). However, Laiho and Prescott (2004) found CWD to be of minor importance in the nutrient cycles of northern coniferous forests. More recently, CWD effect on organic matter composition in the mineral soil was shown to diminish rapidly with depth (Krzyszowska-Waitkus et al. 2006). Also, thus far, a significant CWD-produced soil organic carbon (SOC) increase has not been reported. The absence of SOC imprint may relate to limited availability of adsorption

V. Pichler (✉) · E. Gömöryová · M. Homolák
Department of Natural Environment, Faculty of Forestry,
Technical University in Zvolen, T. G. Masaryka 24,
960 53 Zvolen, Slovak Republic
e-mail: pichler@vsld.tuzvo.sk

E. Gömöryová
e-mail: egomory@vsld.tuzvo.sk

M. Homolák
e-mail: homolak@vsld.tuzvo.sk

M. Pichlerová
Department of Landscape Planning and Design,
Faculty of Ecology and Environmental Sciences,
Technical University in Zvolen,
Zvolen, Slovak Republic
e-mail: mpichler@vsld.tuzvo.sk

W. Skierucha
Department of Metrology and Modelling of Agrophysical
Processes, Institute of Agrophysics, Polish Academy
of Sciences, Doswiadczalna 4, 20-290 Łublin, Poland
e-mail: w.skierucha@ipan.lublin.pl

sites, as soil particle surfaces eventually become saturated (Mayer 1994). Therefore, our search focused on andic soils, whose adsorption properties in relation to various compounds have been intensively investigated (e.g., Tanikawa and Takenaka 1999). With regard to SOC, andic soils contain allophanes and amorphous Fe-compounds as important SOC-binding agents (Shoji et al. 1993), which contribute to the formation of highly stable metal–humus–clay complexes. In addition, additional andic soils properties make them suitable candidates for possible detection of a quantitative, CWD-produced SOC increase: Andosols are characterized by uniform solute transport (Magesan et al. 2003) and physical protection of SOC inside soil aggregates (Chevallier et al. 2010). In addition, the abundance of polygalacturonase-producing fungi causing wood pectin degradation (Sato 1976; Green et al. 1996) could lead to a faster than usual decomposition of the downed logs of beech. It has, therefore, been our hypothesis that these characteristics would facilitate the formation of an at least temporary CWD-produced organic carbon increase in soil with beech CWD.

Materials and methods

Study area

Our investigation was conducted in Vtáčnik, an important and strict beech (*Fagus sylvatica* L.) primeval forest preserve located in the Tertiary Volcanic Range of the West Carpathian Arc, Slovakia (48°37′32″N, 18°38′49″E, 1,100 m a. s. l.). The area falls into a cool mountainous and humid region with mean annual temperature and precipitation, averaging 3.0 °C and 950 mm (1961–1990), respectively (Faško and Štastný 2002; Šťastný et al. 2002). Local soil developed on andesite slope deposits. The soil unit according to FAO (2006) is Dystric Andosol with a clayey loam texture. The clayey fraction represents ca. 20–29 % of the fine earth mass. The amorphous/crystalline Fe_2O_3 ratio is high (0.75) within the top 50 cm and the percentage of allophane in the clayey fraction increases with depth from ca 0.30 to 0.34 (Šály and Mihálik 1977). The surface humus form is moder with a litter horizon (OL), a fragmented horizon (OF), and a thin humus horizon (OH). Three downed logs of beech were selected within the forest segment the age of which varies from 180 to 210 years. All selected logs were at the stage of transiting from decay class (DC) 4 to DC 5 sensu Maser et al. (1979) and Sollins (1982). This means that the logs were resting on the ground, devoid of bark and twigs, and having a round to oval shape. Their texture contained some blocky pieces and their wood was soft, but without powdery structure. The log fragments were 6–12 m long and 50–60 cm in diameter.

Soil sampling and analyses

Three soil profiles were opened beneath the downed logs in the plane perpendicular to their axial orientation. Each soil profile with CWD was 0.6 m deep and paired with another soil profile without CWD, ca. 3–5 m apart. Stoniness within the concerned soil depth (0–60 cm) was determined as the sum of: (1) the relative volume of stones (20–200 mm) and boulders (>200 mm), which is proportional to their relative area on the profile wall in soil pits (Folk 1951; Alexander 1982), and (2) the volume of gravel (2–20 mm). The latter volume was measured in undisturbed soil samples (200 cm^3), also collected for the determination of fine earth bulk density from 5 depths (0–10, …, 40–50 cm).

