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Method and Timing of Rye Control Affects Soybean Development and Resource Utilization

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ABSTRACT

Cover crops provide environmental and soil quality benefits, yet their adoption into production agriculture has been limited. This study was conducted to determine the influence of the growth stage and method of rye (*Secale cereale* L.) control on soybean [*Glycine max* (L.) Merr.] development and resource utilization. Fall-planted rye was controlled the following spring using a stalk chopper (mechanical) or glyphosate (chemical) at the second-node, boot, and anthesis growth stages near Boone, IA, in 2002 and 2003. Regrowth from mechanical rye control in 2002 depleted soil water until rye matured. Maximum light interception by soybean was reduced by as much as 43 and 30% in chemical and 51 and 23% in mechanical control compared with the no-rye check in 2002 and 2003. Dry matter (DM) accumulation was reduced by as much as 267 and 907 g m^{-2} in chemical and mechanical control in 2002 compared with the check. In 2003, the range in DM accumulation was 242 g m^{-2}. Rye delayed pod maturity in both years by as much as 7.9 d. Producers who adopt these methods of rye management can expect delayed soybean maturity and reduced DM accumulation.

Cover crops reduce soil erosion, increase water infiltration, retain soil water, improve soil tilth, and provide weed suppression (Teasdale, 1996; Sarrantonio and Gallandt, 2003). Rye is often selected as a cover crop in the northern USA based on its winter hardiness (Sarrantonio and Gallandt, 2003) and comparatively low cost (Sustainable Agriculture Network, 1998). Rye has also been recognized for scavenging residual soil nitrate after corn (*Zea mays* L.). Strock et al. (2004) reported that during a 3-yr period in Minnesota in a moderately well-drained soil, NO_3–N loss was reduced 13% for a corn–soybean cropping system with a rye cover crop following corn than with no rye cover crop. Nevertheless, rye cover crop systems have not been widely adopted for reasons including yield depression (Thelen et al., 2004; Reddy 2001; Liebl et al., 1992; Eckert, 1988) and profitability (Reddy, 2001, 2003).

Chemical methods of rye control are effective (Sarrantonio and Scott, 1988; Raimbault et al., 1990); however, uncertainty exists relating to the critical period between chemical rye control and soybean planting. Ruffo et al. (2004) waited from 7 to 15 d between rye chemical control and soybean planting and reported no yield differences between rye and no-rye treatments in their 2-yr study in Illinois. Reddy (2003) waited 2 wk between chemical desiccation of rye that was 100 to 120 cm tall and found no soybean yield differences compared with no-rye treatments in a 3-yr study in Mississippi.

Mechanical methods of rye control allow practitioners to reduce chemical inputs or utilize a method of cover crop control in organic crop production (Creamer et al., 1995; Ashford and Reeves, 2003). Sales of organic products have increased 20% annually in the USA since 1989, resulting in a significant increase in the number of farmers that employ organic practices (Duram, 1998). Although mechanical cover crop control may have beneficial environmental effects from reduced chemical inputs, cover crop regrowth has been identified as a problem (Creamer and Dabney, 2002).

Timing of mechanical rye control also affects the success of control measures. Ashford and Reeves (2003) examined the effect of rye growth stage on control using mechanical management and reported that the flag leaf growth stage is too early to achieve effective control (observed 16%), but waiting until early milk can result in complete kill. They also reported that chemical control (glyphosate label rate 1.68 kg a.i. ha^{-1}) results in equal control (95%) at the flag leaf, anthesis, early milk, and soft dough growth stages. In the upper Midwest, timing of cover crop control must be balanced with subsequent main-crop planting date to realize yield potential.

Although studies have examined the effects of method or timing of rye cover crop management (Ashford and Reeves, 2003; Creamer et al., 1995; Liebl et al., 1992; Munawar et al., 1990), more information is required on the interaction between method and timing of rye control on soybean resource utilization and development. Detecting soybean developmental differences between check and cover crop treatments may provide management information to reduce yield depression of subsequent crops and increase adoption of rye cover crop systems. Our objective was to determine the influence of the growth stage and method of rye control on soybean development and resource utilization.

MATERIALS AND METHODS

Field studies were conducted at the Agricultural Engineering Research Center in Boone County, IA (42°01′ N, 93°45′ W; 341 m above sea level), from October 2001 through October 2003. In 2001–2002, the soil was a Spillville loam (fine-loamy, mixed, superactive, mesic Cumulic Hapludolls) and in 2002–2003, a Clarion loam (fine-loamy, mixed, superactive, mesic Typic Hapludolls). 'Rymin' rye was planted at

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Abbreviations: AB, annual broadleaf; AG, annual grass; DM, dry matter; DOY, day of year; PAR, photosynthetically active radiation.

4 328 151 seeds ha^{-1} with a Marliss[1] (Marliss Division/Sukup Manufacturing Co., Jonesboro, AR) drill in 19-cm row widths in late September and early October of each year following corn grain harvest.

The experimental design was a randomized complete block with treatments arranged in a split-plot with four replications. Main plots were mechanical or chemical rye control applied in the spring. Subplots were timing of rye and were five rows (3.8 m) wide by 28.9 m and 12.2 m long in 2002 and 2003, respectively. Chemical control was a glyphosate [*N*-(phosphonomethyl)glycine] (Roundup UltraMax) application at a rate of 1.41 kg a.i. ha^{-1}. Mechanical control was achieved using a Buffalo (Fleischer Manufacturing Inc., Columbus, NE) stalk chopper with one pass in 2002 and two passes in 2003, which left approximately 15 cm of rye stubble. To increase the effectiveness of the mechanical treatment, weights (240 kg) were added above the blades of the stalk chopper in 2003. Timing of rye control occurred at one of three growth stages: second-node visible (7), boot (9.8), or anthesis (10.5.1), corresponding to Feeke's decimal code for cereals (Zadoks et al., 1974). These stages were reached on day of year (DOY) 127, 134, and 143 in 2002 and 132, 140, and 150 in 2003, respectively. Subplots with no rye within each main plot were established by killing rye with glyphosate (0.70 kg a.i. ha^{-1} Roundup UltraMax) in the spring approximately 1 wk after green-up (DOY 106 and 105 in 2002 and 2003, respectively). Check treatments were maintained weed free for the entire growing season with additional glyphosate and hand weeding as necessary. All other subplots received no additional vegetation control until soybean reached approximately R4 (DOY 2[illegible] and 224 and in 2002 and 2003; Ritchie et al., 1994), when all subplots were sprayed with glyphosate (0.70 kg a.i. ha^{-1} Roundup UltraMax) to eliminate weeds.

Immediately before imposing each chemical or mechanical treatment to rye, biomass samples were collected from three 0.25 m^2 quadrats placed over four rows of rye randomly throughout each subplot. All rye biomass was clipped at the soil surface and dried at 70°C in a forced-air oven until a constant weight was achieved.

