Soil organic carbon dynamics in *Populus deltoides* plantations using RothC-model in the Indo-Gangetic region of India

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Soil organic carbon (SOC) change can arise because of changes in land use, land management and climatic conditions. Modelling approach helps in proper choice of management practices for soil carbon build-up. In this context, RothC is a promising model for estimation of SOC changes in different land-use systems. In the present study, RothC model was used to predict the development of SOC in *Populus deltoides* plantation during three rotations in three agro-climatic zones of the Indo-Gangetic region, India. The result reveal that RothC fairly predicts SOC. Root mean square error for Lower Gangetic Region (LGR), Middle Gangetic Region (MGR) and Trans Gangetic Plain (TGP) was 2.75, 4.94 and 1.30 respectively, while comparing modelled and measured data. Model efficiency was 0.25, 0.36 and 0.89 for LGR, MGR and TGP respectively. The rate of change of measured SOC was 1.0, 1.59 and 1.51 mg ha^{-1} year^{-1} for LGR, MGR and TGP respectively, whereas the rate of change of simulated SOC was higher, i.e. 1.16 and 1.89 mg ha^{-1} year^{-1} for LGR and UGR respectively, and lower for TGP (0.97 mg ha^{-1} year^{-1}).

Keywords: Management practices, *Populus deltoids*, simulation models, soil organic carbon.

SOIL organic carbon (SOC) is vital for ecosystem functions having a major influence on soil structure, water-holding capacity, CEC and the ability of soils to form complexes with metal ions and store nutrients[1]. SOC content in the soil depends on the land-use system, type of management practice and age of plantation[2]. There is an increasing concern about the soil quality vis-à-vis organic carbon content in soils due to global warming and enhanced carbon dioxide (CO_2) concentration from the atmosphere[3–5]. Therefore, choosing long-term management practices which can add SOC and still provide economic benefits to the farmers is an urgent need to offset the carbon emissions and fulfil the Kyoto and more recent commitments, e.g. the United Nations Framework Convention on Climate Change (UNFCC) 21st Conference of the Parties in Paris (2015). In this context, poplar (*Populus deltoides*)-based short-rotation forestry plantation can play an important role.

Poplar, primarily an exotic species in India, is being grown as agroforestry or pure plantations in more than 312,000 ha in the entire Indo-Gangetic region of North India[6]. Systematic introduction of exotic poplars in India took place more than seven decades ago, and more than 600 clones and 266 open-pollinated seed families have been introduced in the country from different part of the world. *P. deltoides* has high growth rate (mean annual increment of 20–25 m^3 ha^{-1} year^{-1}) in India[6]. The deciduous nature of the species during winter makes it suitable for agroforestry. The annual returns from its cultivation are high, due to which it is cultivated by farmers on a large scale. Depending upon growth rate and market demand, the species is harvested at a short rotation of 5–9 years. Due to higher returns, it is replanted on the same farmland.

Computer models involving dynamics of SOC are useful for the simulation of carbon sequestration in soils. Different factors like management, fertilization, tillage, crop rotation[7,8] or other external factors, i.e. climate change[9] have been incorporated into various simulation models for predicting future changes in SOC[10–13]. These models are useful in improving our understanding of carbon turnover processes in the soil[14]. Worldwide, various soil models (Q, ROMUL, RothC, Soil CO_2/RothC and Yasso07) and plant–soil models (CENTURY, Coup-Model and Forest-DNDC) are used for studying soil carbon stock dynamics. However, the decision to use these models depends on the availability of input data, their simplicity, and whether modelled and measured values are good or unsatisfactory[15]. RothC is one of a group of models that has performed well for SOC[13]. It has been used in over 80 countries for different climates including tropical and temperate (humid subtropical, Mediterranean and maritime)[7,10,16,17]. Guo *et al.*[18] used RothC for experiments in northern China, and reported that it accurately simulated the changes in SOC. The present study was conducted using the RothC model to ascertain the SOC potential of poplar plantations in the Indo-Gangetic region and determine how continuous rotations of poplar on the same site will affect SOC.

Populus deltoides Bartr. ex Marsh plantations were selected at three different locations in the Lower, Middle and Upper Gangetic regions in India. These represent three different climates, viz. subtropical, humid subtropical and semiarid for the Lower Gangetic Region (LGR), Middle Gangetic Region (MGR) and Trans Gangetic Plains (TGP) respectively. Table 1 provides details of the study sites.