Soil samples for organic carbon content determination, weighing approx. 100 g were collected from 0.1 m soil layers (0.0–0.1 m, …, 0.4–0.5 m) along three vertical lines, 0.2 m apart. The central sampling line intersected the respective longitudinal axis of each downed log. A total of 90 samples were collected. Soil samples were air-dried, ground, and passed through a 2-mm mesh sieve. Visible plant residues were removed manually with a pair of tweezers and by electrostatically charged stick. The C content in the fine earth (<2 mm) was determined by Vario MACRO Elemental Analyzer (CNS Version; Elementar, Hanau, Germany), which employs the dry combustion method. Because we knew the bulk density and volume of the soil (i.e. fine earth plus soil pores, without coarse fragments with diameter >2 mm), SOC stock was computed by summing the C content in all five 0.1-m layers, separately for the topsoil (0.0–0.3 m) and subsoil (0.3–0.5 m) at each sampling point according to

$$\mathrm{SOCS} = \sum_{i=1}^{j} \mathrm{BD}_i \times \mathrm{SOCC}_i \times d_i \times (1 - \mathrm{cf}_i) \qquad (1)$$

where SOCS, i, j, BD_i, SOCC_i, d_i, and cf_i are, respectively, SOC stock (kg m^{-2}), respective soil layer index, number of soil layers within topsoil and subsoil ($j = 3$ or $j = 2$, respectively), soil bulk density (kg m^{-3}), SOC concentration (kg kg^{-1}), i-th soil layer thickness ($d_i = 0.1$ m for all i), and volumetric fraction of gravel, stones, and boulders (m^3 m^{-3}).

Data evaluation

Exponential function $y = a\,e^{-kx}$, where a, k represent parameters affecting location and concaveness, respectively, was fitted on the SOC concentration (y) versus soil depth (x) relationship. The Shapiro–Wilck test (Shapiro and Wilk 1965) and Anderson–Darling test (Snedecor and Cochran 1991) were used to assess whether sampled SOC

Table 1 Student's *t* test of differences in bulk density and stoniness between bare soils and soils underneath coarse woody debris (CWD)

Depth (m)	*n*	Soil bulk density (kg m^{-3})				*t*	Stoniness (m^3 m^{-3})				*t*
		With CWD		Without CWD			With CWD		Without CWD		
		$\bar{x}$	σ	$\bar{x}$	σ		$\bar{x}$	σ	$\bar{x}$	σ	
0.0–0.3	18	638.90	81.72	428.22	29.30	0.68	0.26	0.03	0.25	0.04	1.55
0.3–0.5	12	760.38	73.96	562.99	23.51	1.63	0.36	0.01	0.34	0.04	0.94

n observations per cell, $\bar{x}$ arithmetic mean, σ standard deviation

Significant differences: * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$

concentration data followed normal or log-normal distribution. If the sample distribution significantly deviated from normal towards log-normal distribution, log-normal transformation was applied. As a result, SOC concentration and SOC stock differences between soils with and without CWD were tested by Student's *t* test (Sokal and Rohlf 1995) on log-transformed or original data, respectively.

Results

Average soil bulk density and stoniness, as important variables that affect SOC stock, are given in Table 1. With regard to these properties, no significant differences between soils underneath and next to downed logs were detected. Besides showing the complete SOC concentration dataset, Fig. 1 also displays SOC concentration (y) versus soil depth (x) relationship, fitted by exponential equations

$$y = 0.24\mathrm{e}^{-1.97x} \tag{2}$$

(Eq. 2: soil with CWD)
and

$$y = 0.20\mathrm{e}^{-2.10x} \tag{3}$$

(Eq. 3: soil without CWD)

Mean squared error (MSE) for Eqs. 2 and 3 was 4.4×10^{-3} and 3.7×10^{-3}, respectively.

