

Gibberellic Acid Promotes Early Growth of Winter Wheat and Rye

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Abstract

Winter wheat (*Triticum aestivum*) planting in Nebraska is recommended for mid Sep but summer crops are often harvested around Oct 1. Also, weather may delay planting. Could gibberellic acid (GA₃), a growth stimulant, overcome the delayed seedling growth from late planting? Irrigated field trials were planted from 2005 to 2010 applying GA₃ to wheat seed of cvs. Goodstreak and Wesley. In 2005, dip, spray and furrow GA₃ applications to seed were tested. Dip and spray gave similar results. Furrow application was calculated too costly. Further tests used seed dips. In 2006 to 2008 planting, wheat was planted about 15 Sep, 1 Oct and 15 Oct. Trials planted in 2007 and 2008 included winter rye (*Secale cereale*) cv. Rymin. Heights in mid Nov showed a reduction with later planting. When planted about 1 Oct and 15 Oct, the delayed growth of Goodstreak, compared to planting two weeks earlier, was fully overcome by GA₃ at 250 ppm. For Wesley, 1000 ppm GA₃ was needed to nearly overcome later planting. Rymin rye gave an intermediate response between the two wheat cultivars. Spring and summer heights were not affected by GA₃. Spring biomass, yield and harvested seed germination showed no GA₃ effect. In later trials (planted in 2009 and 2010), the cytokinin 6-benzyl adenine (6BA) was added to GA₃ to stimulate tiller formation. In the 1st year, 6BA at 2000 ppm depressed height, weight and yield without tiller promotion. Repeating the trial with lower rates (31 - 125 ppm 6BA) did not offer an additional advantage to GA₃. The results indicate that seed application of GA₃ can overcome delayed growth resulting from delayed planting of winter wheat and rye under irrigation. This procedure is recommended and is being used by growers who report satisfaction from the benefit and low cost, <US\$ 3.00 ha⁻¹.

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Keywords

Plant Growth Regulator, Gibberellin, Planting Aid, Wind Erosion, Soil Erosion, Cover Crop, Crop Rotation

1. Introduction

The desired planting date for winter wheat in Nebraska is around 15 September [1]. However, many summer crops, e.g., dry bean (*Phaseolus vulgaris*) and potato (*Solanum tuberosum*) grown in the state and region are rotated with wheat and are harvested normally in late Sep and early Oct [2] [3]. Stimulating seedling growth of wheat planted later to make up for a two-week delayed planting would allow later planting [4] and establish the crop for protection against wind erosion of soil [5]. This would make winter wheat and summer crops more compatible.

Gibberellin, first identified from a pathogenic fungus [6], is a family of natural growth promoters of which GA₃ may be the most active in stimulating stem elongation [7]. Recently, GA₃ bioassays for stem growth were reported on common bean [8] and winter wheat [9] demonstrating differential sensitivity of cultivars and growth habits. In wheat, popular cultivars in irrigated production are semi-dwarf and tend to be less sensitive to GA₃ than non-semi-dwarf or tall cultivars [10] [11]. Therefore to identify relative effects of GA₃ on these two types of winter wheat, the cultivars Goodstreak [12], a tall type, and Wesley [13], a semi-dwarf type, were field tested using the rate guidelines reported from growth chamber tests [9].

Wheat height genetics is complex and determined by many *Rht* (“Reduced Height”) genes. Depending on their reaction to exogenous GA₃, the *Rht* genes are classified into two groups, GA₃-sensitive (synthesis mutants) and GA₃-insensitive [14]. Dwarfism in wheat lines carrying GA₃-sensitive genes is due to either the absence of or a modified spectrum of endogenous gibberellin. These genes are involved in GA₃ biosynthesis and normal growth can be restored by exogenous GA₃. Goodstreak and Wesley are hard red winter wheat cultivars adapted to the region around western Nebraska [12] [13]. Goodstreak grows to a conventional height (“tall”) and has a long coleoptile. Wesley is a semi-dwarf, about 15% shorter than Goodstreak, with a short coleoptile and carries the GA₃-sensitive gene *Rht8c* (*Rht8*) in addition to the GA₃-insensitive gene *Rht-B1b* (*Rht1*). *Rht8c* is agronomically the most important dwarfing gene for many wheat cultivars [15]. Semi-dwarf cultivars, e.g., Wesley, may emerge erratically when planted late or in dry soil [4]. Goodstreak and Wesley are excellent for comparing conventional and semi-dwarf cultivars for their sensitivity to seed-applied GA₃ in a field environment.

Another aspect is to stimulate seedling growth of a grass cover crop to resist wind erosion during the winter followed by planting a summer crop such as potato. Winter rye is used as a cover crop [16] and for pasture [17]. Similar to wheat, rye may have dwarf genes related to GA₃ mutants [14]. The cultivar Rymin is a medium tall type [18].

The main objective of this study was to hasten fall growth of irrigated winter wheat when planted later than recommended using GA₃ for improved pre-winter seedling establishment. The second objective was to determine whether there were long-lasting negative effects of GA₃ into the spring and summer. A third objective was to determine whether the addition of 6BA, a cell division promoter (cytokinin) [7], to GA₃ would promote tiller production. In addition to winter wheat, the response of winter rye to GA₃ at different planting dates was included in two trials.

