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Pyrogenic carbon content and dynamics in top and subsoil of French forests

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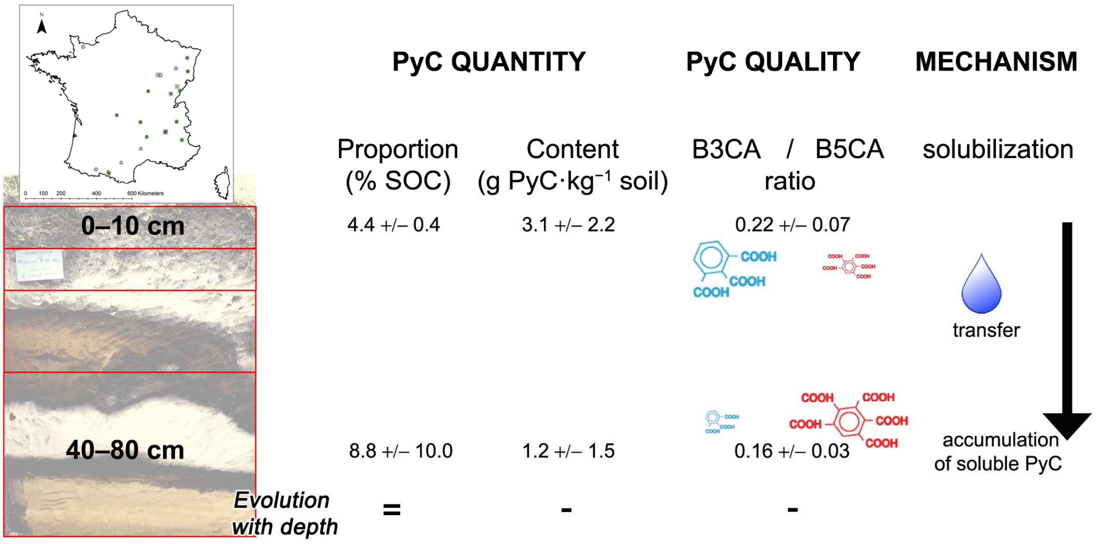
Graphical Abstract



Abstract

Pyrogenic carbon (PyC) may leave the soil surface where it is deposited, either through degradation, lateral transport or transfer within the profile. However, PyC has been seldom measured in the subsoil. We estimated the quantity and molecular composition of PyC in the topsoil and subsoil of 22 French forests with diverse soil types and vegetation cover. While the absolute PyC content decreased with depth, its proportion to the soil organic carbon remained constant or tended to increase. The benzene polycarboxylic acids pattern indicated that more condensed structures were found in the subsoil. Our results show that PyC transfers through the soil profile, probably as soluble fraction, and tends to accumulate in the subsoil, specifically in podzolic soils.

Keywords: pyrogenic carbon; benzene polycarboxylic acids; soil type; solubilization; subsoil; forest soils;

Soil pyrogenic carbon (PyC) represents about 10–15% of total soil organic carbon (SOC) worldwide (Forbes et al., 2006; Preston and Schmidt, 2006; Bird et al., 2015; Reisser et al., 2016 and references therein) and can locally reach up to 35–45% (Schmidt et al., 1999; Skjemstad et al., 2002).

Deep (> 30 cm) SOC accounts for a significant amount of total SOC (Jobbágy and Jackson, 2000), and is older and more stable than surface SOC (Rumpel and Kögel-Knabner, 2010; Balesdent et al., 2018). This raises the question of how much PyC contributes to deep SOC stocks. However, to date, studies on PyC have mostly focused on surface soils, where the PyC is deposited after a fire. Only a few studies report PyC in deeper soil horizons (e.g., Rodionov et al. 2006; Guggenberger et al., 2008; Rodionov et al. 2010; Vasilyeva et al., 2011; Abney et al., 2017) and out of the 55 studies considered in the meta-analysis of Reisser et al. (2016), only 4 considered a complete soil profile. Since PyC has to be transferred from the surface to reach deeper soil layers, its quality may be prone to changes with depth that have not been studied yet.