A good match between organic carbon concentration data from soil with CWD and the log-normal distribution ($P = 0.51$), but a disagreement with the normal distribution ($P = 0.05$), was suggested by the Anderson–Darling test and Shapiro–Wilck test ($P = 0.01$). Our assessment of the differences between organic carbon concentrations in soils with and without CWD by the *t* test, applied to log-transformed data (Table 2), indicated that CWD effect on SOC concentration persisted within the top 0.5 m layer. After inserting SOC concentration data, soil bulk density, and stoniness into Eq. (1), we obtained SOC stock values (also Table 2). The corresponding organic carbon content differences between soils with CWD and without CWD were statistically significant for both topsoil and subsoil.

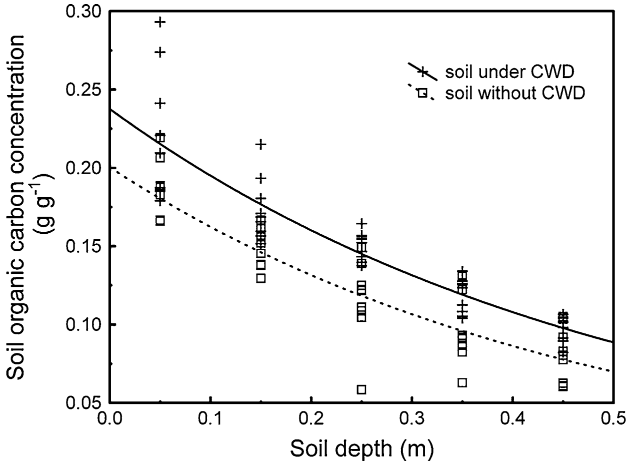

Fig. 1 Soil organic carbon concentration decrease with depth in the Vtáčnik Andosol with and without coarse woody debris (CWD), fitted by exponential function

Discussion

In terms of SOC concentration and its change with depth, our data are very similar to the results reported for Andosols in other parts of the world, e.g., in Costa Rica (Aran et al. 2001) and Ecuador (Tonneijck and Jongmans 2008). Small absolute values of the k (exponential) coefficients in both Eqs. 2 and 3 and an almost linear appearance of the relationship is in contrast with the typically exponential decrease of SOC concentration with soil depth (e.g., Bernoux et al. 1998). One reason for such a moderate non-linearity of the SOC decrease probably consists in the rising concentration of allophane and Fe-compounds with soil depth. At the same time, MSE is bigger for Eq. 2, apparently owing to pronounced log-normality of SOC distribution in the topsoil (0.0–0.3 m), with several values approaching 0.30 kg kg^{-1}.

Remarkably, the differences between organic carbon concentrations in soils with and without CWD at Vtáčnik are in sharp contrast to results obtained during similar investigations in non-andic soils. For instance, Busse (1994) and Spears et al. (2003) detected only topsoil-limited

Table 2 Student's *t* test of differences in soil organic carbon concentration and stock between bare soils and soils underneath coarse woody debris (CWD)

Depth (m)	*n*	Soil organic carbon concentration (kg kg^{-1})				*t*	Soil organic carbon stock (kg m^{-2})				*t*
		With CWD		Without CWD			With CWD		Without CWD		
		$\bar{x}$	σ	$\bar{x}$	σ		$\bar{x}$	σ	$\bar{x}$	σ	
0.0–0.3	27	0.20	0.01	0.13	0.01	2.44*	28.37	2.66	12.53	1.57	4.19**
0.3–0.5	18	0.11	0.01	0.07	0.01	3.21*	10.71	1.44	5.20	0.76	6.55***

n observations per cell, $\bar{x}$ arithmetic mean, σ standard deviation

Significant differences: * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$

(e.g., within 0.00–0.05 m), small or no organic carbon increase in soil with CWD in temperate forests. In fact, the respective differences at Vtáčnik are several times larger than the long-term land use history effects on forest soils (e.g., Stevens and van Wesemael 2008). Data on SOC contents in soils underneath downed logs are extremely rare, but Kahl (2011) found no difference in organic carbon pools in soil with CWD and control (0.0–0.2 m). However, his isotopic study based on δ^{13}C showed that the dead wood decay led to the formation of a clear isotopic footprint in the soil with CWD, in that a portion of the SOC under dead wood had been exchanged. Our observations indicate that such qualitative imprint may materialize into a quantitative imprint in the presence of mineral surfaces, protecting SOC from intense respiration, such as in andic soils. When considered in SOC stock terms, fluctuating stoniness and soil bulk density values must be considered. Otherwise, intrinsic connections between SOC concentration and stoniness (Schaetzl 1991; Tate et al. 2005; Ahmed et al. 2012) can obscure the true CWD effect. In our case, the calculated SOC stock difference between soil with CWD and without CWD primarily resulted from SOC concentration, since the stoniness in both plots was practically identical.

