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Control of Cereal Rye with a Roller/Crimper as Influenced by Cover Crop Phenology

Steven B. Mirsky,* William S. Curran, David A. Mortensen, Matthew R. Ryan, and Durland L. Shumway

ABSTRACT

Adoption of reduced tillage practices have been driven by the need to enhance soil quality, minimize field labor time, and scale up farm size. However, concerns about increased reliance on herbicides and demand for organically grown foods call for adoption of production practices that can reduce both tillage and herbicide use. This research study assessed the influence of planting and termination dates on mechanical cover crop control efficacy to limit tillage and herbicide use using a roller/crimper. A thermal-based phenological model using growing degree days (GDD; base 4.4°C) was developed to predict cereal rye (*Secale cereale* L.) growth stage. Mechanical control of cereal rye increased as rye matured. Variations in cereal rye cultivar growth rates were observed; however, they responded similarly to rolling when terminated at the same growth stage. Consistent control was achieved at a Zadoks growth stage 61 (rye anthesis). A thermal-based phenological model separating the effects of heat units accumulated in the fall ($Fall_{GDD}$) from those accumulated in the spring ($Spring_{GDD}$) best predicted the phenological development of cereal rye. Predicting when cereal rye can be successfully controlled using a roller/crimper along with the use of the thermal-based phenological model should aid growers in decision-making regarding cereal rye planting and termination dates.

The shift toward conservation tillage (e.g., no-till) has improved soil physical, chemical, and biological properties, all indicators of soil quality (Uri, 2000). Increased adoption of no-till has been facilitated in part by the introduction of herbicide-resistant crops and the accompanying use of effective and affordable broad spectrum herbicides (Raimbault et al., 1990; Curran et al., 1996; Young, 2006). Indeed, the widespread adoption of herbicide-resistant crops and no-tillage methods has resulted in an increase in glyphosate [2-(phosphonomethylamino) acetic acid] use (USDA–National Agricultural Statistics Service, 2004; Young, 2006), and a subsequent increase in glyphosate-resistant weeds (Preston, 2004; Dauer et al., 2007). At the same time, herbicides continue to be the most commonly detected pesticide group in both surface and groundwater (Gilliom et al., 2007). These herbicide-related concerns, coupled with the demands of a rapidly growing organic crop production sector (Liebman and Gallandt, 1997; Organic Farming Research Foundation, 1998), requires a focus on maintaining crop protection in minimum tillage systems while reducing reliance on herbicide use.

Cover crops represent a cropping practice that has the potential to reduce herbicide reliance and minimize tillage while improving soil fertility (Decker et al., 1994), reducing soil erosion (Langdale et al., 1991), sequestering soil carbon (Sainju et al., 2002), increasing soil water infiltration and storage (Munawar et al., 1990), and suppressing weeds (Teasdale and Daughtry, 1993). At present, a number of federal and state departments of agriculture and environment are offering incentives to adopt winter cover crops to help reduce soil loss, and improve surface and groundwater quality (Resource Enhancement and Protection Act of Pennsylvania, 2007; MDA, 2008).

Cereal rye is a winter annual cover crop widely used throughout the United States because of its winter hardiness, high biomass production, and recalcitrant residue (Hoffman et al., 1993; Wilkins and Bellinder, 1996). Additionally, compared with other cereal grains, cereal rye produces the greatest levels of biomass and is more easily integrated into crop rotations because it matures more rapidly, allowing earlier establishment of the following cash crop (Stoskopf, 1985). Cereal rye cover crops also serve as a "catch crop" or sink for nutrients allowing more to be retained from field applied manure applications.

In the absence of herbicides, cereal rye cover crops are typically terminated with tillage or with mowing when no-tillage is desired. In conservation tillage systems, mowing has several drawbacks including the risk of regrowth, accelerated residue decomposition, and patchy distribution of the surface residue (Wilkins and Bellinder, 1996; Creamer and Dabney, 2002). Uniformity of coverage of surface soil from cover crop residue is critical for optimizing weed suppression (Teasdale and Mohler, 2000). A roller/crimper represents a viable alternative to mowing and tillage (Fig. 1). With this implement, the residue is deposited uniformly on the soil surface. In contrast to mowing, the resulting layer of rye residue persists for a longer

S.B. Mirsky, Sustainable Agricultural Systems Laboratory, USDA–Agricultural Research Service, 10300 Baltimore Ave., Bldg. 001, Rm. 117, BARC-W, Beltsville MD 20705; W.S. Curran, D.A. Mortensen, and M.R. Ryan, Dep. of Crop and Soil Sciences, Pennsylvania State Univ., 116 Agricultural Sciences and Industries Bldg., University Park, PA, 16802; D.L. Shumway, Dep. of Statistics, Pennsylvania State Univ., 326 Thomas Bldg., University Park, PA, 16802. Received 15 Apr. 2009. *Corresponding author (steven.mirsky@ars.usda.gov).

