Prediction of soil 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 soil organic carbon (SOC) is strongly affected by topography, it is logical to utilise digital terrain modelling (DTM) to predict current levels of SOC and thereby assess the potential capacity of soils to sequester additional carbon. A recently developed DTM-based concept of accumulation, transit and dissipation zones of the land surface can be applied to carry out this prediction. Generalization techniques of digital terrain modelling can be used to systematically upscale predictions of SOC from micro- (field) to meso- (regional) to macro- (national) scales. Objective of this work was to illustrate a DTM-based approach for prediction of SOC content at micro-, meso- and macroscales. Three areas were selected for the study: (1) Microscale prediction – the Miniota Precision Agriculture Research Site, Manitoba; (2) Mesoscale prediction – an area of Southern Manitoba between US border and the cities of Brandon and Portage La Prairie; and (3) Macroscale prediction – a portion of Alberta, Saskatchewan and Manitoba. Relationships between SOC content and accumulation, transit and dissipation zones were previously found for the Miniota site including soils typical of Black Chernozems. To illustrate the scaling-up procedure to the meso- and macroscales, the results of this microscale prediction where extrapolated to broader ecological districts and regions with similar parent materials, land forms, and Chernozemic soils. Prediction maps of SOC content were developed at three different scales based on the spatial distribution of three landform elements within typical areas of the Black Soils Zone of the Canadian prairies. The methodology can provide an objective and replicable prediction for SOC, considering the relative adequacy of soil data available for broad areas as compared to topographic data. This DTM-based methodology can be linked with other expert models for a more quantitative prediction of SOC sink capacity.

INTRODUCTION

Estimation of the carbon sink capacity of soils for different scales of assessment is a unique and urgent problem (Fan et al., 1998). The carbon sink capacity is directly related to the current levels of organic carbon in soils. Since the spatial distribution of soil organic carbon (SOC) is strongly affected by topography, it is logical to utilise digital terrain modelling (DTM) (Moore et al., 1991; Florinsky, 1998) to predict current levels of SOC and thereby assess the potential capacity of soils to sequester additional carbon. A recently developed DTM-based concept of accumulation, transit and dissipation zones of the land surface (Florinsky, 2000; Florinsky et al., 2000) can be applied to carry out this prediction (Florinsky et al., 1999). Generalization techniques of digital terrain modelling (Florinsky, 1991) can be used to systematically upscale predictions of SOC from micro- (field) to meso- (regional) to macro- (national) scales. Objective

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of this study is to illustrate a DTM-based approach for prediction of SOC content at micro-, meso- and macroscales.

