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Potential changes in Czech forest soil carbon stocks under different climate change scenarios

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ABSTRACT: Detailed inventory data (*n* = 3,930; approximately one representative sampling point per 650 ha) on soil organic carbon (SOC) to a depth of 30 cm has been used to characterize carbon content in forest soils in the Czech Republic across all altitudinal vegetation zones and forest ecological series. This data set was used to predict the most probable changes in soil carbon content in the altitudinal vegetation zones due to global warming. The mean value of the SOC content in forest soils of the Czech Republic was determined to be 62.6 ± 17.2 $t \cdot ha^{-1}$. Under different warming scenarios the major SOC loss was observed at an altitude of 700–900 m a.s.l. Using a pessimistic emission scenario in the climatic model (i.e. predicted temperature change by +4.24°C), losses of C from forest soils in the Czech Republic, or potentially in central Europe, could be as high as 13% of the current carbon stock in forest soils.

Keywords: oxidizable soil carbon content; altitudinal vegetation zone; ecological series

Soil is given special attention in the context of its potential to be a significant sink or source of atmospheric carbon. Carbon stocks and their changes are investigated throughout the globe at national and sub-national scales (Falloon et al. 2007). Forest soils contribute significantly to the carbon sink of forests, the only stable ecosystems with a long-term production cycle. Sequestration of atmospheric CO_2 in forest soil may prove to represent a more stable and long-lasting solution to C sequestration compared to aboveground biomass (Ladegaard-Pedersen et al. 2005). According to Liski et al. (2002), in Central Europe in 1990 the forest soil C sink was almost as large as the tree biomass C sink. Currently, forest soils, including peat soils, store about 69% of the total forest C pool (Dixon et al. 1994; Scharlemann et al. 2014).

At the global scale, the general trend of the soil organic carbon (SOC) stock related to expected global change is not known very well: although there are some exceptions, generally SOC increases with higher latitude and altitude due to temperatures which decrease the decomposition rate of SOC. Decomposition is the result of respiratory activity which is, as the cluster of enzymatic reactions, strongly dependent on the temperature. This dependence is demonstrated by the value of Q_{10} parameter, which indicates an increase of respiration rate by the temperature increase up to 10°C. Q_{10} generally amounts the value of 2 (Pavelka et al. 2007).

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Thus, the sensitivity of carbon efflux via autotrophic and heterotrophic respiration is greatly affected by the temperature increase resulting in a decrease in SOC stocks. However this generally accepted effect of temperature on C budget may or may not be valid at regional scales, where the impact of warming may induce either sequestration – improved conditions for the photosynthetic assimilation, i.e. longer growing season, early start or delayed end of active carbon assimilation, or an increase of the C release due to warmer conditions (Kurz-Besson et al. 2006). Rodeghiero and Cescatti (2005) analysed the impacts of soil type, species composition and land-use history on soil respiration for representative forest types along an elevation gradient in the Italian Alps observing a positive correlation between Lang's rain factor and total SOC. In contrast, Callesten et al. (2003) explored the relationship between SOC and climate and soil quality in Nordic forest soils (Sweden, Finland, Norway, Denmark) concluding that SOC was positively correlated with temperature only within a particular range of latitude and longitude. Bottner et al. (2000), in his unique soil transplant experiment simulating a south to north climate shift, demonstrated that the climate shift would increase the carbon mineralization rate. Kurz-Besson et al. (2006) analysed the rate of litter decomposition in eight pine forests with a climatic latitudinal gradient (40–60°) suggesting that the forest floor could be a source or sink of carbon distinctively depending on local climatic conditions. Global climatic change permanently enhanced the atmospheric CO_2 concentration, which resulted in an increase in nitrogen decomposition and as a consequence stimulated the increase in primary production – the combined nitrogen and carbon fertilization (Calesten et al. 2003). This process resulted in an increase in litter inputs to the soil. Moreover, the rate of decomposition, litter quality (Vogel et al. 2005), length of the growing season, biogeochemical feedbacks of the soil, nutrient cycles, insect outbreaks and fire regimes (Euskirchen et al. 2010) would also be altered.

