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# Characterising effects of management practices, snow cover, and soil texture on soil temperature: Model development in DNDC

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Agro-ecosystem models, such as the DNDC (DeNitrification and DeComposition) model are useful tools when assessing the sustainability of agricultural management. Accuracy in soil temperature estimations is important as it regulates many important soil biogeochemical processes that lead to greenhouse gas emissions (GHG). The objective of this study was to account for the effects of snow cover in terms of the measured snow depth (mm of water), soil texture and crop management in temperate latitudes in order to improve the surface soil temperature mechanism in DNDC and thereby improve GHG predictions. The estimation of soil temperature driven by the thermal conductivity and heat capacity of the soil was improved by considering the soil texture under frozen and unfrozen conditions along with the effects of crop canopy and snow depth. Calibration of the developed model mechanisms was conducted using data from Alfred, ON under two contrasting soil textures (sandy loam vs. clay). Independent validation assessments were conducted using soil temperatures at different depths for contrasting managements for two field sites located in Canada (Guelph, ON and Glenlea, MB). The validation results indicated high model accuracy ($R^2 > 0.90$, EF $\geq 0.90$, RMSE $< 3.00$ °C) in capturing the effects of management on soil temperature. These developments in soil heat transfer mechanism improved the performance of the model in estimating $N_2O$ emissions during spring thaw and provide a foundation for future studies aimed at improving simulations in DNDC for better representations of other biogeochemical processes.



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**Nomenclature**

| | |
|---|---|
| $a_v$ | Air content ($m^3\ m^{-3}$) |
| $a$ | Average canopy albedo |
| $b$ | Soil texture specific empirical coefficients |
| BD | Soil bulk density ($kg\ m^{-3}$) |
| $C_a$ | Volumetric heat capacity of the air particles present in the medium ($J\ m^{-3}\ K^{-1}$) |
| $C_n$ | Volumetric heat capacity of the solid particles present in the medium ($J\ m^{-3}\ K^{-1}$) |
| $C_o$ | Volumetric heat capacity of the organic particles present in the medium ($J\ m^{-3}\ K^{-1}$) |
| $Cp\ (\theta)$ | Volumetric heat capacities ($J\ m^{-3}\ K^{-1}$) of the porous medium |
| $\overline{C}_p$ | Apparent volumetric heat capacity of soil ($J\ m^{-3}\ K^{-1}$) |
| $C_w$ | Volumetric heat capacities ($J\ m^{-3}\ K^{-1}$) of the liquid phase |
| $d$ | Damping depth (m) |
| d | Index of agreement |
| $D_h$ | Thermal diffusivity of the soil ($m^2\ s^{-1}$) |
| $D_s$ | Snow depth (m) |
| EF | Modelling efficiency |
| F | Weighting factor taken as the ratio of the average temperature gradient in the $j$th component to the temperature gradient in the continuous medium |
| $f_s$ | Empirical snow parameter ($m^{-1}$) |
| L | Latent heat of fusion of ice ($J\ kg^{-1}$) |
| $L_c$ | Transmission of solar radiation for the soil-crop system |
| $LAI$ | 1-sided leaf area index ($m^2\ m^{-2}$) |
| ME | Mean error |
| $q$ | Flow of water ($m\ s^{-1}$) |
| $R^2$ | Coefficient of determination |
| RF | Crop residue factor |
| RMSE | Root Mean Square Error |
| T | Temperature (°C) |
| $T_a$ | Annual average air temperature |
| $T_{max}$ | Maximum temperature of the year |
| t | Time (day) |
| $t_0$ | Initial time (day) |
| z | Space coordinates (m) |
| $\theta$ | Volumetric soil water content ($m^3\ m^{-3}$) |
| $\theta_i$ | Volumetric ice content ($m^3\ m^{-3}$) |
| $\rho_i$ | Density of ice ($kg\ m^{-3}$) |
| $\varnothing$ | Volume fraction of the $j$th component |
| $\lambda\ (\theta)$ | Apparent thermal conductivity of the soil ($W\ m^{-1}\ K^{-1}$) |
| $j$ | Number of different components dispersed in a medium |
| $\kappa$ | Extinction coefficient |
| $\tau$ | Angular time period (day) |
| $\omega$ | Angular frequency ($day^{-1}$) − defined as $\omega = \frac{2\pi}{\tau}$. |

## 1. Introduction

Soil is a complex, dynamic and living system, critical in regulating below-ground processes, which in turn can affect carbon budgets and trace gas emissions. Nitrous oxide ($N_2O$) is a greenhouse gas (GHG) and is a product of microbial activities as a result of the biogeochemical processes, such as nitrification and denitrification, occurring within the nitrogen (N) cycle. It is regulated by soil moisture content, available N and oxygen availability, which in turn are also influenced by soil temperature (Granli and Bockman, 1994). The global warming potential (GWP) of $N_2O$ is 298 times that of carbon dioxide ($CO_2$) and contributes approximately 6.24% to the overall global radiative forcing (Butterbach-Bahl, Baggs, Dannenmann, Kiese, & Zechmeister- Boltenstern, 2013) as well as representing a nutrient loss. It is estimated that approximately 60% of the total $N_2O$ emitted to the atmosphere is derived from soils, roughly a third of which is produced by agricultural activities (IPCC, 2013). Soil reactive N processes such as nitrification (ammonium oxidation to nitrate), denitrification (reduction of nitrate ($NO_3^-$) or nitrite ($NO_2^-$) to $N_2$ or $N_2O$) and nitrate ammonification have been mainly attributed as the biological pathways of $N_2O$ production in addition to environmental factors, microbial community structure and location within the soil matrix.

Research has shown that over-winter GHG emissions contribute a large proportion of the total annual emissions from agricultural soils in cold climates (Smith, Grant, Desjardins, Lemke, & Li, 2004; Virkajärvi, Maljanen, Saarijarvi, Haapala, & Martikainen, 2010; Wagner-Riddle et al., 2007). Increases in atmospheric $N_2O$ emissions during freeze-thaw cycles have been related to fluctuations in soil temperatures and occur following freezing at colder temperatures (Wagner-Riddle et al., 2007) or immediately after thawing has started with soil temperatures over 0 °C (Singurindy, Molodovskaya, Richards, & Steenhuis, 2009). The burst of $N_2O$ flux due to soil freezing and thawing at spring thaw have been attributed to an enhanced period of microbial activity (Wagner-Riddle, Hu, van Bochove, & Jayasundara, 2008) due to increased nutrient availability, and the physical release of $N_2O$ trapped at depth during winter, while others have reported soil water content being the primary regulator (Groffman & Tiedje, 1989). It has been well documented that microbial activities in soil are stimulated by increasing temperature (Biederbeck & Campbell, 1973; Pietikäinen, Pettersson, & Bååth, 2005). Thus an accurate estimation of soil temperature under cold, humid continental climates is highly important in predicting $N_2O$ emissions during this period.

Soil temperature is controlled by several factors, such as the topography of the soil, soil texture, and soil water content, which are spatially variable (Zheng, Hunt, & Running, 1993). Solar radiation and air temperature are the main drivers of soil temperature, but it is also influenced by many other factors such as precipitation, soil texture, and moisture content as well as the type of surface cover including plant canopy, crop residue, snow, etc (Paul et al., 2004). Soil temperature is dependent on the interaction between soil thermal conductivity and moisture content which are also influenced by the soil texture/type (Barry-Macaulay, Bouazza, Wang, & Singh,

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