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Process-based modeling of temperature and water profiles in the seedling recruitment zone: Part I. Model validation

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ABSTRACT

Process-based modeling provides greater spatial and temporal information of the soil environment in the shallow seedling recruitment zone across field topography where measurements of soil temperature and water may not sufficiently describe the zone. Hourly temperature and water profiles within the 75 mm recruitment zone for 75 days after seeding were simulated for Canadian Prairie conditions from the process-based Simultaneous Heat and Water (SHAW) model using local and non-local microclimatic data. Measured and modeled soil cover and spring wheat vegetative cover were used to parameterize the model. Heat and water transfer was simulated through surface residue, early vegetation and soil. Simulations were evaluated using model efficiency, root mean square deviation, and components of mean squared error. The greatest amount of error in simulated soil temperature was lack of correlation in the fluctuation pattern over time, followed by bias of the simulation. Soil temperature simulations had model efficiency of 0.87, overestimation of 0.4 °C, and a RMSD of 2.1 °C averaged across all topographical factors and soil depths. Simulations of soil water had low model efficiency and RMSD of 0.55 MPa. Average absolute bias for soil water was 0.27 MPa which reflected predominantly positive bias at the soil surface and 0–25 mm soil layer and negative bias in the 25–50 and 50–75 mm soil layers. Process-based modeling using microclimatic information was shown to provide representative simulations of the soil environment for all depths of the seedling recruitment zone.

1. Introduction

The environment in the seedling recruitment zone evolves as a result of above-ground microclimate, soil surface conditions, and soil properties. A wide range of seedling recruitment microsites with varying soil environmental conditions regulate seedling recruitment within the recruitment zone (Harper, 1977). To represent the environmental heterogeneity within the seedling recruitment zone, the soil profile is considered as a series of horizontal layers. The greatest exchange of energy and water occurs at the soil surface, subjecting the seedling recruitment zone to frequent and intense environmental alterations (Oke, 1987). Sources of variability in soil properties with depth and topography can be important in modeling the seedling recruitment zone across heterogeneous soil and topographic conditions.

The seedling recruitment zone has been shown to be quite shallow. The maximum mean recruitment depth in situ across species, sampling times, and tillage practice was less than 42 mm (du Croix Sissons et al., 2000). As well, recruitment depth maxima for spring wheat were 40–41 mm using Beta models of thermal and hydrothermal time (Bullied et al., 2014). The amount of tillage influences the mean weed seedling recruitment depth, and a shift toward reduced tillage on the Canadian Prairies has resulted in shallower seedling recruitment depths compared to conventional tillage (Van Acker et al., 2004).

The recruitment of seeds can be influenced by specific properties of the soil such as temperature, water, texture, structure, soil atmosphere, nutrient content, and organic matter (Egley, 1986; Bullied et al., 2012); however, the two most general predictors of seedling recruitment are the processes of soil heat and water transfer in the soil (Forcella et al., 2000; Bradford, 2002; Leguizamón et al., 2005). Soil heat and water movement in the soil associated with seedling recruitment are quantified by either direct measurement or estimation of properties associated with each process. The condition of the recruitment microsite at a given time and location are represented by the state variables of soil

Abbreviations: DAP, days after planting; DOY, day of year; DTE, days to emergence; DTM, days to maturity; GDD, growing degree days; ME, model efficiency; MSE, mean squared error; RMSD, root mean square deviation; SHAW model, Simultaneous Heat and Water model.

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heat and water transfer (soil temperature and water potential). Soil temperature and soil water potential are often a result of interactions between heat and water, as well as other specific soil properties that influence the processes of soil heat and water transfer (Gardner, 1955; Cary, 1966; Campbell and Gardner, 1971).

Simulating the microsite environment in the seedling recruitment zone involves the use of atmospheric conditions that influence the shallow soil layer through the processes of soil heat and water transfer through the atmosphere–soil continuum (Flerchinger and Hardegree, 2004; Al-Mulla et al., 2009; Bullied et al., 2012). This requires either direct measurement of atmospheric microclimate at the field site or the use of locally available atmospheric data. Microclimatic modeling of soil heat and water is a way to avoid repeated temporal and spatial sampling of the microsite. Furthermore, models of coupled soil temperature and soil water have been developed to simulate the seedling recruitment zone environment from atmospheric conditions (Flerchinger and Pierson, 1997; Šimůnek et al., 2008).

The seedling recruitment zone can be difficult to measure due to rapid changes in microclimatic conditions acting on the shallow soil layer. Spatial and temporal fluctuations of temperature and water within the seedling recruitment zone during the early growing season require frequent measurements to capture the status of the changing soil environment. Many temperature sensors are required to accurately represent vertical and horizontal thermal gradients within the recruitment zone across heterogeneous field topography. Measuring water near the soil surface is more difficult since a sensor that can measure water in fine-scale layers of the seedling recruitment zone is currently not available (Tsegaye et al., 2004).

