Weed Science 2012 60:389–393

Influence of Time of Emergence on the Growth and Development of Wild Oat (*Avena fatua*)

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Successful control of wild oat in cereal crops requires an accurate prediction of the developmental stages of wild oat plants that emerged during the growing season. The main objective of this research was to evaluate wild oat growth and to predict the phyllochron of wild oat plants that emerge at various times in the Red River Valley region of Minnesota and North Dakota. Field experiments were conducted in 2002 and 2003 in Crookston, MN, and Fargo, ND. Four emergence cohorts were established in 4 successive wk. Research plots were arranged in randomized complete blocks with six replications. From the naturally emerged wild oat population, 10 randomly selected plants per plot were evaluated for plant height, leaves on main stem, tillers per plant, total leaves per plant, days to flag leaf emergence and to heading, biomass per plant, and seeds per plant. Haun's numerical cereal development scale was regressed on days after emergence (DAE), day length (DL), growing degree days (GDD), or photothermal units (PTU). Wild oats that emerged first required more time for flag leaf emergence and heading, were taller, and had more biomass, leaves, tillers, and seed production than wild oat plants that emerged later. Wild oat phyllochron intervals were 5.3 d, 94 GDD, or 1,468 PTU, regardless of emergence timing. These data suggest that wild oat phyllochron is primarily driven by air temperature and is relatively stable during the extended emergence period. Later-emerging wild oat plants, although not as competitive as earlier emerging ones, still have the potential to contribute to the seed bank if left uncontrolled.

Nomenclature: Wild oat, *Avena fatua* L. AVEFA.
Key words: Growing degree days, photothermal units, phyllochron.

Wild oat, a weedy species of wide distribution, abundance, and competitiveness, is of paramount economic importance in cereal production. Wild oat invasion has been associated with reduced grain yields, diminished grain grade and quality, elevated dockage losses and cleaning costs, and increased use of chemical and cultural control measures (Sharma and Vanden Born 1978). In the Red River Valley region of Minnesota and North Dakota, approximately 79% of wheat (*Triticum aestivum* L.) and 72% of barley (*Hordeum vulgare* L.) hectares were infested with wild oat, according to a survey in 1979 (Behrens and Strand 1979). In North Dakota, wild oat occurred in 66% of the surveyed small grain fields in 1978 (Behrens and Strand 1979), 60% in 1979 (Behrens and Strand 1979), 32% in spring 2000 (Zollinger et al. 2003), and 41% in summer 2000 (Zollinger et al. 2003).

Effective control of wild oat primarily depends on correct timing of chemical applications which, in turn, relies on accurate predictions of wild oat morphological development (Cudney et al. 1989). Wild oat biology has previously been studied. Miller et al. (1982) and Morrow and Gealy (1983) reported means and ranges for wild oat plant height, tillers per plant, seeds per panicle, and days to panicle emergence. Research on wild oat phenology and growth rate has been very limited, and the range for the wild oat phyllochron was vastly different among studies (Ball et al. 1995; Cudney et al. 1989). None of these studies, however, have investigated the influence of emergence timing on wild oat biology and morphological development.

Data are largely unavailable on whether differences in emergence timing lead to differences in growth and development in wild oat. Wild oat emergence was observed to extend up to 30 d after initial seeding (Sharma et al. 1976). Winter wheat yield was reported to be linearly reduced each day that wild oats were present after emergence in Australia (Wilson 1979). Cousens et al. (1991) observed that the wild oat canopy continued to increase throughout the growing season, compared with that of cereal crops. Understanding wild oat growth and development based on different emergence times are key pieces of information needed for optimum and consistent control of wild oat. The ability to accurately predict the phyllochron of wild oat plants emerged over an extended period will provide practical assistance for field examination of appropriate growth stages for successful chemical control. The objectives of this study were (1) to evaluate the growth and development of wild oat plants emerged at different times, and (2) to predict the phyllochron of wild oat plants emerged at different times.

