

## Modeling site-specific wild oat (*Avena fatua*) emergence across a variable landscape

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The spatial and temporal pattern of wild oat emergence in eastern Washington is affected by the steep, rolling hills that dominate this landscape. The objective of this study was to assess the impact of landscape position and crop residue on the emergence phenology of wild oat. Emergence of a natural wild oat infestation was characterized over two growing seasons (2003 and 2004), at two wheat residue levels (0 and 500 g m<sup>-2</sup>), and at five landscape positions differing in slope, aspect, and elevation in a no-till winter wheat field. Wild oat emerged 1 to 2 wk earlier at south-facing landscape positions than at north-facing landscape positions. Crop residue delayed wild oat emergence by 7 to 13 d relative to bare soil at south-facing positions in 2003 and had a reduced effect on emergence at north-facing landscape positions. Therefore, preserving surface residues tended to synchronize emergence across the landscape and may facilitate better timing of weed control where residue is present. Emergence of wild oat was modeled as a function of thermal time adjusted by water potential using a Weibull function. Temperature explained more variation in the model than water potential. This model explained much of the variability in wild oat emergence among landscape positions over these 2 yr and may be useful as a tool to predict the timing of wild oat emergence. Results also indicate that site-specific modeling is a plausible approach to improving prediction of weed seedling emergence.

**Nomenclature:** Wild oat, *Avena fatua* L., AVEFA; winter wheat, *Triticum aestivum* L.

**Key words:** Crop residue, microclimate, site-specific management, soil moisture, soil temperature.

The ability to predict the time of seedling emergence is an important step toward increasing the timeliness and efficiency of chemical and cultural weed control measures (Forcella et al. 1993). Because the intensity of crop–weed competition is affected by the timing of weed emergence relative to the crop phenological development (Blackshaw 1993; Conley et al. 2003; O'Donovan et al. 1985), timely weed control is a key component for maximizing crop yield potential. Controlling weed seedlings that emerge early may help to reduce competition during the critical phase of crop seedling establishment (Black and Dyson 1997), but later emerging cohorts may escape control and contribute to the soil seed bank. Therefore, understanding the factors that regulate the time of weed emergence is crucial for both short- and long-term crop production goals.

The time of weed germination and emergence in the field is influenced by environmental factors, such as, light, soil temperature, soil moisture, and soil atmosphere (Forcella et al. 2000). The response to these environmental factors, however, is modulated by seed age (Rice and Dyer 2001), dormancy (Benech-Arnold et al. 2000), and genetic variation (Naylor and Jana 1976). Soil temperature is often considered the primary environmental factor regulating emergence. Temperature affects the alleviation and induction of dormancy (Symons et al. 1987), and increasing temperatures accelerate germination (Probert 2000) and seedling elongation rate (Carberry and Campbell 1989). The cumulative effect of temperature, expressed as thermal time, has been correlated with the processes of after-ripening (Christensen et al. 1996) and seedling elongation (Oryokot et al. 1997).

Furthermore, the amplitude of diurnal temperature fluctuations stimulates germination in some species by providing an indication of conditions that favor seedling establishment (Benech-Arnold et al. 1988, Thompson et al. 1977).

Moisture can also play a significant role in regulating the pattern of emergence by modulating the effects of temperature on after-ripening. Temperature and moisture interact, such that, as temperature increases, lower seed moisture is needed to achieve maximum after-ripening in wild oat (Foley 1994). In the field, seed moisture content will fluctuate, and full hydration is likely to follow rainfall events. In annual ryegrass (*Lolium rigidum* L.) for example, seed subjected to longer and more frequent hydration lost dormancy faster than seed subjected to shorter or less-frequent hydration events (Gallagher et al. 2004). Furthermore, seed hydration events of 2 or 10 d increased the rate of subsequent after-ripening compared with untreated seed. Therefore, variations in the thermal and hydric conditions within the seed bank may contribute to variability in the observed patterns of seedling emergence.

In agricultural fields, tillage and residue management affect soil temperature, soil moisture, and weed seed distribution in the soil profile. Tillage incorporates crop residues and weed seeds from the surface into the soil profile (Clements et al. 1996; Yenish et al. 1992). Yenish et al. (1992) found that 67% of weed seeds are retained at the soil surface in no-till systems, with seed densities decreasing logarithmically with depth. In contrast, moldboard plowing distributed seeds evenly throughout the top 19 cm of the soil profile. Deeply buried seeds are buffered against temperature

and moisture fluctuations and require longer to emerge compared with seeds at the soil surface (Benvenuti et al. 2000). Similarly, crop residues can also dampen the amplitude of diurnal and seasonal temperature fluctuations, preserve soil moisture, and extend the duration of weed emergence during dry periods (Bristow 1988). As a result, emergence may be delayed if seedlings are being recruited from greater depth (Bullied et al. 2003; du Croix Sissons et al. 2000) or if seeds are covered by residue (Teasdale and Mohler 1993).

Variations in slope, aspect, and elevation can also affect seasonal and diurnal temperature and moisture conditions in the soil seed bank. South-facing slopes receive higher irradiance than north-facing slopes, whereas upslope positions are better drained than footslope positions (Page 2004). In complex landscapes, these variations create a wide range of microsites that can promote site-specific patterns of weed emergence.

