Modelling of carbon flux in grassland ecosystems in Ukraine

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Abstract
For the better understanding of the dynamics of soil organic matter (SOM) in the natural grassland ecosystem, a simple process-based model is proposed and validated using the values of whole soil respiration (WR) and the microbial soil respiration (MR) measured in Chernozem and Kastanozem soils in Ukraine. Measured input values for the validation were light fraction C (LFC), clay content and plant biomass including shoot and root biomass, daily soil temperature and volumetric water content at 15 cm depth and daily air temperature and precipitation. As an influx of C to the soils, NPP was calculated by Chikugo model using annual temperature and precipitation. For the measured whole soil respiration rate, estimated WR value without root respiration showed close fitting under the drier conditions, probably because of the restricted root respiration. Under the wetter conditions, c.a. 50% of the WR would be attributed to root respiration. For the measured microbial respiration rate, the model estimation fitted well with measured values. These results suggested that the proposed model successfully simulated the decomposition processes in the natural grassland ecosystems.

Key Words
Modelling, soil organic matter dynamics, soil respiration, natural grassland ecosystems.

Introduction

Soil respiration, i.e. carbon dioxide (CO_2) emission from soils has been studied widely, as a major process of carbon dynamics between atmospheric carbon (780 Pg C) and soil organic carbon (1550 Pg C). In the Eurasian steppe, Chernozem and Kastanozem soils, which develop under short- or tall-grass steppe vegetation, spread out from areas near the Black Sea to northern Kazakhstan in a belt. These soils are important not only because of their high productivity of crops but also of their high accumulation of carbon. Though detailed studies on SOM dynamics are required in urgent, little is known about the relationship between in situ soil respiration, net primary productivity, soil temperature and moisture content, and soil properties in this region. So the objectives of this study are (i) to offer a process-based model to simulate the SOM dynamics using measurable soil properties, and (ii) to validate the model by in situ soil respiration rates measured in 2 grassland sites in Ukraine.

Methods

Theory of Carbon Flux Model

According to the relationship between the potentially mineralizable OM and soil properties in Kadono *et al.* (2008), the following SOM dynamics model was proposed (Figure 1). In this model, all C fluxes are calculated in daily step. Since SOM is supplied by plant material, estimation of net primary productivity (NPP) is required for the model. NPP is the difference between whole plant photosynthesis (gross primary productivity; GPP) and plant respiration annually. In natural ecosystems, the annual NPP can be estimated by Chikugo model (Uchijima and Seino, 1985), using annual air temperature and precipitation. Daily NPP is estimated by the proportional distribution of the annual NPP to daily air temperature, if it is higher than 4 °C. The calculated daily NPP is allocated to shoot, root in 0-10 cm depth and root in 10-50 cm depth, referred to as NPP_{shoot} ((1) in Figure 1, NPP_{root} in 0-10 cm (2) and NPP_{root} in 10-50 cm (3). Plants use the NPP for growth of the shoot and root biomass and exudates from root, such as mucilage, organic acid and polysaccharide. The NPP_{shoot} and a portion of NPP_{root} in 0-10 cm (NPP_{root} – exudates in 0-10 cm) are added to the potentially mineralizable C (PMC) pool annually, corresponding to (1) and (5), respectively in Figure 1. In this model, the exudates are assumed to be decomposed immediately (6) (Luo *et al.* 2001).

The PMC is calculated by the regression equation obtained in Kadono *et al.* (2008), using light fraction carbon (LFC; < 1.60 g/cm^3) and clay content. This PMC pool is decomposed at the rate constant (k), which is dependent on soil temperature and moisture. The temperature dependency of the rate constant is assumed to follow the Arrhenius model, and usually set at Q_{10} (15-25 °C) of 2.0, or apparent activation energy of 49.5

kJ/mol. The dependency of the rate constant on soil moisture is assumed to follow that in the Rothamsted Carbon model (Coleman and Jenkinson 1996). They calculated the moisture factor, which is multiplied to the rate constant and ranges from 0.2 to 1.0, according to the water deficiency. In this model, the moisture factor was calculated according to the proportional distribution between 1.0 at maximum volumetric water content (VWC) and 0.2 at minimum VWC recorded in the soil. Therefore, the daily rate constants are calculated by daily soil temperature and moisture data, and at the daily rate constant, PMC is decomposed in daily time step (4).