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Abbreviations: AIC, Akaike information criterion; GDD, growing degree days; EG, effective growth stage.

Fig. 1. Photograph of a front-mounted roller/crimper constructed by Pennsylvania State University. The roller/crimper is 3.2 m in length by 51 cm diameter by 3.2 mm thickness and weighs 1520 kg.

period enhancing weed suppression, moisture retention, and soil conservation (Creamer and Dabney, 2002; Morse, 2001).

The susceptibility of cereal rye to mechanical control is dependent on growth stage (Creamer and Dabney, 2002). Although little research has centered on evaluating control of cereal rye with a roller/crimper, previous work has shown that control of cereal cover crops improves with increasing plant maturity (Ashford and Reeves, 2003). However, much of this work assumes a fixed fall planting date. Experiments in which fall planting and spring termination dates are varied would allow for testing mechanical control of cereal rye with a roller/crimper across a continuum of growth stages.

Practical decision support tools are needed that use phenological models to accurately predict cover crop developmental stage. Such forecasting tools could be used to estimate timing of spring cover crop termination and also aid in crop rotation planning. Environmentally driven (i.e., temperature, photoperiod, and soil moisture) phenological models have been developed to aid growers in crop cultivar and field selection, insect and plant disease forecasting (Wang, 1960), and more recently for weed emergence prediction (Forcella et al., 2000; Myers et al., 2004). Extending phenological models to include cover crops will provide needed decision support for farmers.

Cereal grain crop phenology depends on temperature and photoperiod (Travis et al., 1988; Mirschel et al., 2005); however, soil moisture and N limitations can accelerate cereal development (Davidson and Campbell, 1983; Mirschel et al., 1995). Historical use of these models in cereals has centered on yield prediction (Yan and Wallace, 1998; Porter and Gawith, 1999; Streck et al., 2003). Additional models have been developed to predict cereal biomass accumulation, which is strongly influenced by soil moisture and N availability (Feyereisen et al., 2006). As a result, mechanistic models were employed to incorporate plant physiological processes and extend the inference domain of the models. However, simple descriptive phenological models provide a practical alternative where prediction of grain development is not required. Making such models relational with growth stage would provide a useful decision framework for determining the optimum dates for fall planting and spring termination. Therefore, the goals of this study were to (i) determine the susceptibility of cereal rye to rolling/crimping over a range of growth stages; (ii) determine if rye suppression is influenced by fall planting date; and (iii) evaluate the relationship between cereal rye phenological development and thermal time with thermal-based predictive models.

METHODS

Cereal rye suppression experiments were conducted from 2004 to 2006 at the Russell E. Larson Agricultural Research Center near Rock Springs, PA (40°44′ N, 77°57′ W) where 'Aroostook' and 'Wheeler' cultivars were grown and rolled with a roller/crimper. The experimental design was a modified split-plot arranged with cover crop cultivar (two cultivars) and termination date (four termination dates) as main plots and date of fall establishment (six planting dates) as subplots. Planting date was nested within cultivar treatments and the experiment was replicated four times. Individual subplots were 1.5 by 2.3 m. The experiment was initiated in the fall of 2004 and repeated again in 2005 in an adjacent field. The study was conducted on a Hagerstown silt loam soil (fine, mixed, mesic Typic Hapludalfs) with a soil pH of 6.5 and organic C content of 20 g kg^{-1}. Aroostook was selected because of its winter hardiness and common use in the region and Wheeler because it is reported to retain more allelochemicals with maturation than other rye cultivars and therefore may be more weed suppressive (Reberg-Horton et al., 2005). Cereal rye was seeded six times on 10-d intervals from 25 August to 15 October (±2 d). The following spring, cover crops were rolled/crimped on 10-d intervals from 1 to 30 May (four termination dates). In both years, the previous crop was spring-planted oat (*Avena sativa* L.) that was disked and cultimulched before planting. Rye was seeded in 19-cm rows at 126 kg ha^{-1} using a 1.8 m wide Great Plains (3P605NT) small-plot drill. Ammonium sulfate was broadcast-applied at a rate of 71 kg N ha^{-1} in March of each year to stimulate rye growth and development to ensure a competitive cover crop.