Thus, the information on soil carbon content and its dynamics under different climatic conditions are necessary to understand.

The present study aims are focused on examining the relation between SOC and site climatic conditions. The Central European landscape and local climatic conditions are characterized by the dominance of altitudinal over latitudinal zonality. Hence, we hypothesize that a shift of altitudinal vegetation zones due to the warming, and related changes in temperature and precipitation, can bring some indication on the future SOC in the individual forest altitudinal zones.

MATERIAL AND METHODS

Between the years 1993 and 2004, a detailed inventory of the SOC in organic and mineral layers of forest soils in the Czech Republic was carried out by the Forest Management Institute. A total amount of 3,930 sampling points across every combination of local forest typology of the Czech Republic, i.e. 9 altitudinal vegetation zones (Zlatník 1976) and 8 basic ecological series (Plíva 1984), were analysed.

Carbon content. A total of 6,130 soil samples of H, A and B horizons were taken to a maximum depth of 30 cm. All 6,130 samples were used for SOC content estimation based on the wet oxidation. In addition, 300 samples were used for bulk density determinations for mineral soil. H horizons thicker than 5 cm were sampled as well – that thickness related to the use of a physical cylinder (of 10 cm in diameter). The thickness of organic and mineral layers was measured and the bulk density of carbon concentrations (%) was determined. With respect to data comparison, the only analytical procedure was applied for all the samples, i.e. wet oxidation using potassium bichromate and sulphuric acid. Furthermore, the bulk density of organic horizon and mineral horizon was determined for each combination of the ecological series and altitudinal vegetation zones (the number of existing combinations: 58; total n = 300) in order to calculate the absolute oxidizable carbon content (mg C·ha^{-1}) up to a depth of 30 cm (SOC_{30}) in both the organic and mineral layers. SOC stock was calculated according to Eq. 1 (Schwartz, Namri 2002):

$$Q_i = C_i D_i E_i (1 - G_i) \tag{1}$$

where:

Q_i – SOC stock (mg·ha^{-1}) in the soil layer i with thickness E_i (m),

C_i – carbon concentration (%),

D_i – bulk density (g·cm^{-3}),

G_i – rock fragment content.

The SOC_{30} content at the sampling point was reported as the sum of the absolute SOC_{30} contents of the combined organic and mineral soil layers. The SOC_{30} content was calculated for every existing combination of altitudinal vegetation zones and ecological series. The mean SOC_{30} content weighted by the areas of ecological series at the altitudinal vegetation zones was estimated for each altitudinal zone.

Climatic conditions. For each altitudinal vegetation zone, its mean annual temperature and mean annual precipitation amount were derived from the Forest and Forest Management Report of the Czech Republic prepared by Ministry of Agriculture of the Czech Republic (Forest Management Institute 2008). To characterize the climate at the individual altitudinal vegetation zones, Lang's rain factor [mean annual precipitation amount (mm) divided by mean annual temperature (°C)] was used. The dependence of SOC_{30} and Lang's rain factor on altitude was evaluated using the TableCurve 2D software (Version 5, 2009).

Predictions of the soil carbon stock changes. The tested hypothesis presumed that the soil organic carbon content of a particular altitudinal vegetation zone (AVZ) is closely related to the mesoclimatic parameters. Then, under warming, the changes in temperature and precipitation would generate a new equilibrium of SOC which would then tend towards the AVZ at lower altitudes, i.e. with higher temperatures and lower rates of precipitation. Thus, the new SOC content would thus also converge to the current SOC content of the site located at a lower altitude.