Factors mainly responsible for affecting the CWD-produced SOC increase into subsoil probably include leaching and vertical mixing by soil organisms. Harmon and Sexton (1995) showed that CWD may release considerable amounts of leachate, especially under humid conditions. We speculate that organic matter was immobilized and stabilized during its transport in the form of metal–humus–clay complexes, preferably inside soil aggregates—a feature typical of Andosols (Chevallier et al. 2010). It is therefore very likely that quantitative SOC imprint is substrate-specific, determined by the presence of free adsorption sites provided by allophanes and amorphous Fe-compounds.

Conclusions

A significant organic carbon increase in soil with CWD, especially in the subsoil, has not been detected before. Therefore, our investigation aimed at the possible CWD imprint in an andic soil featuring noticeable amounts of allophane and amorphous Fe-compounds. Soil organic carbon analysis showed that concentration differences in soils with and without CWD reached 0.04–0.07 kg kg^{-1} within the top 0.5 m soil layer, corresponding to 5.51–15.84 kg m^{-2} in terms of SOC stock. Their significance was supported by the *t* test. Our results underscore the status of Andosols as valuable natural history archives, enabling the study of even subtle soil-forming processes. Appropriate measures should be taken to protect and conserve these soils as proposed by Kleber and Jahn (2007), not least because of their role as an active carbon sink.

Acknowledgments This contribution is the result of the project implementation: Extension of the centre of Excellence "Adaptive Forest Ecosystems", ITMS: 26220120049, supported by the Research & Development Operational Program funded by the ERDF (30 %), APVV-0580-10, awarded by the Research and Development Agency (40 %), as well as VEGA 1/0252/11 (30 %), supported by the Scientific Grants Agency of the Ministry of Education and the Slovak Academy of Sciences.

References

Ahmed A-RA, Pichler V, Homolák M, Gömöryová E, Nagy D, Pichlerová M, Gregor J (2012) High organic carbon stock in a karstic soil of the Middle-European Forest Province persists after centuries-long agroforestry management. Eur J For Res. doi:10.1007/s10342-012-0608-7

Alexander EB (1982) Volume estimates of coarse fragments in soils: a combination of visual and weighing procedures. J Soil Water Conserv 37:62–63

Aran D, Gury M, Jeanroy E (2001) Organo-metallic complexes in an Andosol: a comparative study with a Cambisol and Podzol. Geoderma 99:65–79

Bernoux M, Arrouays D, Cern CC, Bourennane H (1998) Modeling vertical distribution of carbon in oxisols of the western Brazilian Amazon (Rondonia). Soil Sci 163:941–951

Busse MD (1994) Downed bole-wood decomposition in lodgepole pine forests of central Oregon. Soil Sci Soc Am J 58:221–227

Chevallier T, Woignier T, Toucet J, Blanchart E (2010) Organic carbon stabilization in the fractal pore structure of Andosols. Geoderma 159:182–188

FAO (2006) World reference base for soil resources. World soil resources reports, 103. Food and Agriculture Organization of the United Nations, Rome

Faško R, Štastný P (2002) Mean annual precipitation totals. In: Miklós L, Maráky R, Klinda J (eds) Landscape atlas of the Slovak Republic. Ministry of Environment of the Slovak Republic, Bratislava, p 99

Folk RL (1951) A comparison chart for visual percentage estimation. J Sediment Petrol 21:32–33

Green F, Kuster TA, Highley TL (1996) Pectin degradation during colonization of wood by brown-rot fungi. Recent Res Dev Plant Pathol 1:83–93

Hafner SD, Groffman PM, Mitchell MJ (2005) Leaching of dissolved organic carbon, dissolved organic nitrogen, and other solutes from coarse woody debris and litter in a mixed forest in New York State. Biogeochemistry 74:257–282

Harmon ME, Hua C (1991) Coarse woody debris dynamics in two old-growth ecosystems. Bioscience 41:604–610