The roller/crimper used in this experiment was manufactured from cylindrical steel well casing material (3.2 m length by 51 cm diameter by 3.2 mm thickness) with metal slats spaced 10.2 cm apart and welded onto the cylinder in a chevron pattern (after Ashford and Reeves, 2003, see Fig. 1). The roller/crimper weighed 1520 kg and was front mounted to a tractor. The tractor was driven at 7.2 km h^{-1}, rolling the rye perpendicular to the direction of sowing, thereby laying the cover crop down in a unidirectional pattern. Soybean [*Glycine max* (L.) Merr.] (Chemgro 3340) was no-till drilled (432,400 seeds ha^{-1}) into the cereal rye residue in 19-cm rows 10 d after the cover crop was rolled. Soybean was planted with a Great Plains (1006NT) no-till drill in the same direction as the rye was rolled.

Growing degree days and precipitation (Fig. 2 and 3) are based on climate data recorded at a weather station located within 0.25 km of the experiment. Supplemental irrigation (2 cm in May 2005 and 2.5 in May and June 2006) was provided to ensure soybean establishment. Cover crop growth stage was assessed within sub-subplots at each termination date using the Zadoks decimal plant development scale (Zadoks et al., 1974). Cereal rye control (% rye mortality) was determined 6 wk after each termination date using a visual rating where a score of 0%

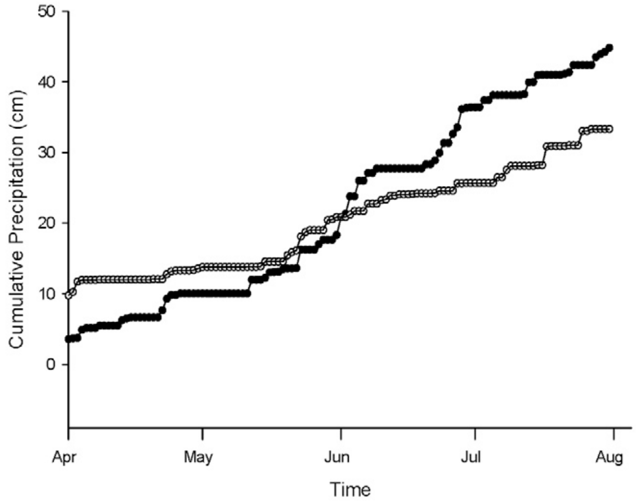

Fig. 2. Cumulative daily precipitation for 2005 (closed circles) and 2006 (open circles) in Rock Springs, PA, for the 2005 and 2006 cropping seasons.

represented no control and 100% complete control relative to the untreated control plots.

Cereal Rye Phenology and Percentage Control

Cereal rye control (%) over a range of cereal rye growth stages was modeled with the following three parameter logistic model (adapted from Ritz and Streibig, 2005):

$$Y = \frac{d}{1+\exp\{b[\log(x)-\log(e)]\}} \qquad [1]$$

where Y is cereal rye control (%); d is the % control at the upper growth stage limit; e is the growth stage producing a response half-way between d and the lower limit (rye growth stage at which 50% control is achieved); b is the slope around e; and x is the growth stage. In the three-parameter logistic function, the lower limit is equal to zero. The effective cereal rye control threshold was set at 85%. The 85% level was chosen as a the inter-specific competition threshold based on the common industry standard for acceptable weed control using herbicides and is hereafter referred to as the effective growth stage 85 (EGS85); specifically when the lower range of the standard error interval is greater than the 85% control threshold. This is analogous to the term effective dose commonly used when evaluating herbicide efficacy with dose response models (Ritz and Streibig, 2005).

