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Model development in DNDC for the prediction of evapotranspiration and water use in temperate field cropping systems

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ABSTRACT

This paper integrates recent research to improve, test, and verify the process based DeNtrification DeComposition (DNDC) model to estimate evapotranspiration (ET) through a revised FAO Penman–Monteith approach. ET estimates along with biomass and soil water content for spring wheat and corn were improved and found to be in good agreement with the observations at three field sites in eastern Canada (Ottawa). The statistical evaluations (RMSE (mm day^{-1}) and R^2) of ET for the newly revised model (0.88 and 0.76 for corn and 0.93 and 0.78 for wheat) showed improvements over DNDC93 (1.95 and 0.22 for corn and 1.62 and 0.09 for wheat) which used the Thornthwaite equation for estimating potential evapotranspiration. In addition, evaluations of water use efficiency for corn and wheat showed good agreement between observations and the modified model. The study demonstrates the interdependencies of ET with biomass production and soil/atmosphere water balance.

1. Introduction

Crop production is affected worldwide by the availability of water resources. Evapotranspiration (ET) is a common process in agricultural hydrology that plays an important role in determining exchanges of energy and mass between the hydrosphere, atmosphere and biosphere (Sellers et al., 1996). In agriculture, the accurate estimation of ET, which is a measure of the crop and soil water losses to the atmosphere, can help formulate beneficial management options for maximizing production such as choice of crop and cultivar type, drainage requirements, water table control, irrigation amount and scheduling, and scheduling of farm machinery use to minimize soil compaction. In order to obtain a comprehensive picture of the water cycle in agriculture, reliable estimates of ET including evaporation from soil, plant and water surfaces and transpiration by vegetation, is essential. Evapotranspiration, which is highly dependent on crop, weather and soil conditions, is highly variable in space and time (Hanson, 1991). Understanding these variations is crucial for managing water resources.

Potential evapotranspiration (PET) for a crop is defined as the maximum possible water loss that takes place from a large vegetation-covered land surface with adequate water content. The concept of the reference evapotranspiration was introduced to study the evaporative demand of the atmosphere independently of crop type, crop development and management practices. PET values measured or calculated at different locations or in different seasons are comparable as they refer to ET in relation to a living grass reference crop (Allen et al., 1998). It is often used by agronomists as a measure of potential water stress on crops and for water resource management. The difference and ratio in the PET and ET values are used in agriculture and water resource management at high spatial resolutions as an indicator of crop water deficits (Yao, 1974).

Some ET measurement techniques include soil and plant weighing lysimeters, soil water budgets, eddy covariance, etc (Wilson et al., 2001). However, *in situ* measurements of ET have generally been difficult to obtain (Thom and Oliver, 1977; Wilcock et al., 1978). Each of the techniques introduces a unique set of particular assumptions, technical difficulties, measurement errors and biases. While lysimeter measurements of ET have been found to be costly and present difficulties in set up and maintenance; eddy covariance technique require large areas for adequate sampling. On the other hand, water budget methods of ET measurement require several calibrated profiles of sap flow (Wilson et al.,

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2001). Hence direct and indirect methods of measuring evapotranspiration are costly and require time investment of highly qualified personnel (Gowda et al., 2008).

A variety of models exist to estimate evapotranspiration based on readily available climatological parameters, and for some of them using the concept of PET. These methods can be grouped into four categories: (1) water budget (e.g., Guitjens, 1982), (2) mass-transfer (e.g., Harbeck, 1962), (3) combination (e.g., Penman, 1948), (4) based on single climatological parameters such as radiation (e.g., Priestley and Taylor, 1972), or temperature (e.g., Blaney-Criddle, 1950; Thornthwaite, 1948).

In the Penman–Monteith equation, climate data are used to calculate reference evapotranspiration based on a short grass area with the integration of factors for stomatal resistance, albedo and boundary layer resistance. The Penman–Monteith equation is a simple representation of the physical and physiological factors governing the evapotranspiration process. It includes all parameters that govern energy exchange and corresponding latent heat flux (evapotranspiration) from uniform areas of vegetation. Because there is still a considerable lack of information for different crops, the Penman–Monteith equation is often employed to estimate the standard reference ET regardless of crop type (Allen et al., 1998). Apart from the site location, the Penman–Monteith equation is relatively data intensive and requires air temperature, humidity, radiation and wind speed for daily, weekly, or monthly calculations.