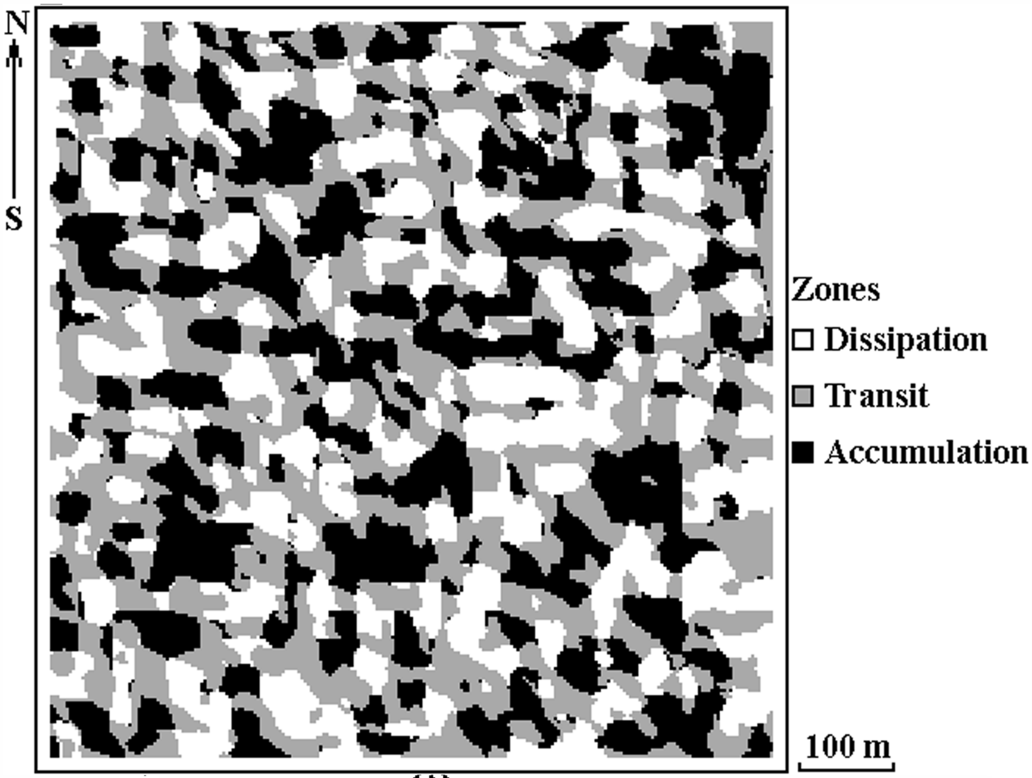
MATERIALS AND METHODS

Three areas were selected for the study. For microscale prediction, we used a site located 20 km north-east of the village of Miniota, Manitoba, at the Miniota Precision Agriculture Research Site at Bell Farms (Fig. 1). The site measures 809×820 m. For mesoscale prediction, we selected a part of the Southern Manitoba between US border and the cities of Brandon and Portage La Prairie (Fig. 2). The area measures 2×1° (146×111 km). For macroscale prediction, we used a territory of Alberta, Saskatchewan and Manitoba (Fig. 3). The area measures 31×11° (approximately 2000×1225 km).

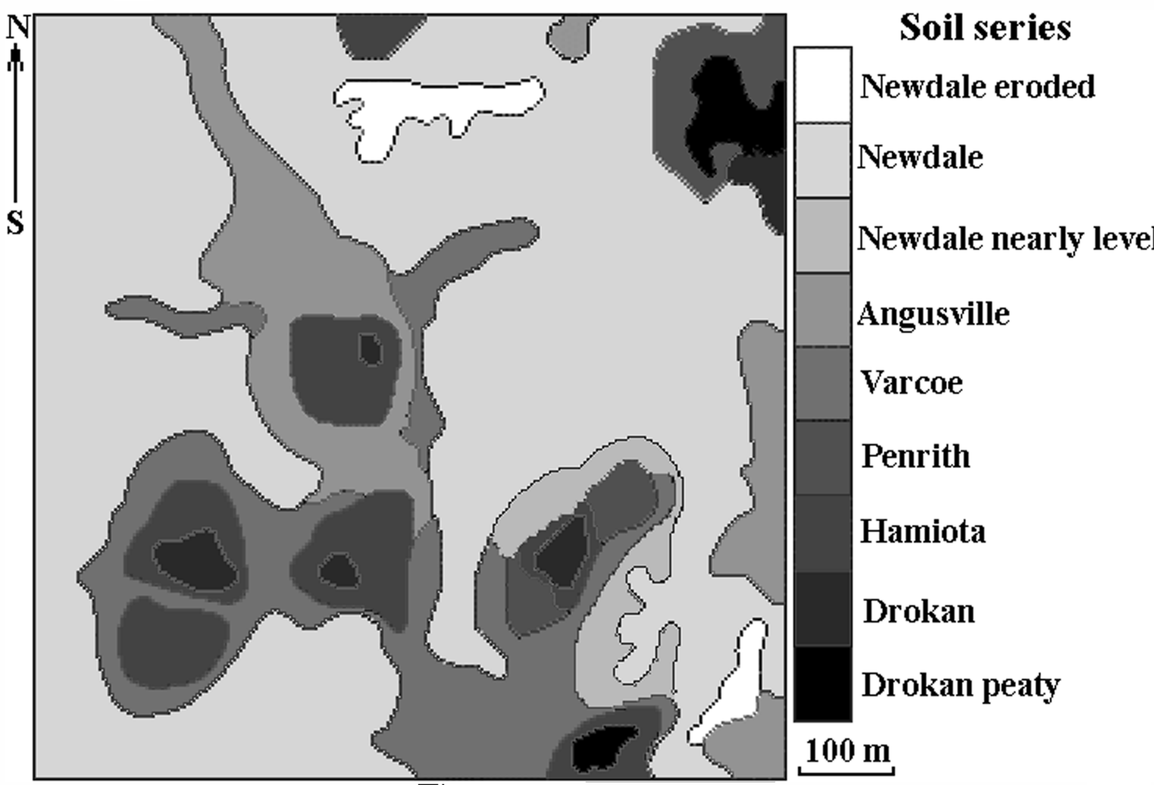
For the microscale, an irregular digital elevation model (DEM) based on 4211 points was constructed with a GPS technique. We converted the irregular DEM into a regular one by the Delaunay triangulation and a piecewise smooth interpolation. The grid interval of the regular DEM was 15 m. For mesoscale, we used a DEM derived from the Canadian Digital Elevation Data based on National Topographic System maps at the 1:250,000 scale (62 G topographic chart) produced by the Centre for Topographic Information, Natural Resources Canada. The DEM of the study area included 16,352 points, the grid size was 1000 m. For mesoscale, 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 (6098×9268 m at 49° and 4650×9284 m at 60°).