Drivers explaining PyC stocks in soil have been often related to fire properties. However, in a recent global study, Reisser et al. (2016) showed that soil properties like pH or clay content had a stronger impact on the PyC concentration than fire characteristics, land use or climate. It is yet unclear if this global picture still holds at a landscape or regional scale.

In this study, we took advantage of a large network of forest sites and an established PyC characterization and quantification method to address the following research questions:

- Does PyC contribute significantly to total SOC in the subsoil?
- Does PyC quality evolve with depth?

We explored the effects of depth and of two potential drivers (soil class and vegetation type) on PyC quantity and quality using a balanced design.

We analysed soil samples collected from sites of the French national network for the long term monitoring of forest ecosystems (‘‘RENECOFOR’’). This network consists of 102 sites in managed forests, with even-aged stands. Mineral soil samples of the network were collected by layers up to 1-m depth to ensure comparability among sites and facilitate subsequent sampling to monitor SOC evolutions. Here, we chose to focus on samples collected at two depths: 0–10 cm, hereafter topsoil and 40–80 cm, hereafter subsoil. Details related to sample collection are available in Soucémarianadin et al. (2018a). We selected 22 sites, out of the entire network, to cover a diversity of soil classes and vegetation types. Soil classes were the following: (i) entic Podzols, (ii) eutric Cambisols and (iii) dystric Cambisols (IUSS Working Group, 2015). Forest vegetation was separated into two types with stands dominated by either (i) coniferous [silver fir (*Abies alba* Mill.) or Norway spruce (*Picea abies* (L.) H. Karst.)] or (ii) deciduous [beech (*Fagus sylvatica* L.)] trees. Study plots were mainly found in midslope or upslope positions (Table S1).

Bulk < 2 mm-sieved soil samples were ground and carbon concentrations were determined by dry combustion. Samples with carbonates were first decarbonated (Harris et al., 2001).

PyC was measured using the benzene polycarboxylic acids (BPCA) molecular marker method, which consists of extracting organic molecular markers specific from PyC (Glaser et al., 1998; Brodowski et al., 2005). We followed the protocol described in

Wiedemeier et al. (2013). We used a conversion factor of 2.27 (Glaser et al., 1998) to calculate PyC proportion (% SOC) and content (g PyC·kg^{-1} soil). While this ratio has been criticized in the literature (e.g., Schneider et al., 2010), we used it to compare our values with previous reports of PyC quantitative estimates (Reisser et al., 2016). We also used the distribution patterns of BPCA markers as a quality indicator of the PyC. High proportion of B5CA and B6CA were indicative of more condensed and aromatic material (Wiedemeier et al., 2015), while B3CA and B4CA were the product of small condensed units of 3 aromatic rings minimum (Ziolkowski et al., 2011).

We used paired t-test and multivariate models (see Soucémarianadin et al. (2018b) for details) to assess the effects of the three factors (depth, soil class and vegetation type) on the quantity and quality of PyC using R software (R Core Team, 2016). A generalized least squares function (Pinheiro et al., 2016) was used for the linear mixed models, with forest site as a random effect. Model selection was implemented with a top-down strategy.

The mean PyC content in these French forest topsoils was 3.1 g PyC·kg^{-1} soil, representing 4.4% of total SOC (Table 1). This proportion was comparable to topsoils in Switzerland (0.6–4.7% of total SOC; Reisser, 2018) and in the “Centre” region of France (mean PyC = 5.3% of total SOC; Paroissien et al., 2012). However, our average PyC proportion to SOC was relatively low when compared to global values that average 13.7% of total SOC (Reisser et al., 2016). This could be linked to the ongoing fire suppression over Europe that started in the 18th century (Pyne, 1997). The mean distribution of total BPCA among the four markers (Fig. 1; Table S2) was quite similar to what have been measured in Swiss forest topsoils (Reisser, 2018). In these topsoils, B5CA represented a proportion of total BPCA (23–51%; Reisser, 2018) similar to the one we observed in French forest soils. We also observed similar B6CA proportions to those reported in topsoils of alpine Leptosols (about 25%; Eckmeier et al., 2013). However, a few samples had very different proportions of B5CA and B6CA (Fig. S1). Specifically, the PyC in HET09 topsoil had a very low B5CA proportion (6%; Fig. S1), while PyC in HET21 and SP25 subsoils displayed relatively low B6CA (5% and 1%, respectively) and high B5CA proportions (52% and 55%, respectively; Fig. S1). Moreover, given the relative proportion of B6CA, around 30% (Fig. 1; Table S2), we assumed that soot contribution to total PyC had been minimal (e.g., Li et al., 2015) and that the PyC present in these forest soils originated mostly from biomass burning through forest fire. Historical records showed that charcoal had been produced on-site in some of these forests (Table S1). However, no trace of kilns was observed on the sampling plots and although anthropogenic charcoal production might have constituted a source of PyC in some of our study plots, it is thus unlikely to be significant.

