

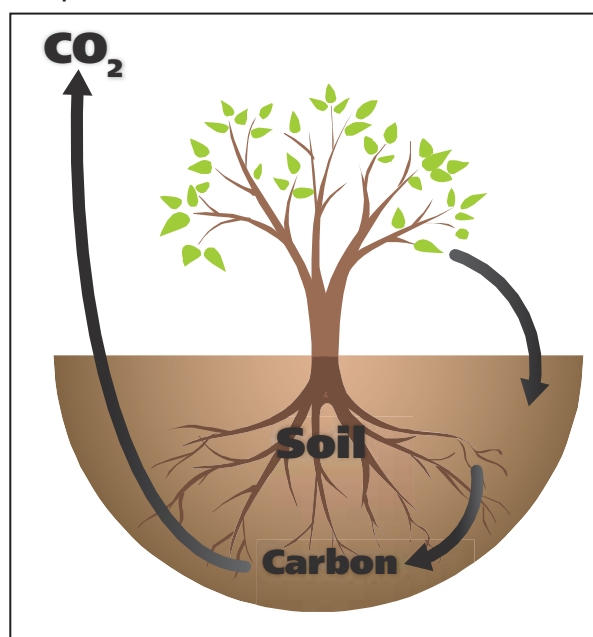
3. Model-based soil carbon monitoring

MODEL-BASED SOIL CARBON MONITORING SYSTEM

A model-based soil carbon monitoring system consists of a model of soil carbon, input data to the model and results on soil carbon calculated (Figure 4). This basic structure is similar between systems although details may vary (e.g. Kurz *et al.*, 1992; 2009; Post *et al.*, 2001; Liski, Perruchoud and Karjalainen, 2002; Liski *et al.*, 2006; Lagergren *et al.*, 2006; Ogle and Paustian, 2005). Input of carbon to soil over time is estimated based on biomass information. Cycling of carbon in soil is simulated using the soil carbon model. As a result of this simulation, estimates are obtained for the components of the soil carbon budget, such as i) the carbon pool of soil; ii) changes in the carbon pool of soil over time; and iii) carbon dioxide emissions from soil as a result of decomposition of organic carbon compounds in soil (heterotrophic soil respiration).

FIGURE 4

A schematic presentation of a model-based soil carbon monitoring system. Input of carbon to soil is estimated based on biomass information. Cycling of carbon in soil is simulated using a soil carbon model. Results are obtained for the carbon pool of soil over time and soil carbon dioxide emissions



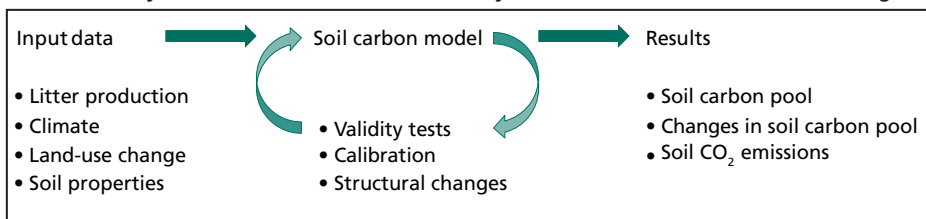
The soil carbon models used in model-based soil carbon monitoring systems are generally dynamic rather than static models. The essential difference between these model types is that the dynamic models account for the element of time, unlike the static models. The dynamic models are considered to be more suitable for simulating carbon cycling in soil, because the carbon pool of soil consists of different age classes and these classes may respond to changes in conditions in different ways. Consequently, changes in the carbon pool of soil do not depend only on conditions at a particular moment but also on conditions in the past. The dynamic models are able to account for this behaviour, whereas the static models are not. It is worth pointing out that the simplest IPCC Tier 1 and 2 methods, commonly applied when there is only limited information, are based on static models (emissions factors or soil carbon contents by land-use category, etc.), whereas an application of a dynamic model belongs to a more advanced Tier 3 methodology in the current IPCC classification.

There are already established dynamic soil carbon models that can be used and have been used as parts of model-based soil carbon monitoring systems, such as CENTURY (Parton *et al.*, 1987); RothC (Coleman and Jenkinson, 1996); SOILN (Eckersten and Beier, 1998); ROMUL (Chertov *et al.*, 2001); Yasso or Yasso07 (Liski *et al.*, 2005; Tuomi *et al.*, 2009; 2011). From the point of view of a user, these models differ from each other in complexity and requirements of input information (Peltoniemi *et al.*, 2007). The complex models need more complicated and more detailed input information than the simple models. Yasso07 and RothC (Coleman and Jenkinson, 1996) are examples of simple soil carbon models requiring only basic input data, whereas CENTURY and ROMUL represent more complicated soil carbon models with more demanding input data requirements.