The concept of topographically expressed accumulation, transition and dissipation zones (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


N
S
Zones
Dissipation
Transit
Accumulation
100 m

(A)


N
S
Soil series
Newdale eroded
Newdale
Newdale nearly level
Angusville
Varcoe
Penrith
Hamiota
Drokan
Drokan peaty
100 m

(B)

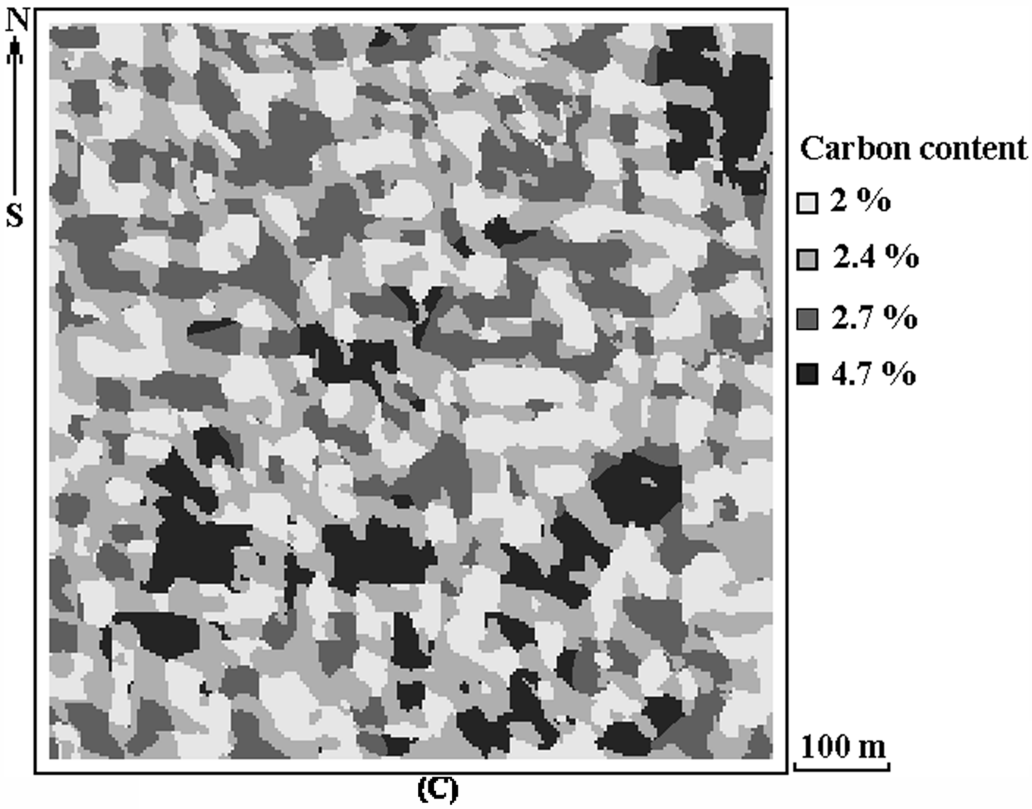


Fig. 1. Microscale – Miniota Site: (a) Accumulation, transit and dissipation zones, (b) Soil series, (c) Prediction of the spatial distribution of carbon content.