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Table 1. Treatment details

Treatment number	Location	Latitude and longitude	Altitude (m)
Lower Gangetic Region (LGR)	Dr Rajendra Prasad Central Agricultural University, Pusa, Bihar	30°54′N; 75°48′E	53
Middle Gangetic Region (MGR)	G.B. Pant University of Agriculture and Technology, Pantnagar, Uttrakhand	29°08′N; 79°20′E	223
Trans Gangetic Plains (TGP)	Panjab Agricultural University, Ludhiana at Balachaur, SBS Nagar, Punjab	31°6′N; 76°23′E	355

Table 2. Data requirement for RothC

Parameters	LGR	MGR	TGP
Average monthly temperature	14.5–31.15	12.5–30.2	11.8–30.5
Total annual precipitation (mm)	1276	1702	106.7
Total annual open pan evaporation (mm)	1246	201.7	119.8
Soil depth (cm)	30	30	30
Clay content (%)	34.1	33	9.9
DPM/RPM*	0.25	0.25	0.25

*The value suggested by Coleman and Jenkinson[20] was used.

At the TGP and MGR sites, pure plantations of poplar were raised, whereas in LGR poplars were grown in agroforestry with wheat as the associated crop. The data for nine years were used at MGR and LGR. For TGP, data were available only for seven years, as the rotation age in this region is less. The plantations were raised at a spacing of 5 × 4 m. The average height of trees at LGR, MGR and TGP was 23.4 m, 24.2 m and 26.9 m respectively. The average diameter of trees at LGR, MGR and TGP was 40.5 cm, 26.6 cm and 28.7 cm respectively. Leaf litter was collected using wooden traps placed randomly below the tree canopies. Soil samples were collected during the initial stage of the plantations. The clay per cent of the soil was measured using international pipette method[19].

The RothC model considers the effect of soil type, moisture content, temperature and plant cover on SOC conversion processes[20]. SOC stock comprises five compartments as functions of speed of decomposition. Four of these are considered active – (i) easily decomposed plant material (DPM, remains in the soil for 0.17 years), (ii) microbial biomass (BIO, 1.69 years), (iii) resistant plant material (RPM, 2.31 years), (iv) humified organic matter (HUM, 49.5 years) and (v) passive inert organic matter (IOM, with mean residence time of 50,000 years). The DPM and RPM compartments decompose and become BIO and HUM, and they contribute CO_2 to the atmosphere. The model includes a function that adjusts the proportions of BIO, HUM and CO_2, according to the soil clay content. IOM (tonne ha^{-1}) is obtained from Falloon *et al.*[15] as follows

$$IOM = 0.049 \times SOC^{1.139}, \quad (1)$$

where SOC is the soil organic carbon (tonne ha^{-1}).

The model requires providing plant residues entering the soil on a monthly basis. The partition between the plant residues that enter the soil is given as a function of the default values originating from the DPM/RPM ratio. Agriculture and cultivated grasses have a DPM/RPM ratio of 1.44; bushes and grasses – 0.67, and tropical or deciduous forests – 0.25. The input parameters in the model are mean temperature, monthly mean precipitation, mean monthly evaporation, clay content, soil depth, monthly C input from plant residues, organic fertilizers, and the number of months for which the soil is covered. Table 2 provides details of the input parameters used in the present study.

RothC-26.3 model simulation was done in two stages – initialization and prediction. In the initialization stage, it was assumed that the SOC content measured in the systems achieves a condition of equilibrium[21]. The RothC model was run in inverse mode to obtain the quantity of C that enters the soil each year to maintain the specific initial SOC content measured in the experiment. This can be achieved using the inverse mode of RothC. Equilibrium condition at the start of the experiment was achieved by running RothC iteratively for 10,000 years. Equilibrium run requires IOM value, which was calculated from eq. (1)[15]. Equilibrium run determines the initial distribution of C in four compartments, viz. DPM, RPM, BIO and HUM necessary for the model to function along with its radiocarbon. The DPM/RPM ratio used was 0.25 as recommended by RothC (by default) for tropical and deciduous forests. Table 2 provides the detailed inputs required for equilibrium run. The weather (monthly temperature, rainfall and evaporation; clay % and soil depth), land management (plant residue, FYM and soil cover) and DPM/RPM ratio were used in direct mode for the nine-year rotation.

