Prediction of the soil organic carbon content at micro-, meso- and macroscales by digital terrain modelling

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Abstract

Estimation of the carbon sink capacity of soils for different scales of assessment is an urgent problem. Since the spatial distribution of the soil organic carbon (SOC) is affected by topography, it is logical to utilise digital terrain modelling (DTM) to predict a spatial distribution of current levels of the SOC content and thereby assess the potential capacity of soils to sequester additional carbon. A DTM-based concept of accumulation, transit and dissipation zones of the landsurface can be applied to provide this prediction, and to upscale systematically the prediction from micro- (field) to meso- (regional) to macro- (national) scales. Objective of this work was to develop a DTM-based method for prediction of the spatial distribution of the SOC at micro-, meso- and macroscales. Three areas within the Black Soils Zone of the Canadian prairies were selected for the study: (1) the Miniota Precision Agriculture Research Site (microscale), (2) a part of the southern Manitoba (mesoscale), and (3) the provinces of Alberta, Saskatchewan and Manitoba (macroscale). Digital elevation models (DEMs) of these areas and selected soil information were used as initial data. We derived digital models of horizontal and vertical curvatures from the DEMs. Then, maps of accumulation, transit and dissipation zones were obtained by combination of data on horizontal and vertical curvatures. Relationships between the SOC content of the A horizon and accumulation, transit and dissipation zones were found for the Miniota site. To carry out the scaling-up procedure, the microscale relations between the SOC content of the A horizon and microtopography were extrapolated to meso- and macrotopography of broader ecological districts with similar soils, parent materials and landforms. Then, we used maps of accumulation, transit and dissipation zones to produce predictive maps of the SOC content of the A horizon at three different scales. The method developed can provide an objective and replicable prediction for the SOC content at different scales, and may be linked with models for prediction of soil carbon sink, dynamics of the soil organic matter, and the soil inorganic carbon.

Keywords: digital terrain modelling, soil organic carbon, prediction, upscaling

Introduction

Estimation of the carbon sink capacity of soils for different scales of assessment is an urgent problem (Lal *et al*., 1997; Houghton *et al*., 1998). The carbon sink capacity is related to the current levels of the soil organic carbon (SOC). At the same time, the spatial distribution of the SOC is affected by topography. This resulted from a dependence of the SOC content on the spatial differentiation of organic matter accumulation and moistening according to landsurface morphology (Kovda, 1973; Moore *et al*., 1993; Arrouays *et al*., 1998; Bergstrom *et al*., 2001). So, it is logical to apply methods of the digital terrain modelling (DTM) (Moore *et al*., 1991; Shary *et al*., 1991; Florinsky, 1998a) to predict current levels of the SOC content and thereby assess the potential capacity of soils to sequester additional carbon.

A DTM-based concept of accumulation, transit and dissipation zones of the landsurface (Shary *et al*., 1991; Florinsky, 2000; Florinsky *et al*., 2000) can be applied to carry out this prediction at a microscale (Florinsky *et al*., 2002). The use of the concept in predictions of soil properties includes (a) determination of average values of a soil property within accumulation, transit and dissipation zones (depressions, midslopes and crests, correspondingly) of a plot area, and (b) extrapolation of these values to accumulation, transit and dissipation zones of a broader territory marked by similar soil, hydrologic, geomorphic and climate conditions. Prediction results can be represented as a map including polygons of accumulation, transit and dissipation zones characterised by particular values of the soil property under study.

Methods of the digital terrain modelling are scale independent, so the concept of accumulation, transit and dissipation zones can be used at any scale. Shape, boundaries, and sizes of accumulation, transit and dissipation polygons are changed in upscale passing from one scale to another, that is, in upscale going from one resolution of DTMs to another because of generalisation of spatially distributed topographic data. This automatically leads to similar generalisation of the geometry of a related predictive map of the soil property.

Upscale prediction of the soil carbon sink and related soil processes should be based on data generalisation rather than on mechanical summation of areas, amounts, etc. This is due to the fact that the ability to reveal spatial regularities of phenomena and processes under study is unique to map generalisation (Muehrcke, 1972; Jenks, 1981). In this connection, it is reasonable to use the concept of accumulation, transit and dissipation zones in upscale predicting the SOC content. Among other factors, this is because application of the concept solves a question about generalisation rules in this case.

Objective of this study was to develop a DTM-based method to systematically upscale the prediction of the SOC content from micro- (field) to meso- (regional) to macro- (national) scales.