Pioneer Brand '92B84' soybean was planted on DOY 148 and 156 in 2002 and 2003 at 445 000 seeds ha^{-1} using a 76-cm row spacing. Immediately after planting, percentage residue cover was determined according to Laflen et al. (1981). At approximately V2 (DOY 164 and 174 in 2002 and 2003), soybean stand counts were determined from 4.6 m of row in the three interior rows per subplot in 2002 and 0.5 m of one interior row in 2003.

Phenological development of soybean was collected weekly in 2002 and biweekly in 2003 following the procedure described by Ritchie et al. (1994). Sample size consisted of 15 and 10 randomly selected plants per subplot in 2002 and 2003, respectively. All data from the interior rows were collected using nondestructive plant sampling until soybean reached R5, when removing pods from harvest rows was necessary to determine the growth stage. Soybean height was measured from the soil surface to the tip of the longest leaf on the terminal node from the same sample used for phenological development. Soybean plants were harvested for DM determination at the soil surface from 0.5 m of nonharvest row within each subplot every 10 d in 2002 and every 15 d in 2003 and dried at 70°C in a forced-air oven until a constant weight was achieved. Weed composition and density samples were collected from four 1 m^2 quadrats per subplot at R2 (DOY 200 and 204 in 2002 and 2003). In the same quadrats, rye tiller number was also counted. Before harvest, soybean maturity data were collected over time until 95% pod maturity was achieved. Soybean yield is presented in a companion paper (Singer and Kohler, 2005).

Interception of photosynthetically active radiation (PAR) was measured weekly from DOY 175 through 269 in 2002 and DOY 183 through 267 in 2003 between 1200 and 1500 h in full-sun conditions (PAR > 1600 μmol m^{-2} s^{-1}) using a 1-m Sunscan Probe (Delta-T Devices, Cambridge, England). Three to six measurements were collected, depending on weed and rye canopies that were established as a result of rye control, diagonally across the three center rows of each subplot. Three measurements were collected below the soybean canopy, and three measurements were taken at approximately the same location above the soybean canopy, but below the canopy of weeds or rye regrowth, depending on the treatment. Light interception was calculated as the difference between incident and transmitted light divided by incident light.

Gravimetric soil water was collected every 7 to 10 d from the 0- to 15- and 15- to 30-cm soil depths using a soil core with a diameter of 18 mm. Five (2002) and three (2003) soil cores per subplot were combined, weighed wet, and dried in an oven at 100°C until constant weight.

Statistical analysis was conducted by year because the Bartlett test on the full model indicated that variances were not homogeneous for most data sets. Each year was analyzed as a split plot using PROC GLM in SAS (SAS Inst., 2001). Block and block × method interactions were considered random effects while method and timing of rye control were considered fixed effects. All data were subjected to diagnostic analyses to confirm compliance with assumptions for ANOVA. Treatment means were separated using a protected LSD procedure (Little and Hills, 1978) when the *F* test was significant ($P < 0.05$).

RESULTS AND DISCUSSION

Precipitation during the growing season (May–September) was 623 mm in 2002 and 562 mm in 2003 (Fig. 1). Although total precipitation in 2002 exceeded that in 2003, the distribution was more critical for soybean development. Precipitation accumulation in June was 81 mm in 2002 and 150 mm in 2003. The effects of this early dry period and above-average air temperatures in 2002 were evident from V2 through R2.

Rye biomass increased as timing of control was delayed (Table 1). Wagner-Riddle et al. (1994) also concluded that delaying rye control always resulted in higher residue biomass when compared with earlier control. There was a 422 and 409% increase in biomass from second node to anthesis in 2002 and 2003, respectively. The quantity of rye biomass affected percentage soil cover (Table 1). Soil cover was 80 compared with 74% in mechanical vs. chemical control in 2002, but no differences were detected between method of control in 2003. Soil cover was also greater in the boot and anthesis treatments compared with the second-node treatment in both years.

Mechanical rye control was not effective in 2002, resulting in substantial regrowth in the second-node and boot treatments. Ashford and Reeves (2003) reported about 20% control 28 d after treatment using a roller-

[1]Mention of trade names or commercial products is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the USDA.

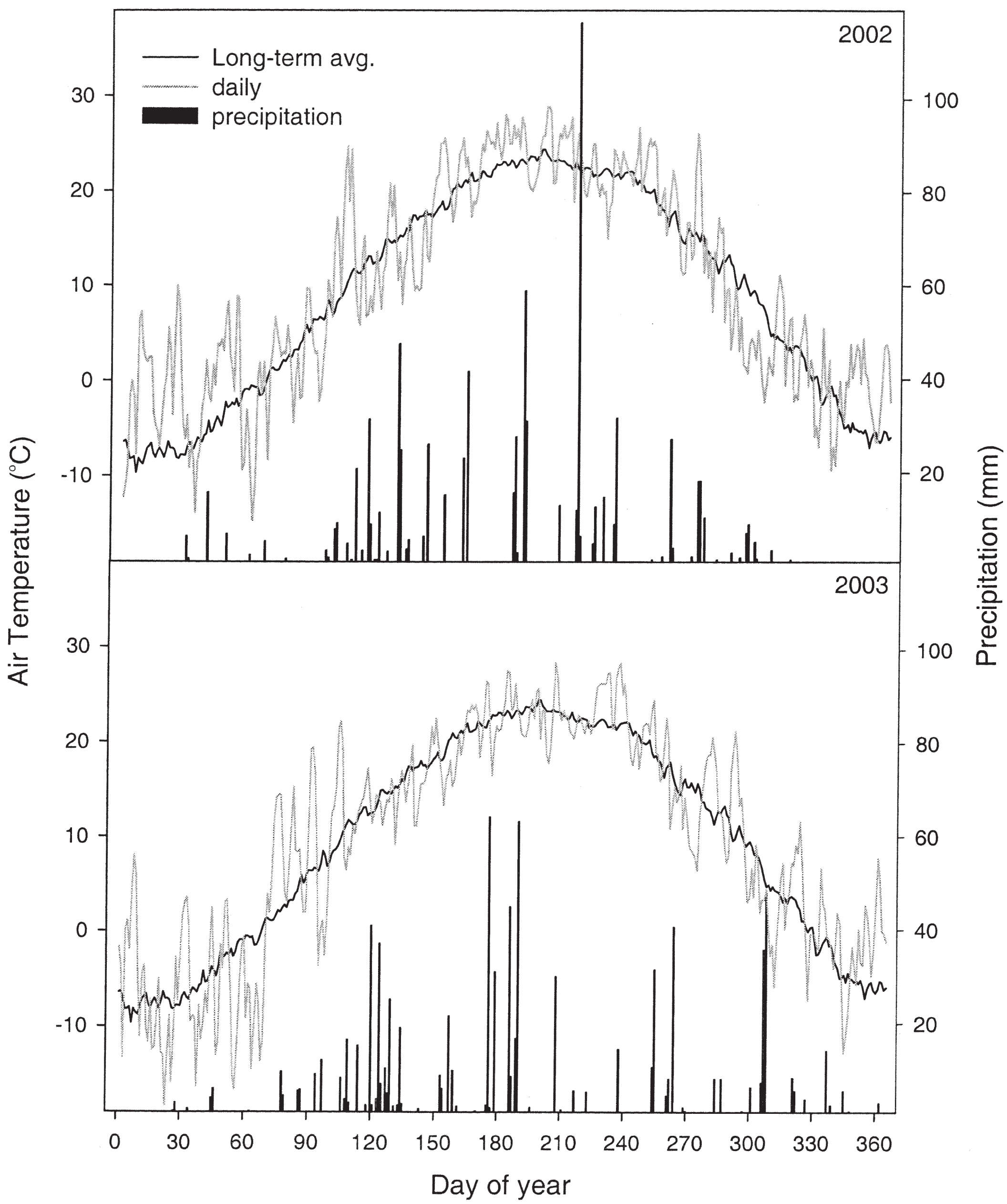

Fig. 1. Daily air temperature and precipitation near Boone, IA, in 2002 and 2003. Long-term average is from 1951–2002.