A function describing the relations between SOC, climate and altitude was developed and applied. The concrete form of the applied model is based on the logistic power peak function expressing the relationship between SOC and altitude, and on the exponential function expressing the relationship between Lang's rain factor and altitude. The carbon loss (C_{loss}) was modelled individually for each altitudinal vegetation zone; the resulting model is calculated as their sum. The simplified mathematical formula of the model is presented by Eq. 2:

$$C_{loss} = \sum_{i=1}^{n} S_i \cdot f(\Delta t, \Delta P) \qquad (2)$$

where:

n – altitudinal zone number,

S_i – area of the altitudinal layer,

f – composite function of the dependence of SOC_{30} and Lang's rain factor on the specific altitudinal zone,

Δt – temperature change,

ΔP – precipitation change.

The model was applied to a range of climates to cover the Intergovernmental Panel on Climate Change climate scenarios as described by the HadCM3 climate model commonly used in Central Europe (Kalvová et al. 2002) with low (B1), middle (A1T) and high (A2) CO_2 emission scenarios. For the specific situation of the Czech Republic the used climate scenario predicts the temperature differences up to +1.38, +2.59 and +4.24°C and precipitation differences of about –1% for the year 2075 for all climate scenarios with the reference to the baseline period 1961 to 1990 (Trnka et al. 2007).

RESULTS

The resulting map of the SOC_{30} stock in forest soils of the Czech Republic is presented in Fig. 1. The map is based on the carbon content sampling realized within all AVZs.

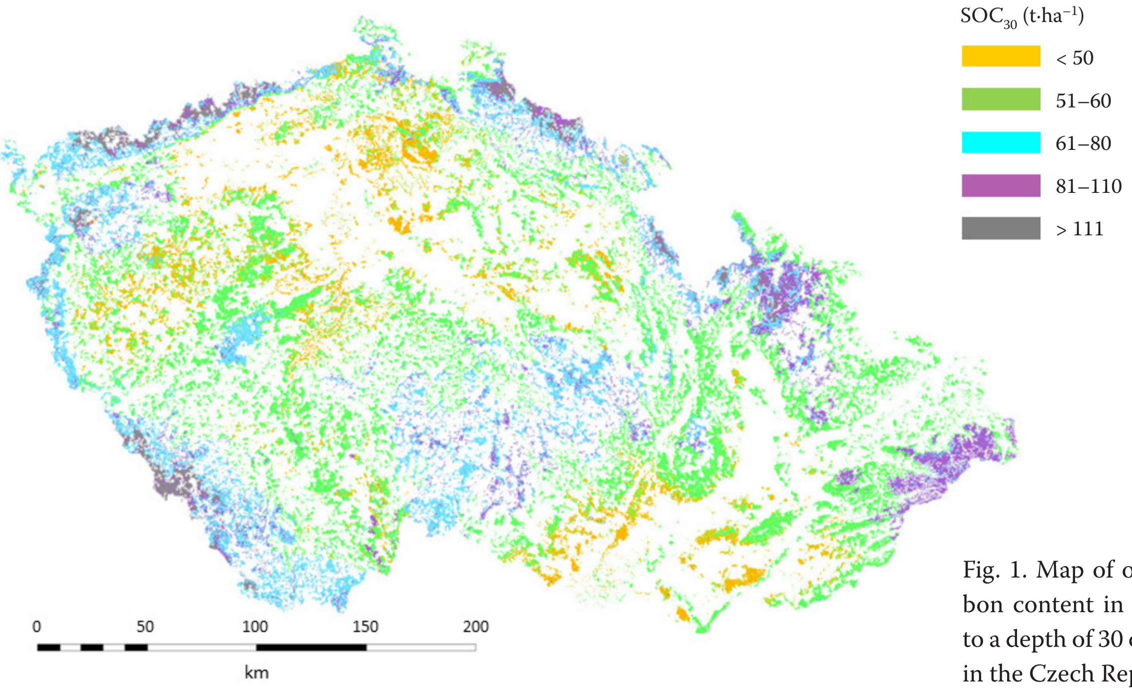

Fig. 1. Map of organic carbon content in forest soils to a depth of 30 cm (SOC_{30}) in the Czech Republic

