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Vernalization response of plants grown from spikelets of spring and fall cohorts of jointed goatgrass

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Jointed goatgrass is most commonly described as a winter annual species. However, it has been observed to produce spikes in spring crops, apparently without being exposed to vernalizing conditions. A controlled environment study was conducted to determine the reproductive response of jointed goatgrass plants grown from seeds of fall- and spring-emerging parent plants to various vernalization durations. Winter wheat was included as a control. Winter wheat spikelet production was dependent on vernalization, and the number of spikes per plant was 10-fold greater if the plants were exposed to 4 C for 10 wk. In contrast, jointed goatgrass spike production without vernalization remained as high as 50% of that produced by plants exposed to 10 wk of vernalization conditions. Jointed goatgrass is thus not as dependent on vernalization for reproduction as the comparative winter wheat standard. Apparently, jointed goatgrass is more a facultative rather than an obligate winter annual. Rotating to a spring-seeded crop should not be expected to completely prevent jointed goatgrass seed production. Fields rotated to spring wheat to eliminate jointed goatgrass seed production should be monitored, and jointed goatgrass should be hand pulled or otherwise controlled to ensure zero seed production.

Nomenclature: Jointed goatgrass, *Aegilops cylindrica* L. AEGCY; winter wheat, *Triticum aestivum* L. 'Madsen'.

Key words: Reproductive tiller index.

Jointed goatgrass is a troublesome winter annual grass weed that infests winter wheat fields in the Pacific Northwest and Great Plains regions of the United States. It is capable of causing large reductions in wheat yield and quality (Anderson 1993; Donald and Ogg 1991; Fleming et al. 1988). Jointed goatgrass seeds persist in the soil for up to 5 yr, providing a source for future jointed goatgrass infestations (Donald and Zimdahl 1987).

Vernalization is defined as the exposure of a plant or an imbibed seed to a chilling treatment that accelerates the rate at which a plant reaches the reproductive stage, and it is regarded as critical to floral initiation (Chouard 1960). Apical meristems of winter wheat and barley (*Hordeum vulgare* L.) have been shown to require exposure to cool temperatures (1 to 11 C) in order for floral initiation to occur as a response to a long photoperiod (Hay and Ellis 1998). The exact temperature and duration of exposure to temperatures required for vernalization differs among species and among cultivars within a species. In the absence of vernalization vegetative growth is prolonged and floral initiation delayed (Richardson et al. 1986). Vernalization may also be accomplished by exposing the embryo of an imbibed seed to chilling temperatures (Hay and Ellis 1998). Thus, it may be possible for spring cohorts of winter annual species to have accelerated floral development if these plants developed from imbibed seeds that were exposed to cool temperatures.

Although classified as a winter annual, jointed goatgrass and other winter annual grasses will initiate floral development and seed formation in spring-emerging plants if vernalization conditions are met (Donald 1984). Donald (1984) described jointed goatgrass as having a quantitative vernalization requirement. Imbibed jointed goatgrass seed exposed to 3 ± 2 C for 8 wk flowered 120 d after chilling treatments, whereas plants not exposed to chilling temperature took twice as long to flower. Moreover, a strong linear relationship was found to exist between the vernalization duration and the days to flowering.

A recommended strategy for jointed goatgrass management is to plant a spring crop or summer fallow in lieu of winter wheat to prevent jointed goatgrass seed production and to deplete the soil seedbank. Once the soil seedbank is sufficiently depleted, yield and quality losses are reduced when winter wheat is grown again.

Recently, growers and researchers have observed jointed goatgrass spike production in spring-planted crops. If viable seeds were produced by spring-germinating jointed goatgrass, the perceived benefits of planting spring crops would be reduced. Moreover, spring cereal grain yield and quality might be reduced. Currently, it is not known if jointed goatgrass seed production in spring crops originates through incomplete control before spring crop seeding, seed production from vernalized seeds, or true spring biotypes of jointed goatgrass.

The objective of this study was to determine quantitative vernalization requirements of three jointed goatgrass cohorts in comparison with winter wheat as measured by vegetative and reproductive growth.

Materials and Methods

Jointed goatgrass spikelets of three cohorts were collected during August 1998 near Gooseberry, OR. The collection site was in the first year of spring cereal production and had traditionally been in a winter wheat—fallow rotation. In 1997 plots were established in a portion of this field for a jointed goatgrass integrated management study, not directly related to this research. Three lots of jointed goatgrass spikelets were isolated from contaminated grain harvested from the field in 1998. Cohort designations included (1) suspected spring cohorts collected from the grower's spring wheat field, (2) known spring cohorts collected from the spring wheat plots within the integrated management study, and (3) known fall cohorts collected from the winter wheat plots within the integrated management study. All jointed goatgrass spikelets were collected from machine harvested winter or spring wheat grain samples. Spikelets were separated from samples by placing the sample in water, stirring for 15 s, and allowing it to settle for 30 s during which spikelets floated to the surface. Spikelets were collected from the surface of the water using a sieve, immediately placed on paper towels, hand blotted to remove excess water, transferred to dry paper towels, and air-dried at 24 C for 4 d. Spikelets were subsequently placed in paper envelopes and stored at 20 C until the initiation of the experiments.