Study areas

Three areas were selected for the study within the Black Soils Zone of the Canadian prairies (Figure 1). For microscale prediction, we used the Miniota Precision Agriculture Research Site located approximately 280 km west of the city of Winnipeg, Manitoba, Canada. The site measures 809×820 m. For mesoscale prediction, we selected a part of the southern Manitoba between 49° and 50° N, and 98° and 100° W. The area measures 146×111 km. For macroscale prediction, we used a territory of the provinces of Alberta, Saskatchewan and Manitoba. The area measures approximately 2000×1225 km.

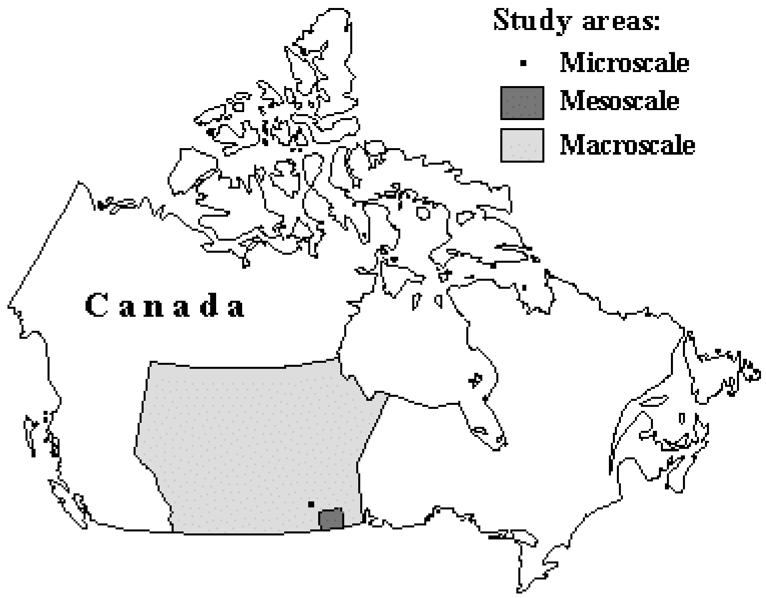

Figure 1 Geographical location of the study areas.

The Canadian prairies are the northern extension of open grasslands in the Great Plains of North America. The area has a continental climate, subhumid to semiarid with long cold winter, short hot summer, low levels of precipitation, and high evaporation. Mean winter temperature is -10°C, and mean summer temperature is 15°C. Mean annual precipitation ranges from 250 mm in Saskatchewan and Alberta to 700 mm in Manitoba (Ecological Stratification Working Group, 1995).

The prairies are largely glaciated with Cretaceous shales underlying the area or at the surface. There are nearly level to rolling landscapes consisting of glacial moraines and lacustrine deposits. Black Chernozems with groves of trembling aspen, balsam poplar, and intermittent grassland are typical in the north of the prairies. The driest shortgrass areas with Brown Chernozems occur in Southwestern Saskatchewan and Southeastern Alberta. The moist mixed grasslands and Dark Brown Chernozems are observed in other parts of the prairies (Ecological Stratification Working Group, 1995). Agriculture is the dominant land use in the prairies.

Materials and Methods

For the microscale, an irregular digital elevation model (DEM) based on 4211 points was constructed with a GPS technique (Florinsky *et al.*, 2002). We converted the irregular DEM into a regular one by the Delaunay triangulation and a piecewise smooth interpolation. The grid interval of the regular DEM was 15 m. For mesoscale, we used a DEM derived from the Canadian Digital Elevation Data files based on the 62 G topographic chart at the 1:250,000 scale (Centre for Topographic Information, 1997). The DEM of the study area included 16,352 points, the grid size was 1000 m. For macroscale, we used a DEM derived from the 5-arc-minute gridded global DEM produced by the NOAA's World Data Center for Marine Geology and Geophysics (NOAA, 1988). The DEM of the study area included 50,625 points and was given by a spheroidal trapezoidal grid with the grid size of 5 arc-minutes (6,098×9,268 m at 49°N and 4,650×9,284 m at 60°N).