Table 1. Areas of ecological series at each altitudinal vegetation zone in the Czech Republic and altitudinal limits of the altitudinal vegetation zones

Altitudinal zone number	Altitudinal vegetation zone range (m a.s.l.)	Area of ecological series (thousands ha)								Total (%)
		extreme	acidic	nutritive	maple	floodplain	pseudogley	gleyed soils	peat	
0	azonal	8	77	2			9	8	4	108 (4)
1	100–350	8	23	38	6	29	32	5		141 (5)
2	350–400	2	81	117	17	4	22	1		244 (10)
3	400–550	8	183	282	37	22	44	1		577 (22)
4	550–600	1	95	228	25		81	4	2	436 (17)
5	600–700	7	207	257	21	10	76	6	2	585 (23)
6	700–900	6	144	65	9		83	12	2	320 (12)
7	900–1,050	2	62	10			16	14	4	108 (4)
8	1,050–1,350	5	15	2			4	8	4	38 (1)
9	1,350–1,450	3	1						2	6 (0.3)
Total (%)		52 (2)	888 (35)	1,000 (39)	114 (4)	65 (3)	368 (14)	58 (2)	19 (1)	2,564 (100)

The lowest elevation of the Czech Republic is 107 m a.s.l.

Higher carbon content in the map corresponds with mountain areas (pink and grey areas). White areas denote non-forested land. The sizes of the areas of individual types of ecological series (ES – determined by the soil and vegetation types) within each AVZ are different with altitude. Not every ES is situated at each AVZ (Table 1). The largest areas are occupied by the nutritive and acidic type of ES. These ES types cover 74% of the forested land of the Czech Republic and contribute to their SOC_{30} stock up to 70%.

The SOC_{30} stock in the organic layer was found to be significantly lower than in the mineral layer (Figs 2a, b) of every ES. The SOC_{30} contents observed for all ES across all AVZ ranged from 39.2 to 159.8 t·ha^{-1}.

The weighted mean of the SOC_{30} stock in forest soils of the Czech Republic was calculated to be 62.6 ± 17.2 t·ha^{-1}. Notably, it results from the areas of the individual ES (Table 1) and the corresponding carbon content (Figs 2a, b). 50% of the forests have a SOC stock ranging from 55 to 70 t·ha^{-1} (Fig.1 – green to blue scale). Finally, the resulting total amount of SOC in forest soils in the Czech Republic was calculated to be approximately 154.5 Mt C. In contrast, gleyed ES showed a specific shape due to the high fluctuation of the SOC content in the mineral layer (Fig. 2b). Its influence is manifested especially in the rapid increase of the mineral layer carbon content and consequently its decrease around 1,200 m a.s.l. (Fig. 3).

The average annual temperature within the AVZ decreased with altitude from 8.9 to 2.3°C (Fig. 4), whereas the average annual precipitation amount increased from 525 to 1,550 mm. The trends of these climatic factors were not linear and the curve of Lang's factor resulted in a significant exponential increase with altitude ($y = 37.725e^{0,002x}$, $R^2 = 0.999$).

Quite different sensitivities of individual AVZ to carbon release connected with warming were found out (Fig. 5a). The biggest decrease in the total SOC