2. Materials and Methods

2.1. Trial Conditions

Between 2005 and 2011, field trials were conducted on winter wheat (*Triticum aestivum* L.) cultivars Goodstreak [12] and Wesley [13] and between 2007 and 2009, on winter rye (*Secale cereale* L.) cultivar Rymin [18] at the Univ. of Nebraska’s Panhandle Research & Extension Center, Scottsbluff (lat. 41.9N, long. 103.7W, elevation 1208 m). Soil was a Tripp fine sandy loam at pH 7.8 - 8.1 and organic matter content of 0.7% - 1.0%. Rainfall and temperature were monitored by the High Plains Regional Climate Center [19]. Trials were conducted under an overhead, linear-move irrigation system applying 9 to 11 cm water in May and June supple-

menting rainfall for a total of about 25 cm. Mean temperatures for May and June were between 15.7°C and 18.5°C. Fertilizer was applied in mid Sep as ammonium nitrate in 2005 and 2006, and as ammonium sulfate plus mono-ammonium phosphate later. Total N was about 200 kg·ha⁻¹. Fields were cleaned of weeds with glyphosate applied in early Sep before first planting. In April, 2,4-D was applied for weed control as appropriate. Geese feeding was deterred by using flash tape attached to poles spaced every 6 m from December to April. All plots in all trials were four rows with spacing of 30 cm. Harvested row length was 6.1 m of 7.6 m planted with the exception of the furrow-application trial in 2005 where the row length was 12.2 m of 15.2 m planted. The targeted seeding rate was 330 seeds m⁻². To accomplish this target, each year, 100-seed samples of Goodstreak and Wesley were weighed and averaged to calculate weight per seed. The seed weight per plot was calculated in order to achieve 2700 - 2800 seeds per plot. In the furrow trial in 2005, the calculation per plot was adjusted for the longer row length. Planting dates were grouped into three periods: 1st planting in mid Sep (14 to 20), 2nd about 1 Oct (28 Sep to 4 Oct), and 3rd in mid Oct (12 to 19). A 12 to 14 day interval was maintained between planting dates in a given year. Harvesting was in the second half of July the following year.

2.2. Chemical Preparation and Applications

Gibberellic acid (GA₃) was applied as Release LC, a 4% a.i. by weight formulation, *i.e.*, 1 g GA₃/30mL, formulation (Valent BioScience Corp., Long Grove, IL). Release LC was serially diluted with water to achieve desired concentrations. In 2009 and 2010, 6-benzyl adenine (6BA) as MaxCel, a 1.9% a.i. by weight formulation (Valent Bioscience) was added to GA₃. For seed dip treatments used in all years, sufficient seed was weighed to plant 20 plots and treat with 1 L of water, GA₃ solution, or GA₃ + 6BA solution. For planting in 2006, 2007 and 2008, Goodstreak seed weight was 1.1 kg/20 plots (about 55,000 seeds); for Wesley, it was 1.6 kg/20 plots, and for Rymin rye, it was 1.2 kg/20 plots. Wheat seed weight for 20 plots in 2005, 2009 and 2010 was about 1.6 kg for Goodstreak and about 2.1 kg for Wesley. The 20-plot seed samples were placed in 4-L Erlenmeyer flasks followed by the treatment solution. The solution and seeds were mixed through rapid shaking and inversion of the flasks for two minutes. Afterwards, the flask was drained of liquid using a sieve to hold the seeds. The seeds were, then, layered on an aluminum tray for air drying with periodic stirring over the next few days. In 2005, for the seed spray, 728 g of Wesley seed, sufficient for 7 plots, was placed on a plastic sheet. Solutions were placed in spray bottles and 200 mL was sprayed using a CO₂ backpack sprayer. After treatment, seeds were removed from the plastic, placed in aluminum trays and air dried. The third application method tested in 2005 was planting Wesley seed into open furrows in the field, followed by spraying the treatment solutions onto the seed with a CO₂ backpack sprayer, and then covering up the seed in the furrow. The experiment breakdown by year is summarized in **Table 1**.

Table 1. Experiment summary by year.

Year planted	Experiment	Cultivar ¹	Application	Treatment ² & Rates
2005	Planting date ³	Goodstreak and Wesley	Seed dip ⁴	GA ₃ @ 1000 ppm
	Seed treatment	Wesley	Seed dip, seed spray ⁵	GA ₃ @ 500, 2000, 4000 ppm
	Furrow	Wesley	Furrow spray ⁶	GA ₃ @ 175, 350, 700, 1400 g·ha ⁻¹
2006				
2007	Planting date	Goodstreak and Wesley	Seed dip	GA ₃ @ 125, 250, 500, 1000 ppm
2008				
2007	Planting date	Rymin rye	Seed dip	GA ₃ @ 125, 250, 500, 1000 ppm
2008				
2009	Cytokinin added	Goodstreak	Seed dip	GA ₃ @ 500 ppm + 6BA @ 0, 125, 500, 2000 ppm
		Wesley	Seed dip	GA ₃ @ 1000 ppm + 6BA @ 0, 31, 63, 125 ppm
2010	Cytokinin added	Goodstreak	Seed dip	GA ₃ @ 250 ppm + 6BA @ 0, 31, 63, 125 ppm
		Wesley	Seed dip	GA ₃ @ 500 ppm + 6BA @ 0, 125, 500, 2000 ppm

¹Goodstreak and Wesley are winter wheat cultivars; Rymin is a winter rye cultivar. ²Water was included in all trials as check. ³Planting dates were mid Sep, about 1 Oct and mid Oct. ⁴Seeds for 20 plots were exposed to 1000 mL of treatment for 2 min then drained and air dried. ⁵Seeds for 7 plots were sprayed with 200 mL of treatment then removed and air dried. ⁶Untreated seeds were planted into an open furrow onto which water or GA₃ was sprayed using a CO₂ sprayer set to apply 94 L·ha⁻¹ carrier and then the furrow was covered.

