Agricultural and Forest Meteorology 188 (2014) 104–120

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

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

Process-based modeling of temperature and water profiles in the seedling recruitment zone: Part II. Seedling emergence timing

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ARTICLE INFO

Article history:
Received 12 April 2013
Received in revised form
12 September 2013
Accepted 9 October 2013

Keywords:
Hydrothermal time
Seedling emergence timing
Seedling recruitment zone
Soil temperature
Soil water
Spring wheat

ABSTRACT

Predictions of seedling emergence timing for spring wheat are facilitated by process-based modeling of the microsite environment in the shallow seedling recruitment zone. Hourly temperature and water profiles within the recruitment zone for 75 days after planting were simulated from the process-based Simultaneous Heat and Water (SHAW) model using local and non-local microclimatic data. Linear mixed-effects models indicated that simulated thermal and hydrothermal time accumulations were similar to measurements. Emergence timing was fitted using the Gompertz equation. Simulations averaged across depth had quicker emergence timing of wheat at inflection by 20 °Cd for thermal time and 23 MPa°Cd for hydrothermal time models, equating to 1.3 days earlier in the DAP model. Seedling emergence rates were similar between simulations and measurements. Simulations for emergence timing with hydrothermal time improved upon thermal time only at the soil surface. The recruitment depth of spring wheat over time was fitted with a Beta function which was positively skewed with early recruitment of a large number of seedlings from a moderate depth and late recruitment by a small number of seedlings from a shallow depth. The time of simulated Beta maxima was greater by 39 °Cd for thermal time and 3 MPa°Cd for hydrothermal time, and 1.5 days less than the measured maxima for the DAP model. The 95% confidence intervals for the fitted simulation and measured Beta functions overlapped for the entire duration of the distribution for all time scale models. Process-based simulations of soil temperature and soil water in the seedling recruitment zone provided representative predictions of seedling emergence timing for spring wheat.

1. Introduction

The seedling recruitment zone is a dynamic environment due to variable climatic influences on heterogeneous layers in the vertical soil profile (Stoller and Wax, 1973; Penning de Vries et al., 1989). The seedling recruitment zone contains many unique temporal and spatial microsites which are defined as the soil environment that has a direct influence on seedling recruitment (Harper, 1977). It is important to model spatial and temporal aspects of recruitment microsites because the seedling recruitment zone is subject to frequent and intense environmental alterations, particularly near the soil surface (Oke, 1987). Detailed spatial and temporal representation of the seedling recruitment zone is needed to predict seedling emergence timing (Bullied et al., 2012b).

Seedling recruitment models are used to predict emergence timing or rate of a particular crop or weed. The hydrothermal time model describes the progression toward germination by integrating temperature and water interactions above minimum temperature and water thresholds into a single time function (Allen et al., 2000; Bradford, 2002; Leguizamón et al., 2005). Hydrothermal time models of seedling recruitment in the field provide results on predictions of establishment and survival of a species based on all the processes that begin with above-ground microclimate and soil related inputs (Allen, 2003). Hydrothermal modeling uses species-specific thresholds to construct emergence models for variable environments such as fields with fluctuating temperature and water potential (Finch-Savage et al., 2000). This type of emergence model accumulates hydrothermal time and seeds progress toward germination and emergence according to the specified minimum temperature and water potential thresholds for a given species (Forcella et al., 2000).

The depth of recruitment influences the likelihood of seedling emergence and the timing of emergence (Mohler, 1993; Grundy

Abbreviations: DAP, days after planting; DOY, day of year; SHAW model, Simultaneous Heat and Water model; TT, thermal time; TTψ, hydrothermal time.

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http://dx.doi.org/10.1016/j.agrformet.2013.10.007

and Mead, 1998). Although depth is not a recruitment driver per se, the recruitment response of seeds differ according to their location in the soil profile requiring depth to be quantified as a factor in the recruitment process (Bullied et al., 2012a). The response of seedling emergence to the depth of recruitment can be defined by a nonlinear relationship in which the greatest emergence potential occurs at the soil surface with a logarithmic decrease in emergence with depth in the soil (Grundy et al., 1996). Large seeds are exposed to greater risk of dehydration at the soil surface because they require more time to imbibe water prior to germination compared to small seeds. As a result, the recruitment responses of large-seeded species such as volunteer wheat exhibit a parabolic relationship with depth (Forcella et al., 2000). In this respect, recruitment depth is needed in addition to soil temperature and soil water to predict seedling emergence timing.