Although absolute PyC content decreased significantly with depth, PyC proportion tended to increase with depth (Fig. 2; Table 1). This increase was however not significant (Table 2). These results suggest a preferential transfer of PyC to the subsoil compared to other SOC moieties. Studies including samples from both topsoil and subsoil (> 30-cm depth) are not common, as shown by the meta-analysis of Reisser et al. (2016), but some previous observations agreed with our results. In Longleaf pine forests of the southern USA, despite PyC content decreasing significantly with depth in most sites, PyC proportion (5–7% of SOC) was independent of depth (Butnor et al., 2017). A tendency for PyC proportion to increase with depth was observed in Russian Chernozems (from 7% to 10% SOC in 0–10 cm and 30–50 cm, respectively), in a mixed-grass savanna in Texas (5–9% BPCA-C at 0–10 cm vs. 7–13% BPCA-C at 10–20 cm) and in black soils of the Southern Alps (Dai et al., 2005; Hammes et al., 2008; Eckmeier et al., 2010). However, non-linear evolutions of PyC proportion with depth have been reported (Rodionov et al., 2006; Hammes et al., 2008; Soucémarianadin et al., 2014) and distribution of PyC proportion in the complete soil profile cannot thus be inferred from our results.

Downwards transfer of PyC by leaching, either through particulate or soluble forms, has been evidenced in various field conditions (Hockaday et al., 2006; Leifeld et al., 2007; Major et al., 2010; Santos et al., 2016). Although PyC quality did not change drastically between the top and deep soil layers (Fig. 1), we observed a significant decrease in B3CA and a concomitant significant increase in more condensed B5CA (Table S2). Abiven et al. (2011) observed that, over time, B5CA tended to preferentially solubilize, contrary to B3CA. These quality changes were also observed when comparing dissolved organic matter and particulate organic matter in rivers (Wagner et al., 2015). Our results therefore suggest a significant contribution of soluble PyC to the deeper soil horizons. Meanwhile, we did not observe any significant change in the B4CA/B6CA or B5CA/B6CA ratios with depth (Table S2). As these ratios are mainly affected by PyC decomposition in soils, this result suggests that no major PyC degradation occurred in our soil profiles (Singh et al., 2014; Guggenberger et al., 2008).

While PyC solubilization seems to be consistent with the BPCA distribution patterns, alternative transfer processes may have occurred. For example, mesofauna could contribute to PyC transfer through bioturbation, but this was probably limited in our coniferous sites and in our acidic soils, which tend to have few earthworms. Particle movement in the soil macro-porosity after PyC fragmentation could have also played an important role in plots where charcoal pieces have been observed (Table S1). Erosion could impact horizontal transfer of PyC in sloping landscapes (e.g., Rumpel et al., 2006; Abney et al., 2017). Further burial of PyC in depositional landforms could affect its vertical distribution (Abney and Berhe, 2018). However this vertical transfer process was unlikely to dominate in our study plots given their geomorphologic position (Table S1) and the absence of colluvial soils in our data set.