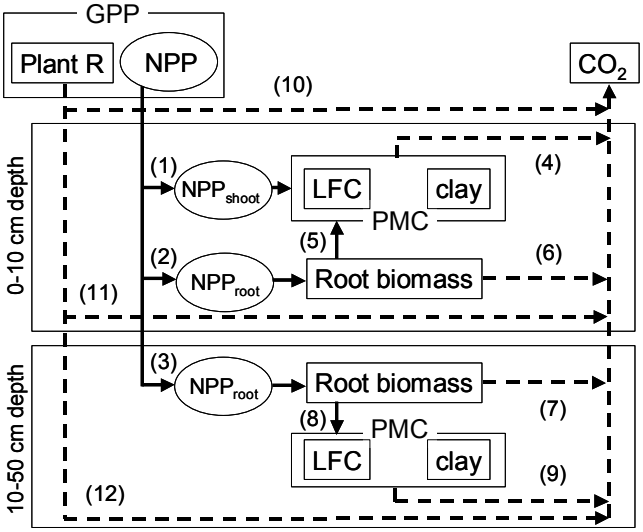

Figure 1. Soil organic matter dynamics model assumed. GPP: gross primary productivity, Plant R: plant autotrophic respiration, NPP: net primary productivity, NPP_{shoot}: NPP allocated to shoot biomass, NPP_{root}: NPP allocated to root biomass, LFC: light fraction (< 1.60 g/cm^3) C, PMC: potentially mineralizable C. Arrows indicate flows of CO_2 (broken line) and organic C (solid line). Numbers indicate the individual flows.

Experimental Sites
Two sites were selected to monitor CO_2 flux and soil temperature and moisture. The measurement of soil respiration was conducted from 2002 to 2004 in the natural grassland sites.

(1) Grakovo Experimental Field (N49° 44', E36° 56', Alt: 154m) is located about 60 km southeast of Kharkov city, northern Ukraine. The meteorological data were assumed same as this city. Mean annual air temperature (MAT) and mean annual precipitation (MAP) were 6.9 ˚C and 536.6 mm, respectively. According to the U.S. Soil Taxonomy, this soil was classified into Pachic Haploxerolls (Soil Survey Staff, 1998). Soil organic carbon accumulation upper 1 m depth in this site is 315 Mg C/ha. Soil texture of the surface layer was classified as LiC.

(2) Askania-Nova Biosphere Reserve (N46° 27', E33° 53', Alt: 27m) is located about 100 km east of Kherson city, southern Ukraine. MAT and MAP were 9.5 ˚C and 386.4 mm, respectively. The virgin fescue-feather grass steppe area has been reserved for more than 100 years. According to the U.S. Soil Taxonomy, this soil was classified into Calcic Haplustolls (Soil Survey Staff, 1998). Soil organic carbon accumulation upper 1 m depth in this site is 150 Mg C/ha. Soil texture of the surface layer was classified as LiC.

Measurement of in situ soil respiration rate for validation of output data of the model
Soil respiration rate was measured several times during growing season by closed-chamber method (Anderson, 1982) using handy type Infra-red CO_2 analyzer (Anagas CD98, Environmental Instruments, Leamington Spa, UK) or CO_2 monitor (GH-250E, Sensonix Japan). The difference in the equipments did not affect the measurement of soil respiration. For the measurement of whole soil respiration (WR) rate, aboveground part of grasses were cut, chambers (φ = 10.5 cm, height = 20 cm) were inserted 5 cm into the soil, and increased CO_2 concentration during 30 minutes were measured after the chamber was sealed. Though diameter and height of chambers used in 2002 were 20.8 cm and 12 cm, respectively, and the chambers were inserted 2 cm in the soils, no difference in WR was observed between the two types of chambers.