The performance of the model was ascertained by comparing, pairs of SOC data, observed and predicted during the years of plantations[13]. The statistics used was

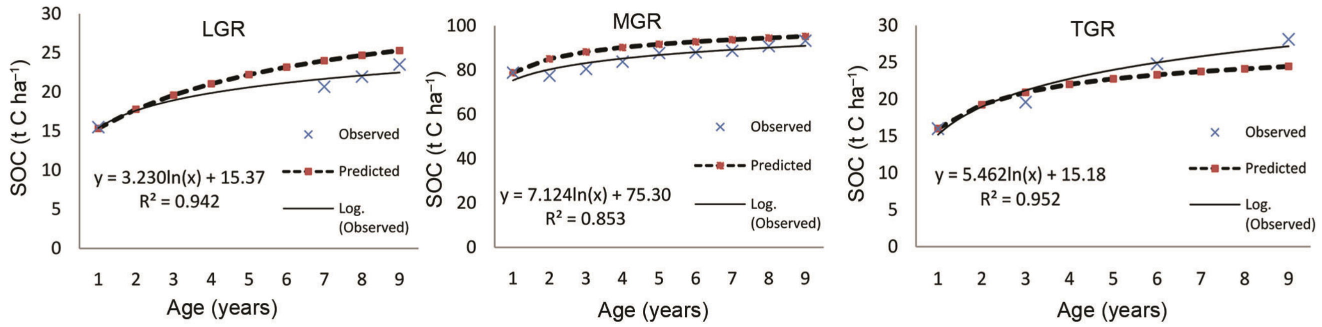

Figure 1. Soil organic carbon (SOC) in the three regions. The symbols (x) show the mean measured quantities for 0–30 cm and solid lines show the model results.

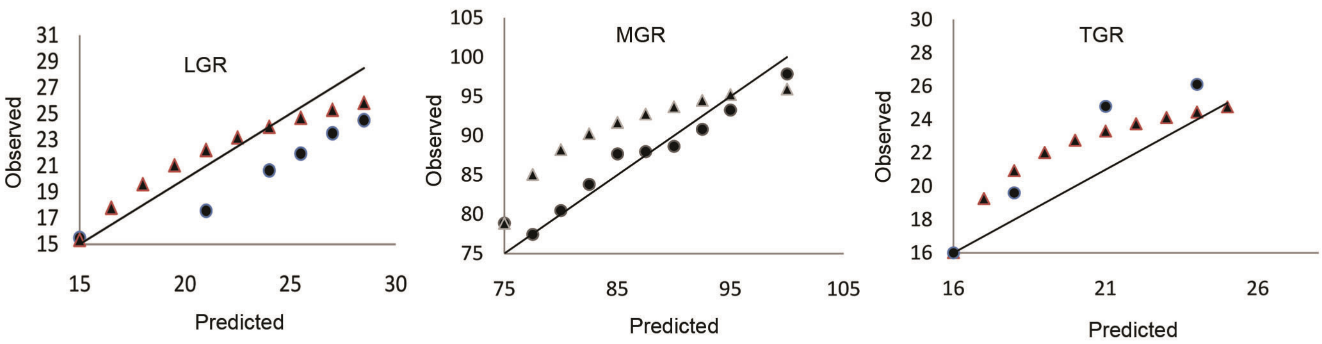

Figure 2. Measured (•) versus modelled (▲) SOC. The lines indicate the 1 : 1 relation.

Table 3. Statistics describing performance of the model for each region

Treatment	Root mean square error	Model efficiency	Relative error
LGR	2.75	0.25	14.11
MGR	4.94	0.36	4.69
TGP	1.30	0.89	1.37

root mean square error (RMSE), efficiency of the model (EF) and relative error (ER). RMSE ranged from 0 to ∞, EF from −∞ to 1 and ER from −∞ to +∞.

The measured and modelled SOC values were plotted for comparison and accuracy of modelling of SOC obtained through RothC. Figures 1 *a–c* shows the fits between measured and modelled data for the Indo-Gangetic region. RothC-modelled SOC values in LGR varied from 15.35 (initial) to 25.84 mg ha^{-1} (after nine years), whereas the measured values varied from 15.50 to 24.5 mg ha^{-1} (Figure 1 *a*). In MGR, the modelled values ranged from 78.84 to 95.92 mg ha^{-1}, whereas the measured values varied from 78.85 to 97.86 mg ha^{-1} (Figure 1 *b*). In TGP, modelled values varied from 16.02 to 24.76 mg ha^{-1}, compared to measured values which ranged from 16.01 to 28.12 mg ha^{-1} (Figure 1 *c*). It was observed that RothC did not predict much variation compared to the estimated values.