The concept of topographically expressed accumulation, transition and dissipation zones (Shary *et al*., 1991; Florinsky, 2000; Florinsky *et al*., 2000) is based on the following assumptions. Gravity-driven overland and intrasoil transport can be interpreted in terms of divergence or convergence, and deceleration or acceleration of flows (Shary, 1995). Flow tends to accelerate when vertical landsurface curvature (k_v) is positive, and to decelerate when k_v is negative. Flow diverges when horizontal landsurface curvature (k_h) is positive, and converges when k_h<0. Flow convergence and deceleration result in accumulation of substances in soils. At different scales, the spatial distribution of accumulated substances can depend on the distribution of the following landforms: (a) landforms marked both by convergence and deceleration of flow, that is, both by k_h<0 and by k_v<0 (accumulation zones); (b) landforms offering both divergence and acceleration of flow, that is, both k_h>0 and k_v>0 (dissipation zones); and (c) landforms that are free of a concurrent action of flow convergence and deceleration as well as divergence and acceleration, that is, values of k_h and k_v have different signs or are zero (transition zones). The concept allows one to reveal depressions, midslopes and crests (topographically expressed accumulation, transit and dissipation zones) using digital models of k_h and k_v derived from a DEM.

For the micro- and mesoscales, we derived digital models of k_h and k_v from the DEMs by the method of Evans (1980). For the macroscale, we derived digital models of k_h and k_v from the DEM by the method of Florinsky (1998b). Derivation of all k_h and k_v digital models was carried out with LandLord software (Florinsky *et al*., 1995). Maps of accumulation, transit and dissipation zones (Figures 2a, 3a and 4a) were obtained by combination of k_h and k_v data.

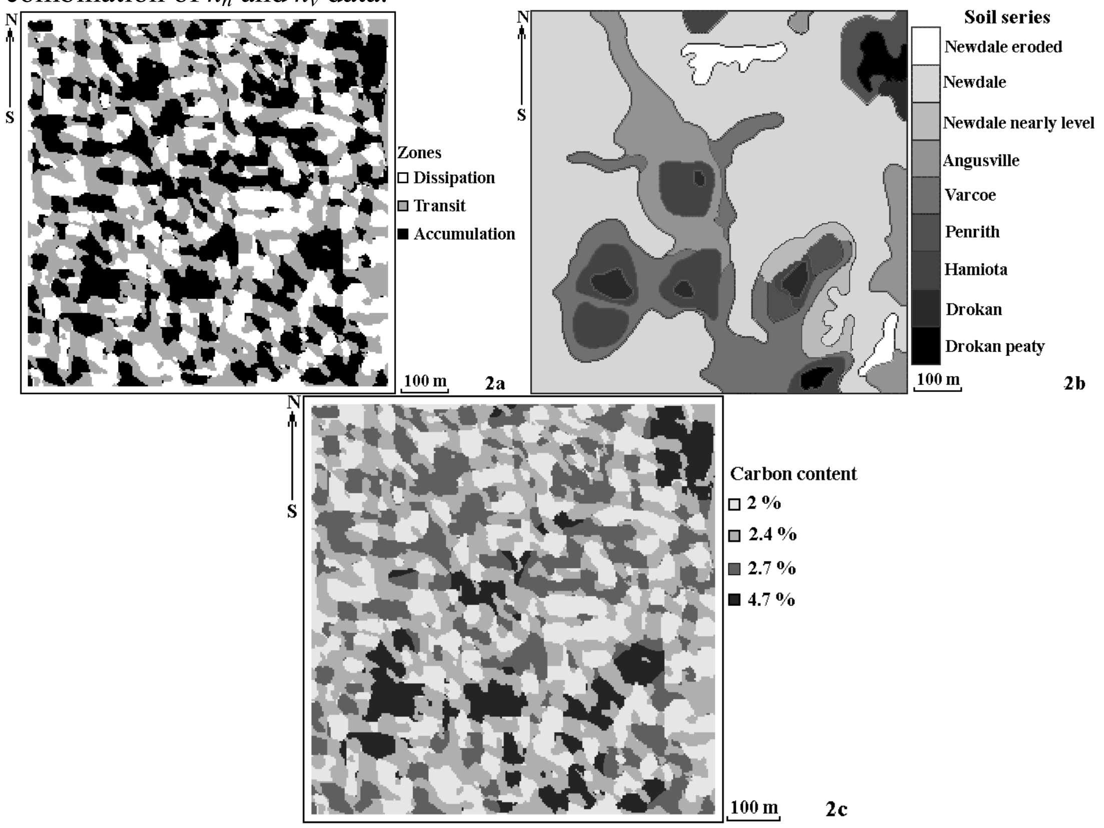

Figure 2 Microscale – the Miniota Site.