2.3. Data Collection and Analysis

Heights were measured from the ground or base to the tip of the longest leaf between 12 and 20 Nov prior to the onset of winter, between 20 Mar and 8 Apr, between 7 and 22 May, and in July prior to harvest. Biomass was measured in May by removing upper portion of plants from 0.91 m of two rows (0.56 m²) from each plot, weighing samples for fresh weight and after several days in a plant dryer, weighing for dry weight of same samples. Plots were harvested directly and grain weighed between 12 and 28 Jul. Grain fresh and dry weights were measured and yields were adjusted to 12.5% moisture. Germination percentages of wheat seeds from samples harvested in 2007, 2008 and 2009, from trials planted in 2006, 2007 and 2008, were determined using a standardized method [20]. In 2005, the planting date experiment consisted of 12 treatments in 6 replications in an RCBD; the seed treatment experiment was 8 treatments replicated 6 times in an RCBD, and the furrow experiment contained 5 treatments in 5 replications in an RCBD. In all other trials (planted 2006 to 2010), the cultivars were tested separately and could not be directly compared. Each trial consisted of main plots based on five GA₃ rates (2006, 2007, 2008) or five GA₃-6BA treatments (2009, 2010) in Latin Square designs with 5 replications. Each main plot was split into three strips, each at one of the three planting dates (mid Sep, about 1 Oct, mid Oct). Data from each trial were analyzed separately, except when years were combined, using SAS Proc ANOVA. Treatment means were separated using least significant differences (SAS Institute).

3. Results

3.1. GA₃ Application Method and Rate Response (2005)

Planted in 2005, an initial field test was conducted to determine whether applying GA₃ to seed of cultivars Goodstreak and Wesley would affect early seedling growth of late-planted seed. Heights measured in mid Nov showed that dipping seeds for a short time in 1000 ppm GA₃ significantly increased the heights of both cultivars when planting was 2 and 4 weeks later than the mid Sep recommendation for the Nebraska Panhandle (Table 2). When planted at the recommended date, GA₃ did not affect seedling height. Untreated seedlings resulting from later planting as expected were smaller being younger (Table 2). The measurements showed that applying GA₃ to seed was able to compensate for the loss of growing time. This was significant with “Goodstreak” where the height of seedlings from 1000 ppm GA₃-treated plants seeded on 28 Sep were as tall as water-treated plants seeded two weeks earlier (Table 2). Likewise, GA₃-treated plants seeded on 12 Oct were as tall as the checks seeded on 28 Sep. With Wesley where GA₃ treatment significantly promotes height, the promotion was not sufficient to overcome the two-week delay in seeding (Table 2). Although there were height differences between planting dates and cultivars, the GA₃-induced promotion of height did not last through the winter and spring as there was no difference between treated and check plants (Table 2). GA₃ had no effect on lodging of Goodstreak. Although there was a significant difference in yield between the two cultivars, there was no GA₃ or planting date effect except for the last planting of Wesley (Table 2). Seed treatments with GA₃ using a 1 to 2 min dip or a directed spray were compared on Wesley in 2005. Application of 500 ppm GA₃ as a seed dip increased height in November (Table 3). When GA₃ was applied as a spray onto seed, significant height promotion in Nov was measured with 4000 ppm. GA₃ did not affect post winter height or yield (Table 3). However, there was no difference between the seed treatment methods comparing each GA₃ rate. Another method to expose seeds to GA₃ is to spray the material during planting into the open furrow on and around the seed. Table 4 showed that application of 700 g·ha⁻¹ (7500 ppm GA₃) would be needed to increase pre winter seedling height of Wesley.

3.2. Planting Date and GA₃ Rate Response (2006, 2007, 2008)

Field trials in 2006, 2007 and 2008 compared the seed dip application of GA₃ at different rates and planting at different dates on Goodstreak and Wesley. Across years, GA₃ applied at 500 ppm to Goodstreak and planted in mid Sep significantly increased seedling height measured in Nov (Table 5). When planted later, however, less GA₃ (125 - 250 ppm) stimulated growth of Goodstreak. In Wesley, height was increased by 1000 ppm GA₃ in two of three years and by 250 ppm in 2006 (Table 5). Both later planting dates showed height increases by 250 ppm GA₃ in all years. The height of seedlings for both cultivars was lowered with later planting. Adding 250 ppm GA₃ to Goodstreak allowed seedlings planted in early October to attain the same growth as untreated seedlings planted in mid Sep (Table 5). Likewise, 500 ppm GA₃ promoted Goodstreak seedlings planted

Table 2. Plant height, lodging and yield of winter wheat cultivars Goodstreak and Wesley planted at three dates with seed dipped in water or gibberellic acid (GA₃) at 1000 ppm, 2005-2006.

Cultivar	Planting Date	GA ₃ ³ ppm ⁴	Plant height ¹			Lodging	Yield ²
			17 Nov 05	24 May 06 cm	30 Jun 06	30 Jun 06 %	14 Jul 06 mg·ha ⁻¹
Goodstreak	14 Sep 05	0	16.2 B ⁵	102 A	106 A	83 A	5.17 D
		1000	16.7 AB	100 A	103 AB	87 A	5.00 D
	28 Sep 05	0	10.8 D	95 B	103 AB	83 A	5.19 D
		1000	17.9 A	94 B	105 A	79 A	5.16 D
	12 Oct 05	0	6.9 E	86 D	102 AB	0 B	6.03 D
		1000	10.9 D	83 D	100 B	4 B	5.94 D
Wesley	14 Sep 05	0	17.5 A	90 C	94 C	12 B	9.18 A
		1000	16.8 AB	90 C	91 C	13 B	9.48 A
	28 Sep 05	0	12.6 C	86 D	89 C	4 B	8.63 AB
		1000	16.2 B	86 D	89 C	8 B	9.08 AB
	12 Oct 05	0	7.1 E	74 E	81 D	0 B	8.04 BC
		1000	9.8 D	72 E	80 D	4 B	7.46 C
GA ₃ seed treatment (G)			*** ⁶	ns	ns	ns	ns
Planting date (P)			***	***	***	***	ns
Cultivar (C)			ns	***	***	***	***
G*P			***	ns	ns	ns	ns
G*C			**	ns	ns	ns	ns
P*C			ns	ns	**	***	***
G*P*C			ns	ns	ns	ns	ns

¹Seeds were dipped in water or 1000 ppm GA₃ for 1 to 2 min, air-dried for a week, and then planted. ²Plant height was measured from ground to the highest leaf tip. ³Yield was adjusted to 12.5% kernel moisture. ⁴1 inch = 2.54 cm, 1 lb·a⁻¹ = 1.1209 kg·ha⁻¹, 1 ppm = 1 mg·L⁻¹. ⁵Mean separation for each column using least significant difference at $P < 0.05$. ⁶ns = not significant at $P < 0.05$; *, **, *** = significant at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

Table 3. Plant height and yield of winter wheat cultivar Wesley planted on 28 Sep 05 with seed treated with water or gibberellic acid (GA₃) by dip or spray¹, 2005-06.