In addition to the whole soil respiration, measurement of microbial soil respiration (MR) rate using a trenching technique was conducted in 2002 to 2004 (Grakovo) and in 2003 to 2004 (Askania-Nova), as follows:

After aboveground part of grasses were cut, chambers were inserted 10 cm into the soil, the soils in the chambers were separated from the ground at the depth, and a plastic net was attached to retain the soil on the bottom of each chamber. This treatment was conducted on the first measurement each year. Just before the measurement of CO_2 emission, the bottom of the chamber was covered by plastic bag to exclude CO_2 diffusion from subsurface layers. Therefore, soil respiration emitted from this type of chamber is assumed to be microbial respiration, without plant root respiration and further addition of NPP into soil in each year.

Soil properties and plant biomass
In Grakovo, soil samples were collected at the depth of 0-5, 10-15, 20-25, 30-35, 40-45 and 50-55 cm on May 11, 2003. In the grassland site in Askania-Nova, soils were sampled at the depths of 0-10, 20-30, 40-50, 70-80 and 100-110 cm on Apr. 29, 2004. All soil samples were air-dried and sieved to 2 mm for physicochemical analysis. Contents of light fraction (LF) were determined as follows. Briefly, 10 g aliquots of air-dried soil were dispersed in sodium iodide solution (1.60 g/cm^3) and centrifuged at 2600 *g* (modified from Spycher *et al.* 1983). Material in the supernatant was considered to be LF (mostly partially decomposed plant residues), whereas that in the sediment was HF (more fully-decomposed residues and mineral material). Carbon contents in LF (LFC) were measured by dry combustion with an NC analyzer (Sumika, NC-800-13N). Contents of sand (2-0.02 mm), silt (0.02-0.002 mm) and clay (< 0.002 mm) were measured by sieving and the pipette method (Gee and Bauder, 1986) for surface (0-10) soil samples. Soil bulk density of 100 ml core samples taken at the depths of 0-5, 10-15 and 50-55 cm were measured in 3 replications for each site.

Since coarse (> 2 mm) plant materials are usually not included in the soils after sieving, one of the major differences between in situ soil respiration and in vitro C mineralization is the existence of the larger plant materials in the former measurement. In this study, aboveground (shoot) and belowground (root) biomass in a unit area (15 × 50 cm) was measured. Shoot biomass was collected and weighted after oven drying at 110 ˚C. Root biomass was collected with soils at certain depths, each soil was enclosed in a flexible mesh bag, and the roots were separated from soil by washing the mesh bag in water. After washing, roots and sand remained in the bag were dipped into another bucket of water, and they were separated by floatation of the roots. The roots were oven dried and weighted. This experiment was conducted in 3 and 2 replications in Grakovo and Askania-Nova, respectively, in the summer of 2003. Carbon content in the plant biomass was set at 45% (Kudeyarov and Kurganova, 1998) in this study.

Results and discussion
Validation of the proposed model for whole soil respiration
The estimated whole soil respiration rate without root respiration rate (WR-RR; (4)+(6)+(7) in Figure1) and measured WR are shown in Figure 2. In Grakovo 2002 and in Askania-Nova, estimated values for WR-RR fitted the values of measured WR, while in Grakovo 2003 and 2004, measured WR was more than 2 times higher than the simulated WR-RR. This would be partly due to the large variation of plant respiration, probably caused by the annual precipitation as NPP. Hanson *et al.* (2000) reported root respiration usually accounts for c.a. 50% of whole soil respiration, it varied 10% to 90% among the previous studies.