Hydrothermal models have been developed to predict the emergence phenology of common agricultural weeds based on seasonal variations in temperature and precipitation (Forcella 1993; Harvey and Forcella 1993; King and Oliver 1994). Air temperatures and precipitation were generally good predictors of seedling emergence in these models, but their accuracy was improved with the incorporation of soil water and soil temperature measurements (Leblanc et al. 2003; Roman et al. 2000). Although it has been demonstrated that hydrothermal emergence models can be parameterized to account for the variable effects of tillage systems on flat landscapes (Roman et al. 2000), it is not clear whether these models can be applied to landscapes with variable topography and soils.

The Palouse region of eastern Washington is characterized by steep, rolling hills with spatially and temporally variable temperature and moisture conditions. It is a highly productive dry-land agricultural region with emphasis in small grain crop production. It offers an ideal natural laboratory for the in situ study of seedling emergence across the microenvironments of a highly diverse landscape. Wild oat is one of the most widely distributed and economically important weed species in this region. Information regarding the influence of landscape position and crop residue on wild oat emergence is lacking. The objectives of this study were (1) to determine the influence of landscape position and crop residue on site-specific temperature, moisture, and wild oat emergence phenology; and (2) to develop a thermal-time model, adjusted for water potential, to predict wild oat emergence.

## Materials and Methods

### Site Description

Field plots were established in November of 2002 and 2003 at the Cook Agronomy Farm (formerly the Cunningham Agronomy Farm), 5 miles northwest of Pullman, WA (46°47'N, 117°5'W). Soils correspond to the Palouse (Pachic-Ultic Haploxeroll)–Thatuna (Oxyaquic Argixerolls)–Naff (Typic Argixerolls) association, with pH of 6.4, organic matter ranging from 1.7 to 4%, and silt loam texture. The topography is typical of the Palouse area of eastern Washington, with an average slope of 11% and elevation ranging from 773 to 815 m. The 30-yr average precipitation for the

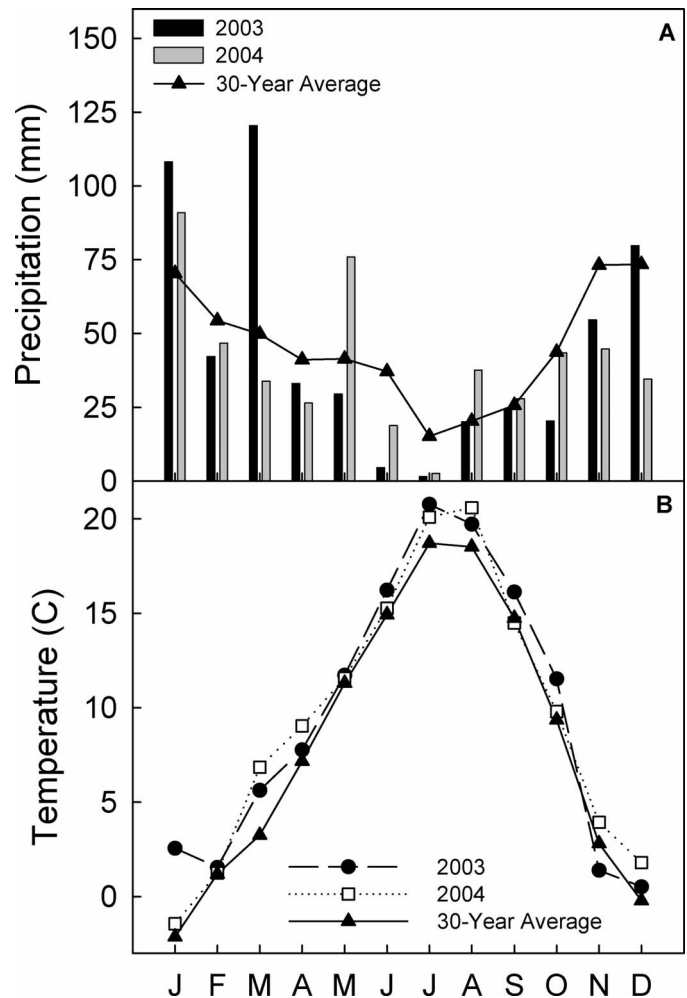


FIGURE 1. (A) Monthly precipitation and (B) mean air temperature in 2003 and 2004 at the U.S. Department of Agriculture–Agricultural Research Service, Palouse Conservation Field Station. Thirty-year averages are shown for reference and are based on the 1971 to 2000 period.

region is 527 mm, with approximately 50% occurring from November to February (Figure 1).

### Field Experiment

Plots were established within a no-till winter wheat crop seeded into spring wheat residue, in a field naturally infested with wild oats. The plots were located at five landscape positions along a north–south transect: south shoulder, south midslope, valley, north midslope, and north shoulder. The elevation difference between the valley and shoulder landscape positions approached 10 m, and the slope gradients for the shoulder, midslope, and valley positions were about 3.5%, 9.5%, and 2%, respectively. Three 8-m<sup>2</sup> plots were established at each landscape position with 10 m between plots. Dry, spring wheat residue from the previous year was removed from all plots. Each plot was divided into two subplots, and residue was uniformly redistributed by hand at a rate of either zero (residue removed) or 500 g m<sup>-2</sup>. A permanent 1-m<sup>2</sup> quadrat was centered within each subplot, surrounded by a 0.5-m buffer zone. From February through June, seedlings of wild oat that emerged within each permanent quadrat were counted weekly and removed with

TABLE 1. ANOVA for the field experiment consisting of the main effects and interactions of landscape position (site), crop residue (res), and time. Wild oat emergence is expressed as cumulative emergence (CE) and cumulative percentage of final emergence (CE%).