Materials and Methods

Field trials were conducted in 2002 and 2003 in Crookston, MN (47°46′N, 96°37′W) and Fargo, ND (46°52′N, 96°47′W). Both sites are located in the Red River Valley and were specifically managed to encourage increases in the wild oat seed bank. Four emergence cohorts were developed. Cohort 1 germinated in week 1 of the experiment, cohort 2 in week 2, cohort 3 in week 3, and cohort 4 in week 4. The experiments were arranged in randomized complete blocks with six replications. At each location–year, each cohort contained six 0.61-m by 0.61-m plots. All cohorts were allowed to germinate naturally. From the naturally emerged wild oat population, 10 individual plants were selected randomly and numbered within each plot. A cohort was considered established at that point. In plots reserved for later-emerging cohorts, wild oat seedlings were suppressed with a 1% glyphosate solution sprayed to wet with a handheld spray bottle. This allowed for the selection of newly emerged seedlings in cohort 2. This process was repeated until all four cohorts were established. The establishment dates for emergence cohorts at each location–year are provided in Table 1. Based on weather records, neither of the two

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DOI: 10.1614/WS-D-11-00204.1

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Table 1. Establishment dates of wild oat emergence cohorts in Crookston, MN, and Fargo, ND (2002 to 2003).

	Crookston		Fargo	
	2002	2003	2002	2003
Cohort 1	May 16	May 1	May 15	May 1
Cohort 2	May 24	May 8	May 23	May 8
Cohort 3	May 29	May 13	May 29	May 12
Cohort 4	June 4	May 22	June 5	May 21

locations had any soil moisture deficits in the years the study was conducted. On a weekly basis, individual plants were evaluated for plant height, number of green leaves on main stem, number of tillers, and number of total green leaves. Number of leaves on main stem was counted nondestructively at weekly intervals up to the four-leaf stage. Flag leaf emergence (defined as when the flag leaf sheath on the main stem completely emerged from the leaf sheath of the penultimate leaf boot) and heading (defined as when the panicle on the main stem completely emerged from the leaf sheath of the flag leaf) dates were also recorded. Two weeks after heading, individual plants were harvested, and panicles per plant were recorded. This allowed for most panicles to be emerged while minimizing seed shattering risk. Plants were dried for 1 wk at 40 C and weighed, and seeds per plant were counted. Data were subjected to PROC MIXED (SAS 2009; SAS 9.2 software, SAS Institute Inc., Cary, NC 2009) for ANOVA. Location–year and block were treated as random effects; whereas emergence cohorts were considered a fixed effect. Data were combined over four location–years because no interaction was detected between emergence cohorts and environments ($P \leq 0.05$). Least square means and corresponding least significant differences ($P \leq 0.05$) of emergence cohorts were generated from the combined data for plant height, leaves on main stem, total leaves per plant, tillers per plant, biomass per plant, panicles per plant, seeds per plant, days to flag leaf emergence (DTF), and days to heading (DTH).

Growing degree-days (GDD) was defined as the summation of degree days (Tn) according to Wang (1960), where