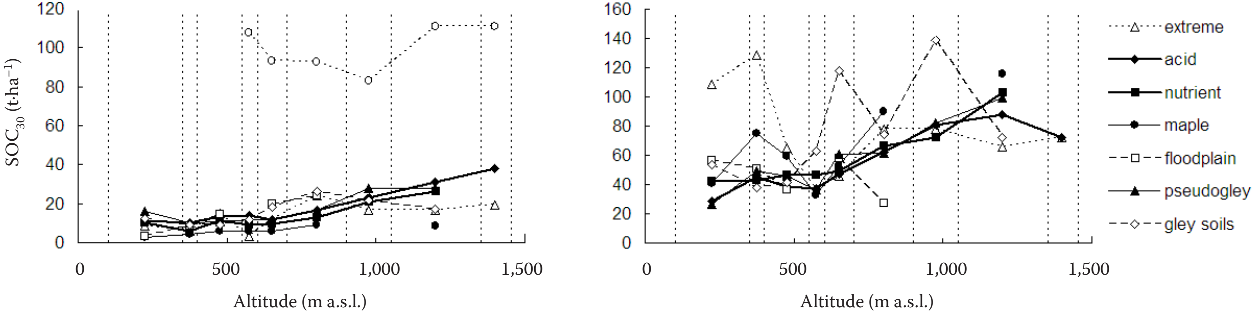

Fig. 2. Absolute carbon content to a depth of 30 cm (SOC_{30}) in organic (a) and mineral (b) layers in the ecological series of forest soils in the Czech Republic; AVZ 1–9 – altitudinal vegetation zones according to Table 1

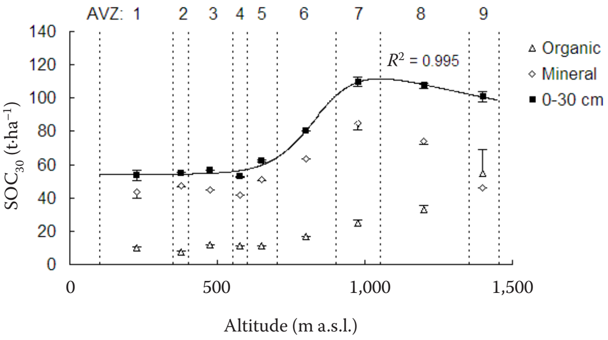

Fig. 3. Carbon content to a depth of 30 cm (SOC$_{30}$) in organic and mineral soil and combined summed layers in forest soils of the Czech Republic.

error bars – standard errors, AVZ 1–9 – altitudinal vegetation zones according to Table 1

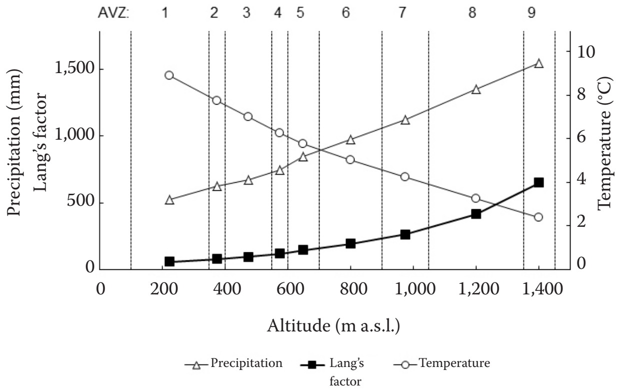

Fig. 4. Dependence of average annual air temperature, annual precipitation amount, and Lang's rain factor on altitude

AVZ 1–9 – altitudinal vegetation zones according to Table 1

stock with warming is predicted for forest soils at the altitudes of 700–900 and 900–1,050 m a.s.l., under the A1T scenario, i.e. warming by 2.59°C. It means a decrease by about 30 and 41% of the current SOC. In contrast, forests soils up to 550 m a.s.l. showed negligible changes in SOC. On the other hand, an increase of SOC is expected at high altitudes. At the AVZ of 1050–1350 m a.s.l. the SOC content is expected to be higher under a warming scenario by up to 2°C, whereas AVZ between 1,350 and 1,450 m a.s.l. show an increase by up to 4°C.