Source of variation	2003			2004		
	df	CE <sup>a</sup>	CE%	df	CE	CE%
Block (site)	4	ns <sup>b</sup>	***	4	**	*
Crop residue (res)	1	ns	ns	1	ns	ns
Site × res	4	ns	*	4	ns	ns
<i>Error A = replicate(site × res)</i>		(22.4) <sup>c</sup>	(23.5)		(25.9)	(18.1)
Time	16	***	***	14	***	***
Site × time	64	***	***	56	***	*
Res × time	16	ns	ns	14	ns	ns
Site × res × time	64	ns	ns	56	ns	ns
<i>Error B = residual error</i>		(163)	(161)		(134)	(112)

<sup>a</sup> CE and CE% were log- (CE + 1) and  $2 \times \arcsin(\sqrt{CE\%/100})$ -transformed, respectively.

<sup>b</sup> Abbreviations: ns, not significant; \*\*\*  $P < 0.001$ ; \*\*  $0.001 \leq P < 0.01$ ; \*  $0.01 \leq P < 0.05$ .

<sup>c</sup> Satterthwaite approximation of error degrees of freedom.

minimal soil disturbance. The winter wheat within each quadrat was trimmed back three times to facilitate the evaluation of emergence.

A randomized complete-block design was used to test the effect of crop residue on the emergence phenology of wild oat, where each landscape position represented a block. Within a year, data were compiled as cumulative emergence and cumulative percentage of final emergence, where the last day of sampling served as 100%, and all previous dates were scaled accordingly. Cumulative emergence and cumulative percent emergence were log- and arcsin-transformed, respectively, to correct for nonconstancy error variance (Neter et al. 1996). A mixed model (PROC MIXED)<sup>1</sup> was used to conduct a repeated measures analysis on both variables (SAS 1998; Schabenberger and Pierce 2002). The variability within replicates was modeled as a random effect, and the degrees of freedom were calculated using the Satterthwaite approximation (Satterthwaite 1946) for all tests of fixed effects. We hypothesized that there would be an interaction between landscape position and residue (i.e., block by treatment). Because true replication of a landscape position was not feasible, the three plots within each landscape position were treated as replicates, and all possible interactions were included in the repeated measures analysis (Table 1). As a result, the significance of the landscape effect may have been overestimated as it was tested against the crop-residue error term.

## Environmental Monitoring

Beginning in March 2003, hourly soil temperatures were measured at 2 cm depth in one block of each of the five landscape positions and in each residue subplot, with thermistors connected to a HOBO data logger.<sup>2</sup> In each subplot, water content was monitored in the top 5 cm of the soil profile with a ThetaProbe<sup>3</sup> on a weekly basis throughout the spring. The ThetaProbe measures soil volumetric water content based on the impedance of an alternating current introduced into a fixed volume of soil. In July 2003, the data loggers were removed from the field and reinstalled in November in an adjacent field where winter wheat had been planted for the second year of the study. Soil moisture measurements were resumed when emergence began in the spring of 2004. Air temperatures and precipitation were recorded nearby at the U.S. Department of Agriculture–Ag-

ricultural Research Service (USDA-ARS), Palouse Conservation Field Station (46°45'N, 117°12'W) (Figure 1).

## Seed Bank Estimation

The natural wild oat seed bank was sampled to determine the variance in seed bank size between replicates within a position and among landscape positions themselves. In early March of both years, twenty soil cores (1.9 cm diameter by 10 cm deep) were randomly taken within the buffer zone surrounding each plot. Samples were bulked for each subplot, hydro-elutriated, and the number of wild oats seeds recorded to estimate the size of the seed bank.

## Theory and Model Development

The emergence phenology of wild oat was modeled as a function of cumulative thermal time (cd) adjusted for soil water potential ( $TT_w$ ). This is similar to a traditional thermal-time ( $TT$ ) model, but modified to account for inhibited emergence under dry (low-water potential) conditions. We assumed that  $TT_w$  accumulated according to the temperature and water potential of incubation in relation to the base temperature and base-water potential for wild oat germination. Thus,  $TT_w$  was accumulated on a daily basis as follows:

$$TT_w = TT \times FWP \quad [1]$$

where  $TT$  and  $FWP$  represent thermal-time accumulation and the water-potential adjustment factor, respectively. Thermal time was accumulated hourly according to Campbell and Norman (1998), using a base temperature ( $T_b$ ) of 1 C for wild oat germination (Cousens et al. 1992). The water-potential adjustment factor ( $FWP$ ) restricted  $TT$  accumulation during periods of limiting water according to the following function:

$$FWP = \begin{cases} 1, & \text{for } \psi_{soil} \geq \psi_{FC} \\ 0, & \text{for } \psi_{soil} \leq \psi_b \\ 1 \xrightarrow{\text{linear}} 0, & \text{for } \psi_{FC} \leq \psi_{soil} \leq \psi_b \end{cases} \quad [2]$$

where  $\psi_{soil}$ ,  $\psi_{FC}$ , and  $\psi_b$  represent the soil water potential, the water potential at field capacity, and the base-water potential for wild oat germination, respectively. A  $\psi_b$  of -1.2 megapascal (MPa) was determined in the laboratory using

nondormant wild oat and  $\psi$  imposed by polyethylene glycol solutions (PEG8000)<sup>4</sup> (Page 2004). Daily  $\psi_{soil}$  for *FWP* were linearly interpolated from weekly data. Soil water potential was calculated from soil water content  $\theta_v$  using the following equation, developed for no-till Palouse silt loam (Kenny 1990):