Multivariate models showed that PyC quantity (content) and quality (relative proportion of B3CA) were influenced by soil class, while vegetation type was only marginally influential in B6CA distribution (Table 2). PyC proportion was higher in Podzols subsoils than in both Cambisols subsoils (Fig. 2). This could be due to an increased solubilization in Podzols caused by the podzolization process itself, during which transfer of organic matter and sesquioxides takes place (Lundström et al., 2000; Buurman and Jongmans, 2005). High dissolved PyC concentrations were indeed measured in the E horizon of Podzols from sites that experienced severe burning around 100 years prior to sampling (Santos et al., 2017). Similar to OC, PyC was shown to be retained and to accumulate in podzolic B horizons (Soucémarianadin et al., 2014; Santos et al., 2017). In these horizons, PyC was associated with the fine fraction and PyC content was correlated with sesquioxide content (Soucémarianadin et al., 2014). PyC accumulation was also observed in other soil types rich in Fe and Al oxides (Major et al., 2010; Cusack et al., 2012; Rumpel et al., 2012). These previous observations suggest that dissolved PyC is likely to be stabilized in the subsoil of podzolic soils either through organo-mineral or organo-metallic complexes.

The marginal effect of vegetation type on PyC content, proportion and quality compared with soil class may be linked to the time frame that needs to be considered for PyC evolutions. In these managed forests, trees were planted and current species may not reflect species composition over the last centuries, which is the time frame related to PyC turnover. Conversely, soil class encompassed long temporal scale (millennium) matching PyC longer turnover and infrequent inputs into the soil, resulting in patterns over longer timescale.

A few conclusions could be drawn from the observations we made in the soil profiles of these twenty-two French forest sites. First, PyC transferred to and accumulated in the subsoil in all soil types. Second, PyC appeared to transfer downwards preferably through solubilization, specifically in podzolic soils. Third, the accumulation of PyC in the subsoil was soil class dependent, but not related to present vegetation. Yet, our investigation presents certain limitations and more studies on PyC in the complete soil profile should be carried on in diverse soil types to further improve our understanding of PyC transfer and accumulation in mineral soils.

Acknowledgments

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References

Abiven, S., Hengartner, P., Schneider, M.P.W., Singh, N., Schmidt, M.W.I., 2011. Pyrogenic carbon soluble fraction is larger and more aromatic in aged charcoal than in fresh charcoal. Soil Biology and Biochemistry 43, 1615-1617.

Abney, R.B., Berhe, A.A., 2018. Pyrogenic carbon erosion: Implications for stock and persistence of pyrogenic carbon in soil. Frontiers in Earth Science 6, 26.

Abney, R.B., Sanderman, J., Johnson, D., Fogel, M.L., Berhe, A.A., 2017. Post-wildfire erosion in mountainous terrain leads to rapid and major redistribution of soil organic carbon. Frontiers in Earth Science 5, 99.

Balesdent, J., Basile-Doelsch, I., Chadoeuf, J., Cornu, S., Derrien, D., Fekiacova, Z., Hatté, C., 2018. Atmosphere-soil carbon transfer as a function of soil depth. Nature 559, 599-602.

Bird, M.I., Wynn, J.G., Saiz, G., Wurster, C.M., McBeath, A., 2015. The pyrogenic carbon cycle. Annual Review of Earth and Planetary Sciences 43, 273-298.

Brêthes, A., Ulrich, E., Lanier, M., 1997. RENECOFOR : Caractéristiques Pédologiques Des 102 Peuplements Du Réseau : Observations De 1994/95. Office national des forêts, Département des recherches techniques, Fontainebleau, France, 573 pp.

Brodowski, S., Rodionov, A., Haumaier, L., Glaser, B., Amelung, W., 2005. Revised black carbon assessment using benzene polycarboxylic acids. Organic Geochemistry 36, 1299-1310.

Butnor, J.R., Samuelson, L.J., Johnsen, K.H., Anderson, P.H., González Benecke, C.A., Boot, C.M., Cotrufo, M.F., et al., 2017. Vertical distribution and persistence of soil organic carbon in fire-adapted longleaf pine forests. Forest Ecology and Management 390, 15-26.

Buurman, P., Jongmans, A.G., 2005. Podzolisation and soil organic matter dynamics. Geoderma 125, 71-83.