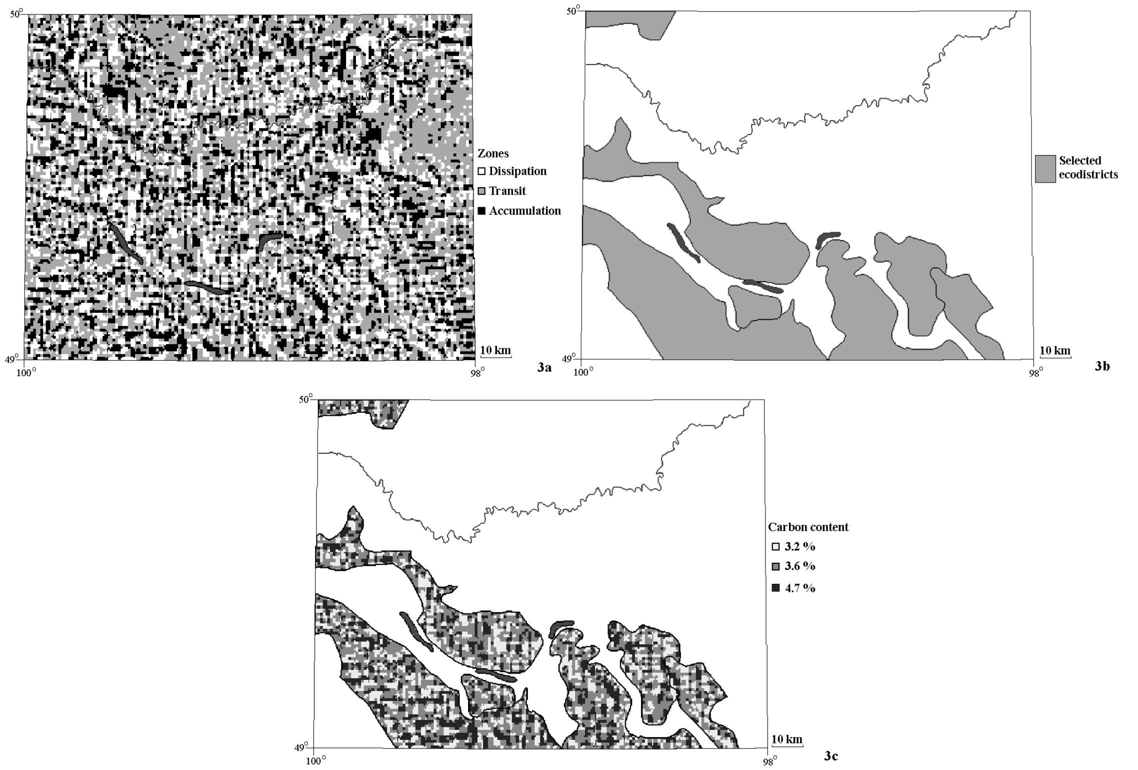

Figure 3 Mesoscale – the Southern Manitoba.