Application method	GA ₃ ¹ ppm ⁴	Plant height ²			Yield ³
		17 Nov 05	24 May 06 cm	14 Jul 06	14 Jul 06 mg·ha ⁻¹
Seed dip	0	14.0 C ⁵	77	91	9.58
	500	17.5 AB	77	90	9.78
	2000	19.0 A	78	90	9.42
	4000	17.5 AB	77	90	9.41
Seed spray	0	15.0 BC	79	91	9.59
	500	17.8 AB	77	90	9.57
	2000	17.8 AB	80	90	9.12
	4000	19.2 A	77	90	9.59
GA ₃ rate (G)		** ⁶	ns	ns	ns
Seed application (A)		ns	ns	ns	ns
G*A		ns	ns	ns	ns

¹Seeds were dipped for 1 to 2 min or coated using a CO₂ sprayer, drained, air-dried for a week, and then planted. ²Plant height was measured from ground to the highest leaf tip. ³Yield was adjusted to 12.5% kernel moisture. ⁴1 inch = 2.54 cm, 1 lb·a⁻¹ = 1.1209 kg·ha⁻¹, 1 ppm = 1 mg·L⁻¹. ⁵Mean separation for each column using least significant difference at $P < 0.05$. ⁶ns = not significant at $P < 0.05$; *, **, *** = significant at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

Table 4. Plant height and yield of winter wheat cultivar Wesley planted on 28 Sep 05 with water or gibberellic acid (GA₃) applied into an open furrow onto seeds¹, 2005-06.

Application method	GA ₃ ¹ g·ha ⁻¹ ⁴	Plant height ²			Yield ³
		17 Nov 05	24 May 06 cm	14 Jul 06	14 Jul 06 mg·ha ⁻¹
Furrow	0	13.6 B ⁵	73	88	8.81
	175	13.4 B	74	87	8.35
	350	14.4 AB	75	87	8.19
	700	16.7 A	74	88	8.62
	1400	14.8 AB	73	88	8.30

¹Untreated seeds were planted into an open furrow onto which water or GA₃ was sprayed using a CO₂ sprayer set to apply 94 L·ha⁻¹ carrier and then the furrow was covered. ²Plant height was measured from ground to the highest leaf tip. ³Yield was adjusted to 12.5% kernel moisture. ⁴1 inch = 2.54 cm, 1 lb·a⁻¹ = 1.1209 kg·ha⁻¹, 1 oz·a⁻¹ = 70 g·ha⁻¹. ⁵Mean separation for each column using least significant difference at $P < 0.05$.

Table 5. Plant height in mid Nov of winter wheat cultivars Goodstreak and Wesley planted at three dates with seed treated with water or gibberellic acid (GA₃) in 2006-07, 2007-08 and 2008-09.

Planting date	GA ₃ ¹ ppm ²	“Goodstreak”				“Wesley”			
		2006	2007	2008	Mean	2006	2007	2008	Mean
mid Sep ⁴	0	11.3	16.5	13.7	13.7	15.6	19.4	16.0	16.9
	125	12.8	16.6	13.7	14.3	16.7	18.9	15.4	17.0
	250	13.1	16.7	14.1	14.5	17.9	20.2	16.3	18.1
	500	14.2	20.1	14.3	16.1	19.8	20.1	16.9	19.0
	1000	15.8	22.7	17.6	18.5	21.2	22.6	19.7	21.2
early Oct	0	8.3	11.0	8.6	9.2	9.4	13.1	10.2	10.8
	125	10.9	12.6	9.6	11.0	10.3	13.4	10.2	11.3
	250	13.1	15.6	11.6	13.4	12.0	14.5	11.5	12.6
	500	16.1	17.9	13.7	15.9	14.0	15.1	13.0	14.0
	1000	16.8	20.3	16.6	17.7	15.6	17.8	16.0	16.4
mid Oct	0	4.5	6.7	6.7	5.9	5.3	7.5	6.9	6.5
	125	5.7	7.8	8.1	7.1	6.2	7.9	7.3	7.1
	250	6.8	9.7	8.4	8.0	7.1	8.6	8.3	7.9
	500	7.5	10.3	10.0	9.1	7.2	9.4	8.7	8.3
	1000	8.2	12.0	11.0	10.3	7.8	10.4	9.4	9.1
LSD 0.05		2.0	1.3	1.7	1.2	1.5	1.3	1.2	1.2
GA ₃ treatment (G)		***5	***	***	***	***	***	***	***
Planting date (P)		***	***	***	***	***	***	***	***
G*P		*	***	**	***	*	ns	**	***