Three statistics (RMSE, EF and ER) were employed to ascertain the agreement between measured and modelled values (Table 3). The agreement between the modelled and measured data was satisfactory as the RMSE value for LGR, MGR and TGP was 2.75, 4.94 and 1.30 respectively. Thus, TGP-modelled values were close to the measured values. Model efficiency was 0.25, 0.36 and 0.89 for LGR, MGR and TGP respectively. This indicates that the agreement is better in TGP. The relative error was 14.11, 4.69 and 1.37 for LGR, MGR and TGP respectively. Scatter plots between measured and modelled SOC values revealed good relationships between modelled and measured data for SOC (Figure 2). However, it indicated slight underestimation of SOC for TGP.

The measured and RothC-modelled SOC values for the first rotation (nine years) were found to be within limits for RMSE, EF and ER. This indicates that RothC fairly predicts SOC. Using the same set of data and expecting that in the short term not much change in climatic parameters is expected, SOC data were simulated for three rotations (nine years each) for 27 years (Table 4). It was observed that after the second rotation SOC was 29.4, 100.9 and 26.9 mg ha^{-1} in LGR, MGR and TGP respectively. After the third rotation it was 32.1, 104.5 and 28.5 mg ha^{-1} in LGR, MGR and TGP respectively (Table 4).

The rate of change of measured SOC was 1.0, 1.59 and 1.51 mg ha^{-1} $year^{-1}$ for LGR, MGR and TGP respectively (Table 4). The rate of change of simulated SOC for the first rotation was higher, viz. 1.16 and 1.89 mg ha^{-1} $year^{-1}$

Table 4. Rate of change (mg C ha^{-1} $year^{-1}$) in measured and simulated soil organic carbon (SOC) sequestration

	Measured SOC			Simulated SOC						
Region	Initial SOC	After first *R*	ROC*	Initial SOC	After first *R* (A)	ROC	After second *R* (B)	ROC over first *R* (A)	After third *R* (C)	ROC over (B)
LGR	15.5	24.5	1	15.34	25.84	1.16	29.4	0.39	32.09	0.29
MGR	78.85	97.86	1.59	78.84	95.92	1.89	100.97	0.56	104.51	0.39
TGP	16.01	28.12	1.51	16.02	24.76	0.97	26.94	0.24	28.50	0.17

*ROC, Rate of change of SOC over initial SOC (mg ha^{-1} $year^{-1}$); *R*, Rotation.

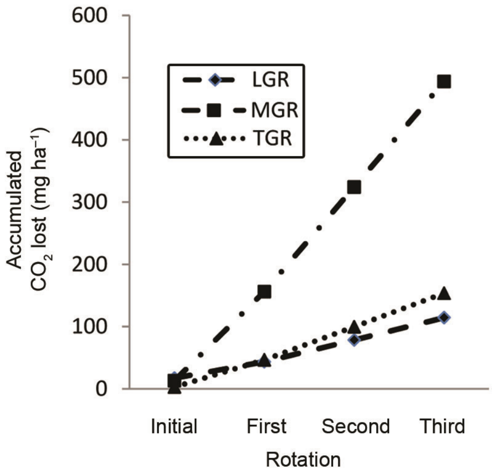

Figure 3. Simulated accumulated carbon dioxide lost during three rotations of poplar with a nine-year rotation.

for LGR and UGR respectively, and lower for TGP (0.97 mg ha^{-1} $year^{-1}$) as compared to measured SOC. In the second and third rotations, the rate of change of SOC decreased to 0.39 and 0.29 mg C ha^{-1} $year^{-1}$ for LGR, 0.56 and 0.39 mg C ha^{-1} $year^{-1}$ for MGR and 0.24 and 0.17 mg C ha^{-1} $year^{-1}$ for TGP respectively (Table 4). SOC additions over generations have led to flattening of the curve for all sites showing soil tending towards saturation level of organic carbon.

Figure 3 depicts the accumulated CO_2 lost during the simulation period. It was found that CO_2 lost had a steep increasing trend MGR and at end of the third rotation (27th year), the CO_2 lost was 493.81 mg ha^{-1}. LGR and TGP contributed lesser CO_2 to the atmosphere than MGR. CO_2 lost at end of the third rotation was 114.41 and 153.56 mg ha^{-1} in LGR and TGP respectively.