$$\psi_{soil} = 2 \times 10^{-3}(\theta_v/0.49)^{-4.4}. \quad [3]$$

In both years,  $TT_w$  accumulation was initiated after late-fall rains in mid-November. However, because soil temperatures were not monitored on site from mid-November 2002 to March 2003,  $TT_w$  was estimated using daily maximum and minimum soil temperature at 10 cm recorded at a nearby weather station. Thermal time was cumulated each day by prorating the degree-days between the daily maximum ( $T_x$ ) and minimum ( $T_n$ ) temperatures that were above  $T_b$ . To estimate  $T_x$  and  $T_n$  at 2 cm from the daily air and soil temperatures, the following equation was used:

$$T(2) = T_{mean} \pm A(0)^{(-2/D)} \quad [4]$$

where  $T_{mean}$  is the mean daily soil temperature and  $A(0)$  is the amplitude of the temperature wave at the soil surface (Campbell and Norman 1998); the latter was approximated using daily air temperatures. The damping depth ( $D$ ) was calculated following Campbell and Norman (1998).

For each treatment, the cumulative percent emergence as a function of  $TT_w$  was modeled using a modified Weibull function (Dumur et al. 1990):

$$p(t) = \begin{cases} 0, & t < t_0 \\ 1 - \exp\left[-\left(\frac{t - t_0}{a}\right)^b\right], & t \geq t_0 \end{cases} \quad [5]$$

where  $p(t)$  is the expected cumulative emergence (%) at time  $t$ ;  $t_0$  is the  $TT_w$  for initial emergence;  $a$  is a scale parameter; and  $b$  is a shape parameter. The observed cumulative emergence (%),  $y(t)$ , was modeled as a binomial variable (i.e.,  $y(t) \sim \text{BIN}[n, p(t)]$ ). The parameters  $t_0$ ,  $a$ , and  $b$  were estimated by the maximum-likelihood method, using the *nlminb* procedure of S-Plus.<sup>5</sup> The binomial distribution was chosen because of the biological and probabilistic interpretation of emergence and also to accommodate the nonhomogeneity of error variance found in the data set. The valley position in 2004 was excluded during model fitting because of the very low emergence ( $< 1$  seedling  $\text{m}^{-2}$ ).

## Results and Discussion

The interaction of landscape position with time was highly significant for cumulative emergence and cumulative percent emergence in both years (Table 1). Cumulative wild oat emergence displayed differences in both the timing of initial emergence and the total number of seedlings emerged among landscape positions and years (Figure 2). In 2003, emergence at the two south-facing landscape positions began in mid to late March, 7 d before the valley, north shoulder, and north midslope positions. Initial emergence in 2004 was first observed at the south midslope in late March, followed a week later by the south shoulder and north midslope positions. The timing of final emergence was similar among landscape positions and was reached in mid-May in 2003 and in early June in 2004. Final wild oat emergence was variable among landscape positions and years, ranging from

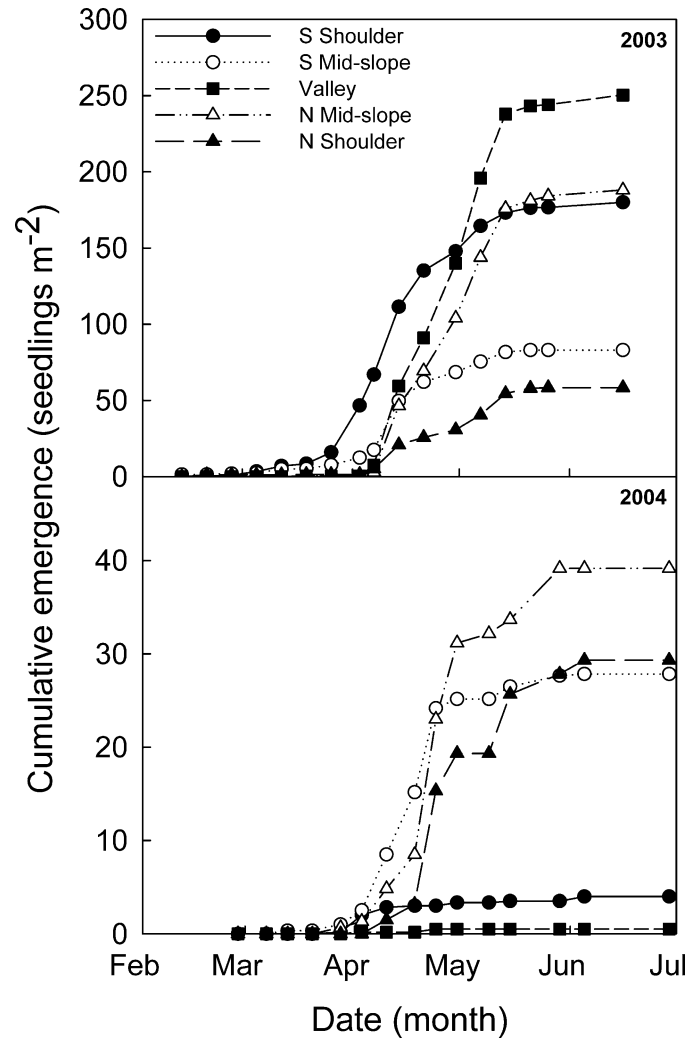


FIGURE 2. Cumulative wild oat emergence as a function of landscape position in 2003 and 2004 on the Cook Agronomy Farm. Values are averaged across residue treatments.

7 to 568 seedlings per subplot (1  $\text{m}^2$ ) in 2003 and from 0 to 95 seedlings per subplot in 2004.