Thermal time, using growing degree days, was used to predict growth stage using regression models. Growing degree days (GDD) were calculated using the following equation:

$$\mathrm{GDD} = \frac{\mathrm{T_{max}} + \mathrm{T_{min}}}{2} - \mathrm{T_{base}} \qquad [2]$$

where T_{max} is the maximum daily temperature, T_{min} the minimum daily temperature, and T_{base} the base temperature set at 4.4°C (Nuttonson, 1958). Cumulative GDD is the summation of daily GDDs between planting and termination dates (Fig. 3). The phenological models used to predict cereal

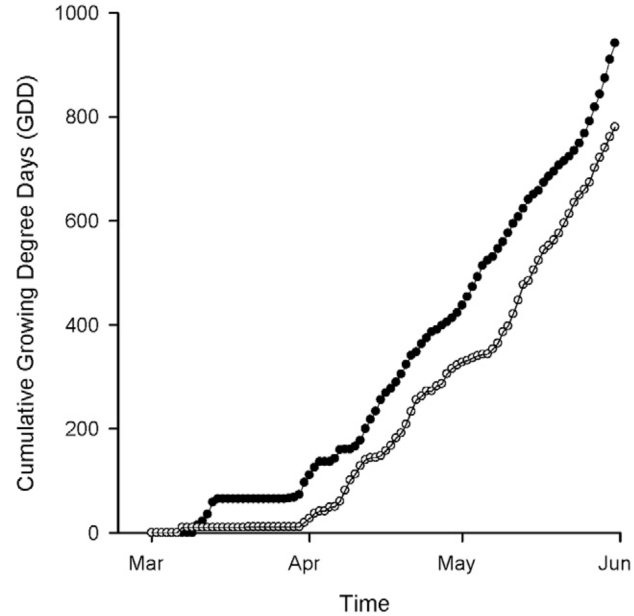

Fig. 3. Cumulative daily growing degree days (GDD) for 2005 (open circle) and 2006 (closed circles) in Rock Springs, PA, for the 2005 and 2006 cropping seasons. Growing degree days were calculated by the following equation: GDD = $[(T_{max} + T_{min})/2] - T_{base}$, where T_{max} is the maximum daily temperature, T_{min} the minimum daily temperature, and T_{base} is the base temperature (4.4°C) (Nuttonson, 1958).

rye growth stage were structured in one of three ways. One was driven solely by cumulative heat units in the spring starting 1 March (Nuttonson, 1958) and ending at the date of rolling ($\mathrm{Spring_{GDD}}$); one by cumulative heat units from the fall starting at rye planting plus the spring ($\mathrm{Total_{GDD}}$); and one by the separate effects of spring and fall heat units ($\mathrm{Fall_{GDD}}$ and $\mathrm{Spring_{GDD}}$). The $\mathrm{Spring_{GDD}}$ and $\mathrm{Total_{GDD}}$ models are commonly used to evaluate crop growth and development (Nuttonson, 1958; Teasdale et al., 2004). The $\mathrm{Fall_{GDD}}$ and $\mathrm{Spring_{GDD}}$ model was included because timing of fall cereal rye planting can influence the development of cereal rye (Fowler, 1982, 1983). Growth stage data collected in the sub-plots were fitted with linear regression using the following thermal-based phenological models:

$$\text{Growth stage} = b_0 + b_1(\mathrm{Spring_{GDD}}) \qquad [3]$$

$$\text{Growth stage} = b_0 + b_1(\mathrm{Total_{GDD}}) \qquad [4]$$

$$\text{Growth stage} = b_0 + b_1(\mathrm{Fall_{GDD}}) + b_2(\mathrm{Spring_{GDD}}) \qquad [5]$$

where growth stage is the Zadoks developmental stage, β_0 is the intercept, β_i are parameter coefficients defining the slope of the equation and the proportional relationship between $\mathrm{Fall_{GDD}}$ and $\mathrm{Spring_{GDD}}$.

Data Analysis

Analysis of variance was conducted using the MIXED procedure in SAS/STAT (SAS Institute, 2004) to test the effects of year, cultivar, and planting and termination dates on control of cereal rye using a modified split-plot design. An arcsine square root transformation was completed on percentage control data to address requirements of a normal distribution.

Table 1. Analysis of variance for percentage control of cereal rye as influenced by year, cultivar, termination date, and planting date.

Effect	% Control
	$P > F$
Cover crop (CC)	0.0036
Termination date (TD)	<0.0001
CC X TD	<0.0001
Planting date (PD)	<0.0001
CC X PD	0.4005
TD X PD	0.1982
CC X TD X PD	0.9886
Year	0.2407

Table 2. Mean cereal rye control as influenced by planting date (year, cultivar, and termination date pooled). Similar letters indicate no significant difference (*P* < 0.05) using the Tukey-Kramer method.

Planting date	Control
	%
25 August	79 a
5 September	77 ab
15 September	73 bc
25 September	70 cd
5 October	67 de
15 October	63 e

Table 3. Mean cereal rye control as influenced by cultivar × termination date (year and planting date pooled). Similar letters among both columns indicate no significant difference (*P* < 0.05) using the Tukey-Kramer method.