The RothC model has been applied in crops, grasslands, and forest soil systems, and also in agroforestry[22]. In the present study, SOC followed the order MGR > LGR > TGP (Figure 1 and Table 4). SOC is controlled by the nature/quality of clay in soils and land use[23]. MGR and LGR had higher clay content (Table 2). Relatively high clay content favours moisture condition for organic matter decomposition in soils and hence helps in increasing SOC[24].

Three different statistics employed for comparing measured and modelled data showed satisfactory results as RMSE value for LGR, MGR and TGP was 2.75, 4.94 and 1.30 respectively. RMSE values with the RothC model are reported in the range 2%–30% (refs 13, 16, 18 and 25). EF was 0.25, 0.36 and 0.89 for LGR, MGR and TGP respectively. González-Molina *et al.*[25] also reported EF range from 0.32 (grasslands) to 0.90 (forests) and concluded that RothC performs better in agriculture and forest land compared to grasslands and rangelands.

Scatter plots between measured and modelled SOC values revealed good relationships between modelled and measured data for SOC (Figure 2), which is in accordance with the observations of Zimmermann *et al.*[17], who also reported strong relationships between modelled and measured data (1 : 1 line) for different SOC pools in soils from temperate grasslands to arable and alpine pasture sites. Barančíková *et al.*[26] reported that the RothC modelled and observed values are fairly close to each other and RothC is a good model for the prediction of SOC.

Simulated SOC at TGP was lower than that of LGR at the end of the third rotation. However, CO_2 release was higher in TGP compared to LGR. This may be because TGP experiences very high temperatures up to 44°C for a few days in May and June. The high temperature results in CO_2 release from organic inputs[27,28]. Since RothC only captures average temperature of the region as input, it is not able to simulate the occurrence of high temperature; therefore simulated SOC at TGP is lower. The increasing temperature will expedite the decomposition of soil organic matter and tend to increase SOC loss in the future[29].

The rate of change of simulated SOC for first rotation was higher and it decreased with each rotation, though SOC increased in each rotation. The reduction in SOC in subsequent rotations was due to enriched carbon levels under the plantations. Friggens *et al.*[30] did not record any increase in net ecosystem C stock 12 or 39 years after planting in two native species (*Betula pubescens* and *Pinus sylvestris*). Similar trend was observed by Barančíková *et al.*[26], who reported that in almost all sites, the organic carbon stock increased. The highest rate was observed in the first 20 years. In the next decades, the increase in SOC was slower, while in the last six years no changes in SOC stock were observed.

On the basis of our results, it can be concluded that the RothC-26.3 model is suitable for the estimation of SOC stock changes in poplar plantations in the Indo-Gangetic region of India. The RMSE and ME value ranges suggests that the RothC-modelled values are close to the observed values of SOC in the Indo-Gangetic region. Simulation for three rotations of poplar suggests that the rate of increase per year in SOC decreases as the number of rotation increases. This also suggests that planting poplar on same land for multiple rotations is not deleterious from the point of view of SOC content and such plantations must be encouraged.