crimper to kill a rye cover crop at the flag-leaf growth stage. In 2002, the high level of rye regrowth in the second-node and boot treatments in mechanical control affected soybean stand density (Table 1). A method × timing interaction was observed for stand density in 2002. In chemical control, stand density was similar between the second-node and boot treatments (322 780 and 311 124 plants ha^{-1}) and the anthesis and check treatments (369 045 and 365 997 plants ha^{-1}). In mechanical control, stand density decreased as timing of control was delayed from the second node to boot to anthesis treatments (312 917, 287 096, and 270 418 plants ha^{-1}) compared with the check (345 017 plants ha^{-1}). No differences in stand density were observed in 2003.

Soil Water

Soil water depletion and recharge followed precipitation events (Fig. 2). Treatment separation occurred during periods of low precipitation. Only 2002 data are presented because few differences were observed in 2003 because of more timely precipitation during the growing season and more effective mechanical rye control. In 2002, soil water content reached a high of 0.2302 kg kg^{-1} in the 0- to 15-cm soil depth on DOY 193 in the chemical control at anthesis treatment. A low of 0.0910 kg kg^{-1} was recorded on DOY 184 in the mechanical control second-node treatment in the 0- to 15-cm soil depth.

In chemical control, rye residue increased with de-

Table 1. Timing of rye control ANOVA results for spring rye biomass, soil cover, and soybean stand density in 2002 and 2003, near Boone, IA.

		Spring biomass		Soil cover		Soybean density	
Timing†		2002	2003	2002	2003	2002	2003
	n	g m^{-2}		%		plants ha^{-1}	
Second node	8	143	138	73	52	317 848	255 862
Boot	8	350	328	83	66	299 110	282 104
Anthesis	8	604	564	86	78	319 732	354 270
Check	8	0	0	54	32	355 507	268 983
LSD (0.05)		89	85	7	13	9 668	NS
ANOVA	df	$P > F$					
Method (M)	1	0.225	0.844	0.028	0.174	0.000	0.208
Timing (T)	3	0.000	0.000	0.000	0.000	0.001	0.298
M × T	3	0.970	0.943	0.209	0.975	0.004	0.197

† Second node, boot, and anthesis correspond to Feeke's Growth Stages 7, 9.8, and 10.5.1, respectively.

layed timing of control. Consequently, the second-node treatment had the smallest quantity of residue covering the soil surface compared with control at anthesis, which had the greatest quantity of rye residue. Soil water content in the 0- to 15-cm soil depth was greater in the anthesis treatment by 0.0325 kg kg^{-1} compared with the second-node treatment on DOY 178.

Mechanical control in the second-node treatment exhibited rapid soil water depletion during the first dry-down period from DOY 165 through 184. The mechanical check without rye exhibited the greatest soil water content during the first dry-down period because rye in the other mechanical treatments was not effectively controlled in 2002 and utilized soil water during regrowth.

The second dry-down period in 2002 was between DOY 189 and 216. In mechanical control, rye regrowth matured and was no longer competing for water by DOY 189. The no-rye check had the lowest soil water content. This result was observed at both soil depths and displayed a maximum difference in the 15- to 30-cm depth of 0.0152 kg kg^{-1} between the boot and check treatments. The second-node, boot, and anthesis treatments had greater soil water content because soybean developed slower and exhibited delayed water use.

In chemical control, the second dry-down period was characterized differently from the 15- to 30-cm soil depth than the 0- to 15-cm depth. The 116 mm of precipitation received during this period was not sufficient to increase soil water content in the 15- to 30-cm soil depth. During this period, weed competition in the second-node treatment hastened soil water depletion in both soil depths although these differences were not significant.

Contradictory data have been presented on cover crops' effect on soil water content. Facelli and Pickett (1991) reported that the presence of litter increases water availability by decreasing rates of evaporation from the soil surface. In contrast, Weaver and Rowland (1952) found that as much as one-third of a daily rain may be retained by the litter and evaporate directly without becoming available to the plants. Results from this study indicate that increasing rye residue can increase soil water content during vegetative growth. Rye regrowth, however, may lead to rapid soil water depletion, especially during periods of low precipitation.

Rye Regrowth and Weed Suppression

Rye tiller counts at the R2 soybean growth stage (DOY 204 and 200 in 2002 and 2003) reflect the effectiveness of the initial method and timing treatments (Table 2). No difference was detected among timing treatments in mechanical control in 2002. In 2003, tiller density decreased by 60% between the second-node and boot treatments in mechanical control. It is unclear why tiller number increased between the boot and anthesis treatments. Chemical control was effective at all rye growth stages, which is consistent with conclusions by Munawar et al. (1990).

Rye residue and regrowth had a significant effect on weed suppression. The ability of a cover crop to suppress weed growth is related to the amount of biomass it produces (Liebman and Davis, 2000) and amount of inhibiting chemicals released by the cover crop (Mohler and Teasdale, 1993; Teasdale, 1996). Delaying rye control increased rye biomass, which increased ground cover and reduced weed density and competition. A method × timing interaction was detected for total weed density in both years (Table 2). Total weed number decreased in chemical control between second-node and anthesis treatments but was unchanged among timing treatments in mechanical control in 2002. Rye regrowth probably reduced total weed densities in mechanical control. In 2003, similar total densities between second node in chemical and mechanical control and among timing treatments in mechanical control may be related to the type of equipment used for mechanical control. The rolling stalk chopper chopped rye biomass, which probably facilitated a more rapid decay than the standing rye in chemical control. Greater soil light interception and the surface soil disturbance caused by the stalk chopper may have influenced weed density. Facelli and Pickett (1991) suggested that weed suppression is a consequence of the mechanical barrier created by the cover crop residue.

