Ecological Modelling 321 (2016) 46–63

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

Factors controlling Nitrous Oxide emission from a spruce forest ecosystem on drained organic soil, derived using the CoupModel

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ARTICLE INFO

Article history:
Received 26 May 2015
Received in revised form 6 October 2015
Accepted 27 October 2015

Keywords:
Nitrous Oxide
Drained organic soil
CoupModel
Generalized likelihood uncertainty estimation (GLUE)
Spruce forest
Emission controlling factor

ABSTRACT

High Nitrous Oxide (N_2O) emissions have been identified in hemiboreal forests in association with draining organic soils. However, the specific controlling factors that regulate the emissions remain unclear. To examine the importance of different factors affecting N_2O emissions in a spruce forest on drained organic soil, a process-based model, CoupModel, was calibrated using the generalized likelihood uncertainty estimation (GLUE) method. The calibration also aims to estimate parameter density distributions, the covariance matrix of estimated parameters and the correlation between parameters and variables information, useful when applying the model on other peat soil sites and for further model improvements. The calibrated model reproduced most of the high resolution data (total net radiation, soil temperature, groundwater level, net ecosystem exchange, etc.) very well, as well as cumulative measured N_2O emissions (simulated 8.7 ± 1.1 kg N_2O ha^{-1} year^{-1} ($n = 97$); measured 8.7 ± 2.7 kg N_2O ha^{-1} year^{-1} ($n = 6$)), but did not capture every measured peak. Parameter uncertainties were reduced after calibration, in which 16 out of 20 parameters changed from uniform distributions into normal distributions or log normal distributions. Four parameters describing bypass water flow, oxygen diffusion and soil freezing changed significantly after calibration. Inter-connections and correlations between many calibrated parameters and variables reflect the complex and interrelated nature of pedosphere, biosphere and atmosphere interactions. This also highlights the need to calibrate a number of parameters simultaneously. Model sensitivity analysis indicated that N_2O emissions during growing seasons are controlled by competition between plants and microbes for nitrogen, while during the winter season snow melt periods are important. Our results also indicate that N_2O is mainly produced in the capillary fringe close to the groundwater table by denitrification in the anaerobic zone. We conclude that, in afforested drained peatlands, the plants and groundwater level have important influences on soil N availability, ultimately controlling N_2O emissions.

1. Introduction

Forests on drained organic soils are hotspots for Nitrous Oxide (N_2O) emissions (Maljanen et al., 2003; Von Arnold et al., 2005; Ernfors et al., 2007; Martikainen et al., 1993; Maljanen et al., 2011). The main reason is the release of nutrients from old stored organic matter as a result of anthropogenic drainage and subsequent aerobic decomposition (Martikainen et al., 1993; Regina et al., 1996). The released ammonia (NH_3) can be taken up and incorporated into organisms or further processed by microbes; in the latter case, N_2O is only one nitrogen species produced and/or consumed (Firestone and Davidson, 1989). In many northern countries, peatlands have been extensively drained for agriculture and forestry; for example, in Sweden, forest on drained organic soils now covers 15,000 km^2 (Ernfors et al., 2007). Based on a fertility index (soil C/N ratio), it has been estimated that these areas emit 2.8 Gg N_2O year^{-1} corresponding to almost 1 Tg CO_2eq year^{-1} (Ernfors et al., 2007). More information is required on soil–atmosphere N_2O flux exchange and the factors that control emissions, both for annual national reporting (UNFCCC, 1997) and to consider climate change mitigation options (Ojanen et al., 2010).

A complex set of influencing factors are known to regulate emissions. The most important prerequisites for N_2O formation are: available mineral N, partly depleted oxygen content and a carbon

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http://dx.doi.org/10.1016/j.ecolmodel.2015.10.030
0304-3800/

source for use by denitrifying organisms (Wijler and Deleiche, 1954; Conrad, 1996). Other reported regulating factors include soil pH (Simek and Cooper, 2002; Weslien et al., 2009; Bakken et al., 2012) and soil nitrogen fertility which, for drained soils, could be expressed as a C/N ratio (Klemedtsson et al., 2005). The seasonal emission pattern is closely linked with soil moisture, temperature, drying/wetting cycles and freeze/thaw events, all of which are further influenced by large scale meteorological conditions and anthropogenic management practices (Smith et al., 2003; Koponen et al., 2006; Groffman et al., 2009). Therefore, predicting N_2O emissions requires a combined soil–plant–atmosphere approach that can describe the multitude of controlling factors and their interactions (Gundersen et al., 2012; Butterbach-Bahl et al., 2013; Smith, 2010).

Currently, detailed process-based models – Ecosys (Grant, 1991), DNDC (Li et al., 1992) CoupModel (Jansson and Moon, 2001), DAYCENT (Parton et al., 2001), ANIMO (Hendriks et al., 2011) and MicNit (Blagodatsky et al., 2011) – are able to describe the complex dynamic processes of the atmosphere–plant–soil continuum and hence allow researchers to study the interactions between emissions and abiotic and biotic factors (Butterbach-Bahl et al., 2004; Klemedtsson et al., 2008; Blagodatsky and Smith, 2012). However, a general problem of applying these models to simulate N_2O emissions is that the information/measurements are often not sufficient compared to the model's demands (e.g. CoupModel and DAYCENT use more than 300 parameters); this could significantly affect model predictability (van Oijen et al., 2011; De Bruijn et al., 2011; Lamers et al., 2007; Groffman et al., 2009). To improve understanding and model performance with respect to N_2O fluxes it is thus essential to quantify the parameter uncertainties and hence assess the model predictions in a quantitative manner (Butterbach-Bahl et al., 2013; Lamers et al., 2007). So far, model calibration has mostly been undertaken for mineral soils in N_2O flux simulations, e.g. (van Oijen et al., 2011; Metivier et al., 2009; Lehuger et al., 2009; Tonitto et al., 2007; de Bruijn and Butterbach-Bahl, 2009; Nylinder et al., 2011). However, for organic soils, we know of no studies in which model calibration and uncertainty analysis have been taken into account when modeling N_2O flux.