¹Seeds were dipped in water or GA₃ for 1 to 2 min, air-dried for a week, and then planted. ²1 inch = 2.54 cm, 1 lb·a⁻¹ = 1.1209 kg·ha⁻¹, 1 ppm = 1 mg·L⁻¹. ³Plant height was measured from ground to the highest leaf tip, and were measured on 20 Nov 06, 13 Nov 07, and 19 Nov 08. ⁴Planting dates were: 20 Sep 06, 18 Sep 07, and 18 Sep 08 for mid Sep; 4 Oct 06, 2 Oct 07, and 2 Oct 08 for early Oct, and 16 Oct 06, 12 Oct 07, and 15 Oct 08 for mid Oct. ⁵ns = not significant at $P < 0.05$; *, **, *** = significant at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

in mid Oct to attain the same growth as untreated ones planted two weeks earlier. The situation was similar with Wesley except that 1000 ppm GA₃ was needed for the seedlings planted later to compensate for the two weeks lost time (Table 5). Measuring plant height after winter, late March to harvest in July, there was little effect by GA₃ on either cultivar (Table 6). Delaying planting significantly shortened plants in spring but there were no differences in the final plant height (Table 6). Plant weights were taken in mid spring which showed that these were slightly depressed by GA₃. However, planting date had a more pronounced effect with plants having less weight with later planting (Table 7). Yields were not affected by GA₃ and did not significantly differ between mid Sep and early Oct planting. A main concerns of late planting of winter wheat is that there would not be a

Table 6. Post-winter plant height of winter wheat cultivars Goodstreak and Wesley planted at three dates with seed treated with water or gibberellic acid (GA₃), mean of 2006-07, 2007-08 and 2008-09.

Planting date	GA ₃ ¹ ppm ³	“Goodstreak”			“Wesley”		
		Early spring ²	Mid spring	Pre-harvest	Early spring	Mid spring	Pre-harvest
				Plant height ⁴ , cm			
mid Sep ⁵	0	12	50	87	15	48	74
	125	12	49	85	15	48	73
	250	12	50	85	15	47	71
	500	12	46	85	15	47	72
	1000	12	47	87	15	44	69
early Oct	0	9	50	87	11	44	69
	125	9	48	85	11	45	70
	250	9	47	85	11	43	67
	500	10	46	86	12	43	68
	1000	10	42	87	12	42	66
early Oct	0	7	38	86	9	41	68
	125	8	39	86	9	41	68
	250	8	38	86	9	41	67
	500	9	36	87	9	39	67
	1000	8	36	90	10	37	66
LSD 0.05		1	4	-	1	3	5
GA ₃ treatment (G)		*** ⁶	***	ns	***	***	ns
Planting date (P)		***	***	ns	***	***	***
G*P		ns	ns	ns	ns	ns	ns

¹Seeds were dipped in water or GA₃ for 1 to 2 min, air-dried for a week, and then planted. ²Plant height was measured on 20 Mar 07, 24 Mar 08, and 8 Apr 09 (early spring readings); on 7 May 07, 19 May 08, and 22 May 09 (mid spring readings), and on 5 Jul 07, 17 Jul 08, and 16 Jul 09 (pre-harvest readings). ³1 inch = 2.54 cm, 1 lb·a⁻¹ = 1.1209 kg·ha⁻¹, 1 ppm = 1 mg·L⁻¹. ⁴Plant height was measured from ground to the highest leaf tip. ⁵Planting dates were: 20 Sep 06, 18 Sep 07, and 18 Sep 08 for mid Sep; 4 Oct 06, 2 Oct 07, and 2 Oct 08 for early Oct, and 16 Oct 06, 12 Oct 07, and 15 Oct 08 for mid Oct. ⁶ns = not significant at $P < 0.05$; *, **, *** = significant at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

sufficiently tall plant to reduce soil erosion [5] and this would reduce yield. These experiments did not show a yield effect concerning planting date because of small plot size. In large scale studies and in farmer’s fields, such yield reductions due to soil erosion are routinely observed. Planting in mid Oct did have significantly less yield of Goodstreak than the earlier planting (Table 7). Wesley was not affected as much. There was no difference in germination of harvested seed between planting dates or GA₃ rates (Table 7).

3.3. Addition of 6BA to GA₃ (2009 and 2010)

In the 2009 planted trials, 6BA, a cytokinin, was added at 125, 500 and 2000 ppm to GA₃ at 500 and 1000 ppm to Goodstreak and Wesley, respectively. 6BA-GA₃ mixtures were applied to seeds. As observed earlier, these GA₃ rates increased plant height in November and had no significant effect on spring biomass, tiller number or yield (Table 8). Adding 6BA at 125 and 500 ppm had no effect but 2000 ppm had a deleterious effect on height compared to GA₃ alone, on plant weight compared to untreated, and on grain yield (Table 8). Later planting dates, as observed previously, also had a depressing effect. Due to the negative effect of 6BA, in 2010, lower 6BA and GA₃ concentrations were applied. 6BA at 31, 62 and 125 ppm were added to 250 ppm for Goodstreak and 500 ppm for Wesley. At these rates, GA₃ with or without 6BA had no effect at the recommended planting date (Table 9). At the two later planting dates, GA₃ had a promotive effect on height but 6BA had no effect in addition to that of GA₃ alone (Table 9). Notably, there was no promotion of tiller formation by 6BA, the rationale for its addition.

3.4. Rye Response to GA₃ (2007 and 2008)

In a preliminary trial on rye cv. Rymin planted in 2006, GA₃ applied at 1000 and 4000 ppm to seed stimulated November height of plants seeded in October (data not shown). In 2007 and 2008 planted trials, rye was treated

Table 7. Plant weight, yield and seed germination of winter wheat cultivars Goodstreak and Wesley planted at three dates with seed treated with water or gibberellic acid (GA₃), mean of 2006-07, 2007-08 and 2008-09.