$$Tn = [(T_{\max} + T_{\min})/2] - Tb. \quad [1]$$

T_{max} and T_{min} are the daily maximum and minimum air temperatures, respectively. Tb is the base temperature below which the process of interest ceases (Wang 1960). T_{max} and T_{min} were obtained from the Northwest Research and Outreach Center weather station (www.nwroc.umn.edu/Weather/WeatherRecords/index.htm) for Crookston, MN (2002 to 2003) and from North Dakota Agricultural Weather Network (http://ndawn.ndsu.nodak.edu) for Fargo, ND (2002 to 2003). Analogous to the GDD model for wheat, the daily T_{max} was restricted to 21 C from emergence to the two-leaf stage and to 27 C from the three-leaf stage to flag leaf emergence (Bauer et al. 1984). When T_{min} for the day was less than 5 C, it was considered 5 C (Cudney et al. 1989). The Tb was set to 0 C (Bauer et al. 1984). Sunrise and sunset times for the four location–years were obtained from Naval Oceanography Portal (www.usno.navy.mil/USNO/astronomical-applications/data-services) and were used to calculate day length (DL). Photothermal units (PTU) were calculated as the product of degree days (Tn) and DL (Nuttonson 1948). To construct a meteorologically based model for predicting wild oat development stages, the Haun scale numerical designations were regressed on the accumulated days after emergence (DAE), DL, GDD, or PTU for each emergence cohort, using data pooled across four location–years because no crossover interactions were detected among locations and years ($P \leq 0.05$)(Haun 1973). Six Haun-scale growth stages were used: 1, 2, 3, 4, 7, and 10. These represented the first, second, third, and fourth leaf on the main stem, flag leaf emergence, and heading, respectively. Flag leaf emergence and heading growth stages were assumed empirically to be equal to the 7th and 10th leaf (Haun 1973). The regression slopes were compared among emergence cohorts, and no difference was found ($P \leq 0.05$). Therefore, grand regression models of the Haun-scale growth stages vs. independent variables of DAE, DL, GDD, or PTU were constructed using data pooled across four location–years and four emergence cohorts. Intercepts of the regressions were set to zero because, in this study, emergence was defined as when the coleoptile of the first leaf just became visible.

Results and Discussion

Sharma et al. (1976) reported that maximum emergence of wild oat was reached 17 d after seeding and no further emergence occurred 30 d after seeding. Martinson et al. (2007) found that maximum wild oat emergence (100%) in the Red River Valley of MN and ND was reached 28 to 42 d after initial emergence. The four cohorts, each 1 wk apart, were chosen to represent this extended emergence period. Significant difference was found among emergence cohorts on plant height, leaves on main stem, total leaves per plant, tillers per plant, biomass per plant, panicles per plant, seeds per plant, DTF, and DTH ($P \leq 0.05$)(Tables 2 and 3).

Wild oat plant height ranged from 65 to 95 cm at harvest (Table 2), which was in general agreement with previous studies (Miller et al. 1982). Differences among cohorts did not show until 21 DAE when plants in cohort 4 were found to be shorter than those in cohort 3. Cohort 3 was consistently taller than the other three cohorts from 35 to 70 DAE. Cohort 2 was very similar to cohort 1 and was only taller than cohort 1 at 42, 49, and 56 DAE. Cohort 4 was shorter than cohort 3 from 21 DAE on, but was taller than cohort 1 at 35 and 42 DAE. From 49 to 70 DAE, cohort 4 was consistently shorter compared with the other three cohorts. At harvest, wild oat plants that emerged first (cohort 1) were the tallest (95 cm), followed by plants that emerged in cohorts 2 and 3 (88 cm). Plants in cohort 4 were the shortest (65 cm) and were shorter than those in cohort 1 by about 30%.

Number of leaves on main stem progressed similarly in cohort 1 to 3 (Table 2). Wild oat plants in cohort 4 had, on average, three leaves on the main stem at harvest; whereas plants in the other three cohorts had four leaves. Total leaves per plant were very similar in the first two cohorts (Table 2). Cohort 3 had more total leaves per plant than did cohorts 1 and 2 at 49, 56, and 70 DAE. Cohort 4 produced fewer total leaves per plant than did the other three cohorts from 49 to 70 DAE and had the least total leaves per plant at harvest, averaging 31 leaves per plant, compared with 44 to 49 total leaves per plant in cohorts 1 to 3. Cohort 1 had the most total leaves per plant at harvest, possessing 18 more leaves per plant than cohort 4 had.

Tillers per plant were also affected by emergence time (Table 2). Wild oat plants that emerged earlier (cohorts 1 to 3) had more tillers, compared with those in cohort 4. Similar

Table 2. Least square means and least significant differences (LSD) of plant height, photosynthetically active leaves on main stem, total leaves per plant, and tillers per plant of wild oat emergence cohorts based on days after emergence (DAE). Data presented are pooled across four location–years.