Weed suppression depended on life cycle and control measure. Teasdale (1996) reported that rye residue was more effective in controlling perennial weeds than an-

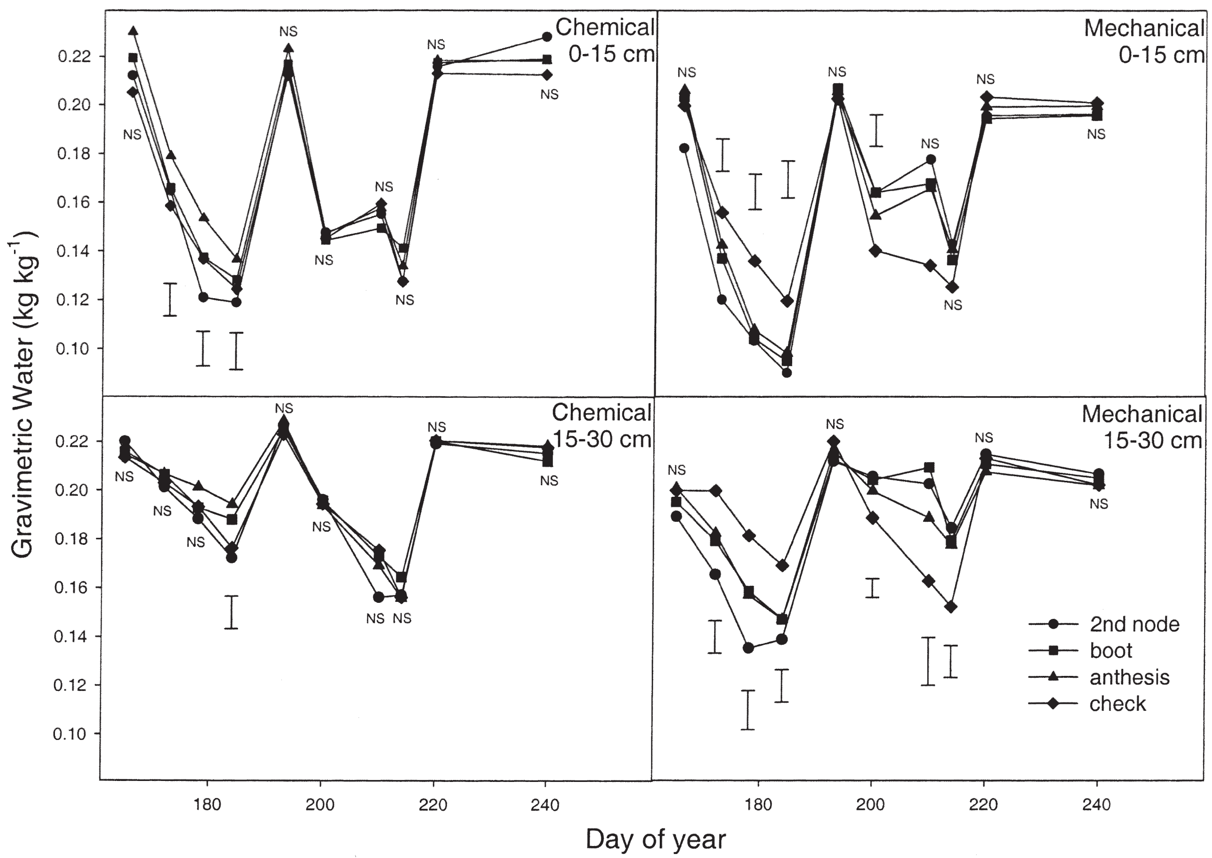

Fig. 2. Gravimetric soil water content in chemical and mechanical rye control at three growth stages and a no-rye check from the 0- to 15- and 15- to 30-cm soil depths at different sampling dates in 2002. Vertical error bars represent LSD value at $\alpha = 0.05$.

nual weeds. In 2002, the chemical control second-node and boot treatments had greater perennial weed density than the anthesis treatment while no differences in perennial weed density were detected among timing treatments in mechanical control. In 2003, no differences were observed for perennial weed density. Perennial weeds consisted mainly of dandelion (*Taraxacum officinale* Weber in Wiggers) in both years. In 2002, annual broadleaf (AB) weed density, averaged across method, decreased with timing treatment (13, 8, and 5 AB weeds m^{-2} for second node, boot, and anthesis, respectively). In 2003, averaged across timing, chemical control had 3 vs. 9 AB weeds m^{-2} in mechanical control. Annual broadleaf weed density was dominated by *Amaranthus* sp., lambsquarters (*Chenopodium album* L.), and smartweed (*Polygonum pensylvanicum* L.) in both years. Annual grass (AG) weed densities were significant in 2003 when a method × timing interaction was detected. In

Table 2. Timing and method of rye control effects on midseason weed composition and density of annual grasses (AG), annual broadleaves (AB), perennials, and total weed number and rye tiller number in 2002 and 2003, near Boone, IA.

Method	Timing†		Tiller density 2002	Tiller density 2003	AG 2002	AG 2003	AB 2002	AB 2003	Perennial 2002	Perennial 2003	Total 2002	Total 2003
		n	no. m^{-2}		plant no. m^{-2}							
Chemical	second node	4	0	0	8	4	14	5	6	3	27	12
	boot	4	0	0	4	3	10	4	9	1	23	7
	anthesis	4	0	0	1	0	6	1	1	0	8	1
	check‡	4	0	0	0	0	0	0	0	0	0	0
Mechanical	second node	4	134	80	2	5	11	7	0	0	13	12
	boot	4	133	32	4	1	6	12	1	0	11	13
	anthesis	4	112	61	7	6	4	8	0	0	11	14
	check	4	0	0	0	0	0	0	0	0	0	0
	LSD (0.05)§		NS	17	NS	2	NS	NS	3	NS	11	4
	ANOVA	df	$P > F$									
	Method (M)	1	0.000	0.009	0.856	0.122	0.154	0.011	0.000	0.324	0.015	0.015
	Timing (T)	2	0.096	0.003	0.884	0.035	0.029	0.072	0.007	0.174	0.026	0.024
	M × T	2	0.096	0.003	0.063	0.001	0.963	0.058	0.018	0.239	0.051	0.002

† Second node, boot, and anthesis correspond to Feeke's Growth Stages 7, 9.8, and 10.5.1, respectively.
‡ Vegetation counts were zero and omitted from ANOVA analysis.
§ LSD compares timing means for the same method.