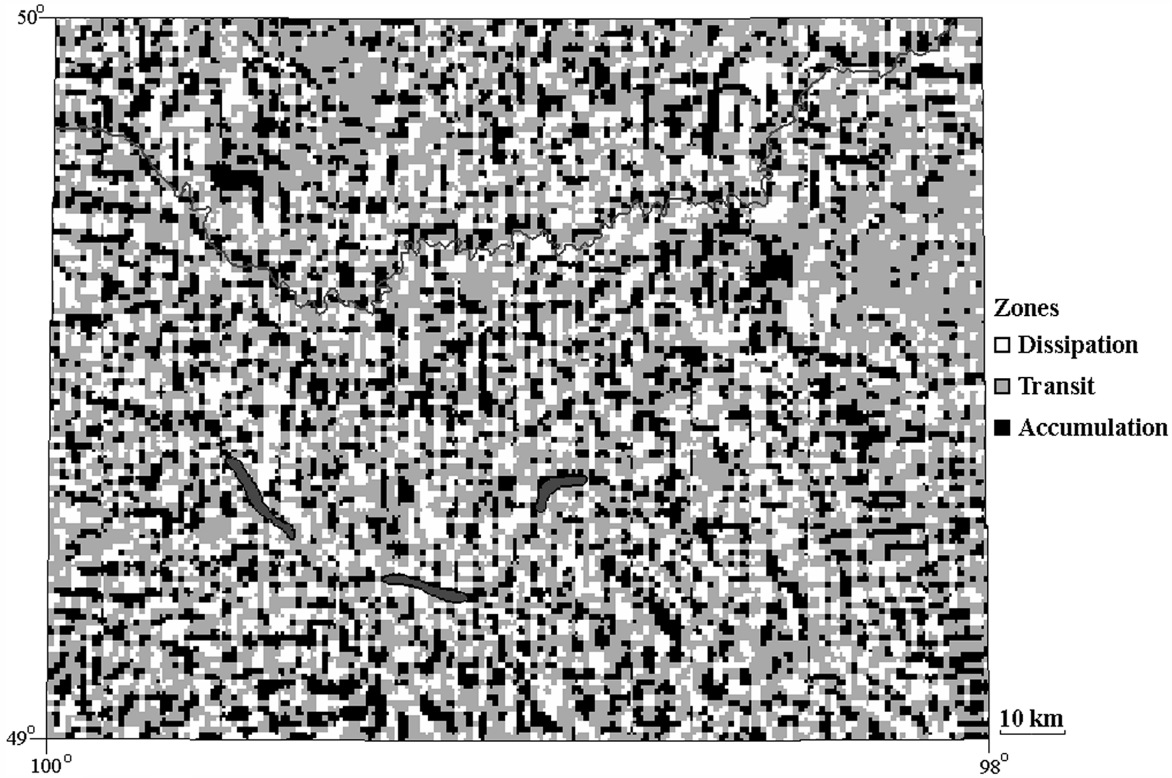
out with LandLord software (Florinsky et al., 1995). Maps of accumulation, transit and dissipation zones (Figs. 1a, 2a and 3a) were obtained by combination of k_h and k_v data.

Relationships between soil carbon content and accumulation, transit and dissipation zones were previously found for Miniota site (Florinsky et al., 1999). These relationships are displayed on the prediction map of soil carbon content at the microscale (Fig. 1c). The Miniota Site includes soils typical of Black Chernozems (Fig. 1b). To illustrate the scaling-up procedure to the meso- and macroscales, the results of this microscale prediction were extrapolated to broader ecological districts and regions with similar parent materials, land forms, and Chernozemic soils (Figs. 2b and 3b) (Canadian Soil Information System).