Planting date	"Goodstreak"					"Wesley"			
	GA ₃ ¹ ppm ⁵	Fresh weight ² kg·m ⁻²	Dry weight kg·m ⁻²	Yield ³ mg·ha ⁻¹	Germination ⁴ %	Fresh weight kg·m ⁻²	Dry weight kg·m ⁻²	Yield mg·ha ⁻¹	Germination %
mid Sep ⁶	0	2.05	0.56	4.40	93	2.60	0.69	5.27	90
	125	2.10	0.61	4.51	95	2.45	0.66	5.11	89
	250	1.91	0.54	4.48	94	2.61	0.71	4.73	92
	500	1.98	0.55	4.27	95	2.50	0.66	5.22	91
	1000	1.86	0.51	4.25	95	2.50	0.67	4.66	91
early Oct	0	1.77	0.51	4.77	95	2.11	0.56	5.03	90
	125	1.71	0.49	4.79	96	2.11	0.56	5.14	89
	250	1.69	0.47	4.73	94	2.14	0.55	4.88	90
	500	1.79	0.47	4.75	95	2.17	0.58	4.85	90
	1000	1.58	0.42	4.63	96	1.97	0.53	4.68	89
early Oct	0	1.33	0.36	4.09	95	1.56	0.40	4.79	91
	125	1.33	0.37	4.01	96	1.47	0.41	4.74	90
	250	1.29	0.36	4.00	96	1.53	0.41	4.49	90
	500	1.21	0.33	3.72	96	1.45	0.40	4.40	90
	1000	1.02	0.28	3.59	96	1.35	0.35	4.13	90
LSD 0.05		0.25	0.07	0.51	-	0.24	0.07	0.69	-
GA ₃ treatment (G)		* ⁷	***	ns	ns	ns	ns	*	ns
Planting date (P)		***	***	***	ns	***	***	**	ns
G×P		ns	ns	ns	ns	ns	ns	ns	ns

¹Seeds were dipped in water or GA₃ for 1 to 2 min, air-dried for a week, and then planted. ²Plant weights (fresh and dry) were measured on 7 May 07, 19 May 08, and 22 May 09 from a sample area of 0.5574 m² from each plot. ³Grain yield was harvested on 12 Jul 07, 24 Jul 08, and 30 Jul 09 from a plot area of 7.5 m². ⁴Germination was determined from seeds sampled from the harvest of each plot only in 2009. ⁵1 inch = 2.54 cm, 1 lb·a⁻¹ = 1.1209 kg·ha⁻¹, 1 ppm = 1 mg·L⁻¹. ⁶Planting dates were: 20 Sep 06, 18 Sep 07, and 18 Sep 08 for mid Sep; 4 Oct 06, 2 Oct 07, and 2 Oct 08 for early Oct, and 16 Oct 06, 12 Oct 07, and 15 Oct 08 for mid Oct. ⁷ns = not significant at $P < 0.05$; *, **, *** = significant at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

at the same rates of GA₃ and planted on the same days as wheat. November heights of Rymin were increased by the GA₃ application at the early and mid Oct plantings (Table 10). Between 250 and 1000 ppm GA₃ was sufficient to overcome the two-week delay in growth resulting from each 2-week delay in planting. In post winter height and weight measurements, there was no GA₃ promotion although later planting date did reduce height and weight in the spring (Table 10). Rye was not taken to harvest since its use is as a cover crop into which summer crops such as potato are planted.

4. Discussion

4.1. Application Methods

In earlier studies on applying GA₃ to wheat to stimulate stem or coleoptile elongation, the hormone was added to hydroponic solutions [21], injected weekly into the plant [22], soaked into germination paper [23], or applied to greenhouse soil to saturation [24]. These were greenhouse or growth chamber studies and would not be practical in a field situation or commercial use. In early 2005 [9], a growth chamber study on wheat indicated that direct seed and furrow applications of GA₃ could stimulate stem growth of several cultivars. Using this information, the study was continued under field conditions. There was a significant November height response for Wesley to GA₃ but there was no significant difference between direct application to seeds via a 2-min-dip or a spray. A furrow application of GA₃ on Wesley likewise showed a response. Significant height promotion was achieved with 700 g·ha⁻¹. With GA₃ at US\$ 1.15/g, the cost would be an exorbitant US\$ 800/ha or US\$ 325/a which is economically infeasible and further study on furrow application was discontinued.

Table 8. Plant height on 17 Nov 09, fresh weight on 18 May 10, tiller number on 21 May 10, and yield on 28 July 10 of winter wheat cultivars Goodstreak and Wesley planted at three dates with seed treated with water, gibberellic acid (GA₃) or GA₃ plus 6-benzyl adenine (6BA) in 2009-10.

		Goodstreak				Wesley			
GA ₃ ¹	6BA	Height ²	Weight	Tiller	Yield	Height	Weight	Tiller	Yield
ppm ³	ppm	cm	kg·m ⁻²	#/plant	mg·ha ⁻¹	cm	kg·m ⁻²	#/plant	mg·ha ⁻¹
17 Sep 09 planting									
0	0	9.1	1.96	5.8	3.75	10.1	1.62	5.4	4.18
4	0	14.1	1.86	5.6	3.56	14.2	2.14	5.6	4.60
4	125	15.1	1.76	8.3	3.65	14.9	1.92	4.8	4.45
4	500	13.7	1.65	7.5	3.48	14.2	1.66	5.4	4.22
4	2000	10.1	1.12	6.1	2.88	9.6	0.67	6.4	1.73
30 Sep 09 planting									
0	0	6.4	1.88	4.1	3.63	6.8	1.35	5.6	4.32
4	0	10.7	1.63	4.9	3.58	11.1	1.20	4.8	3.98
4	125	11.3	1.56	5.7	3.39	11.6	1.44	4.6	3.95
4	500	10.2	1.43	5.6	3.29	10.5	1.06	5.4	3.92
4	2000	8.0	0.82	6.0	2.82	6.6	0.17	6.6	1.41
19 Oct 09 planting									
0	0	1.9	1.10	4.2	2.66	2.0	1.00	6.3	3.72
4	0	3.5	0.55	5.2	2.21	3.6	0.58	5.5	2.84
4	125	3.8	0.67	5.3	2.66	3.6	0.50	5.6	2.55
4	500	3.6	0.43	5.6	2.56	3.4	0.22	7.1	1.79
4	2000	2.3	0.13	5.0	1.71	1.6	-	0	0.33
LSD0.05		1.2	0.41	-	0.92	1.7	0.55	2.5	0.69
Treatment (T)		****	***	ns	*	***	***	ns	***
Plant date (P)		***	***	*	***	***	***	ns	***
T*P		***	ns	ns	ns	**	**	ns	*