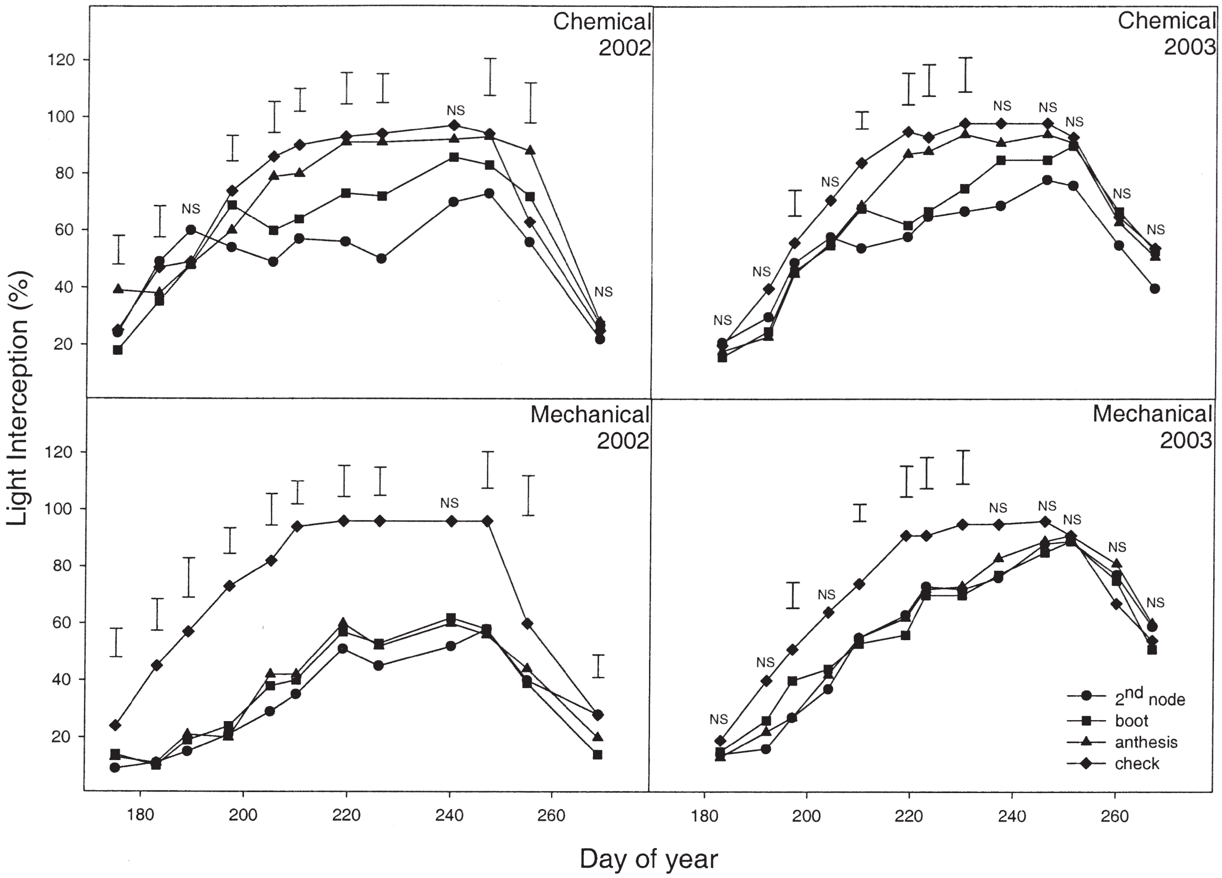

Fig. 3. Light interception in chemical and mechanical rye control at three growth stages and a no-rye check at different sampling dates in 2002 and 2003. Vertical error bars represent LSD value at $\alpha = 0.05$.

chemical but not mechanical control, second-node AG densities were higher than anthesis densities. Foxtail (*Setaria* sp.) was the only AG identified in either year.

Light Interception

A method × timing interaction for light interception was observed during the majority of the sampling times in both years (Fig. 3). In chemical control, rye residue intercepted light until soybean reached approximately 17 cm. Because the quantity of rye residue varied with time of control, residue from the second-node and boot treatments was insufficient to suppress weed establishment, which then reduced light interception of soybean. On DOY 205 in 2002, weeds intercepted 43, 25, and 0% PAR in the second-node, boot, and anthesis treatments. In 2003 on DOY 206, weeds intercepted 9, 6, and 0% PAR in the second-node, boot, and anthesis treatments. The anthesis treatment provided sufficient residue to minimize weed establishment and had similar light interception as the check at most sampling times. At DOY 226 in 2002, mean light interception was 51, 72, 91, and 94% for the second-node, boot, anthesis, and check treatments. In 2003 on DOY 230, mean light interception was 67, 75, 94, and 97% for the second-node, boot, anthesis, and check treatments. Lower weed densities in the second-node treatment probably had the greatest influence on increasing light interception in 2003.

In mechanical control, rye regrowth reduced total light interception by soybean. On DOY 205 in 2002, rye intercepted 34, 17, and 13% of PAR in the second-node, boot, and anthesis treatments. In 2003 on DOY 206, rye intercepted 16, 13, and 11% of PAR in the second-node, boot, and anthesis treatments. No treatment effects were observed among timing treatments except on DOY 269 in 2002 and DOY 192 in 2003. Timing treatments had lower light interception than the check except for the second-node and anthesis treatments on DOY 269 in 2002 and the boot treatment on DOY 192 in 2003. These results were consistent in both years but exacerbated in 2002 because of insufficient rye control and soybean water stress. On DOY 226 in 2002, mean light interception was 45, 53, 52, and 96% for the second-node, boot, anthesis, and check treatments. In 2003 on DOY 230, mean light interception was 72, 70, 73, and 95% for the second-node, boot, anthesis, and check treatments. In 2003, light interception in the check and timing treatments converged around DOY 245 because rye regrowth had matured and the late-season chemical application killed weeds that were intercepting light.

Soybean Growth

Soybean growth from emergence to R7 was assessed based on the number of nodes on the main-stem, similar to the system used by Pedersen and Lauer (2004). Method × timing interactions were observed for most