Termination date	Aroostook	Wheeler
	——% control——	
1 May	41 b	21 a
10 May	79 d	71 c
20 May	88 ef	86 e
30 May	94 f	93 f

Logistic-response curves were used to examine the relationship between cover crop growth stage and mechanical control using the dose response curve package (drc) in R 2.4 (R Development Core Team, 2006). We performed *t* tests to test for differences at the EGS85 × year and cultivar; all estimates of parameter coefficients were included in this analysis. Linear regression, used to determine the relationship between growth stage and GDD, was completed with the linear model package (lm) in R 2.4. Preliminary multiple linear regression analyses indicated significant cultivar effects for most phenology models; consequently all analyses were conducted separately for each cultivar. The adjusted coefficient of determination (R^2) was used as indication of goodness of fit. The Akaike information criterion (AIC) was used for model selection (Johnson and Omland, 2004). The adjusted R^2 and the AIC were used because both penalize for an increasing number of model parameters. Mean comparisons were performed using the Tukey-Kramer method ($P < 0.05$) in SAS version 9.1 (SAS Institute, 2004).

RESULTS AND DISCUSSION

Cereal Rye Control by Julian Date

Cultivar, planting date, termination date, and the interaction between cultivar and planting date significantly influenced cover crop control (Table 1). Rolling was most effective on cereal rye planted early in the fall (Table 2) and terminated later in the spring (Table 3). Aroostook was more effectively controlled at earlier termination dates than Wheeler, and both responded similarly at the later two termination dates (Table 3). Control of Aroostook at the first termination date ranged from 5 to 80%, and Wheeler from 5 to 45% (Fig. 4); neither cultivar reached the EGS85 at the first termination date. Generally, inter-annual variation in control was greater for Aroostook rye; this was particularly evident at earlier termination dates (Fig. 4). This suggests a cultivar-specific difference in response to early spring environmental conditions that will be addressed in greater detail in the phenological growth stage section. The variation in control between cultivars diminished with delay in cover crop termination date (Fig. 4). By the 10 May termination date, Aroostook rye was effectively controlled if planted on 25 August. Rolling rye on 20 May resulted in effective cereal rye control for all planting dates except 5 and 15 October for Aroostook and 25 September through 15 October for Wheeler. By 30 May, control of both cultivars was similar, ranging from 82 to 98%.

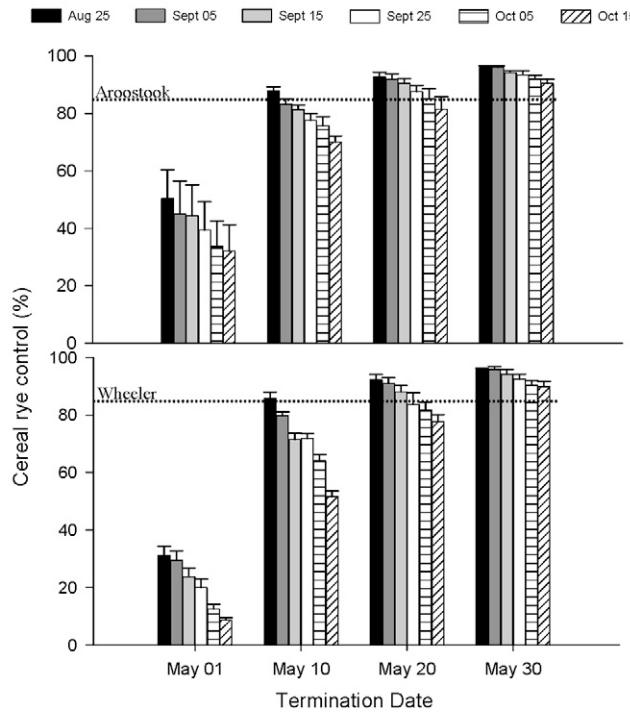

Fig. 4. Percentage control of cereal rye cultivars 6 wk after rolling/crimping by cultivar, planting date, and termination date (years pooled). Acceptable control of cereal rye cover for planting date and termination date combinations was achieved at the 85% control threshold. Bars represent standard error of the means.