Validation of the proposed model for microbial soil respiration
The measured microbial soil respiration (MR) includes the CO_2 flux of (4), and all the separated root biomass are assumed to be entered to PMC (Figure 1). The initial pool of PMC for each year was assumed to be 870 and 881 g C m^{-2} in Grakovo and Askania-Nova, respectively. The estimated and measured MR are shown in Figure 3. Estimated annual MR for 2002, 2003 and 2004 was 318, 326 and 397 g C/m^2/y, respectively in Grakovo, while in Askania-Nova 338, 351 and 375 g C/m^2/y, respectively. Except for the 2 measured values in 2003, estimated MR values well simulated the measured MR in Grakovo.

Conclusion
For the better understanding of SOM dynamics in the Eurasian steppe, a model using measurable soil properties was provided and validated for the whole soil respiration (WR) and the microbial soil respiration (MR) measured in Chernozem and Kastanozem soils under the natural grassland ecosystems. Measured input values for the validation were light fraction C (LFC), clay content and plant biomass including shoot and

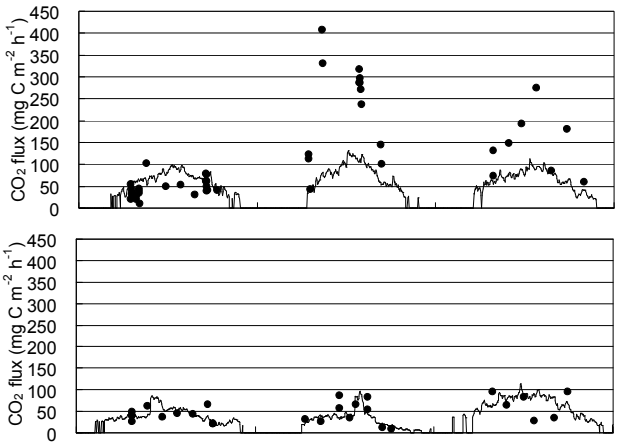

Figure 2. Measured in situ whole soil respiration (circle) and estimated whole soil respiration without root respiration (line) in Grakovo (upper) and in Askania-Nova (lower).

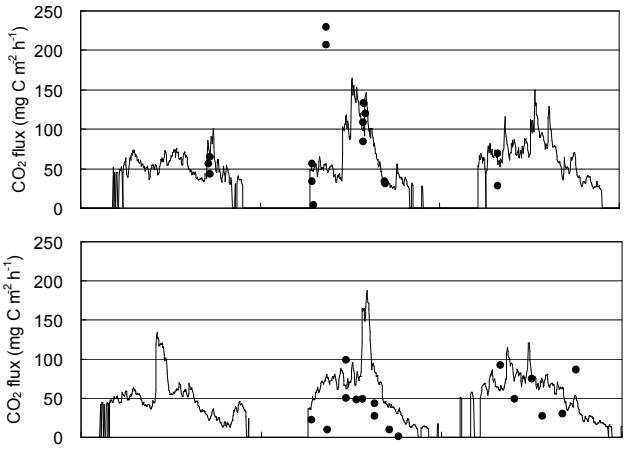

Figure 3. Measured in situ microbial soil respiration (circle) and estimated microbial soil respiration (line) in Grakovo (upper) and in Askania-Nova (lower).

root biomass, daily soil temperature and volumetric water content at 15 cm depth and daily air temperature and precipitation. As an influx of C to the soils, NPP was calculated by Chikugo model using annual temperature and precipitation. For the measured whole soil respiration rate, estimated WR value without root respiration showed close fitting under the drier conditions, probably because of the restricted root respiration. Under the wetter conditions, c.a. 50% of the WR would be attributed to root respiration. For the measured microbial respiration rate, the model estimation fitted well with measured values. These results suggested that the proposed model successfully simulated the decomposition processes of PMC as well as the distribution of NPP_{root} to PMC and root exudates in natural grassland ecosystems.

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