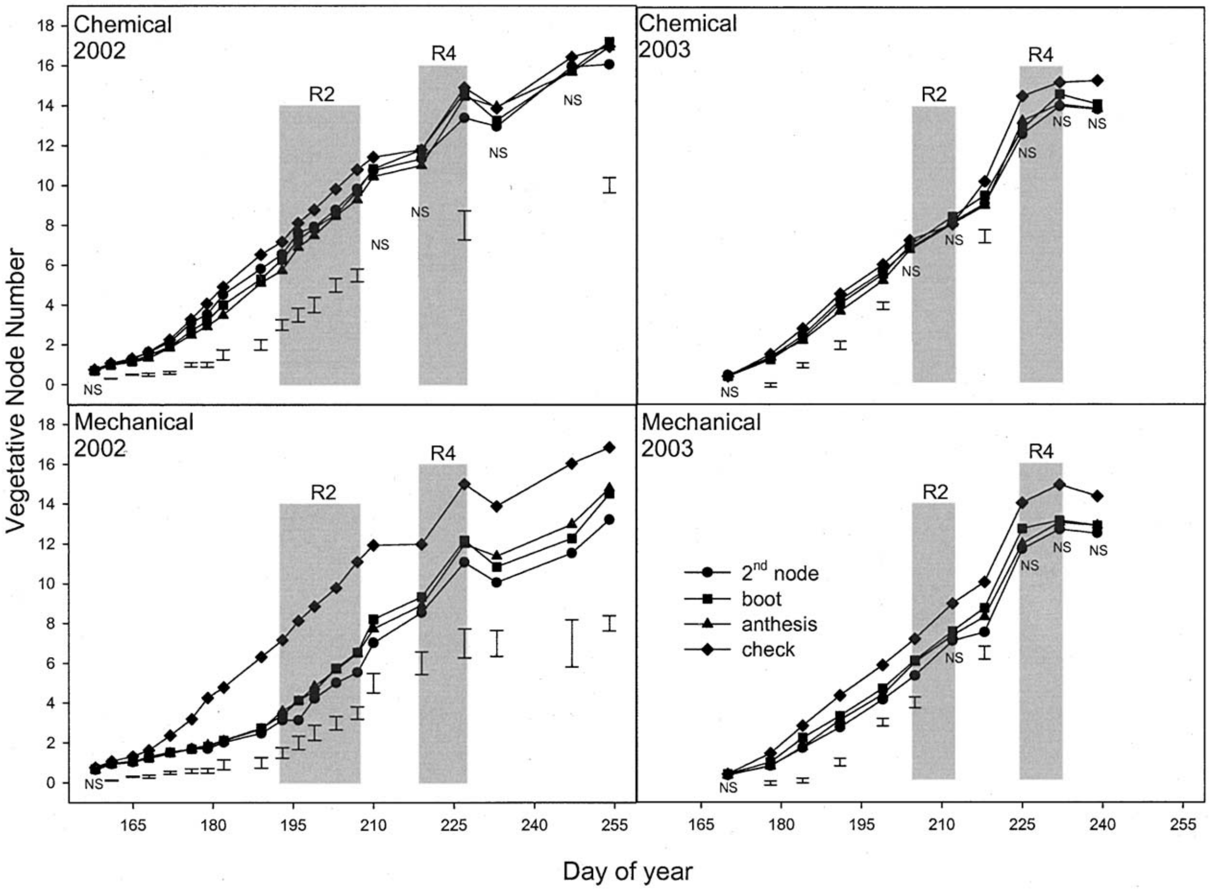

Fig. 4. Soybean main-stem node development in chemical and mechanical rye control at three growth stages and a no-rye check at different sampling dates in 2002 and 2003. Vertical error bars represent LSD value at α = 0.05.

observations in 2002 and when differences were detected in 2003. In chemical control, all timing treatments developed more slowly than the check from the second sampling period until DOY 210, when treatments had similar main-stem node development (Fig. 4). At DOY 254, all treatments except the second-node timing treatment had similar node number (17.0 vs. 16.1). In 2003, differences in node number in chemical control treatments were less evident. The check and the second-node timing treatment had similar node numbers at DOY 170, 178, 191, 199, and 204 while the boot and anthesis treatments had lower node number from DOY 184 through 199. The greater weed pressure in the second node-treatment may have accelerated growth in this treatment to increase light interception. At DOY 218, the check had greater node number than the chemical timing treatments, and this trend continued until DOY 239 even though the last three observations were not significantly different.

In mechanical control, separation of treatments occurred at the second sampling date in both years (Fig. 4). The number of soybean nodes increased more rapidly in the check than all of the timing treatments. Node development in the second-node treatment decreased at DOY 196 and remained lower for the duration of the growing season compared with the boot and anthesis treatments, although differences were not always significant. In general, node development was similar between the boot and anthesis treatments in 2002. In 2003, the check treatment also exhibited more rapid node development compared with the timing treatments. At DOY 204 and 218, the second-node treatment exhibited slower node development than the boot and anthesis timing treatments, but these differences were not as consistent as in 2002. Although no method $\times$ timing interaction was detected for the last three measurements in 2003, timing was highly significant. During this 15-d period, timing treatments had similar node number (12.5, 13.6, and 13.4), but these were all lower than the check (14.3, 15.1, and 14.9).

Another measure of plant development was soybean height (Fig. 5). In 2002, although differences were detected among chemical control treatments, soybean height only varied by 5 to 10 cm from the shortest to the tallest treatment throughout the growth period. One trend in chemical control in 2002 was a separation between check and second-node soybean heights from boot and anthesis heights. From DOY 193 to DOY 254, the second-node and check treatments had similar plant height. Effects of etiolation can be used to describe this result. Because weed densities were greater in this treatment, competition for light probably caused soybean height to increase more rapidly. In a study on soybean development in different stubble heights, Hovermale et al. (1979) reported that soybean in high stubble (35–40 cm) was taller than soybean grown in low

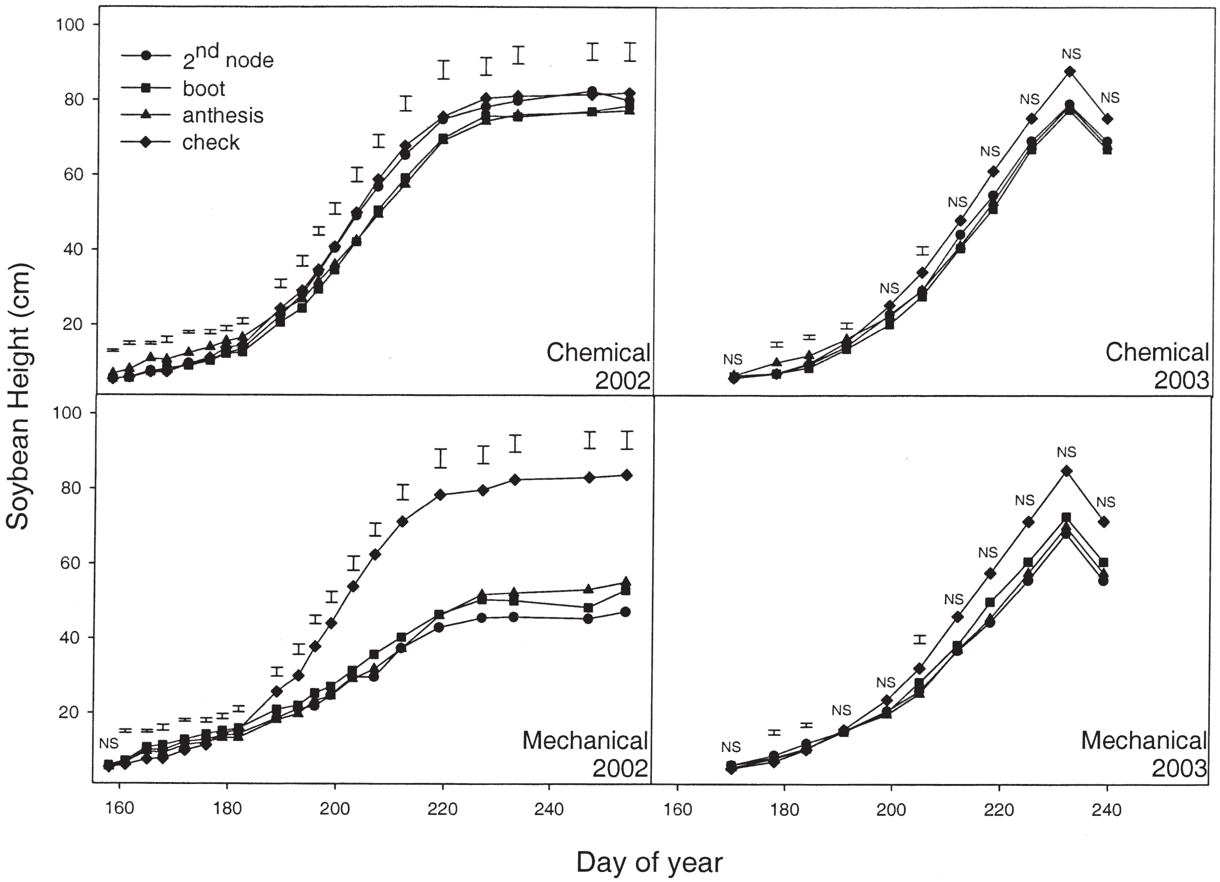

Fig. 5. Soybean plant height in chemical and mechanical rye control at three growth stages and a no-rye check at different sampling dates in 2002 and 2003. Vertical error bars represent LSD value at α = 0.05.

stubble (10–20 cm). In 2003, fewer differences were observed in soybean height in chemical control although the trend indicated taller plants in the check compared with timing treatments after DOY 205.