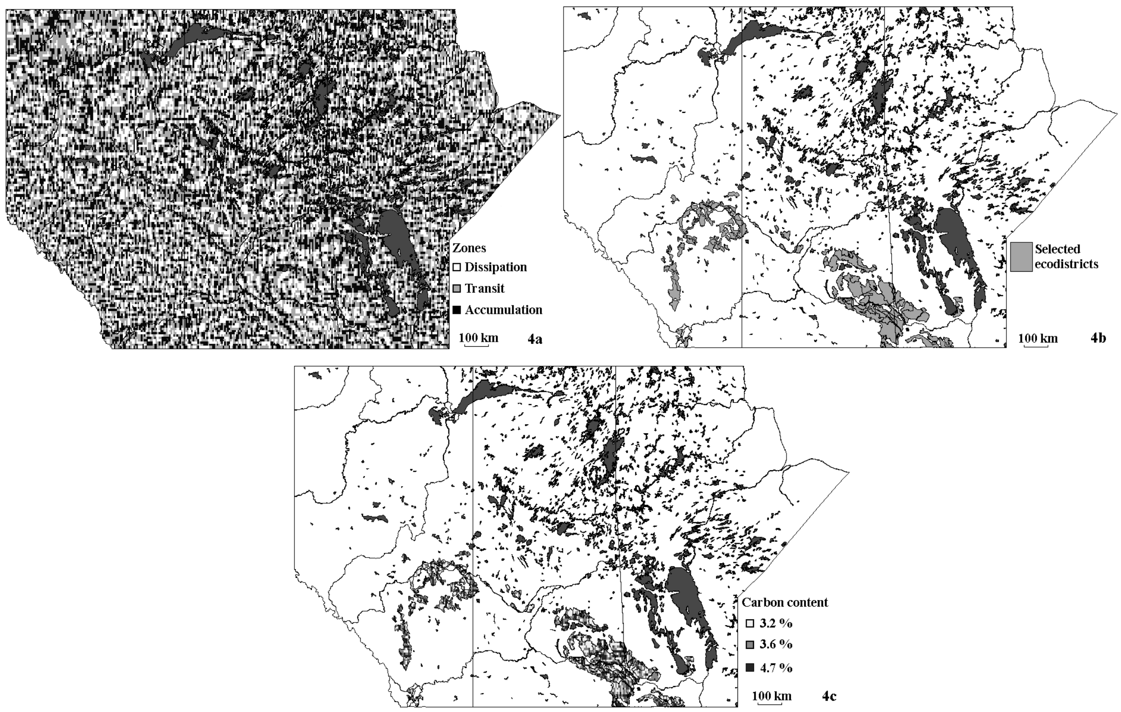

Figure 4 Macroscale – Alberta, Saskatchewan and Manitoba.

Relationships between the SOC content of the A horizon and accumulation, transit and dissipation zones were previously found for the Miniota site (Florinsky *et al.*, 2002). These relationships were used to produce a predictive map of the SOC content of the A horizon at the microscale (Figure 2c). The Miniota Site includes soils typical of Black Chernozems (Figure 2b). To carry out the scaling-up procedure, these microscale relationships were extrapolated to the meso- and macrotopography of broader ecological districts with similar soils (Black Chernozems), parent materials (morainal) and landforms (hummocky, undulating and knoll and kettle forms with slopes of 1–9%) (Figures 3b and 4b). These ecological districts were identified using the National Soil DataBase of the Canadian Soil Information System (MacDonald and Valentine, 1992).

To produce predictive maps of the SOC content of the A horizon (Figures 2c, 3c and 4c), we linked data on accumulation, transit and dissipation zones (Figures 2a, 3a and 4a) and soil data (Figures 2b, 3b and 4b) using ArcView GIS.

Results and Discussion

Maps of accumulation, transit and dissipation zones represent the spatial distribution of microdepressions, microslopes and microcrests within the Miniota site (Figure 2a), mesodepressions, mesoslopes and mesocrests within the Southern Manitoba (Figure 3a), and macrodepressions, macroslopes and macrocrests within the provinces of Alberta, Saskatchewan and Manitoba (Figure 4a). Predictive maps identify the spatial distribution of polygons marked by different average values of the SOC content of the A horizon at three various scales (Figures 2c, 3c and 4c).

In this study, we analysed the SOC content at the A horizon only. However, it is possible to apply the same methodology to predict the SOC content of the solum, if quantitative relationships between this soil property and accumulation, transit and dissipation zones are known. Also, it is possible to use predictive maps produced for estimation of the SOC amounts stored at the A horizon (or the solum) within selected areas.

The DTM-based method developed may be linked with expert models for prediction of soil carbon sink capacity (Fan *et al*., 1998; McConkey *et al*., 1999). Current expert models consider soil and management information but lack appropriately scaled, relative topographic data and a systematic linkage to actual landscapes. The flexibility of this DTM technique can remedy this problem.

The method proposed may be also linked with mathematical models for estimation of a current level and dynamics of the soil organic matter (Smith *et al*., 1997). In this case, initial values of the SOC content in accumulation, transit and dissipation zones may be obtained by mathematical estimation rather than by field survey and laboratory measurements.

In assessing soil carbon sink capacity, it is important to take into account soil inorganic carbon (Ryskov *et al*., 1993; Khokhlova *et al*., 1997). Since spatial distribution of soil carbonates is also affected by topography (Florinsky and Arlashina, 1998; Florinsky *et al*., 2002), it would be possible to apply the method proposed for prediction of the spatial distribution of the soil inorganic carbon at different scales.

The method developed can provide an objective and replicable prediction for the SOC content, considering the relative adequacy of soil data available for broad areas as compared to topographic data. Testing and validation of this approach and the establishment of confidence intervals for the SOC content predictions are critical research requirements that would greatly enhance the capability of the method for evaluating alternative land management impacts on the SOC content in soils as well as predicting probable impacts of pending climate change scenarios on grassland ecosystems.

Conclusions

The DTM-based method for prediction of the SOC content at micro-, meso- and macroscales was developed. The method was applied to predict the SOC content of the A horizon within the Black Chernozems zone of the Canadian prairies at three scales.

The quantitative DTM-based method is an objective approach to systematically upscale the prediction of the SOC content from micro- (field) to meso- (regional) to macro- (national) scales. The method is flexible and can easily be applied to any landscape. The method developed may be linked with models for prediction of soil carbon sink, dynamics of the soil organic matter, and the soil inorganic carbon.

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