	Plant ht				No. of leaves on main stem				Total leaves plant^{-1}				Tillers plant^{-1}			
	cohorts															
DAE	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
	cm															
7	4	3	4	4	1	1	1	1	1	1	1	1	—	—	—	—
14	6	6	7	6	2	2	2	2	2	1	2	2	—	—	—	—
21	8	9	10	7	2	3	3	2	2	3	3	2	—	—	—	—
28	11	13	15	12	3	3	3	3	4	5	5	4	1	1	1	1
35	17	19	26	22	3	3	3	3	8	8	9	7	2	2	2	1
42	26	36	44	34	3	3	3	3	12	15	15	16	3	4	4	5
49	45	54	59	43	4	4	4	3	22	21	29	20	6	6	8	6
56	61	67	70	55	4	4	4	3	25	33	38	25	7	9	11	9
63	77	76	82	63	4	4	4	3	43	40	41	31	12	12	13	10
70	84	84	88	65	4	4	4	3	44	44	47	31	14	13	15	10
77	89	88	—	—	4	4	—	—	47	44	—	—	14	14	—	—
84	95	—	—	—	4	—	—	—	49	—	—	—	15	—	—	—
LSD (0.05)	3				0.3				3				1			

to plant height, cohort 3 produced more tillers per plant than the other three cohorts from 49 to 70 DAE. Cohorts 1, 2, and 4 were similar until 56 DAE at which point cohort 4 ceased in tiller production. Cohort 1, 2, and 3, however, continued to produce new tillers until 84, 77, and 70 DAE, respectively. Tillers per plant averaged 14 to 15 in cohort 1 to 3 and 10 in cohort 4 at harvest. Interestingly, the time required for tiller initiation was the same among emergence cohorts, averaging 32 DAE. Morrow and Gealy (1983) reported an average of 19 tillers per plant for wild oat plants under noncompetitive field conditions in Washington. The difference in tiller numbers between what Morrow and Gealy (1983) found and this study is most likely due to genetic variability of wild oat plants found in different regions (Imam and Allard 1965). Sharma et al. (1977) observed that wild oat tillering occurred 14 to 28 DAE and ceased 42 to 57 DAE, and Morrow and Gealy (1983) observed that wild oat plants continued to produce tillers until frozen. In this study, tiller initiation was similar to the data reported by Sharma et al. (1977), but tiller production continued until 84 DAE (Table 2), which was in agreement with Morrow and Gealy (1983).

Wild oat plants that emerged first (cohort 1) had greater biomass per plant, more panicles per plant, and more seeds per plant, compared with those that emerged later (cohorts 2 to 4) (Table 3). Wild oat plants in cohorts 2 and 3 had fewer panicles per plant and seeds per plant than those in cohort 1 had, but more than those in cohort 4 had. Cohort 4 had less biomass per plant and fewer panicles per plant and seeds per plant than did cohort 1. Morrow and Grealy (1983) observed an average of 41 to 66 seeds per panicle, compared with 30 to 40 seeds per panicle (calculated by dividing seeds per plant by panicles per plant) observed in this study. Wild oat plants were harvested 2 wk after heading to avoid shattering, which may have reduced seeds per panicle in this study.

The DTF emergence averaged 42 to 51 DAE, and DTH averaged 48 to 57 DAE, with heading occurring about 5 to 6 d after flag leaf emergence (Table 3). Based on DTF and DTH, later-emerging wild oat plants had accelerated growth rate compared with those emerging earlier. Wild oat plants in cohort 1 emerged earlier but required the most time to produce a flag leaf (51 DAE) and panicle (57 DAE), whereas plants in cohorts 3 and 4 required the least amount of time to produce a flag leaf (42 to 44 DAE) and panicle (48 to 49 DAE). Miller et al. (1982) reported that days to panicle emergence ranged from 47 to 67 DAE in wild oat plants, similar to DTH (48 to 57 DAE) observed in this study.