Cusack, D.F., Chadwick, O.A., Hockaday, W.C., Vitousek, P.M., 2012. Mineralogical controls on soil black carbon preservation. Global Biogeochemical Cycles 26, 2019.

Dai, X., Boutton, T.W., Glaser, B., Ansley, R.J., Zech, W., 2005. Black carbon in a temperate mixed-grass savanna. Soil Biology and Biochemistry 37, 1879-1881.

Eckmeier, E., Egli, M., Schmidt, M.W.I., Schlumpf, N., Nötzli, M., Minikus-Stary, N., Hagedorn, F., 2010. Preservation of fire-derived carbon compounds and sorptive stabilisation promote the accumulation of organic matter in black soils of the Southern Alps. Geoderma 159, 147-155.

Eckmeier, E., Mavris, C., Krebs, R., Pichler, B., Egli, M., 2013. Black carbon contributes to organic matter in young soils in the Morteratsch proglacial area (Switzerland). Biogeosciences 10, 1265-1274.

Forbes, M.S., Raison, R.J., Skjemstad, J.O., 2006. Formation, transformation and transport of black carbon (charcoal) in terrestrial and aquatic ecosystems. Science of The Total Environment 370, 190-206.

Glaser, B., Haumaier, L., Guggenberger, G., Zech, W., 1998. Black carbon in soils: The use of benzene carboxylic acids as specific markers. Organic Geochemistry 29, 811-819.

Guggenberger, G., Rodionov, A., Shibistova, O., Grabe, M., Kasansky, O.A., Fuchs, H., Mikheyeva, N., et al., 2008. Storage and mobility of black carbon in permafrost soils of the forest tundra ecotone in northern Siberia. Global Change Biology 14, 1367-1381.

Hammes, K., Torn, M.S., Lapenas, A.G., Schmidt, M.W.I., 2008. Centennial black carbon turnover observed in a Russian steppe soil. Biogeosciences 5, 1339-1350.

Harris, D., Horwáth, W.R., van Kessel, C., 2001. Acid fumigation of soils to remove carbonates prior to total organic carbon or CARBON-13 isotopic analysis. Soil Science Society of America Journal 65, 1853-1856.

Hockaday, W.C., Grannas, A.M., Kim, S., Hatcher, P.G., 2006. Direct molecular evidence for the degradation and mobility of black carbon in soils from ultrahigh-resolution mass spectral analysis of dissolved organic matter from a fire-impacted forest soil. Organic Geochemistry 37, 501-510.

IUSS Working Group, 2015. World reference base for soil resources 2014 (update 2015), international soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports.

Jobbágy, E.G., Jackson, R.B., 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecological Applications 10, 423-436.

Leifeld, J., Fenner, S., Müller, M., 2007. Mobility of black carbon in drained peatland soils. Biogeosciences 4, 425-432.

Li, F., Pan, B., Zhang, D., Yang, X., Li, H., Liao, S., Ghaffar, A., et al., 2015. Organic matter source and degradation as revealed by molecular biomarkers in agricultural soils of Yuanyang terrace. Scientific Reports 5, 11074.

Lundström, U.S., van Breemen, N., Bain, D., 2000. The podzolization process. A review. Geoderma 94, 91-107.

Major, J., Lehmann, J., Rondon, M., Goodale, C., 2010. Fate of soil-applied black carbon: Downward migration, leaching and soil respiration. Global Change Biology 16, 1366-1379.

Paroissien, J.-B., Orton, T.G., Saby, N.P.A., Martin, M.P., Jolivet, C.C., Ratie, C., Caria, G., Arrouays, D., 2012. Mapping black carbon content in topsoils of central France. Soil Use and Management 28, 488-496.

Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D., Team, R.C., 2016. Nlme: Linear and Nonlinear Mixed Effects Models.

Ponce, R., Ulrich, E., Garnier, F., 1998. RENECOFOR - Essai de Synthèse sur l'Histoire Des 102 Peuplements du Réseau. Office national des forêts, Département des recherches techniques, Fontainebleau, France, 237 pp.