As expected, earlier planting and later termination dates resulted in increased rye maturity (Table 4). Fowler (1983) reported a similar influence of fall planting time on cereal rye development. The study conducted in Saskatchewan, Canada found that a 1-mo difference in fall cereal rye planting resulted in a 1-wk delay in cereal rye heading. The improved control at later cereal rye growth stages observed in this study (Table 4) is consistent with other winter cereal cover crop studies including those conducted with black oat (*Avena strigosa* Schreb.), wheat (*Triticum aestivum* L.), and cereal rye (Ashford and Reeves, 2003; Creamer and Dabney, 2002). Ashford and Reeves (2003) reported that black oat, wheat, and cereal rye control averaged

Table 4. Cereal rye growth stage (Zadoks) as influenced by cultivar, planting date, and termination date for 2005 and 2006. Table values represent means of the four replications. Variability among replications was not estimable due to the fact that there was no variability among the replications.

Cultivar	Planting date	2005 1 May	2005 10 May	2005 20 May	2005 30 May	2006 1 May	2006 10 May	2006 20 May	2006 30 May
		growth stage (Zadoks)							
Aroostook	25 August	45	55	60	73	58	63	73	85
	5 September	41	53	59	71	58	61	73	85
	15 September	41	50	57	71	57	60	71	83
	25 September	40	49	55	70	55	60	71	83
	5 October	38	41	53	69	53	59	69	80
	15 October	34	41	53	68	52	57	65	71
Wheeler	25 August	45	55	59	71	48	59	70	80
	5 September	39	53	57	71	48	59	67	75
	15 September	39	50	55	70	47	57	66	75
	25 September	37	45	53	67	45	57	64	71
	5 October	34	40	53	67	41	55	62	69
	15 October	32	39	50	63	37	48	58	68

16 to 19%, 81 to 85%, and 95% when rolled at the flag leaf, anthesis, and soft dough stages, respectively. Similarly, Wilkins and Bellinder (1996) found over a 10-fold decrease in cereal rye and wheat regrowth with each 2-wk delay in mowing beginning at the first node growth stage (Zadoks 31).

Cereal Rye Control by Phenological Growth Stage

Percentage cereal rye control was fitted with a three-parameter logistic model (dose response curve) where rye control was dependent on rye growth stage (Fig. 5). Coefficients of this nonlinear regression model are presented in Table 5. The analysis could not be performed by cultivar in 2006 due to lack of observations at earlier growth stages in Aroostook in 2006; however, there was a similar trend between cultivars within the range of data observed (Growth Stage 50 to 85). Cultivars responded similarly and were therefore pooled by year (Table 5) to derive parameter estimates and for estimating the EGS85. Thus, while a Julian date–based analysis revealed differences between cultivars (Table 1), they responded similarly to rolling when the analysis was based on cereal rye growth stages (Table 5).

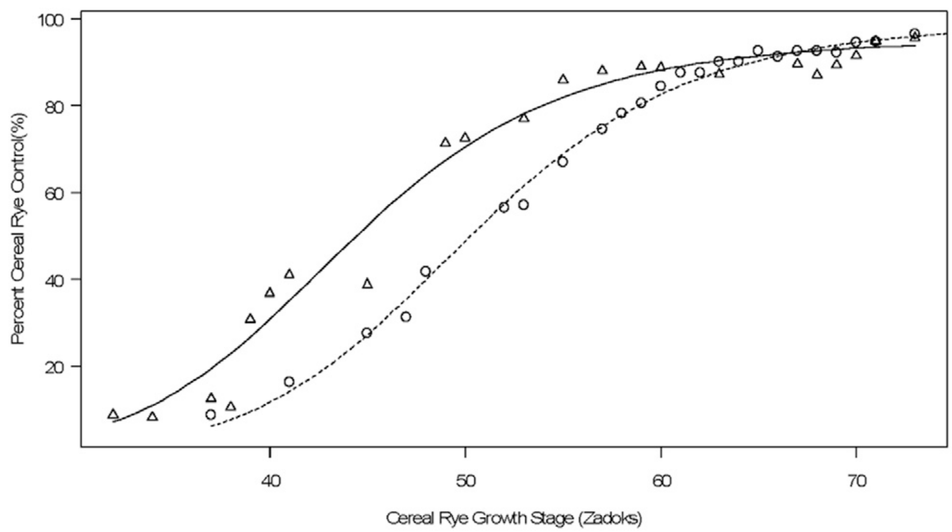

Fig. 5. Percentage cereal rye control in 2005 (triangles) and 2006 (circles) as related to phenological development. The lines represent the fitted three-parameter sigmoidal dose response curve regressions for 2005 (solid line; $y = 95.37/[1 + \exp\{-7.99[\log(x) - \log(43.91)]\}]$ and for 2006 (dashed line; $y = 99.39/(1 + \exp\{-8.90[\log(x) - \log(50.22)]\})$. Data are pooled over cultivar due to no significant cultivar effects.