The input data used by the soil carbon models consist of the most important variables affecting carbon cycling in soil (Figure 5). These variables are commonly i) litter production of vegetation representing the quantity and quality of carbon input to soil; ii) temperature and moisture affecting the decomposition rate of organic matter in soil; and iii) soil characteristics, such as texture, affecting stabilization of organic matter in soil and controlling soil moisture conditions. In addition, whenever land-use change is an important factor affecting soil carbon, it is essential to account for land-use change effects in a model-based soil carbon monitoring system.

FIGURE 5

An application of a model-based soil carbon monitoring system consists of four components: i) input information to a soil carbon model; ii) reliability control of modelling soil carbon cycle; iii) simulation of soil carbon cycle; and iv) results of soil carbon budget



In practice, when choosing a soil carbon model to be used in a model-based soil carbon monitoring system, it is usually necessary to make a compromise between the complexity of the soil carbon model and the availability of the input data (Peltoniemi *et al.*, 2007). The input data required by the complex models may not be available and, for this reason, it may be necessary to use a simpler model. Still, to be useful, the simple model must account for the heterogeneity of conditions in the region of application adequately and be able to describe the effects of the most important factors affecting soil carbon. Only then can the results of the model-based soil carbon monitoring system be reliable and the system able to capture the basic variability of soil carbon pools and the main trends of change in the pools.

An important step in applying a model-based soil carbon monitoring system is an evaluation of the reliability of the results (Figure 5). Information on reliability can be obtained by comparing the results given by the system with measured data. Useful measurements to be used in such a reliability evaluation (including systematic and random error) include data on soil carbon pools, soil carbon changes and decomposition rate of litter or soil carbon.

If it appears that the results of the model-based soil carbon monitoring system deviate from the measurements, the measurements can be used to improve the monitoring system. The data can be used to recalibrate the system or even to modify the structure of the system to make it more suitable for the particular application.

The reliability of results obtained using a model-based soil carbon monitoring system can be estimated in a statistical sense at the scale of the application (landscape, country) provided that uncertainty about the input data to the soil carbon model and the parameter values of the soil carbon model are known. Unfortunately, little attention has been paid to statistical uncertainty about the parameter values of soil carbon models when these models have been developed. Consequently, statistical uncertainty estimates are not available for the parameter values of most soil carbon models. In the absence of the statistical uncertainty estimates, it is still possible to analyse the sensitivity of the results of a soil carbon model to changes in the parameter values. However, it is then not possible to estimate the reliability of the results in a statistical way. When statistical uncertainty estimates are available for the parameter values of a soil carbon model, it is possible to give statistical uncertainty estimates for the results of the model, provided that reliable uncertainty estimates are also available for the input data to this model.

In conclusion, the components of a model-based soil carbon monitoring systems exist and these systems provide a feasible and practicable means to monitor soil carbon. Consequently, model-based systems provide a viable alternative or complement for surveys to monitor soil carbon.

PRACTICAL APPLICATION OF A MODEL-BASED SOIL CARBON MONITORING SYSTEM

In order to apply in practice a model-based soil carbon monitoring system on a national or regional (subnational) scale, it is first necessary to form an overall picture of the task. This involves i) gathering general information about the region in relevant aspects such as vegetation, climate, natural disturbances and management of ecosystems; ii) finding out the availability of input information to the model-based soil carbon monitoring system; iii) deciding upon the time period that the calculations will cover; and iv) finding out the availability of information to test the validity of the system.

After an overall picture has been gained, application of the model-based soil carbon monitoring system can be divided into the following practical steps:

- 1) choice of the soil carbon model to be used
- 2) reliability control: evaluation and possible improvement of the soil carbon model to be used in the application

Steps 1 and 2 result in a suitable soil carbon model for the application.

Deciding or bringing together

- 3) spatial (geographic) calculation units
- 4) litter input data (quantity and quality)
- 5) climate data
- 6) land-use change data

Steps 3 to 6 result in input data by the spatial (geographic) calculation unit of the application.

- 7) determination of initial soil carbon pools to be used in the calculations
- 8) simulation of soil carbon cycling in the region of the application over the study period

Steps 7 and 8 represent the actual soil carbon calculations and give results of the soil carbon budget, namely the pool of soil C, changes in the pool of soil carbon over time and emissions of carbon dioxide from the soil.