The total amount of the SOC loss to a depth of 30 cm over the entire Czech forest estate is influenced not only by the sensitivity of forest soils to warming, but also by the size of the forest area in each AVZ. Although the change of the SOC content due to warming at 700–900 m a.s.l. will be most probably smaller than at 900–1,050 m a.s.l. (Fig. 5a), its contribution to the total SOC loss (carbon content change multiplied by the area) is going to be higher due to its larger area (Table 1, Fig. 5b). It means that the interval of altitudes between 700 and 900 m a.s.l. would be the biggest contributor to the total carbon loss caused by warming (up to 48%), although it represents only 12% of the forested areas in the Czech Republic (Table 1).

The changes in the average SOC stock due to warming were modelled as sums of carbon changes at individual AVZ (Fig. 6). Accordingly, under the scenarios B1, A1T and A2 (1.38, 2.59 and 4.24°C), the SOC content in forest soils of the Czech Republic will amount to 4.9, 6.7 and 7.9 t·ha^{-1}, respectively, which would correspond to the respective total carbon losses of 11.9, 16.4 and 19.2 Mt from forested lands of the Czech Republic. As the current average SOC content of forest soils to a depth of 30 cm amounts to ca. 63 t·ha^{-1}, the predicted total SOC losses for the respective scenarios will reach 7.8, 10.7 and 12.5% of the current SOC stored in forests of the Czech Republic.

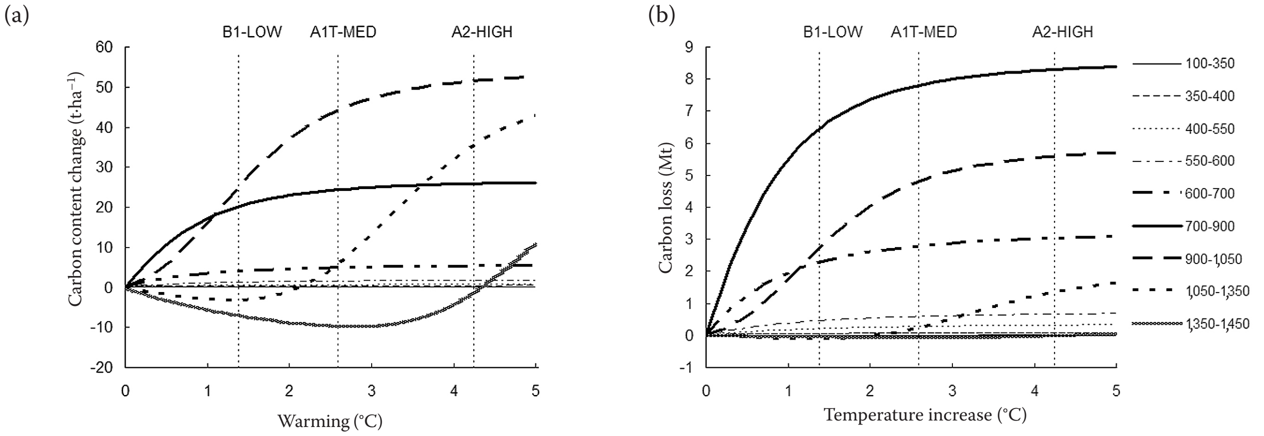

Fig. 5. Prediction of carbon content changes (a) and carbon loss (b) in forested areas in the Czech Republic under warming for current forest altitudinal zones (m a.s.l.)

B1-LOW, A1T-MED, A2-HIGH – warming predicted for the year 2075 by the HadCM3 climate model and CO$_2$ emission scenarios: B1 (low), A1T (medium) and A2 (high), baseline period 1961–1990