Simulating continuous spatial and temporal soil temperature and soil water profiles derived from occasional measurements that are sparsely distributed can provide a more complete description of the seedling recruitment zone. Simulations of the soil environment within the seedling recruitment zone have been used to predict timing of weed seedling recruitment (Masin et al., 2005). The objectives of our study were to (1) simulate hourly soil temperature and soil water profiles for the 75 mm profile depth of the seedling recruitment zone under Canadian Prairie conditions with the process-driven Simultaneous Heat and Water (SHAW) model (Flerchinger, 2000) using measured and modeled soil and vegetative parameters, hourly microclimate and soil temperature data, and intermittent (approximately semiweekly) soil water measurements, and (2) validate the accuracy of the simulations by comparing simulations of soil temperature and soil water to the measurements using model performance indices.

2. Materials and methods

2.1. Field site

Field plots were established in 2003 and 2004 across field topography within an annually cropped field at the Orchard farm immediately west of Graysville, MB in south-central Manitoba, Canada (49°30′N, 98°09′W). The experiment consisted of two opposing hillslope aspects (southwest and northeast), each containing three hillslope positions (summit, backslope and toeslope). Each aspect covered an area of approximately one hectare. The northeast facing hillslope was classified as an Udic Boroll with a loamy fine sand surface texture, the southwest facing summit was a Mollic Udifluvent with a silty clay surface texture, and the southwest backslope and toeslope were a Typic Agriaquoll with a loam surface texture. Clay content of the hillslopes increased downslope (Table 1).

The experiment was organized as a split-plot design on each of the six hillslope positions. Main plots (year) were replicated six times in blocks arranged perpendicular to the hillslope gradient to maximize homogeneous conditions at each hillslope position. Two residue levels (resident and added) were randomized as split-plot factors within each year. Individual plot size for residue level was 2 m × 4 m. Within each residue plot, the soil microclimate properties were measured in three 25-mm depth increments.

The experiment was established on previous soybean (*Glycine max* [L.] Merr.) residue. A residue treatment added 600 g m^{-2} finely chopped oat (*Avena sativa* L.) straw on a dry weight basis to the resident soybean residue to imitate a residue level typical of small grain production. In treatments with added residue, the oat straw was manually spread evenly over the entire plot. Spring wheat (*Triticum aestivum* L., cv. AC Barrie) was spread evenly onto the soil surface at a rate of 500 viable seeds m^{-2} on 6 May (DOY 126) in 2003 and 6 May (DOY 127) in 2004 with a cone seeder mounted on a double disc press drill by removing the seed tubes from the discs. Plots were rotary tilled to a depth of 75 mm to incorporate and distribute the oat straw and wheat seed throughout the depth of the seedling recruitment zone.

2.2. Field measurements

2.2.1. Microclimate

Microclimatic data was monitored at each hillslope position by a weather station with environmental sensors (Onset Computer Corporation, Pocassat, MA). Air temperature was logged hourly at a height of 1.5 m above the soil surface with HOBO™ temperature dataloggers fitted with a solar radiation shield beginning 9 May (DOY 129) in 2003 and 2 May (DOY 123) in 2004. Precipitation was collected with tipping bucket rain gauges at a height of 1.5 m above the soil surface beginning 9 May in 2003 and 2 May 2004. HOBO™ weather station data loggers were installed 26 May (DOY 146) in 2003 and 2 May (DOY 123) in 2004 with hygrometers fitted with a solar radiation shield to monitor hourly relative humidity, silicon pyranometers to monitor hourly total incoming solar radiation (300–1100 nm), and 3-cup anemometers to monitor hourly wind speed. Relative humidity sensors and anemometers were mounted at 1.5 m above the soil surface. Pyranometers were mounted level on a base 15 cm above the soil surface.

Downward and upward solar radiation were instantaneously measured on all plots at intervals throughout the early season with a LI-COR model LI-200 pyranometer and model LI-1000 handheld logger (LI-COR Biosciences, 4421 Superior Street, Lincoln, NE, 68504-0425) as close as possible to solar noon. Downward solar radiation was measured by placing the pyranometer upward-facing on a base parallel to the soil surface, and upward solar radiation was measured by facing the pyranometer downwards 20 cm from the soil surface supported on a wire U-shaped frame.

Simulation was initialized over 1 month prior to seeding and soil measurements to allow for adjustment of the soil temperature and water simulation to the effects of above-ground microclimate. Where environmental data was not available locally, hourly environmental data from the start of simulation (DOY 90) until installation of the environment loggers in the field were obtained from the nearest weather station (Figs. 1 and 2). Air temperature, relative humidity, and precipitation data were obtained from the University of Manitoba weather station at Carman MB, which was 10 km from the experiment site. Hourly solar radiation and wind data were obtained from the North Dakota State University Agricultural Weather Network station at Walhalla, ND (70 km distance). Wind data were equilibrated to the Graysville dataset to account for height of measurement (3 m at Walhalla), surface drag, and topographic differences (Oke, 1987). Precipitation (snow) was obtained from the University of Manitoba weather station at Carman MB at 5–7 DAP during 2004.