Simulated spatial and temporal hydrothermal profiles in the seedling recruitment zone can provide a more complete representation of the recruitment zone to predict seedling emergence timing. Thermal time within the seedling recruitment zone has been used to predict timing of volunteer wheat recruitment from soil temperature measurements (De Corby et al., 2007) and soil temperature simulations (Jame and Cutforth, 2004; Wang et al., 2009a). However, soil water can be more difficult to simulate than soil temperature (Flerchinger and Hardegree, 2004; Wang et al., 2010). Predictions of wheat germination and emergence were not improved when temperature was adjusted by a calculated soil moisture factor, due to the inaccurate simulation of near-surface soil moisture and the calculation of the soil moisture factor (Wang et al., 2009b).

It is not known whether process-based modeling of soil temperature and water can improve upon predictions of wheat emergence timing by temperature alone. To investigate this, hourly soil temperature and water profiles were simulated for a 75 mm depth of the seedling recruitment zone across field topography with the process-driven Simultaneous Heat and Water (SHAW) model (Flerchinger, 2000) using on-site hourly microclimate and soil temperature data, and intermittent (approximately semi-weekly) soil water measurements (Bullied et al., 2014). The objectives of our study were to (1) compare the accumulation of thermal time and hydrothermal time by process-based simulations of soil temperature and water from the SHAW model with that of the measurements for 75 days after planting, (2) validate simulation and measurement models of emergence timing and emergence rate for spring wheat for 60 days after planting, (3) compare simulation and measurement models of recruitment depth for spring wheat, and (4) compare models of emergence timing and recruitment depth using hydrothermal time with that of thermal time.

2. Materials and methods

2.1. Field site

Field plots were established in 2003 and 2004 across field topography within an annually cropped field near 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 1 ha. The northeast facing hillslope was classified as a 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.

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. Soil depth was measured as three 25-mm layers within each plot. Individual plot size was 2 m × 4 m.

The experiment was established on previous soybean (*Glycine max* [L.] Merr.) residue. Residue treatments included the presence or absence of 600 g m^{-2} finely chopped oat (*Avena sativa* L.) straw on a dry weight basis 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. Model description

The Simultaneous Heat and Water (SHAW) model simulates heat and water transfer to a specified depth within a vertical soil column (Flerchinger, 2000). The SHAW model was calibrated with microclimate, vegetative, and soil input data to simulate heat and water movement through the atmosphere–plant–residue–soil continuum for the 75 mm seedling recruitment zone (Bullied et al., 2014). The SHAW model has previously been used to simulate the near-surface soil environment for seedling recruitment predictions (Hardegree et al., 2003; Flerchinger and Hardegree, 2004).

The environment in the soil profile of the SHAW model was represented as a series of 25-mm layers, each defined by a node that was centered within each layer, defined at 0, 12.5, 37.5, and 62.5 mm. The thickness of the surface layer is bounded by the soil surface to midway between the soil surface and the second node. The model simulated temperature and water profiles for the seedling recruitment zone on an hourly basis.

2.3. Thermal time and hydrothermal time

Measured and simulated soil temperatures from Bullied et al. (2014) were each accumulated into thermal time (TT) above a minimum threshold temperature of 0 °C. Soil temperature was also accumulated into hydrothermal time (TTψ) by coupling with soil water potential where thermal accumulation was interrupted by minimum threshold soil water potential (Finch-Savage and Phelps, 1993). For days between intermittent (approximately semi-weekly) soil water potential measurements, where TTψ accumulation was interrupted, precipitation events of 1.5, 1.5, 3.0, and 4.5 mm were used to restart TTψ accumulation for the soil surface, 0–25, 25–50, and 50–75 mm soil layers, respectively. Precipitation amounts of 1.0 mm on the summit to 1.5 mm on the toeslope were needed to increase soil water potential from −1.5 MPa to approximately −0.10 MPa in a 25-mm soil layer, whereas more precipitation was required for the wetting front to reach consecutively lower soil layers. Precipitation events prompted TTψ accumulation for the day of precipitation if the next water measurement was below the water potential threshold, and prompted TTψ accumulation to the next water measurement if the next measurement was above the water potential threshold. The TT and TTψ models were calculated as

$$\mathrm{TT} = \sum_{i=1}^{n} t \quad (1)$$