Harmon ME, Sexton J (1995) Water balance of conifer logs in early stages of decomposition. Plant Soil 172:141–152

Kahl T (2011) Does deadwood leave a footprint in the soil? In: Abstracts of the International Symposium on dynamics and ecological services of deadwood in forest ecosystems: deadwood and dying trees, a matter of life and diversity, Rouyn-Noranda, Québec, Canada, 2011, p 53

Kleber M, Jahn R (2007) Andosols and soils with andic properties in the German Soil Taxonomy. J Plant Nutr Soil Sci 170:317–328

Krzyszowska-Waitkus A, Vance GF, Preston CM (2006) Influence of coarse wood and fine litter on forest organic matter composition. Can J Soil Sci 86:35–46

Laiho R, Prescott CE (2004) Decay and nutrient dynamics of coarse woody debris in northern coniferous forests. Can J For Res 34:763–777

Magesan GN, Vogeler I, Clothier BE, Green SR, Lee R (2003) Solute movement through an allophanic soil. J Environ Qual 32: 2325–2333

Maser C, Anderson RG, Cromack KJ, Williams JT, Martin RE (1979) Dead and down woody material. In: Thomas JW (ed) Wildlife habitats in managed forests. The Blue Mountains of Oregon and Washington. USDA, Portland, pp 78–95

Mayer LM (1994) Relationships between mineral surfaces and organic carbon concentrations in soils and sediments. Chem Geol 114:347–363

Šály R, Mihálik A (1977) Andosols of the West Carpathians. In: Šály R (ed) Proceedings from the ISSS symposium, WG forest soils: soils as a site factor for forests of temperate and cool zones. Department of Soil Science and Geology, University College of Forestry and Wood Technology, Zvolen, Czechoslovakia, pp 185–192

Sato O (1976) The distribution of Pg (green fraction of P type humic acid) and the degree of humification of Pb (brown fraction of P type humic acid) in soils of central Japan. Soil Sci Plant Nutr 22:159–167

Schaetzl RJ (1991) Factors affecting the formation of dark, thick epipedons beneath forest vegetation, Michigan, USA. J Soil Sci 42:501–512

Shapiro SS, Wilk MB (1965) An analysis of variance test for normality (complete samples). Biometrika 52:591–611

Shoji S, Nanzyo M, Dahlgren RA (1993) Volcanic ash soils. Genesis, properties and utilization. Developments in Soil Science 21. Elsevier, Dordrecht

Snedecor GW, Cochran WG (1991) Statistical methods. Iowa State University Press, Ames

Sokal RR, Rohlf FJ (1995) Biometry. Freeman, New York

Sollins P (1982) Input and decay of coarse woody debris in coniferous stands in western Oregon and Washington. Can J For Res 12: 18–28

Spears JDH, Holub SM, Harmon ME, Lajtha K (2003) The influence of decomposing logs on soil biology and nutrient cycling in an old-growth mixed coniferous forest in Oregon, USA. Can J For Res 33:2193–2201

Šťastný P, Nieplová E, Melo M (2002) Mean annual air temperature. In: Miklós L, Maráky R, Klinda J (eds) Landscape atlas of the Slovak Republic. Ministry of Environment of the Slovak Republic, Bratislava, p 98

Stevens A, van Wesemael B (2008) Soil organic carbon dynamics at regional scale as influenced by land use history: a case study in forest soils from southern Belgium. Soil Use Manag 24:69–79

Tanikawa T, Takenaka Ch (1999) Relating sulfate adsorption to soil properties in Japanese forest soils. J For Res 4:217–222

Tate KR, Wilde RH, Giltrap DJ, Baisden WT, Saggar S, Trustrum NA, Scott NA, Barton JR (2005) Soil organic carbon stocks and flows in New Zealand: system development, measurement and modelling. Can J Soil Sci 85:481–489

Tonneijck FH, Jongmans AG (2008) The influence of bioturbation on the vertical distribution of soil organic matter in volcanic ash soils: a case study in northern Ecuador. Eur J Soil Sci 59: 1063–1075

Yavitt JB, Fahey TJ (1985) Chemical composition of interstitial water in decaying lodgepole pine bole wood. Can J For Res 15: 1149–1153