In contrast, mechanical control dramatically reduced soybean height in all timing treatments compared with the check after DOY 189. Among timing treatments, etiolation effects were observed early in mechanical treatments, for approximately the first 30 d (34 and 27 d in 2002 and 2003, respectively) after planting. After this point, resource limitations, such as soil water and light, reduced the plants ability to increase height at the same rate as the check. In 2003, the difference in height between timing treatments and the check and among timing treatments was less pronounced than in 2002. This is attributed to fewer rye tillers because weed densities were similar in both years.

The check treatments reached 95% pod maturity on DOY 265 (2002) and 275 (2003, Table 3). In 2002, a method × timing interaction was detected for pod maturity. In chemical control, similar maturity was observed among timing treatments (6.3, 6.8, and 6.3 d after the check for the second-node, boot, and anthesis treatments). In mechanical control, the second-node treatment exhibited delayed maturity (8.3 d) compared with the boot and anthesis treatments (7.0 and 6.8 d). In 2003, no interaction was observed for pod maturity. Averaged across method of control, second node matured 1.5 d later than the anthesis treatment and at the same time as the boot treatment. One explanation for the observed difference in maturity is the possibility of allelopathy.

Although exact mechanisms are not completely understood, allelopathic effects of residue have been found to decrease germination and vigor of soybean through O_2 depletion or toxicity of CO_2 produced by decomposers feeding on residues (Facelli and Pickett, 1991). Our results are not consistent with those of Moore et al.

Table 3. Timing of rye control effects on soybean pod maturity in 2002 and 2003, near Boone, IA.

		Pod maturity‡	
Timing†		**2002**	**2003**
	n	d	
Second node	**8**	**7.3**	**5.3**
Boot	**8**	**7.9**	**5.0**
Anthesis	**8**	**6.5**	**3.8**
Check	**8**	**0.0**	**0.0**
LSD (0.05)		**0.7**	**1.4**
ANOVA	**df**	$P > F$	
Method (M)	**1**	**0.205**	**0.396**
Timing (T)	**3**	**0.000**	**0.000**
M × T	**3**	**0.034**	**0.393**

† Second node, boot, and anthesis correspond to Feeke's Growth Stages 7, 9.8, and 10.5.1, respectively.

‡ Pod maturity reported as days after check plots reached maturity on day of year 265 and 275 in 2002 and 2003. Pod maturity is equivalent to the R8 growth stage.

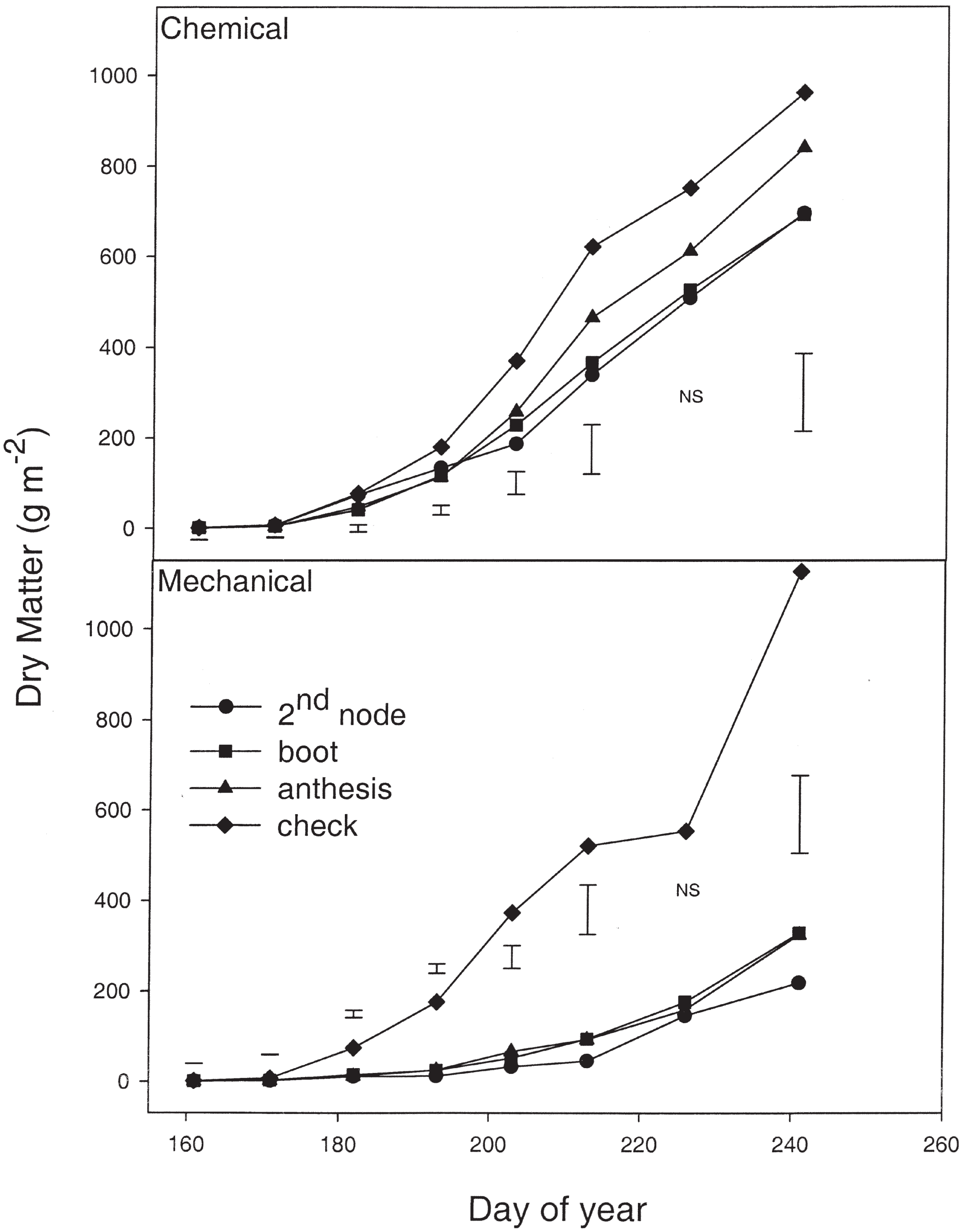

Fig. 6. Soybean dry matter accumulation in chemical and mechanical rye control at three growth stages and a no-rye check at different sampling dates in 2002. Vertical error bars represent LSD value at α = 0.05.