¹Seeds were dipped in water, GA₃, or GA₃ + 6BA for 1 to 2 min, air-dried for a week, and then planted. ²Height was measured from ground to the highest leaf tip; weight was the fresh weight of plants in a sample area of 0.5574 m² in each plot, and tiller number was determined on four plants per plot. ³1 inch = 2.54 cm, 1 lb·a⁻¹ = 1.1209 kg·ha⁻¹, 1 ppm = 1 mg·L⁻¹. ⁴The GA₃ concentration used for “Goodstreak” was 500 ppm and for “Wesley” was 1000 ppm. ⁵ns = not significant at $P < 0.05$; *, **, **** = significant at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

4.2. Planting Date Comparisons

The preliminary trial in 2005 comparing three planting dates suggested that 1000 ppm GA₃ applied to Goodstreak or Wesley and planted later than mid Sep could stimulate November growth. There was no effect observed in spring and summer. A more detailed trial was conducted in 2006, 2007, and 2008. In Goodstreak, a significant GA₃ rate response was observed regardless of planting date and more importantly GA₃ application to seed overcame the lower growth resulting from planting two weeks later. For example, compare mean November height of 250 ppm treated Goodstreak planted in early October to untreated Goodstreak planted in mid Sep (Table 5). Making the same comparison on Wesley showed that this occurred but 1000 ppm GA₃ was needed (Table 5). The data indicated that although Wesley was responsive, it required a higher GA₃ concentration than Goodstreak, supporting growth chamber findings [9], and studies on cultivar responses and the genetics of dwarfing [22]-[24]. A probable, partial explanation for the difference in GA₃ sensitivity between these two cultivars is that Wesley has the *Rht8c* and the *Rht-B1b* genes making it a semi-dwarf with limited endogenous GA₃ and sensitivity to applied GA₃ [15]. Comparing various wheat cultivars, Alan *et al.* [25] concluded that slow-emerging wheat cultivars were stimulated to emerge at the same rate as rapid-emerging ones when seeds were soaked for 4 hours with 200 ppm GA₃. Lower soil temperatures from later planting can slow emergence as well and may be at least partially overcome by GA₃ [24]. The results of this study demonstrated a use of GA₃ seed application for late planting due to dry weather [4], fit into summer crop rotation or due to some delay in wheat planting. The relative response between Goodstreak and Wesley wheats to GA₃ may be analogous to that

Table 9. Plant height on 22 Nov 10, and fresh weight and tiller number on 10 May 11 of winter wheat cultivars Goodstreak and Wesley planted at three dates with seed treated with water, gibberellic acid (GA₃) or GA₃ plus 6-benzyl adenine (6BA) in 2010-11.

Planting date	Goodstreak					Wesley		
	GA ₃ ¹ ppm ³	6BA ppm	Height ² cm	Weight kg·m ⁻²	Tiller #/plant	Height cm	Weight kg·m ⁻²	Tiller #/plant
17 Sep 10	0	0	16.8	1.77	6.6	21.0	3.37	5.4
	4	0	17.0	2.15	5.6	23.8	3.75	7.0
	4	31	16.9	2.34	4.6	20.8	3.14	7.2
	4	62	15.8	2.03	5.6	21.4	3.68	6.6
	4	125	17.1	2.03	6.0	21.8	2.89	7.0
1 Oct 10	0	0	10.1	1.66	5.0	12.2	2.73	5.4
	4	0	13.2	2.04	6.6	16.9	2.79	5.4
	4	31	12.5	1.71	6.0	17.6	2.56	5.2
	4	62	13.7	1.44	5.2	15.7	2.60	5.0
	4	125	13.7	1.51	5.0	15.8	2.24	5.4
17 Oct 10	0	0	7.9	1.06	5.2	7.6	1.37	4.6
	4	0	9.7	1.01	4.8	10.3	1.43	4.6
	4	31	9.8	1.02	4.8	11.4	1.41	4.0
	4	62	10.0	0.94	5.0	9.8	1.35	4.0
	4	125	9.5	1.21	5.0	10.4	1.06	4.8
LSD 0.05			2.0	0.90	-	1.9	0.75	1.7
treatment (T)			⁵	ns	ns	***	ns	ns
Planting date (P)			***	***	***	***	***	***
T*P			ns	ns	ns	**	ns	ns

¹Seeds were dipped in water, GA₃, or GA₃ + 6BA for 1 to 2 min, air-dried for a week, and then planted. ²Height was measured from ground to the highest leaf tip; weight was the fresh weight of plants in a sample area of 0.5574 m² in each plot, and tiller number was determined on four plants per plot. ³1 inch = 2.54 cm, 1 lb·a⁻¹ = 1.1209 kg·ha⁻¹, 1 ppm = 1 mg·L⁻¹. ⁴The GA₃ concentration used for “Goodstreak” was 250 ppm and for “Wesley” was 500 ppm. ⁵ns = not significant at $P < 0.05$; *, **, *** = significant at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

reported in field studies on common bean cultivars Matterhorn and Poncho where GA₃ was applied to foliage to stimulate stem elongation for direct harvest [26]. In both studies, the elongation stimulation by GA₃ was for a relatively short term.