The size of the wild oat seed bank also varied among landscape positions and between years, ranging from 191 to 588 seed  $\text{m}^{-2}$  in 2003 and from 15 to 250 seed  $\text{m}^{-2}$  in 2004 (Table 2). No clear relationship was evident between seed-bank size and recruitment, when examined across landscape positions and years (no statistical analysis performed). The very low emergence at the valley and south-shoulder positions in 2004 (Figure 2) was probably due to the small seed-bank size (Table 2).

## Landscape Position and Emergence

Landscape position was the main factor contributing to variability in wild oat emergence in 2003 and 2004 (Table 1). Emergence and thermal accumulation were initially pooled across residue levels (Table 1). The landscape positions fell into two distinct groups in 2003: (1) the earlier-emerging south-facing landscape positions, and (2) the later-emerging north-facing and valley positions (Figure 3A). The gap between the emergence response curves of these groups (Figure 3A) narrowed when percent emergence was plotted

TABLE 2. Wild oat seed-bank size (0 to 10 cm depth) and seedling recruitment in 2003 and 2004. Seedling recruitment represents final emergence as a percentage of seed-bank size. Recruitment and seed-bank values were averaged across two residue treatments and three replicates and are followed by their standard error (SE).

Position	Seed bank size		Seedling recruitment	
	2003	2004	2003	2004
	seeds m <sup>-2</sup> ± SE		% ± SE	
South shoulder	500 ± 188	30 ± 29	30 ± 14	37 ± 32
South midslope	367 ± 39	59 ± 15	24 ± 8	41 ± 13
Valley	397 ± 176	15 ± 14	53 ± 15	34 ± 33
North midslope	588 ± 236	206 ± 96	44 ± 16	23 ± 4
North shoulder	191 ± 29	250 ± 140	35 ± 14	25 ± 12

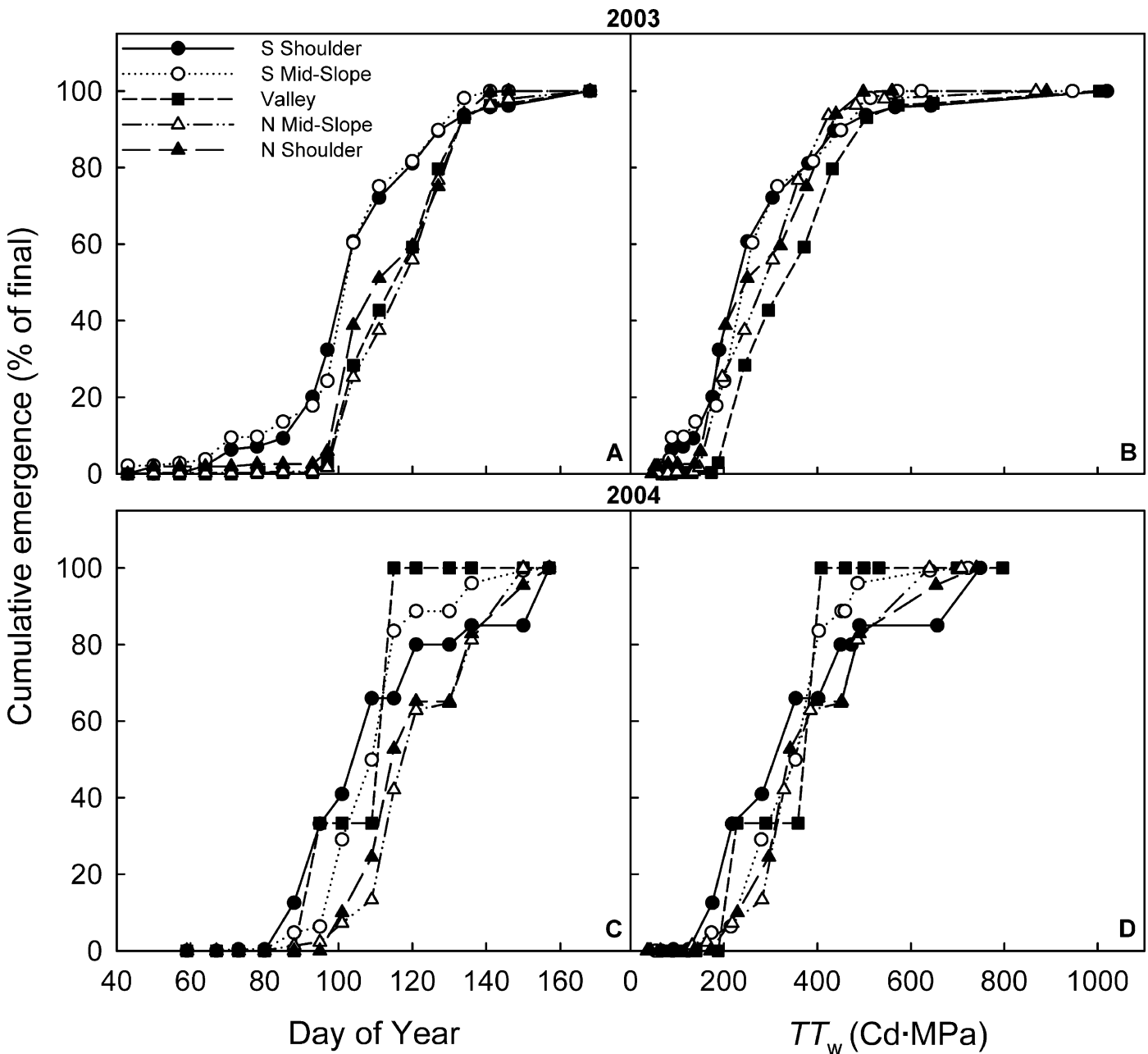


FIGURE 3. Cumulative percentage of wild oat emergence as a function of (A and C) calendar time and (B and D) thermal time adjusted by water potential ( $TT_w$ ) in 2003 and 2004. Values represent means pooled across residue treatments. Units of thermal time adjusted for water potential were averaged across levels of residue and cumulated above  $T_b = 1$  C and  $\psi_b = -1.2$  MPa.

against  $TT_w$  (Figure 3B). This indicates that temperature and moisture differences among landscape positions (Page 2004), as accounted for by  $TT_w$ , explain part of the variation in emergence among landscape positions. Emergence was delayed at the valley positions relative to all other landscape positions on the basis of  $TT_w$ , suggesting that another variable was slowing emergence at that position.