Jointed goatgrass cohorts were tested for seed germinability (Morrow et al. 1982) by placing 25 jointed goatgrass spikelets in a petri dish lined with moistened germination paper. Petri dishes were then placed in a darkened germinator at 20 C. Germination was recorded at 3 and 7 d. Additionally, the number of coleoptiles emerging from each spikelet was counted at 7 d. The germinability test was conducted once using the three cohorts as treatments, and treatments were arranged in a randomized complete block with eight replications.

A growth chamber or greenhouse study was conducted to determine the effects of vernalization duration on the reproductive response of jointed goatgrass grown from spikelets of the three cohorts. Before the initiation of the study, all spikelets and seeds were dusted with a 5% dry formulation of captan [*cis-N*-((trichloro-methyl)thio)-4-cyclo-hexene-1,2-dicarboximide] to prevent fungal infection. Madsen soft white winter wheat was included as a comparative standard (for winter annual species) because it is reported to require 8 wk of exposure at 4 C for vernalization (Steven S. Jones, personal communication). The study included imbibed seed vs. nonimbibed seed treatments. For imbibed treatments, 25 jointed goatgrass spikelets or wheat seeds were placed on germination paper, moistened with deionized distilled water, and the germination papers were loosely rolled and bound with a rubber band (Yenish et al. 1992). The rolls were then placed, on their ends, in a plastic beaker with 2.5 cm of deionized distilled water at the bottom and a plastic bag that covered the beaker. The beakers were placed in an incubator for 48 h at 20 C after which they were moved to a growth chamber set at a constant 4 ± 1 C for vernalization duration treatments of 10, 8, 6, 4, 2, or 0 wk. Nonimbibed treatments were established in a similar manner, but beakers were placed directly into the growth chamber without being placed first in an incubator. Within a vernalization duration treatment, imbibed treatments were initiated 2 d before nonimbibed treatments so that placement in the growth chamber coincided. Also, vernalization duration treatments were placed in the growth chamber at 2-wk intervals so that all treatments were removed on the same day. Upon removal from the vernalization chamber, all treatments were acclimated to 20 C for 48 h in an incubator. Zero-week–imbibed vernalization treatments were prepared and placed in the incubator for 48 h as were the other imbibed vernalization treatments, but then they remained in the incubator an additional 48 h along with the acclimating vernalization treatments. Zero-week–nonimbibed treatments were prepared as were the other nonimbibed vernalization treatments but were placed in the incubator with the acclimating vernalization treatments. Thus, imbibed treatments were in the incubator for 96 h (48 h before vernalization and 48 h after vernalization), and nonimbibed treatments were in the incubator for 48 h. Moisture levels in the beaker were monitored, and deionized distilled water was added as required to ensure that the germination paper remained moist.

After acclimation, two winter wheat seeds or jointed goatgrass spikelets from each imbibition and vernalization treatment having an emerged radicle were transplanted into 3-L pots with an upper diameter of 15 cm, containing a potting soil mix of 60% peat moss and 40% pumice. Individual seeds and spikelets selected for transplanting were representative of the average development observed within each imbibition and vernalization treatment. Seeds or spikelets were placed 2 cm below the soil surface. Pots were placed on greenhouse benches in a randomized complete block arrangement with four replications. The resulting experimental design was a 4 by 2 by 6 factorial arrangement with spring, suspected spring, and fall jointed goatgrass cohorts along with winter wheat, imbibed and nonimbibed treatments, and six vernalization durations.

Pots were watered as required during the experiment. Plant growth stage and spike emergence were evaluated at 2-wk intervals. Metal halide lamps supplemented natural sunlight for a 12-h photoperiod. Light intensity was not measured in this experiment, however, a previous study in the same facility reported a maximum light intensity of 800 to 1,000 $\mu mol\ m^{-2}\ s^{-1}$ (Dotray and Young 1993). Temperatures ranged from 19 to 35 C and 11 to 17 C for daily highs and lows, respectively.