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1. Van Keulen, H., Tropical soil organic matter modelling: problems and prospects. *Nutr. Cycl. Agroecosyst*., 2001, **61**(1/2), 33–39.
2. Rani, S., Benbi, D. K., Rajasekaran, A. and Chauhan, S. K., Litterfall, decomposition and nutrient release patterns of different tree species in Taran Taran district of Punjab, India. *J. Appl. Nat. Sci.*, 2016, **8**(3), 1260–1266.
3. Farage, P. K. *et al.*, The potential for soil carbon sequestration in the tropic dryland farming systems of Africa and Latin America: a modelling approach. *Soil Tillage Res*., 2007, **94**, 457–472.
4. Jones, C. *et al.*, Global climate change and soil carbon stock; predictions from two contrasting models for turnover of organic carbon in soil. *Global Change Biol*., 2005, **11**, 154–166.
5. Paustian, K. O. *et al.*, Agricultural soil as a C sink to offset CO_2 emission. *Soil Use Manage*., 1997, **13**, 230–244.
6. Kumar, Dinesh and Singh, N. B., Status of poplar introduction in India. *For. Bull*., 2012, **12**(1), 9–14.
7. Ludwig, B. *et al.*, Predictive modelling of C dynamics in the long-term fertilization experiment at Bad Lauchstadt with the Rothamsted carbon model. *Eur. J. Soil Sci.*, 2007, **58**(5), 1155–1163.
8. Dendoncker, N. *et al.*, Assessing scale effects on modelled soil organic carbon contents as a result of land use change in Belgium. *Soil Use Manage*., 2008, **24**, 8–18.
9. Falloon, P. *et al.*, Climate change and its impact on soil and vegetation carbon storage in Kenya, Jordan, India and Brazil. *Agric. Ecosyst. Environ*., 2007, **122**, 114–124.
10. Coleman, K. *et al.*, Simulating trends in soil organic carbon in long-term experiments using RothC-26.3. *Geoderma*, 1997, **81**(1–2), 29–44.
11. Jenkinson, D. S. *et al.*, Estimating net primary production from measurements made on soil organic matter. *Ecology*, 1999, **80**, 2762–2773.
12. Kelly, R. H. *et al.*, Simulating trends in soil organic carbon in long-term experiments using the century model. *Geoderma*, 1997, **81**(1–2), 75–90.
13. Smith, P. *et al.*, A comparison of the performance of nine soil organic matter models using datasets from seven long-term experiments. *Geoderma*, 1997, **81**(1–2), 153–225.
14. Malamoud, K. *et al*., Modelling how carbon affects soil structure. *Geoderma*, 2009, **149**, 19–26.
15. Falloon, P. *et al.*, Estimating the size of the inert organic matter pool from total soil organic carbon content for use in the Rothamsted carbon model. *Soil Biol. Biochem*., 1998, **30**, 1207–1211.
16. Falloon, P. and Smith, P., Simulating SOC changes in long-term experiments with RothC and CENTURY: model evaluation for a regional scale application. *Soil Use Manage.*, 2002, **18**(2), 101–111.
17. Zimmermann, M. *et al*., Measured soil organic matter fractions can be related to pools in the RothC model. *Eur. J. Soil Sci.*, 2006, **58**(3), 658–667.
18. Guo, L. *et al*., Application of the RothC model to the results of long-term experiments on typical upland soils in northern China. *Soil Use Manage.*, 2007, **23**(1), 63–70.
19. Piper, C. S., *Soil and Plant Analysis*, Hans Publisher, Bombay, 1966.
20. Coleman, K. and Jenkinson, D. S., Rothc-26.3. *A Model for the Turnover of Carbon in Soil. Model Description and Windows Users' Guide*, Institute of Arable Crops Research, Rothamsted, UK, 2005.
21. Jenkinson, D. S., Harris, H. C. and Ryan, J., Organic matter turnover in a calcareous clay soil from Syria under a two-course cereal rotation. *Soil Biol. Biochem.*, 1999, **31**(5), 687–693.
22. Kaonga, M. L. and Coleman, K., Modelling soil organic carbon turnover in improved fallows in eastern Zambia using the RothC-26.3 model. *For. Ecol. Manage.*, 2008, **256**, 1160–1166.
23. Bhattacharyya, T. *et al.*, Total carbon stock in Indian soils: issues, priorities and management. In *Special Publication of the International Seminar on Land Resource Management for Food, Employment and Environment Security*, Soil Conservation Society of India, New Delhi, 2000, pp. 1–46.
24. Bhattacharyya, T. *et al.*, Landuse, clay mineral type and organic carbon content in two Mollisols–Alfisols–Vertisols catenary sequences of tropical India. *Clay Res*., 2005, **24**, 105–122.
25. González-Molina, L., Etchevers-Barra, J. D. and Paz-Pellat, F., Performance of the rothc-26.3 model in short-term experiments in Mexican sites and systems. *J. Agric. Sci.*, 2011, **149**(4), 415–425; doi:10.1017/S0021859611000232.
26. Barančíková, G. *et al*., Application of RothC model to predict soil organic carbon stock on agricultural soils of Slovakia. *Soil Water Res.*, 2010, **5**(1), 1–9.
27. Kirschbaum Miko, U. F., The temperature dependence of soil organic matter decomposition, and the effect of global warming on soil organic C storage. *Soil Biol. Biochem.*, 1995, **27**(6), 753–760.
28. Conant, R. T. *et al.*, Temperature and soil organic matter decomposition rates – synthesis of current knowledge and a way forward. *Global Change Biol.*, 2011, **17**, 3392–3404.
29. Smith, J., Smith, P. and Wattenbach, M., Projected changes in mineral soil carbon of European croplands and grasslands, 1990–2080. *Global Change Biol.*, 2005, **11**, 2141–2152.
30. Friggens, N. L. *et al.*, Tree planting in organic soils does not result in net carbon sequestration on decadal timescales. *Global Change Biol.*, 2020, **26**, 5178–5188; doi:10.1111/gcb.15229.

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