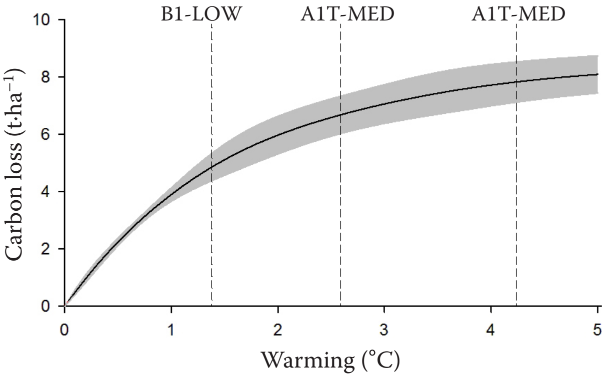

Fig. 6. The predicted carbon loss in forest soils from the top 30 cm of forest soils in the Czech Republic according to the used scenarios of changes due to warming

grey area – 95% confidence band, B1-LOW, A1T-MED, A2-HIGH – warming predicted for the year 2075 by the HadCM3 climate model and CO2 emission scenarios: B1 (low), A1T (medium) and A2 (high), baseline period 1961–1990

DISCUSSION

The current state of the SOC content in forest soils is the result of its long-term formation during various climatic conditions. Due to the significant altitudinal zonality of the Czech Republic, the constructed map shows a wide range of forest soil carbon contents on a relatively small area (Fig. 1).

The relation of SOC content to the altitude is connected with the ratio between net primary production (NPP) and decomposition. Liski and Westman (1997) published the example of boreal forests where under the situation of slight warming some increase of soil carbon stock was predicted due to an increase of their net ecosystem production. Thus enhanced NPP may be higher than the increase in soil organic carbon decomposition. On the contrary, Bottner et al. (2000) predicted 20–25% increases of carbon mineralization rate in the boreal forest soils under the climate shift. It is an open question if these two findings could be valid for the situation of the strongly different altitudinal zones of forest soils in the Czech Republic.

A dominant effect on the final trend between soil carbon content and altitude is attributed to the acidic and nutritive ecological series (i.e. soil and vegetation types) due to their large area they occupy (Table 1). It is necessary to stress that some ES as the peat, gleyed, floodplain and extreme ES not correspond to this general trend of SOC versus altitude. Soil types of the peat ES are Histosols consisting of partially decomposed organic material. They occur at higher altitudes with high water table, high precipitation, low temperatures and low decomposition. Also, Gleysols developed in conditions resulting from prolonged water saturation. These conditions cause an accumulation of organic carbon due to anaerobic conditions and low pH. Thus, for peat and gleyed ES, temperature is not the main limiting environmental factor of decomposition. Water also played an important role in the development of floodplain soil types. However, it should be noted that these above-mentioned four ecological series represent only 8% of the entire Czech forest area and thus their influence on the total trend is marginal.

From the realized inventory it is evident that 50% of the forest soils in the Czech Republic have a SOC stock ranging from 55 to 70 t·ha^{-1}. Smith et al. (2006) calculated the mean value of the SOC stock for European forest soils to be about 96 t·ha^{-1} and Cienciala et al. (2008) suggested the mean C stock of forest soils in the Czech Republic to be 78.4 t·ha^{-1} for the same soil depth, i.e. up to 30 cm. These estimates are in good tolerance with our presented findings.

Under the effects of climate change Lal (2004) expected the Central European region to experience a longer growing season and decreased rate of mineralization leading to a decrease in the soil organic carbon pool because of the enhanced evolution of carbon in the gas form, i.e. carbon dioxide. Moreover, Subke et al. (2003) suggested that this enhanced C evolution from soil organic matter would turn the present carbon sink into carbon sources. On the contrary, Cienciala et al. (2008), using the matrix scenario model (EFISCEN), concluded that there will be no change in soil organic carbon in forest soils in the Czech Republic due to the ongoing climate change and assuming no significant changes in forest management practices.