To produce prediction maps of the spatial distribution of carbon content (Figs. 1c, 2c and 3c), we linked data on accumulation, transit and dissipation zones (Figs. 1a, 2a and 3a) and soil data (Figs. 1b, 2b and 3b) using ArcView GIS.

RESULTS AND DISCUSSION

Prediction maps of SOC content were developed at three different scales (Figs. 1c, 2c and 3c) based on the spatial distribution of three landform elements within typical areas of the Black



50°
49°
100°
98°
Zones
Dissipation
Transit
Accumulation
10 km

(A)

50°
49°
100°
98°
Selected ecodistricts
10 km

(B)

(C)

Fig. 2. Mesoscale – Southern Manitoba (62 G topographic chart): (a) Accumulation, transit and dissipation zones, (b) Ecodistricts with dominant soils of Black Chernozems, morainal parent material, hummocky, undulating and knoll and kettle surface forms, and slopes of 1–9 %, (c) Prediction of the spatial distribution of carbon content.

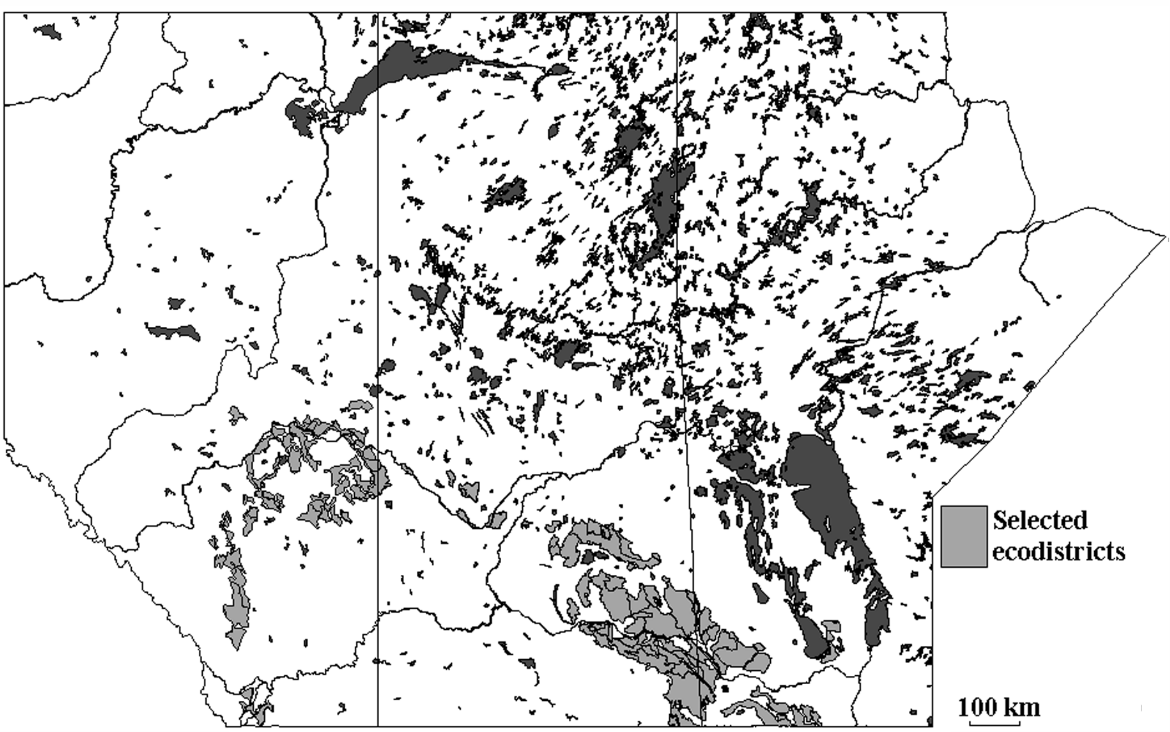
Soils Zone of the Canadian prairies. This methodology can provide an objective and replicable prediction for SOC, considering the relative adequacy of soil data available for broad areas as compared to topographic data.

The DTM-based method developed and the results obtained can be linked with some expert models (e.g., McConkey et al., 1999) for quantitative prediction of soil carbon sink capacity. 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.