The Haun-scale numerical designations, based on main stem morphology, are arranged in chronological order by leaf number plus four additional morphological units (flag leaf extension, boot enlargement, heading, and culm elongation) following the emergence of the flag leaf (Haun 1973). Compared with other cereal growth scales, such as the Zadoks scale (Zadoks et al. 1974), the Haun scale is more definitive, precise, and sensitive to cereal morphology and is thus frequently used for assessing cereal development rate (Baker and Gallagher 1973; Bauer et al. 1984). Regression analyses of wild oat development stages based on the Haun scale were linear for all independent variables (DAE, DL, GDD, and PTU) in this study. In general, DL was not as good a predictor for wild oat development, based on low coefficients of determination (R^2), ranging from 0.672 to 0.694 (Tables 4 and 5). The other three variables (DAE, GDD, and PTU), however, accounted equally well for phyllochron intervals. The R^2 values ranged from 0.983 to 0.988, from 0.975 to

Table 3. Least square means and least significant difference (LSD) of biomass per plant, panicles per plant, seeds per plant, days to flag leaf emergence (DTF), and days to heading (DTH) of wild oat emergence cohorts. Data presented are pooled across four location–years.

	Biomass plant^{-1}	Panicles plant^{-1}	Seeds plant^{-1}	DTF	DTH
	g			d	
Cohort 1	13.6	3.0	120	51	57
Cohort 2	10.9	2.6	91	47	53
Cohort 3	10.6	2.5	87	44	49
Cohort 4	10.1	2.0	61	42	48
LSD (0.05)	3.0	0.4	22	2	2

Table 4. Linear regression parameters of wild oat main stem leaf number in response to days after emergence (DAE), day length (DL), growing degree-days (GDD), and photothermal units (PTU) among four emergence cohorts, from emergence to heading. Data presented are pooled across four location–years.

		DAE		DL		GDD		PTU	
Cohort	*n*	R^2	Slope (P)	R^2	Slope (P)	R^2	Slope (P)	R^2	Slope (P)
1	537	0.983	0.1617 (< 0.0001)	0.694	0.2618 (0.0199)	0.975	0.0098 (< 0.0001)	0.973	0.000625 (< 0.0001)
2	537	0.986	0.1724 (< 0.0001)	0.688	0.2900 (0.0211)	0.984	0.0098 (< 0.0001)	0.983	0.000623 (< 0.0001)
3	677	0.987	0.1819 (< 0.0001)	0.682	0.2879 (0.0211)	0.986	0.0099 (< 0.0001)	0.985	0.000630 (< 0.0001)
4	492	0.988	0.1823 (< 0.0001)	0.672	0.2851 (0.0240)	0.986	0.0096 (< 0.0001)	0.985	0.000611 (< 0.0001)

0.986, and from 0.973 to 0.985 for DAE, GDD, and PTU, respectively (Tables 4 and 5). Phyllochron intervals, calculated as the reciprocal of slope, ranged from 5.5 to 6.2 d, from 101 to 104 GDD, or from 1,587 to 1,637 PTU among emergence cohorts (Table 4). Phyllochron intervals based on combined data across four emergence cohorts were 5.8 d, 102 GDD, or 1,608 PTU (Table 5).

Literature suggests that air temperature is the primary driving force for the morphological development of spring wheat and forage grasses, including crested wheatgrass [*Agropyron cristatum* (L.) Gaertn.] and western wheatgrass [*Pascopyrum smithii* (Rydb.) Á. Löve](Bauer et al. 1984; Frank et al. 1985; Frank and Ries 1990), which corresponds well with the findings from this study. Because PTU did not account for wild oat morphological development better than GDD did, DL apparently did not contribute significantly to model fitness because PTU is the product of DL and Tn. This again reflects the low R^2 values associated with DL in this study. Previous research also suggests that equations using DL as a predictor did not adequately predict wheat phyllochron (McMaster and Wilhelm 1995). The relationship between GDD and the Haun growth scale has been intensively studied, and GDD has been a widely accepted thermal unit for expressing cereal phyllochrons (Ball et al. 1995; Bauer et al. 1984; Frank and Ries 1990; Frank et al. 1985; Moore and Moser 1995). Bauer et al. (1984) reported that days after planting and PTU predicted the phyllochron of spring wheat as well as GDD in most cases, which agrees with the present study.