In contrast to the percentage control analysis by Julian dates, year significantly influenced percentage control as a function of cereal rye growth stage (Table 5). Inter-annual difference arise from plants at earlier growth stages being more susceptible to

Table 5. Coefficients for the nonlinear regression using a dose response model of cereal rye percentage control as a function of phenological development where *Y* is % cereal rye control (%); *d* is the % control at the upper growth stage limit; e is the effective growth stage 50, the growth stage producing a response half-way between *d* and the lower limit; and *b* is the relative slope around e (% control/growth stage) (Ritz and Streibig, 2005). Analysis was conducted by year with cultivars pooled and by cultivar within years to test for significance of parameter estimates. Due to lack of data at the lower range of growth stages for Aroostook rye in 2006, differences in cultivars in 2006 could not be tested. The null hypothesis in this case is formulated as a ratio of estimates, and therefore the *t* test is comparing the observed ratio with a value of 1. The *P* values are probability of getting a *t* statistic greater than the calculated *t* value. Values in parentheses are the standard error.

Model parameters and control threshold	Year comparison			2005 Cultivar comparison		
	2005	2006	*P* value	Aroostook	Wheeler	*P* value
b	–7.99 (0.48)	–8.90 (0.62)	0.247	–8.71 (1.00)	–7.52 (0.86)	0.365
d	95.37 (1.73)	99.39 (1.60)	0.089	94.41 (3.01)	95.81 (3.56)	0.766
e	43.91 (0.39)	50.22 (0.39)	0.001	44.42 (0.70)	43.23 (0.83)	0.271
EGS85	55 (1.41)	61 (0.65)	0.001	54 (2.13)	54 (1.78)	0.931

control in 2005 than in 2006; this tendency is borne out by a lower *e* value (rye growth stage at 50% control) and an EGS85 of 55 in 2005 (confidence interval = ±2.74) compared with 61 in 2006 (confidence interval = ±0.65) (Table 5). This interannual variation may have been due to differences in precipitation. Field conditions in 2005 were atypically dry for the period following rolling compared with the more characteristic early summer precipitation received in 2006 (Fig. 2). We speculate that drier conditions during June 2005 may have enhanced control with the roller/crimper compared with the wetter 2006 field season. While the growth stage for acceptable control ranged from 55 to 61, cereal rye was consistently controlled at a Zadoks growth stage of 61 or greater.

In 2005, effective control was achieved earlier than previous estimates would suggest, while percentage control in 2006 was more consistent with previously reported results (Creamer and Dabney, 2002; Ashford and Reeves, 2003). Convergence of the upper limit parameter on 100% control for a mature cereal rye cover crop was expected. Ashford and Reeves (2003) consistently observed greater than 95% control when rolling cereal grain cover crops at the soft dough growth stage (Zadoks 68). From this analysis we conclude that rye control is driven by growth stage rather than planting or termination dates. In other words, cereal rye response to mechanical injury is driven by growth stage directly and calendar date indirectly. Therefore, tying timing of cover crop control to rye growth stage will result in the greatest consistency in cover crop management.

Growth Stage Predictive Model

The three thermal-based phenological models used to simulate cereal rye development were fitted separately for each cultivar and pooled over years (Table 5). The $\text{Spring}_{\text{GDD}}$ and Fall_{GDD} model accounted for the greatest variation in estimating growth stage and resulted in the lowest AIC values; therefore, this model was selected as the best predictor of cereal rye phenological development (Table 6). Historically, thermal-based phenological models used to predict rye development have focused on yield potential and have not considered the influence of fall heat units (Nuttonson, 1958). However, rye is most commonly used as a cover crop in the northeastern United States, where a wide range of sowing dates (mid-August to late-November) is typical. Recently, a mechanistic cereal growth simulation model has accounted for fall and springtime temperatures in predicting cereal rye biomass accumulation. This model also concludes that fall growing degree days are important in springtime biomass accumulation (Feyereisen et al., 2006). Whereas this mechanistic model can be useful for predicting cover crop biomass, our work set out to link rather simple phenological models that could be readily adapted for farmer use, particularly in the context of cover crop selection and management.