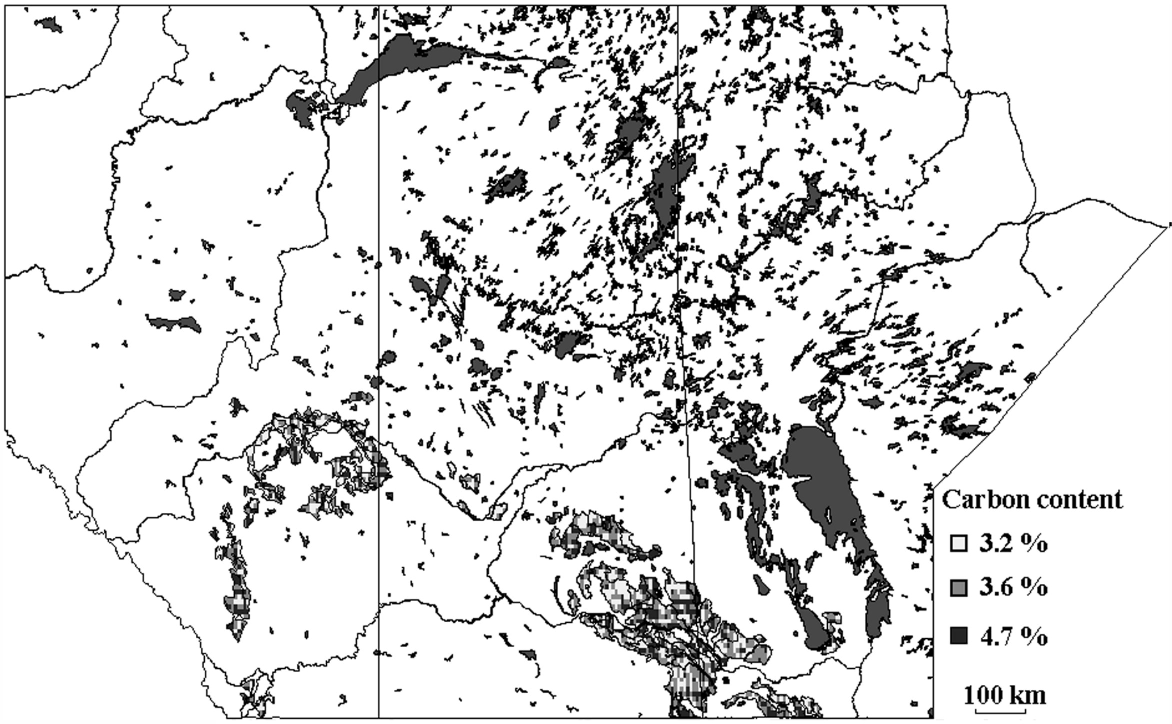
Testing and validation of this approach and the establishment of confidence intervals for SOC predictions, are critical research requirements that would greatly enhance the capability of this methodology for evaluating alternative land management impacts on SOC in soils as well as predicting probable impacts of pending climate change scenarios on prairie agriculture.


Zones
Dissipation
Transit
Accumulation
100 km

(A)


Selected ecodistricts
100 km

(B)



(C)

Fig. 3. Macroscale – Alberta, Saskatchewan and Manitoba: (a) Accumulation, transit and dissipation zones, (b) Ecodistricts with dominant soils of Black Chernozems marked by morainal parent material, hummocky, undulating and knoll and kettle surface forms, and slopes of 1–9 %, (c) Prediction of the spatial distribution of carbon content.

CONCLUSIONS

The DTM-based method for prediction of soil carbon content at micro-, meso- and macroscales was developed. The method was successfully applied to predict soil carbon content within the Black Chernozems zone of the Canadian prairies at three different scales. The method developed can be linked with an expert model for quantitative prediction of soil carbon sink.

This mathematically based DTM methodology illustrates an objective approach for predicting current SOC levels at micro-, meso- and macroscales. The methodology is flexible and can easily be applied to any landscape with topographic data and readily linked with expert system models to statistically quantify predictions of SOC sink capacity.

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