(1994), who reported that no developmental differences occurred in soybean preceded by either rye, wheat (*Triticum aestivum* L.), or triticale (× *Triticosecale* Wittmack) under weed-free conditions. The chemical control anthesis treatment in our study had 8 and 1 weeds m^{-2} in 2002 and 2003, respectively, yet clear developmental differences were detected in both years compared with the check.

Dry Matter Accumulation

Dry matter accumulation exhibited method × timing interactions at all sampling dates except DOY 226 in 2002. In chemical control, the second-node and check treatments had similar DM at DOY 182, but thereafter, the check treatment accumulated DM more rapidly than any timing treatment in chemical control until DOY 241 (Fig. 6). Among timing treatments, separation in DM production occurred at DOY 203, when the second-node treatment had the lowest accumulation. Thereafter, second node and boot had similar DM while the anthesis treatment had intermediate accumulation between the check and the other timing treatments, until DOY 241, when the check and anthesis treatment were similar. At DOY 241, the check had accumulated 962 g

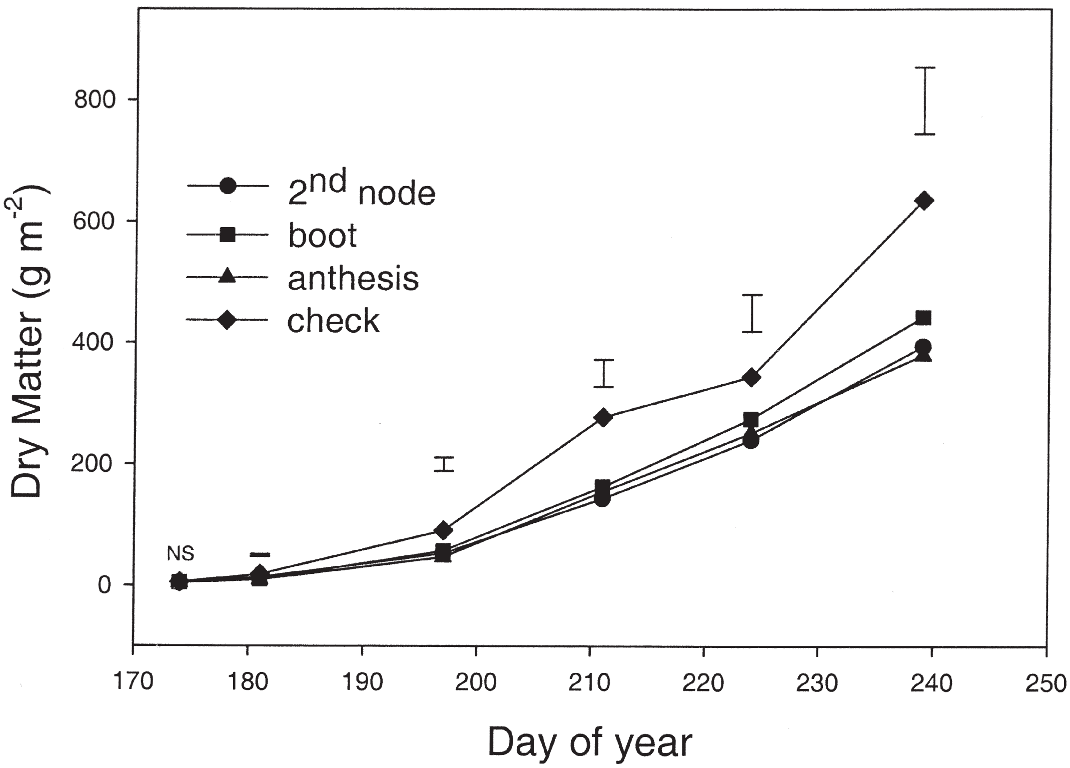

Fig. 7. Soybean dry matter accumulation, averaged across method of control, at three growth stages and a no-rye check at different sampling dates in 2003. Vertical error bars represent LSD value at α = 0.05.

m^{-2} DM compared with 695, 692, and 840 g m^{-2} in the second-node, boot, and anthesis treatments. Soybean light interception paralleled DM accumulation in chemical control. In mechanical control, DM accumulation was similar for all timing treatments during the measurement period and was lower than the check. AT DOY 226, averaged across method, similar DM accumulation occurred among timing treatments (354 g m^{-2}) and was lower than the check (652 g m^{-2}). At DOY 241 in mechanical control, the second-node, boot, anthesis, and check treatments had accumulated 219, 328, 325, and 1126 g m^{-2} DM. Soybean yield (Singer and Kohler, unpublished, 2005) paralleled DM accumulation in mechanical control in 2002 and averaged 1389 kg ha^{-1} for timing treatments compared with the check (3494 kg ha^{-1}). In chemical control, similar yield occurred in the boot and anthesis treatments (2755 kg ha^{-1}), which yielded higher than the second-node treatment (2016 kg ha^{-1}) and lower than the check (3360 kg ha^{-1}; Singer and Kohler, unpublished, 2005).

In 2003, method × timing interactions were only observed at one of six sampling dates. Consequently, all data were averaged across method of control. Differences between the check and timing treatments were evident at DOY 181 and continued until the last sampling date at DOY 239 (Fig. 7). No difference in DM accumulation was observed among timing treatments, presumably because of more effective mechanical rye control. At DOY 239, second node, boot, anthesis, and the check had accumulated 395, 443, 380, and 637 g m^{-2} DM. Singer and Kohler (unpublished, 2005) reported similar yield among timing treatments in mechanical control (1971 kg ha^{-1}), which was lower than the check (2822 kg ha^{-1}), and similar yield between the second-node and boot treatments in chemical control (1982 kg ha^{-1}), which was lower than the anthesis (2419 kg ha^{-1}) and check (2889 kg ha^{-1}) treatments. We cannot attribute differences in DM accumulation in 2003 to differences in stand density or differences in soil water content (data not presented). In 2002 and 2003, soybean was planted 21, 14, and 5 d and 24, 16, and 6 d after chemical and mechanical rye control. Reports in the literature indicate that similar soybean yields were obtained between rye treatments and no-rye checks using the same time periods between rye control and soybean planting as our second-node and boot treatments. In our study, competition from weeds may have reduced DM accumulation. Weed competition is confounded with the time of rye control because we were also interested in the weed suppressive abilities of the different treatments. Nevertheless, our data suggest that causes other than stand reduction, soil water, or weed densities exist for the DM accumulation differences we observed in 2003.

CONCLUSIONS

Chemical and mechanical rye cover crop control at different growth stages presents different management challenges in soybean production systems. Using chemical control before or during stem elongation will most likely require multiple chemical applications to reduce subsequent weed pressure. Using mechanical control when rye is elongating or flowering will result in varying levels of rye regrowth that will interfere with soybean growth and development. The least competitive treatment with soybean in this study was rye chemical control at anthesis. Nevertheless, this treatment reduced DM accumulation in 1 of 2 yr compared with the check. Consequently, producers who choose to adopt these methods of rye cover crop management can expect delayed soybean maturity and reduced DM accumulation.

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