Ponette, Q., Ulrich, E., Brêthes, A., Bonneau, M., Lanier, M., 1997. RENECOFOR - Chimie Des Sols Dans Les 102 Peuplements Du Réseau : Campagne De Mesures 1993-95. ONF, Département des recherches techniques, Fontainebleau, France, 427 pp.

Preston, C.M., Schmidt, M.W.I., 2006. Black (pyrogenic) carbon in boreal forests: A synthesis of current knowledge and uncertainties. Biogeosciences 3, 397-420.

Pyne, S.J., 1997. Vestal Fire: An Environmental History, Told Through Fire, of Europe and Europe's Encounter with the World, Weyerhaeuser Environmental Books. University of Washington Press, Seattle, WA, USA.

R Core Team, 2016. R: A language and environment for statistical computing.

Reisser, M., 2018. Fire's black legacy: The fate of pyrogenic carbon in soils across scales. PhD thesis. 206 pp. University of Zürich, Zürich.

Reisser, M., Purves, R.S., Schmidt, M.W.I., Abiven, S., 2016. Pyrogenic carbon in soils: A literature-based inventory and a global estimation of its content in soil organic carbon and stocks. Frontiers in Earth Science Biogeoscience 4, 80.

Rodionov, A., Amelung, W., Haumaier, L., Urusevskaja, I., Zech, W., 2006. Black carbon in the zonal steppe soils of Russia. Journal of Plant Nutrition and Soil Science 169, 363-369.

Rodionov, A., Amelung, W., Peinemann, N., Haumaier, L., Zhang, X., Kleber, M., Glaser, B., Urusevskaya, I., Zech, W., 2010. Black carbon in grassland ecosystems of the world. Global Biogeochemical Cycles 24.

Rumpel, C., Chaplot, V., Planchon, O., Bernadou, J., Valentin, C., Mariotti, A., 2006. Preferential erosion of black carbon on steep slopes with slash and burn agriculture. Catena 65, 30–40.

Rumpel, C., Kögel-Knabner, I., 2010. Deep soil organic matter---a key but poorly understood component of terrestrial C cycle. Plant and Soil 338, 143-158.

Rumpel, C., Rodríguez-Rodríguez, A., González-Pérez, J. A., Arbelo, C., Chabbi, A., Nunan N., González-Vila, F. J., 2012. Contrasting composition of free and mineral-bound organic matter in top- and subsoil horizons of Andosols. Biology and Fertility of Soils 48, 401–411.

Santos, F., Russell, D., Berhe, A.A., 2016. Thermal alteration of water extractable organic matter in climosequence soils from the Sierra Nevada, California. Journal of Geophysical Research: Biogeosciences 121, 2877-2885.

Santos, F., Wagner, S., Rothstein, D., Jaffe, R., Miesel, J.R., 2017. Impact of a historical fire event on pyrogenic carbon stocks and dissolved pyrogenic carbon in Spodosols in Northern Michigan. Frontiers in Earth Science 5, 80.

Schmidt, M.W.I., Skjemstad, J.O., Gehrt, E., Kögel-Knabner, I., 1999. Charred organic carbon in German chernozemic soils. European Journal of Soil Science 50, 351-365.

Schneider, M.P.W., Hilf, M., Vogt, U.F., Schmidt, M.W.I., 2010. The benzene polycarboxylic acid (BPCA) pattern of wood pyrolyzed between 200 °C and 1000 °C. Organic Geochemistry 41, 1082-1088.

Singh, N., Abiven, S., Maestrini, B., Bird, J.A., Torn, M.S., Schmidt, M.W.I., 2014. Transformation and stabilization of pyrogenic organic matter in a temperate forest field experiment. Global Change Biology 20, 1629–1642.

Skjemstad, J.O., Reicosky, D.C., Wilts, A.R., McGowan, J.A., 2002. Charcoal carbon in U.S. agricultural soils. Soil Science Society of America Journal 66, 1249-1255.