The linear relationships found between the Haun scale designations and the three independent variables (DAE, GDD, or PTU) are supported by numerous studies (Ball et al. 1995; Bauer et al. 1984; Delecolle et al. 1989; Frank and Ries 1990). Cudney et al. (1989) chose a secondary-order equation ($R^2 = 0.97$) over a linear equation ($R^2 = 0.93$) for growth rate estimation and reported a range of 36 to 319 GDD for the phyllochron of wild oat grown in California ($Tb = 5$ C). Ball et al. (1995) reported a phyllochron range of 70 to 80 GDD based on a linear model for wild oat grown in Oregon. The results from this study are comparable to these studies.

It has been documented that wild oat growth and development parameters are influenced by temperature and photoperiod (Sharma et al. 1977). Adkins et al. (1987) found that the period of plant development (emergence to midharvest) decreased as the temperature increased. Thurston (1957) and Somody et al. (1984) found that days to panicle emergence decreased as temperature increased and photoperiod decreased. Wild oat plants that emerged earlier (cohort 1) had greater exposure to longer periods of day length (Summer Solstice occurred on June 21 of each year) than later emerging wild oat plants (cohort 4). Wild oat plants in cohort 4 also emerged and grew during a time of greater heat until accumulation compared with wild oat plants in cohort 1. These two observations agree with previous findings (Adkins et al. 1987; Somody el al. 1984; Thurston 1957) and can potentially explain the accelerated growth rate of later emerging wild oat plants. The linear models constructed in this study, however, suggest that (1) day length may not be as crucial a factor as GDD in wild oat morphological development, (2) delay in emergence up to 3 wk may significantly affect the overall growth of wild oat but may not change the phyllochron interval, and (3) a universal equation can be used to predict main stem leaf number and herbicide application timing for wild oat control.

Table 5. Linear regression parameters of wild oat main stem leaf number in response to days after establishment (DAE), day length (DL), growing degree-days (GDD), and photothermal units (PTU), from emergence to heading. Data presented are pooled across four location–years and four emergence cohorts.

Variable	R^2	Slope (P)
DAE	0.983	0.1737 (< 0.0001)
DL	0.680	0.2890 (< 0.0001)
GDD	0.982	0.0098 (< 0.0001)
PTU	0.982	0.000622 (< 0.0001)

Based on biomass, plant height, leaf number, tillers, and seed production, wild oat plants that emerge first (cohort 1) are more competitive than wild oat plants that emerged later (cohort 4). Other researchers agree (Chancellor and Peters 1972; O'Donovan et al. 1985) but caution that later-emerging wild oat plants can still reduce crop yield (Thill et al. 1994). This information will assist farmers and agricultural professionals in managing wild oat. Most wild oat herbicides recommend application between the two to three or three to four leaf stages. Chancellor and Peters (1976) determined that serious weed vs. crop competition starts before the two to three leaf stage of wild oat. An herbicide application directed at the two to three leaf stage of wild oat should occur, according to these data, between 21 and 28 DAE. During that time, wild oat height is usually under 15 cm, most plants have not begun to tiller, and the overall growth rate is not as rapid as growth observed after 28 DAE. However, these data are not meant to replace scouting but provide farmers and agricultural professionals with additional information to aid in more accurate and timely scouting practices.

In conclusion, wild oat plants that emerged first had greater biomass, had more seed production, were taller, and had more leaves and tillers than did wild oat plants that emerged later. Wild oat plants that emerged early required more time for flag leaf emergence and heading, compared with wild oat plants that emerged later. Even though early emerging wild oat plants are potentially more competitive, later-emerging wild oat plants still have the potential to produce seed and, if left uncontrolled, will continue to contribute to the seed bank. The linear models indicate that wild oat phyllochron is relatively stable among emergence cohorts and is driven primarily by air temperature. Using the linear models for growth stage prediction should assist chemical and cultural control of wild oat in spring cereals in the Red River Valley region of Minnesota and North Dakota.

Acknowledgments

The authors acknowledge Jim Cameron and Mark Ciernia for technical assistance, Drs. Kirk Howatt and George O. Kegode for academic support, and the Minnesota Wheat Growers for partial funding of the project.

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Received December 6, 2011, and approved February 15, 2012.