Comparing the two wheat cultivars to the rye cultivar Rymin, it seems that Rymin was slightly less sensitive to GA₃ than Goodstreak but more than Wesley. This agrees with the observation made using the growth chamber bioassay [9]. Since Rymin is moderately tall, this may indicate a correlation between plant height and seedling growth promotion by GA₃ measured in late autumn.

4.3. Addition of 6-Benzyl Adenine

Since cytokinin growth regulators such as 6BA are known to promote bud break via stimulating cell division [27], there was the possibility that 6BA could promote tiller production in conjunction with the stem growth from GA₃ application. However, as in the growth chamber study [8], 6BA had no beneficial effect and even had a deleterious effect when applied at high concentrations.

5. Conclusions

5.1. Potential Use

This study demonstrated that GA₃ applied directly to seed would stimulate pre-winter seedling growth when seeds were planted from mid Sep to mid Oct. With GA₃ application, a two-week delay in planting could be overcome. This would result in the plant size and stand to be sufficient to resist wind-induced soil erosion during the winter and stabilize the field even though the field was planted later than recommended. This would also

Table 10. Plant heights and weights of the winter rye cultivar Rymin planted at three dates with seed treated with water or gibberellic acid (GA₃), mean of 2007-08 and 2008-09.

Planting date ³	GA ₃ ² ppm ⁴	Plant height ¹			Fresh weight ¹	Dry weight
		November	March/April cm	May	May kg·m ⁻²	
mid Sep	0	16.4	20.0	81	2.7	0.70
	125	15.9	19.5	81	3.0	0.73
	250	16.7	19.3	79	2.7	0.68
	500	15.8	18.4	78	2.9	0.70
	1000	16.9	17.1	80	2.8	0.69
early Oct	0	10.9	14.4	78	2.5	0.63
	125	11.5	13.5	79	2.6	0.62
	250	12.4	13.9	76	2.5	0.65
	500	13.7	13.3	75	2.5	0.63
	1000	15.1	13.2	77	2.5	0.63
early Oct	0	7.2	10.3	66	1.8	0.48
	125	9.7	9.3	65	1.8	0.45
	250	11.2	10.2	65	2.0	0.50
	500	12.0	10.8	63	1.8	0.45
	1000	12.5	10.4	61	1.7	0.43
LSD 0.05		1.1	1.5	4	0.3	0.07
GA ₃ treatment (G)		*** ⁵	ns	ns	ns	ns
Planting date (P)		***	***	***	***	***
G*P		***	ns	ns	ns	ns

¹Plant heights were measured on 12 Nov 07 and 19 Nov 08 (pre-winter), on 20 Mar 08, and 8 Apr 09 (early spring), and on 16 May 08 and 18 May 09; plant weights were measured in May with last height measurements. ²Seeds were dipped in water or GA₃ for 1 to 2 min, air-dried for a week, and then planted. ³Planting dates were: 18 Sep 07 and 18 Sep 08, 2 Oct 07 and 2 Oct 08, and 12 Oct 07 and 15 Oct 08. ⁴1 inch = 2.54 cm, 1 lb·a⁻¹ = 1.1209 kg·ha⁻¹, 1 ppm = 1 mg·L⁻¹. ⁵ns = not significant at $P < 0.05$; *** = significant at $P < 0.001$.

improve crop rotation when wheat is planted after a summer crop that is harvested in late September or early October. Furthermore, GA₃ gives an additional production practice in case of adverse weather resulting in delayed planting. Note that there were differences between the two tested cultivars with respect to the amount of GA₃ needed and the degree of response vis-a-vis planting dates. The differences in cultivar sensitivity to GA₃ can be explained by the semi-dwarf character of the cultivars.

5.2. Economic Considerations

Considering its potential uses, applying GA₃ to seed can be considered as an “insurance policy” but its cost needs to be considered as well. The following cost-estimate will be based on applying 1000 ppm GA₃ to Wesley. The product used in these studies was Release[®] (Valent BioScience) which contains 33.8 g·L⁻¹ (1 g per fl. oz). The non-discounted, retail price of US\$ 1.15 per g GA₃ results in a cost of US\$ 38.87 L⁻¹. Therefore, 1 liter of a 1000-ppm GA₃ solution would cost US\$ 1.15. The label range for application onto wheat would include GA₃ at 1.2 g in 1.2 L (1000 ppm) applied to 45 kg seed. The cost would be US\$ 1.38 per 45 kg. In the studies planted in 2006, 2007 and 2008, 1.6 kg Wesley seed was treated with 1 L of solution via soaking. On a 45-kg basis, this would be equivalent to exposing seed to 28 L which would be impractical. Seed weights were taken before treatment and again after treatment when seeds had dried. Wesley seed gained about 2.5% in weight indicating that about 25 mL of solution was absorbed per kg Wesley seed or about 555 mL per 45 kg which is within the labeled application range with a maximum of 591 mL for 45 kg. Therefore, the laboratory application method should be translatable to practical field application. In working with Nebraska growers, the practical and inexpensive method of GA₃ application is to apply the product with or without fungicides onto seed using a spray nozzle fitted atop of the auger on a wheat planter during the seeding operation. Several growers have reported to me that this has worked excellently and have made this a routine procedure in their operation. With a seeding

rate 300 m^{-2} ($3 \times 10^{-6} \text{ ha}^{-1}$) and a seed weight of 3 g per 100 seeds, the weight of seed is $90 \text{ kg} \cdot \text{ha}^{-1}$. To treat 90 kg (200 lb) of Wesley seed with 1000 ppm GA_3 would calculate to US\$ 2.76 ha^{-1} or US\$ 1.12 a^{-1} . These calculations and grower experiences indicate that on-farm GA_3 seed application to wheat is an inexpensive “insurance policy” against delayed planting due to weather or harvesting of a rotational summer crop such as potato and common bean.

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