Valley positions in 2003 and 2004 were positioned to border the seasonal drainage paths that carry surface water to the field edges. As a result, these positions had higher soil water content and dried out later in the spring than all other landscape positions (Page 2004). Valley positions were sometimes covered by standing water on the day following a heavy spring rain (E. R. Page, personal observation). It is likely that these periods of high soil water contributed to the delay in wild oat emergence from the valley in 2003 (Figures 3A and 3B).

Early emergence at south- and north-facing positions overlapped in 2004, but the speed of emergence thereafter was greater at south-facing positions (Figure 3C). As in 2003, the gap between the emergence response curves of the southern and northern positions (Figure 3C) was reduced when emergence was expressed against  $TT_w$  (Figure 3D). However, the response at the valley position in 2004 was erratic because of the small seed bank (Table 2) and extremely low emergence at that location ( $< 1$  seedling  $m^{-2}$ , Figure 2). Consequently,  $TT_w$  was also unable to account for the pattern of emergence from the valley position in 2004 (Figure 3D), as in 2003 (Figure 3B). Wild oat emergence at the valley position, plotted as a function of thermal time, was delayed relative to the other positions in both years and in a parallel study with an artificial wild oat seed bank (Page, 2004).

Wild oat emergence from flooded soils may be hindered by reductions in the soil-oxygen tension. For instance, wild oat germination was reduced from 90 to 10% after only 9 h under anoxic conditions (Symons et al. 1986). Crop-development models have used soil water-filled pore space (WFPS) to standardize the effects of soil water content and oxygen diffusion on biological processes (Skopp et al. 1990). WFPS is calculated from the soil bulk density, particle density, and water content. Although it is unlikely that our weekly soil moisture determinations would have coincided with the relatively brief periods of flooding, we hypothesize that a water-content adjustment factor, based on WFPS, would help to account for the pattern of wild oat emergence observed from valley positions. Future research should focus on establishing the effect of soil physical parameters and the soil atmosphere on the emergence response of wild oats; continuous monitoring of soil moisture appears to be crucial for obtaining a more accurate model.

### Crop Residue and Emergence

Crop residue delayed wild oat emergence at several landscape positions in 2003 (Tables 1 and 3) but did not significantly affect final wild oat emergence in either year (Table 1). It has previously been suggested that crop residues may delay emergence by dampening the amplitude of soil-temperature fluctuations and reducing soil temperature (Teasdale and Mohler 1993). Crop residue significantly influenced the site-specific pattern of wild oat emergence in 2003 (Table 1). The lack of a measurable response to crop

TABLE 3. Relative days after emergence (DAE) for 25 ( $E_{25}$ ), 50 ( $E_{50}$ ), and 75% ( $E_{75}$ ) of weed seeds under two wheat residue levels (0 and 500  $g\ m^{-2}$ ) at the south-shoulder, south-midslope, valley, north-midslope, and north-shoulder position. DAE was relative to the landscape position and residue combination that reached  $E_{25}$  first.  $E_{25}$  was first reached in bare soil (0  $g\ m^{-2}$  residue) at the south-midslope position on March 31st, 2003.

Position	$E_{25}$		$E_{50}$		$E_{75}$	
	0	500	0	500	0	500
	DAE					
			1			
South shoulder	4	11	5	23	25	37
			1			
South mid-slope	0	13	3	21	26	31
			3			
Valley	22	19	3	26	44	36
			3			
North mid-slope	21	24	1	33	42	42
			2			
North shoulder	18	19	8	32	39	46

residue in 2004 may be because of the small seed-bank size and the reduced seedling emergence in 2004 compared with 2003 (Table 2; Figure 2). The interaction of crop residue and landscape position in 2003 indicated that residue at the south-facing landscape positions delayed initial emergence relative to bare soil (Table 3). Initial emergence, measured as the date of 25% emergence ( $E_{25}$ ), was delayed 7 to 13 d at the south-facing positions but only 1 to 3 d at the north-facing positions in 2003 (Table 3). Results were similar when measured as either  $E_{50}$  or  $E_{75}$ . Because soil moisture was not limiting in spring 2003 (Figure 1), we attribute crop residue responses at south- and north-facing positions to temperature effects (Figures 4A and 4B; Page 2004).