The present study affiliates the altitudinal limitation of net primary production to the impact of two basic climatic factors – temperature and precipitation, which affect both production and decomposition. Rodeghiero and Cescatti (2005), and Euskirchen et al. (2010) confirmed the basic role of climate in soil decomposition showing a positive correlation between soil organic matter to a depth of 30 cm and Lang's factor. Under the conditions of the Czech Republic, precipitation is regarded as the main limiting abiotic environmental factor for forests up to 550 m a.s.l., whereas zones above 600 m a.s.l. are mainly limited by temperature. The sites between those two altitudes (550–600 m a.s.l) are considered to be zonal, i.e. they are affected equally by both temperature and precipitation (Kalvová et al. 2002). Presented findings show a low sensitivity of the SOC_{30} content to temperature changes up to 550 m a.s.l. (Fig. 5) and are in the agreement with the above-mentioned concept. Thus warming will not probably primarily induce any significant changes in the total soil carbon content at these altitudes.

The soil processes such as decomposition and factors affecting this process are still a source of uncertainty (Jones et al. 2005; Xu et al. 2009). Thus, neither the use of short-term measurements of carbon dynamics nor soil warming experiments in the prediction models guarantee that the same trend relations will be valid in the predictions of long-term responses (Vogel et al. 2005). Under such conditions the investigation of real ecosystems, which have developed over a longer time, is a possible way of avoiding the above-mentioned uncertainties. The application of climate scenarios that vary from the optimistic to the pessimistic ones, anticipates the extent of possible future changes in the carbon stock of forest soils under warming. Since the obtained relationship between warming and carbon losses has the shape of a hyperbolic function (Fig. 6), soils would react most sensitively with the carbon loss corresponding to the initial slope of the curve, i.e. approximately up to 1°C of warming. Larger differences in the prediction of carbon losses were found between the optimistic and the middle variant of the emission scenarios in comparison with differences between the middle and pessimistic variants.

It is necessary to stress that the presented analysis examined only the plant-soil-climate interactions; it has not taken into account parameters such as nitrogen availability and management strategies. The possible impact of changes in nitrogen availability on the carbon stock is ambiguous and is at present under active discussion (Magnani et al. 2007; de Vries et al. 2008; Reay et al. 2008).

Our predicted changes in the total SOC loss from forest soils in the Czech Republic due to warming show that the main contributor to this SOC loss will be located in the altitude range of 700–900 m a.s.l. This range accounts for 12% of the total forest area in the Czech Republic. It means that neither current forest management procedures, as defined in the Act No. 289/1995 Coll., nor species composition of the Czech forests (52% of spruce, then mainly pine, beech and oak) are expected to be changed essentially in the next decades due to warming as predicted by the scenario used here (Cienciala et al. 2008). The predicted carbon loss from the entire area of forest soils in the Czech Republic will amount to 21 Mt of carbon (7.8 $t \cdot ha^{-1}$) into the atmosphere if the pessimistic scenario (A2, warming by 4.24°C) occurs. Then, the possible predicted losses of carbon from forest soils of the Czech Republic, or potentially Central Europe, could be as high as 14% of the current total soil organic carbon stock in the soil layers to a depth of 30 cm.

CONCLUSIONS

Under the conditions of Central Europe, particularly in the Czech Republic, climatic conditions which are strongly related to altitudinal zones influence the surface soil carbon content. The obtained dependence of soil carbon content on the altitude shows a different shape within individual ecological series; the general trend shows increases of carbon content up to 1,050 m a.s.l. followed by decreases at higher altitudes. Via the construction of a model using the obtained relationships, it was possible to predict soil carbon losses in forests in the Czech Republic under different climatic scenarios. The model prediction shows that lower altitudes reduce sensitivity to warming. This sensitivity would increase with altitude. A decrease of carbon content due to warming would be evident in the majority of altitudinal zones with the exception of altitudes above 1,050 m a.s.l., where the carbon content would increase with the mild warming scenario. Altitudes of 700–900 m a.s.l. would be the biggest contributor to the total SOC loss. Using the pessimistic scenario (A2, +4.24°C temperature change), the predicted carbon loss from forest soils in the Czech Republic will amount to ca. 21 Mt, i.e. 14% of the total soil carbon stock to a depth of 30 cm.

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