To avoid plant material losses caused by spike disarticulation, plants were destructively sampled for spike production when 50% of the total spikes per pot reached a growth stage that ranged from post-anthesis, Feekes 11.0 (Large 1954), to physiological maturity, Feekes 11.4 (Large 1954). Post-anthesis spikes were characterized as fully emerged by having a flagleaf with closed glumes, by being seed-formation initiated, and by being green, yellow, or purple in color. Mature spikes were fully emerged and completely yellow or brown in color. Winter wheat maturity was more uniform, and disarticulation was not a problem, thus wheat spikes were harvested at maturity (Feekes 11.4). Data collected included tiller and spike numbers per pot. All spikes with any portion emerging from the flagleaf were counted, clipped at the point of attachment to the culm, and collected. A reproductive tiller index was calculated by dividing the number of spikes produced per pot by the number of tillers per pot. Tiller and spike production data are presented as a percentage of the 10-wk vernalization treatment to determine more accurately the differences in vernalization main affect and interactions. Percentage data were calculated by dividing tiller or spike production per pot by the number of tillers in the 10-wk vernalization treatment of each cohort and replication. The experiment was repeated.

Analysis of variance was conducted using a general linear model to examine the main effects and the interactions.

Table 1. Jointed goatgrass (*Aegilops cylindrica L.*) cohort and winter wheat (*Triticum aestivum* L.) tiller and spike production. Results are averaged across vernalization and imbibition treatments.

Cohort	Tillers	Spikes
	No. pot $^{-1}$	No. pot $^{-1}$
Experiment 1		
Suspected spring	148	91
Known spring	155	100
Fall	144	101
Winter wheat	33	15
LSD (0.05)	11	9
Experiment 2		
Suspected spring	92	56
Known spring	97	64
Fall	93	58
Winter wheat	17	10
LSD (0.05)	10	12

There were no differences or interactions between imbibed and nonimbibed seed treatments. Thus, data presented were analyzed as averages of imbibed and nonimbibed treatments. There was a significant experiment run by treatment interaction; thus, results were analyzed and presented separately for each experiment. Treatment means were separated using Fisher's Protected LSD test at the 5% probability level.

Results and Discussion

Germination of jointed goatgrass spikelets was similar for all three cohorts ($P > 0.05$) and ranged from 84 to 95% 7 d after planting (DAP)(data not shown). These results indicate that spring-emerging jointed goatgrass produced viable seeds. Also, the number of coleoptiles per spikelet was similar for each cohort 7 DAP (data not shown). However, it was not determined whether there was an equal amount of seeds per spikelet or whether seed numbers were greater in one cohort because only emerged coleoptiles were counted, and seed dormancy may have affected the results.

Germination of jointed goatgrass and wheat occurred in all vernalization treatments before transplanting into pots. The stages of development of jointed goatgrass ranged from radicle emergence to one-leaf stage. No jointed goatgrass with less than 6 wk vernalization had first-leaf emergence from the coleoptile before transplanting. Winter wheat germination within each vernalization treatment was ≥ 96% with coleoptile or leaf lengths ranging from 2 to 9 cm (data not shown).

The number of days between the transfer to the greenhouse and the initiation of spike emergence for vernalization duration treatments of 10, 8, 6, 4, 2, and 0 wk were 70, 82, 103, 117, 142, and 167, respectively (data not shown). Dates from transplanting to flowering were about one-half of those reported by Donald (1984) and may have been because of different temperature or photoperiod conditions that accelerated growth and development. The number of days between transplant and harvest for 10, 8, 6, 4, 2, and 0 wk vernalization duration were 116, 133, 150, 176, 208, and 208, respectively.

Tiller and spike productions were similar for all jointed goatgrass cohorts when averaged across vernalization treatments (Table 1). The suspected spring jointed goatgrass cohort produced fewer spikes than did the fall jointed goatgrass cohort in Experiment 1, but no differences occurred among cohorts in Experiment 2. Madsen winter wheat produced roughly 80% fewer tillers and spikes than did jointed goatgrass. Likely, differences in these parameters between winter wheat and jointed goatgrass reflect the years of direct and indirect selection that went into the development of Madison winter wheat.

Winter wheat vegetative growth and reproduction after transplantation were influenced by vernalization duration with two- to threefold greater tiller production with 0 wk than with 10 wk vernalization (Table 2). Additionally, winter wheat spike production per pot was reduced by over 80% in Experiment 1, but no difference among vernalization treatments occurred in Experiment 2. Reproductive tiller index declined from nearly 0.9 at a 10-wk vernalization duration to 0.09 and 0.27 at 0 wk in Experiments 1 and 2, respectively, indicating that the reproductive tiller index is a good measure of the vernalization response.

The jointed goatgrass cohorts responded differently from wheat to the vernalization duration, but the response was generally similar for each cohort. There was no clear pattern in tillering response to vernalization duration for any of the jointed goatgrass cohorts in Experiment 1, but the number of tillers progressively increased as the vernalization duration decreased in Experiment 2 (Table 2). In Experiment 1, as the vernalization duration was reduced from 10 to 0 wk the number of spikes of jointed goatgrass cohorts decreased by 27 to 49% but over 80% for wheat. Vernalization treatment did not affect jointed goatgrass or wheat spike production in Experiment 2.