Soil temperature during the month of March appears to be particularly important in determining the timing of wild oat emergence. The mean soil temperature in March was similar among residue levels within a landscape position (Figure 4A).  $TT_w$  accumulation in bare soil in late March exceeded that under residue by an average of 2 Cd and 7 Cd at the north- and south-facing positions, respectively. Although it is likely that the differences in  $TT_w$  at south-facing positions contributed to the earlier emergence from bare soil, the relative impact of such a slight difference in  $TT_w$  on the timing of wild oat emergence is probably small, particularly when compared with the effect of landscape position on  $TT_w$  and emergence. This suggests that  $TT_w$  alone may not account for the residue interaction detected in 2003 (Table 1). Thermal amplitude can also influence dormancy and stimulates germination in several weed species (Benech-Arnold et al. 1988; Martinez-Ghersa et al. 1997). In March 2003, the mean thermal amplitude at south-facing landscape positions was greater in bare soil than under crop residue (Figure 4B). Conversely, the thermal amplitude at north-facing position was similar between residue levels over the same period. Thus, our results suggest that greater thermal amplitude in bare soil may have contributed to earlier wild oat emergence in those plots relative to crop-residue plots at south-facing positions. In contrast, Carmona and Murdoch (1995) found that cool, constant temperatures promoted greater germination in wild oat than higher, alternating temperatures. Although it is clear that crop resi-

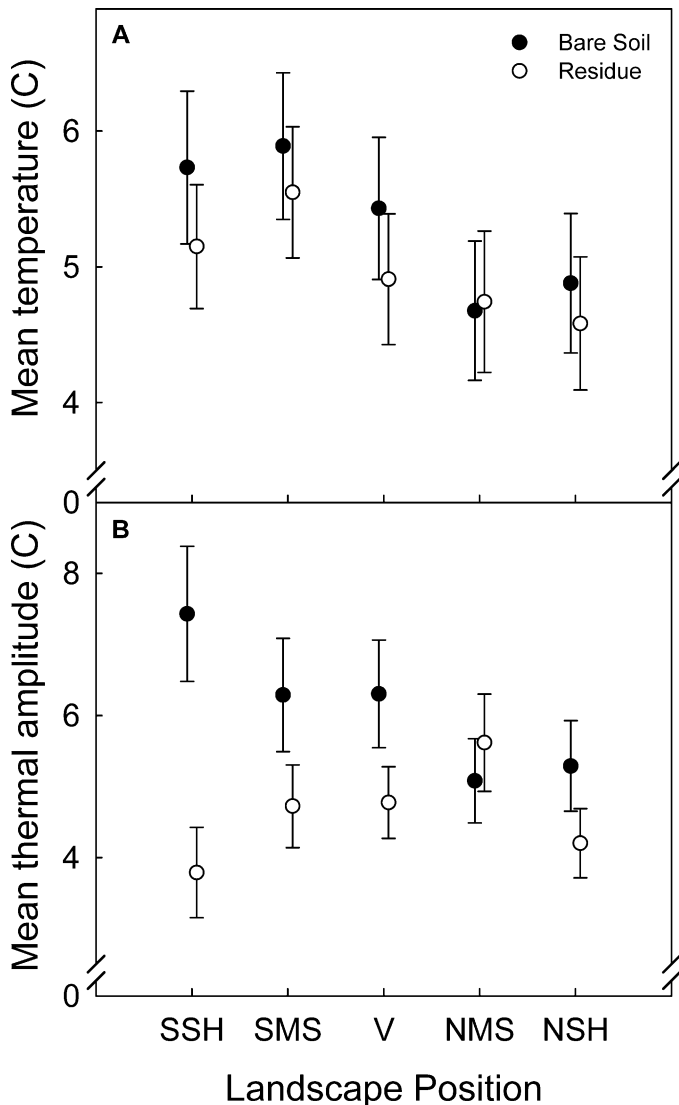


FIGURE 4. (A) Mean soil temperature and (B) thermal amplitude ( $\pm$  SE) in March 2003 from two residue levels, at five landscape positions: south shoulder (SSH), south midslope (SMS), valley (V), north midslope (NMS), and north shoulder (NSH). Thermal amplitude was calculated by subtracting the daily minimum temperature from the daily maximum temperature and averaging across days.

dues can modify microclimate and influence wild oat emergence phenology, further research is needed to elucidate the effect of thermal amplitude on wild oat germination and emergence in the field.

Wild oat emergence from the valley occurred earlier under residue than from bare soil, in contrast to north- and south-facing positions (Table 3). The emergence response from the valley was likely influenced by periods of very high soil moisture, as was previously discussed; however, it is unclear why crop residue would accelerate emergence under these conditions. Nevertheless, the results indicate that, in 2003, maintaining crop residue increased the synchronicity of wild oat emergence, relative to bare soil, by causing a greater delay in emergence at south-facing than north-facing positions and by accelerating emergence at the valley position. It is possible that residue may allow increased control of the wild oat population by a single, more-timely control

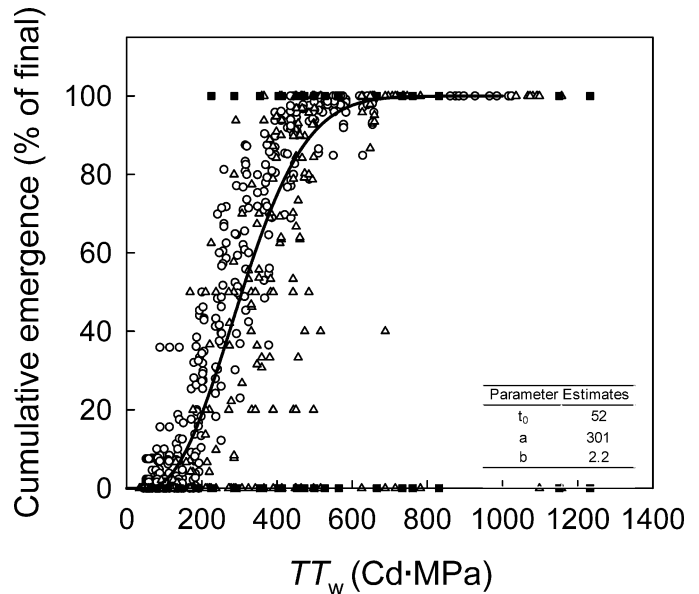


FIGURE 5. Cumulative percentage of wild oat emergence (CE%) from all positions in 2003 ( $\circ$ ), from the valley position in 2004 ( $\blacksquare$ ), and from all other positions in 2004 ( $\triangle$ ) as a function of thermal time adjusted by water potential ( $TT_w$ ). Results represent all observations for all subplots at all observation times ( $n = 960$ ). The Weibull function (—),  $p(t) = 1 - \exp\{-[(TT_w - t_0)/a]^b\}$ , and parameter estimates presented are based on the results from both years, with the exception of the valley in 2004 ( $n = 870$ ).