Soucémarianadin, L.N., Cécillon, L., Chenu, C., Baudin, F., Nicolas, M., Girardin, C., Barré, P., 2018a. Is Rock-Eval 6 thermal analysis a good indicator of soil organic carbon lability? - A method-comparison study in forest soils. Soil Biology and Biochemistry 117, 108-116.

Soucémarianadin, L.N., Cécillon, L., Guenet, B., Chenu, C., Baudin, F., Nicolas, M., Girardin, C., Barré, P., 2018b. Environmental factors controlling soil organic carbon stability in French forest soils. Plant and Soil 426, 267-286.

Soucémarianadin, L.N., Quideau, S.A., MacKenzie, M.D., 2014. Pyrogenic carbon stocks and storage mechanisms in podzolic soils of fire-affected Quebec black spruce forests. Geoderma 217-218, 118-128.

Vasilyeva, N.A., Abiven, S., Milanovskiy, E.Y., Hilf, M., Rizhkov, O.V., Schmidt, M.W.I., 2011. Pyrogenic carbon quantity and quality unchanged after 55 years of organic matter depletion in a Chernozem. Soil Biology and Biochemistry 43, 1985-1988.

Wagner, S., Cawley, K.M., Rosario-Ortiz, F., Jaffé, R., 2015. In-stream sources and links between particulate and dissolved black carbon following a wildfire. Biogeochemistry 124, 145–161.

Wiedemeier, D.B., Abiven, S., Hockaday, W.C., Keiluweit, M., Kleber, M., Masiello, C.A., McBeath, A.V., et al., 2015. Aromaticity and degree of aromatic condensation of char. Organic Geochemistry 78, 135-143.

Wiedemeier, D.B., Hilf, M.D., Smittenberg, R.H., Haberle, S.G., Schmidt, M.W.I., 2013. Improved assessment of pyrogenic carbon quantity and quality in environmental samples by high-performance liquid chromatography. Journal of Chromatography A 1304, 246-250.

Ziolkowski, L.A., Chamberlin, A.R., Greaves, J., Druffel, E.R.M., 2011. Quantification of black carbon in marine systems using the benzene polycarboxylic acid method: A mechanistic and yield study. Limnology and Oceanography: Methods 9, 140-140.

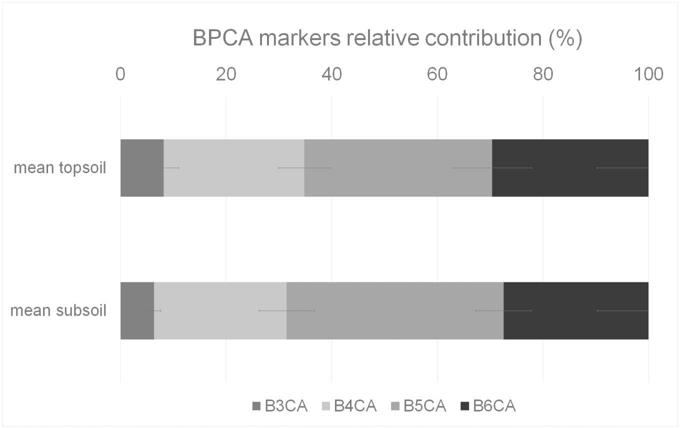
Tables and figures captions

Table 1. Range (mean, minimum, maximum) of PyC proportion (percentage of total SOC) and content (g PyC/kg soil), ratio of B3CA/B5CA markers, SOC content (g OC/kg soil), pH in water and texture for topsoil and subsoil layers in the 22 study plots.

Table 2. Details of models and their significant terms selected to explain variations in PyC quantity and quality in the 22 soil profiles. All models used a gls function (see details in the *Statistical analyses* section). NS (non signifiant): $p > 0.1$; T (trend) $p < 0.1$; * $p < 0.05$; ** $p < 0.01$ and *** $p < 0.001$.

Fig. 1. Mean (± standard deviation) relative distribution of total BPCA among the four BPCA markers in the topsoil and subsoil.

Fig. 2. Comparison of PyC proportion (% of total SOC) in topsoil (0–10 cm) and subsoil (40–80 cm) samples for the 22 forest plots. For each site, a symbol and color represent the corresponding vegetation type and soil class, respectively. Podzols are above (or on) the 1:1 line, whereas the two other soil classes tend to be below the line.