Reproduction tiller index of all jointed goatgrass cohorts and wheat decreased as the vernalization duration was decreased in Experiment 1 (Table 2). However, differences between 10 and 0 wk were much greater for wheat than for any of the jointed goatgrass cohorts. The reproductive tiller indices for 0 wk vernalization was about 50% of that observed with 10 wk vernalization for jointed goatgrass in Experiment 1. The reduction in winter wheat was about 90% for the same comparison. Winter wheat showed a similar decline in Experiment 2, but the reduction was about 70%. Tiller index of jointed goatgrass cohorts decreased as the vernalization duration was reduced from 10 to 6 wk but increased as vernalization was reduced from 6 to 0 wk in Experiment 2. The reason for the variable response could be the differences in the photoperiod duration. In Experiment 1 treatments were moved into the greenhouse on April 9 with harvest dates between August 2 and November 23, 1999. The initial photoperiod was approximately 13 h and increased to approximately 16 h before declining to approximately 12 h. In Experiment 2 treatments were moved into the greenhouse on December 3, 1999 with harvest dates between March 29 and June 28, 2000. The initial photoperiod was 12 h, and supplemental lighting remained steady until mid-March, after which it increased steadily to approximately 16 h. Finnerty and Klingman (1962) discovered that growing various winter annual *Bromus* sp. initially under short photoperiods and then increasing the photoperiod could result in an accelerated floral development. It is possible that increasing the photoperiod duration in Experiment 2 may have accelerated the floral development in the later harvested, shorter vernalization duration treatments.

TABLE 2. Effects of vernalization treatment on tiller and spike production of three jointed goatgrass (*Aegilops cylindrica* L.) cohorts and winter wheat (*Triticum aestivum* L.).

Cohort	Duration of vernalization	Experiment 1 Relative tillers[a]	Experiment 1 Relative spikes[a]	Experiment 1 Reproductive tiller index[b]	Experiment 2 Relative tillers[a]	Experiment 2 Relative spikes[a]	Experiment 2 Reproductive tiller index[b]
	wk	%	%		%	%	
Suspected spring	10	100	100	0.93	100	100	0.75
	8	112	94	0.78	125	113	0.67
	6	114	82	0.67	178	102	0.40
	4	95	43	0.43	165	131	0.47
	2	107	56	0.43	210	185	0.59
	0	116	53	0.45	206	206	0.70
Known spring	10	100	100	0.90	100	100	0.75
	8	93	88	0.85	129	119	0.70
	6	120	78	0.59	155	88	0.42
	4	90	61	0.60	162	136	0.63
	2	111	61	0.51	186	212	0.78
	0	122	73	0.57	134	127	0.67
Fall	10	100	100	0.89	100	100	0.73
	8	98	97	0.89	125	171	0.74
	6	103	81	0.70	137	105	0.47
	4	82	50	0.52	177	178	0.50
	2	113	80	0.65	200	265	0.64
	0	90	51	0.48	192	244	0.63
Winter wheat	10	100	100	0.88	100	100	0.85
	8	106	105	0.87	111	102	0.81
	6	118	109	0.82	128	134	0.90
	4	177	116	0.58	200	162	0.72
	2	173	28	0.15	251	115	0.39
	0	217	18	0.09	336	106	0.27
LSD (0.05)		28	23	0.14	72	NS	0.23

[a] Tillers and spikes expressed as a percentage of the number produced compared with the respective cohort within the 10 wk vernalization treatment of a replication.
[b] Reproductive tiller index is the proportion of tillers within a pot that produced a spike.

Results indicate that jointed goatgrass is less dependent on vernalization to produce viable seeds than is winter wheat. Thus, it may be more accurately described as a facultative winter annual rather than a strict winter annual. Additionally, fall and spring cohorts of jointed goatgrass responded similarly to the vernalization duration.

Jointed goatgrass maturation response to vernalization was similar to that reported by Donald (1984), but flowering took much longer in that study than reported herein. Thus, it could be stated that the response in the current study was also caused by quantitative vernalization. Differences between this study and Donald's may be partially explained by the use of jointed goatgrass collected from Colorado in the earlier study rather than the Oregon origin of the cohorts used in these experiments. Donald also saw a relationship between the date of planting in the greenhouse that affected nonvernalized treatments and may have resulted in the inconsistency between the two runs of the present study. Additionally, the Donald study evaluated tiller and spike weight, whereas results in this study were more conclusive for spike and tiller numbers.

Study results indicated that each of the jointed goatgrass cohorts were able to produce spikes with no vernalization. The minimum probability that a tiller would produce a flower without vernalization was approximately 50%. It is not clear whether a population of spring jointed goatgrass has the potential to become a serious problem in spring cereals as it is in winter wheat. However, implications of this research are that rotating to a spring cereal may not completely eliminate jointed goatgrass seed production in that crop.

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