measure if this phenomenon of synchronization of emergence by residue can be validated by additional research.

### Modeling Wild Oat Emergence

Our  $TT_w$  model accounted for much of the variability in the pattern of wild oat emergence across landscape positions and years (Figure 5). All data points from both years are presented (Figure 5). The fitted Weibull function excluded the results from the valley position in 2004. We chose to exclude the results from that position in 2004 (plotted separately in Figure 5) because of the very low number of emerged seedlings (Figure 2) and consequent erratic emergence curve for that position (Figures 3 and 5). Furthermore, the model parameters did not change when the results from all positions and years were included in the model fitting. This suggests that the results from the valley position in 2004 did not influence model fitting, but rather, their inclusion only diluted the correlation between the fitted function and observed values.

In contrast to previous thermal-time functions, in which  $TT$  began accumulating in the spring (Finch-Savage and Phelps 1993, Roman et al. 2000), we chose to initiate thermal accumulation after late-fall rains, in mid-November. This date was chosen to be representative of seed hydration and, thus, the start of after-ripening for newly shed wild oat seed, although it is likely that short seed-priming events occurred before  $TT$  initiation. As a result, we were able to account for differences in the rate of  $TT$  accumulation among landscape positions during the winter months. During the period from mid-November through the end of February,  $TT$  accumulation at south-facing positions (40 Cd) was double that at north-facing positions (20 Cd). Although it is unclear which biological process this additional  $TT$  may have affected, it was an important component contributing

to the initiation of early emergence at south-facing landscape positions (Figure 3).

Soil water potential was a minor factor, compared with temperature, in modeling wild oat emergence. Soil water potential never fell below  $\psi_b$  in 2003, and remained near field capacity during the emergence period due to high precipitation in March 2003 (Figure 1). However, soil moisture declined during April and early May of 2004, with  $\psi_{soil} < \psi_b$  for a period of 1 or 2 wk, depending on landscape position. Inclusion of the soil-moisture component to our model is justified on a theoretical basis but, in practice, did not improve the model fit. Emergence rate appeared to be unaffected, even during the period when moisture was lower than required for germination (data not shown). It is possible that seeds had already germinated and thus only the emergence process was involved. In addition, it is possible that seed moisture levels do not immediately decrease in accordance with soil moisture levels.

Mechanistic hydrothermal models have been produced to describe the physiological processes of dormancy release (Bauer et al. 1998; Christensen et al. 1996; Gallagher et al. 2004), germination (Roman et al. 1999), and emergence (Roman et al. 2000). Although these models have had some success, they are time-consuming to produce and may be sensitive to the seed accession used during development (Forcella et al. 2000). In contrast, empirical relationships, such as the one described herein, are more easily developed and may offer the simplicity and flexibility needed for field-based applications (Grundy 2003). By producing a single response curve (Figure 5), we have knowingly oversimplified the processes of dormancy release, germination, and emergence. As a result, our model does not allow for the allotment of specific quantities of  $TT_w$  for the completion of each physiological process. However, as the natural seed bank is comprised of seeds that vary in age, vigor, and dormancy, it is likely that these seeds would possess a diversity of  $TT_w$  requirements for dormancy release, germination, and emergence. Rather, the empirical relationship that we report here allows for the wide range of responses that would be expected within a biologically diverse, natural seed bank.

Considering the range of microclimate conditions provided by the diversity in both landscape position and level of crop residue, the  $TT_w$  relationship developed herein appears to be a reasonable representation of the emergence phenology of wild oat in the Palouse region over a 2-yr period and over a range of microsite conditions. Further validation of this model at other sites is needed to allow the development of decision-support systems. However, until such a system is developed, preferentially scouting south-facing landscape positions for the first signs of emergence may provide a benchmark from which to forecast the peak emergence across the landscape. These results also highlight the impact of microsite diversity on the pattern of wild oat emergence and emphasize the importance of measuring or estimating site-specific environmental parameters when developing models to predict emergence across a terrain with variable soils and topography.

## Sources of Materials

<sup>1</sup> SAS Institute, Inc., 100 SAS Campus Drive, Cary, NC 27513-2414.

<sup>2</sup> HOBO H8 Outdoor/Industrial data logger, Onset Computer Corporation, 470 MacArthur Boulevard, Bourne, MA 02532.

<sup>3</sup> ThetaProbe ML2x, Delta-T Devices, 128 Low Road, Burwell, Cambridge CB5 0EJ, U.K.

<sup>4</sup> Polyethylene glycol (PEG) 8000 crystalline powder, Mallinckrodt Baker, Inc. 222 Red School Lane, Phillipsburg, NJ 08865.

<sup>5</sup> S-Plus 6.2 for Windows, S-Plus Statistical Software, Insightful Corp. 1700 Westlake Avenue, North Seattle, WA 98109-3044.

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