Temperature- and radiation based methods, such as the Thornthwaite equation, are some of the earliest methods for estimating ET. However, certain shortcomings are inherent in the method as it only uses daylength and temperature as climatic inputs. Application of this method to short-time periods leads to significant errors which are attributed to the fact that short-term mean temperature is not a suitable measure of net radiation (Grace and Quick, 1988). Moreover, it also does not account for either the lag of temperature with solar radiation arising from the thermal storage in the soil or the effect of water content availability in the region based upon air temperature (Pelton et al., 1960). However, the results of such analyses have been found to be influenced by site, measurement conditions and by bias in weather data collection (Xu and Singh, 2002).

There is also a need to improve a process-based approach to capture the spatial and temporal variability of crop yield and water consumption in important grain producing regions. Seasonal Water Use Efficiency (WUE), defined as the crop yield per unit of water consumed, incorporates the combination of two related agricultural processes of crop growth and water consumption. WUE is a measure of the plant growth and water use and the measure can be used as an important tool for sustainable agriculture for enhancing productivity by optimizing water resources. The calculation of water consumption for WUE takes into account measurements of ET on a field scale.

Process-based models in agriculture have increasingly been applied as a valuable means to assess the environmental impacts of anthropogenic activities and to provide information for policy decisions (Jarecki et al., 2008; Kariyapperuma et al., 2011; Parton et al., 1988; Smith et al., 2002; Wolf et al., 2012). Process-based models, such as DNDC, are mathematical models which provide the prospect of integrating contributing biogeochemical processes based on C, N and water cycles. They ensure that a mass balance of C, N and water is maintained (Smith et al., 2002). These kinds of models help evaluating the environmental footprint of agricultural products from a systems perspective by including inter-dependent factors such as soil carbon, GHG emissions, and productivity. By comparing measurements and model predictions, continuous improvements are brought, to these models to enhance our understanding of the complex interactions between crops and their physical environment. The accurate estimation of water exchange temporal dynamics between crops, soil, and air is necessary for predicting biomass production as well as numerous soil processes such as leaching, decomposition, immobilization, mineralization, and denitrification. All these processes are critical for characterizing C and N dynamics in agroecosystems (Smith et al., 2008).

Climate variables such as, precipitation, temperature, solar radiation, relative humidity and wind speed along with initial soil profile conditions such as temperature, water content and mineral N are the main drivers for prediction of soil and crop processes in these models (Smith et al., 2010). In order for models to capture the effects of climatic variability and management practices on crop growth it is critical that they accurately estimate the main hydrological processes such as ET, runoff, and leaching. Increased concentrations of nitrous oxide (N_2O) are of concern as it contributes to the greenhouse effect (IPCC, 2013). Flux measurements can be used to verify simulation models such as DNDC for estimating N_2O fluxes from agricultural soils under different scenarios. Soil moisture is an important factor for microbial nitrification and denitrification which are critical to the determination of N_2O emissions (Abdallah et al., 2009). The difference between the amount of precipitation and soil water content in the soil profile is often used to infer ET. Hence an improvement to the ET estimation routine in DNDC would help to further improve the water budget in the model. The development of models that are capable of capturing the spatial and temporal variability of crop yield and water consumption also provides a means to better comprehend WUE for agricultural lands and study the impact of water shortage and excess.

Several developments have been made to the DNDC model in recent years to improve the effects of temperature, water and nutrient stress on biomass production (Kröbel et al., 2011). The objectives of this study were to: (i) use detailed water vapour flux, biomass and auxiliary data from sites in eastern Canada to further develop and parameterize the model, (ii) test the revised model for predicting ET, biomass and WUE using independent data, iii) compare the performance of the revised model to previous model versions and (iv) investigate the predictive capability of the improved model for the evaluation of the impact of climate on crop growth.

2. Materials and methods

2.1. Site description

The measurements used in this study were obtained from three fields with brunisolic clay loam soil located on the Canadian Food Inspection Agency experimental farm in Eastern Canada (Ottawa, ON) (45.3°N, 75.8°W, 91 m a.s.l.). The crops of interest were corn (*Zea mays* L.) and spring wheat (*Triticum aestivum* L.) grown in experimental fields designated as Fields 14, 19 and 25 which will be henceforth referred to as F14, F19 and F25 and crop years of interest were 1996 (F19), 1998 (F25) and 2006 (F14) for corn and 2003 and 2005 (F14) for spring wheat respectively for the growing season (May–October). These sites were selected because they had a wide range of measurements including daily ET, biomass measured several times over the growing seasons and soil water content which should help in the development of a more robust model. Tower-based eddy covariance systems were used to measure actual evapotranspiration at the field scale on a half-hourly time step (Pattey et al., 2006). These data were screened and aggregated to daily and seasonal evapotranspiration as described in Pattey et al. (2001). The flux measuring systems were installed at least at 2-m height above the plant canopies. The eddy-covariance measuring system consists of a three-dimensional ultrasonic anemometer