While both cultivars were more strongly influenced by SpringGDD, Aroostook development was more strongly influenced by spring heat units (Table 6). Such a difference may account for the Julian date differences in maturation (Table 3) since heat units in the spring of 2006 were greater than that in 2005 (Fig. 3). Vernalization may, in part, also be responsible for the differences in cultivar response to early spring heat units since timing of fall planting can influence cold-tolerance of cereal rye and therefore, its vernalization requirements (Fowler and Gusta, 1977; Nuttonson, 1958;). Additionally, these requirements can vary by species and cultivar ranging from 1.1 to 3.9°C and from 20 to 55 d (Nuttonson, 1958). Aroostook matured earlier than Wheeler; the cultivar-specific growth and control responses observed in this study underscore the need for cultivar level data when defining cover-crop performance in local growing regions. Given the accelerated springtime growth, Aroostook may be a better suited cover crop for the Mid-Atlantic region because it would allow for earlier planting of the cash crop.

Regionally specific thermal-models may prove to be a practical alternative to mechanistic models in guiding farmer decision making. These models may be limited in years of extreme climate and soil nutrient availability. For example, acceleration in phenology attributed to drought stress and N deficiency was observed for winter cereals in an irrigation and N fertility experiment on sandy soils (Mirschel et al., 2005). However, the greatest acceleration in phenological development has been observed postanthesis, with variations still in an acceptable range for cover crop management (5–6 d for moisture and 1–2 d for N deficiency).

CONCLUSION

Cereal rye control improved with cover crop developmental stage. While cultivar growth rates differed, cereal rye control was consistent across cultivars at a given growth stage. At a Zadoks growth stage of 61 (anthesis) or greater cereal rye was consistently controlled. Typically, more matured larger plants have greater multi-functionality as they provide greater surface residue, which enhances water infiltration and weed suppression and reduces soil surface evaporation (Decker et al., 1994; Langdale et al., 1991; Munawar et al., 1990; Teasdale, 1996).

Table 6. Thermal-based phenological models predicting cultivars of cereal rye phenological development (years pooled). The parameter estimates characterize the effects of growing degree days (GDD) on growth stage of two cereal rye cultivars. Included are adjusted R2 values and Akaike Information criteria (AIC) for goodness of fit and model selection, respectively. The parameter β_0 is the intercept, β_1 and β_2 are parameter coefficients defining the slope of the equation and the proportional relationship between Fall_{GDD} and $\text{Spring}_{\text{GDD}}$.

	Thermal models	β_0	Total β_1	Fall β_1	Spring β_2	Adj. R^2	AIC
Aroostook	$\text{Spring}_{\text{GDD}}$	21.08	–	–	0.067	0.88	1130
	$\text{Total}_{\text{GDD}}$	35.96	0.017	–	–	0.34	1452
	Fall_{GDD} and $\text{Spring}_{\text{GDD}}$	15.19	–	0.007	0.068	0.93	1031
Wheeler	$\text{Spring}_{\text{GDD}}$	18.74	–	–	0.064	0.87	1121
	$\text{Total}_{\text{GDD}}$	29.83	0.018	–	–	0.43	1402
	Fall_{GDD} and $\text{Spring}_{\text{GDD}}$	11.11	–	0.009	0.064	0.96	882

While the practice outlined in this article can reduce the need for tillage and herbicide use, careful monitoring and rotation planning is required to properly time control of the cover crop and align the growing periods of the cash and cover crops. It is also important to be cognizant of the moisture status of fields in the springtime as allowing continued vegetative growth of the cover crop, particularly during low-precipitation spring conditions may result in depletion of stored soil moisture (Liebl et al., 1992; Williams et al., 2000).

The identification of susceptible growth stages for mechanical control coupled with simple thermal-based phenological models that predict cereal rye development provides useful information to help guide adoption of cereal rye as a cover crop. Extending the findings outlined herein is time sensitive; spurred by state and federal incentives and an increasing understanding of the impact of surface water runoff into environmentally sensitive catchments like the Chesapeake Bay, farmer interest in adopting cover crops is higher than ever (Resource Enhancement and Protection Act of Pennsylvania, 2007; MDA, 2008). Future work should focus on linking cover crop growth measurements at multiple sites within a region to existing weather databases. In this way, locally adapted forecasting models could be refined and spatially explicit information on planting and termination dates could be made available through web-based decision-support applications. The ability to fit cover crops into crop rotations requires farmers to estimate the growing period of the cover and cash crop. Implementation research that helps define management windows could help guide decision of when and what type of cover crop is compatible within a particular farming system.

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