One widely used model calibration method to bridge the gap between model requirements and available data and to quantify the parameter uncertainty is "generalized likelihood uncertainty estimation (GLUE)" (Beven, 2006). The core assumption of this method is "equifinality" which means that there are many model constructions or many parameter sets that could produce a similar empirical output (Beven and Binley, 1992; Beven, 2006). Thus, GLUE does not seek the best fit to the measured data but utilizes an ensemble of model simulations that represent equally good results by using informal likelihood measures, normally defined as thresholds of subjective criteria (e.g. coefficient of determination, R^2) (Beven, 2006). The accepted model ensemble minimizes the parameter uncertainties and at the same time provides statistical information, e.g. variance/covariance matrix, correlations between the parameters and the variables, offering excellent opportunities to analyze the importance of different parameters and processes on individual fluxes (Jansson, 2012; Nylinder et al., 2011; Lamers et al., 2007; Klemedtsson et al., 2008).

The overall main objective of this study was to analyze the N_2O flux and its regulators in detail by using the GLUE method to examine a detailed process based model, the CoupModel (Jansson and Moon, 2001), using a well-established dataset for a spruce forest on drained organic soil, the Skogaryd site (Klemedtsson et al., 2010). The CoupModel was chosen since it features and focuses on soil physics appropriate for modeling organic soils (Jansson, 2012). Data for model calibration include N_2O fluxes over three years measured using manual chambers (Ernfors et al., 2011), and a one year complete dataset on C cycling combining eddy covariance NEE flux data and detailed forest production measurements (Meyer et al., 2013) plus a number of high resolution abiotic data sets (Klemedtsson et al., 2010). The soil temperature and moisture data measured at four soil depths made it possible to evaluate the dynamics of soil N cycling and hence N_2O production down the entire soil profile. Specific objectives of this study were: (1) to demonstrate the possibility of modeling N_2O emissions for drained organic soils; (2) to provide calibrated parameter density distributions, the covariance matrix of estimated parameters and correlation between parameters and variables, which are essential to know for model application on other sites with similar properties; and (3) to identify key factors controlling N_2O emissions.

2. Materials and methods

2.1. Model description

The CoupModel platform (coupled heat and mass transfer model for soil–plant–atmosphere systems), is an updated version of the previous SOIL and SOILN models (Jansson and Moon, 2001). The main model structure is a one-dimensional, vertical layered soil profile. Water and heat flows are calculated based on estimated soil physical characteristics by two coupled partial differential equations: Richard's equation and Fourier's law including the convective flow (Jansson and Halldin, 1979). To account for a possible bypass flow, the model uses an empirical approach where the sorption capacity of the matrix is scaled (Jarvis and Jansson, 1989). Thus, water entering any soil layer at a rate higher than the sorption capacity is allocated to bypass flow and thus directly transferred to the next layer (Espeby, 1992). At the soil surface, soil evaporation and snow dynamics are calculated by the energy balance approach, assuming that the net radiation would be balanced out by the turbulent sensible heat flux and latent flux and also the soil heat flow (Alvenäs and Jansson, 1997; Gustafsson et al., 2004; Klemedtsson et al., 2008). The plant is simulated using a "big leaf" model where the water transpiration and hence plant soil water uptake is calculated by the Penman–Monteith equation (Monteith, 1965). C and N dynamics are simulated both in the soil and in the plant, driven by the canopy-intercepted radiation, regulated by multiplicative response functions of air temperature, and plant availability of water and N (Jansson et al., 2007). Two vegetation layers are simulated, the trees and understory plants, assuming mutual competition for light interception, water uptake and soil N (Jansson and Karlberg, 2011). The newly assimilated C is allocated to different compartments of the plants –leaves, stem, coarse roots and fine roots – by assuming a fixed allocation parameter for each compartment (Klemedtsson et al., 2008). At the same time, the plants loose C through growth and maintenance respiration. Plants also continuously loose C via litterfall both from above and belowground tissues, with different fixed litterfall rates (Jansson and Karlberg, 2011). The allocation of N to different plant compartments follows, to a large extent, the pattern of C by use of C/N ratios. The dynamics of the soil organic matter are simulated with first order kinetics by using two pools, litter and humus, governed by response functions of soil temperature and moisture. In this study we consider historically stored peat as humus and fresh plant detritus as litter. The soil microorganisms are implicitly included in the soil litter pool (Svensson et al., 2008a). The soil anaerobic fraction/microsite is then calculated using the "anaerobic balloon" concept, as in the DNDC model (Norman et al., 2008). For nitrification simulation, the CoupModel takes into account response functions of soil temperature, soil moisture, ammonia concentration and soil pH (Norman et al., 2008). Each sub-chain of denitrification is explicitly calculated and activity is influenced by soil temperature, soil pH, content of N in the anaerobic microsites and soil anaerobic fraction (Jansson and