BPCA markers relative contribution (%)
0
20
40
60
80
100
mean topsoil
mean subsoil
B3CA
B4CA
B5CA
B6CA

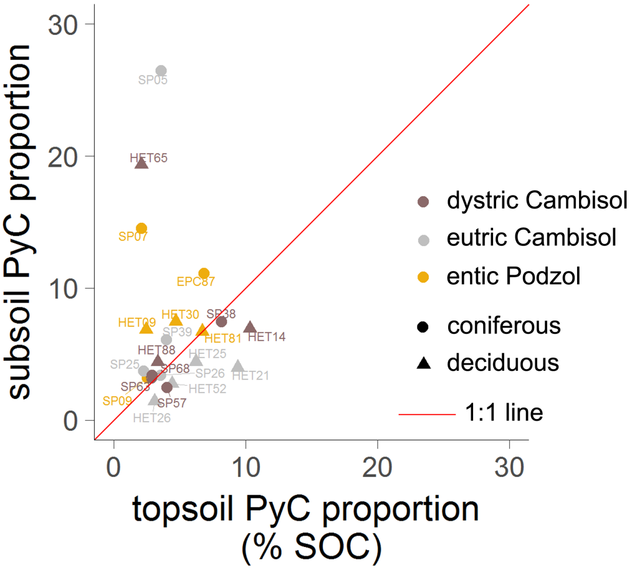

30
20
10
0
subsoil PyC proportion
SP05
HET65
SP07
EPC87
HET30
SP38
HET09
SP39
HET81
HET14
HET88
HET25
SP25
SP68
SP26
HET21
SP63
HET52
SP09
SP57
HET26
● dystric Cambisol
● eutric Cambisol
● entic Podzol
● coniferous
▲ deciduous
1:1 line
0
10
20
30
topsoil PyC proportion
(% SOC)

Table 1. Range (mean, minimum, maximum) of PyC proportion (percentage of total SOC) and content (g PyC/kg soil), ratio of B3CA/B5CA markers, SOC content (g OC/kg soil), pH in water and texture for topsoil and subsoil layers in the 22 study plots.

Factor	classes		PyC proportion (% SOC)			PyC content (g BPCA-C/kg soil)			B3CA/B5CA ratio			SOC content (g/kg soil)			pHwater			clay content (%)*			sand content (%)*		
DEPTH		n	mean	min.	max.	mean	min.	max.	mean	min.	max.	mean	min.	max.	mean	min.	max.	mean	min.	max.	mean	min.	max.
	topsoil	22	4,4	1,9	10,3	3,1	0,8	10,4	0,22	0,12	0,41	72,4	22,3	147,1	5,0	4,1	7,5	27	6	45	32	1	83
	subsoil	22	8,8	1,4	44,3	1,2	0,1	6,1	0,16	0,09	0,2	13,4	3,3	42,4	5,9	4,6	8,7	20	5	53	42	6	85
	All	44	6,6	1,4	44,3	2,2	0,1	10,4	0,19	0,09	0,41	42,9	3,3	147,1	5,5	4,1	8,7	23	5	53	37	1	85

* data from Ponette et al. (1997).

Table 2. Details of models and their significant terms selected to explain variations in PyC quantity and quality in the 22 soil profiles. All models used a gls function (see details in the *Statistical analyses* section). NS (non signifiant): $p > 0.1$; T (trend) $p < 0.1$; * $p < 0.05$; ** $p < 0.01$ and *** $p < 0.001$.

Response variable	Transformation	Predictors in final model and level of significance	n[a]
PyC proportion	1/	depth^{NS} + soil^{NS} + depth × soil^{T}	44
PyC content	1/sqrt	depth*** + soil**	44
B3CA	1/	depth** + soil^{T}	44
B5CA	1/	depth**	43
B6CA	no	veg^{T} + soil^{NS} + veg × soil^{T}	42
B4CA	1/	no significant factor	44

[a] outliers were identified with Cook's distance.