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Timing applications of growth regulators to alter spring cereal development at high latitudes

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Plant growth regulators (PGRs) are commonly used in commercial farming to control lodging in cereals. PGRs have been shown to alter yield formation and plant stand structure, other than the straw length. To study their potential in Northern growing conditions PGRs and their application time impacts on plant stand structure and yield formation in tall and short statured cultivars of barley, oat, and wheat were studied in the field. Crop stands were sprayed with the gibberellin biosynthesis inhibitors CCC (chlormequat chloride CCC), Moddus (Trinexapac-ethyl TE), or with ethylene-releasing Cerone (ethephon ETH) at the recommended times or at an earlier growth stage. CCC applied at Zadoks growth scale (ZGS) 13–14 increased and ETH applied at ZGS 39–40 reduced grain yield of oat by 370 kg ha^{-1} and 270 kg ha^{-1}, respectively. In wheat, CCC applied at ZGS 31–32 reduced grain yield by 480 kg ha^{-1}. This yield reduction was associated with lower grain yield production by the main head and particularly lower single grain weight. In barley cv. Kymppi, ETH and TE treatments promoted yield formation, whereas in cv. Saana they tended to reduce yield. Early applied PGRs reduced stem height at 14 days after treatment irrespective of species or stem stature, but at maturity no constant PGR effect was noted. Excluding the stem length, PGRs did not modify plant stand structure or yield formation markedly.

Key words: chlormequat, barley, oats, wheat, plant growth regulators, ethephon, growth, tillering, plant height

Introduction

Production of vegetative and head-bearing tillers in cereals is controlled by genotype and environment (e.g. Langer 1972, Batten 1985, Peltonen-Sainio 1999). High latitudes, long days and high sowing rates suppress initiation and growth of tillers in spring-sown cereals (Peltonen-Sainio and Järvinen 1995, Peltonen-Sainio 1999). There are indications that plant growth regulators (PGRs), used to control lodging, may alter tiller performance. Antigibberellins applied at early growth stages altered cereal response to photoperiod; e.g. apical development rate was slowed and tillering increased in wheat (*Triticum aestivum* L.) and oat (*Avena sativa* L.) grown under long day conditions (Hutley-Bull

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and Schwabe 1982, Craufurd and Cartwright 1989, Peltonen-Sainio and Rajala 2001). Chlormequat chloride (CCC) increased tiller number in barley (*Hordeum vulgare* L.) and triticale (X *Triticosecale* Wittmack), when applied as a seed treatment (Naylor et al. 1989) and in winter barley when applied prior to or during tillering (Naylor et al. 1986). Enhanced tillering in barley, oat and wheat was reported to follow early application of ethephon and trinexapac-ethyl in the greenhouse (Rajala and Peltonen-Sainio 2001). Early application of CCC in a mixture with herbicides has been recommended in some production manuals. This is claimed to potentially enhance cereal root growth and tillering.

Yield formation in cereals depends partly on the capacity to accumulate and store carbohydrates in stems (and leaf blades and sheaths) and mobilise them during grain filling (Austin et al. 1977, Bidinger et al. 1977, Blum et al. 1991, Davidson and Chevalier 1992). Chlormequat chloride and ethephon treatments increased the total amount of water-soluble carbohydrates in wheat culms (Knapp et al. 1987) and dry matter accumulation in culm and upper leaf parts in barley (Ma and Smith 1992). These findings indicate that PGRs may have potential to enhance the build up of reserve assimilates. Long-strawed cultivars are considered to be more stress resistant and more yield stable over environments than short-stature cultivars (Ehdaie and Waines 1989, Mäkelä et al. 1997). This may partly be a consequence of the larger stem capacity and hence, better ability to store reserve assimilates that are used later for grain filling (Aggarwal and Sinha 1984, Shakiba et al. 1996, Blum et al. 1997). On the other hand, reduced demand of assimilates for stem elongation in short-stature cultivars may direct additional carbohydrates for yield formation, expressed as increased number of fertile florets at anthesis and greater harvest index (HI), as noted in semi-dwarf wheat cultivars (Miralles and Slafer 1995, Gent and Kiyomoto 1998).

This study was conducted in the field to monitor the response of tiller growth and productivity to CCC and the two other most commonly used PGRs, ethephon and trinexapac-ethyl, applied early and at the recommended times in barley, oat and wheat cultivars. In an additional experiment different sowing rates were used for barley cv. *Saana* to study a possible seeding rate X PGR (CCC) interaction. Both short and tall cultivars of each crop were included in order to gauge the effect of stem length and PGR applications and their potential interaction for yield formation. Grain number, single grain weight and HI measured in this study are important parameters for describing assimilate flow and distribution to harvestable plant parts.

Material and methods

Field experiments were conducted at Viikki Experimental Farm, University of Helsinki, Finland between 1996 and 1998 (exp 1) and in 2000 (exp 2), and at Jokioinen, MTT Agrifood Research Finland in 2000 (exp 2). In exp 1, three sub-experiments, one for each species, were arranged in completely randomised split-plot designs, for which the cultivars were the main plots and PGR treatments were split across them. Each species was represented by a tall and short stature cultivar, plant heights (tall versus short within the same crop species) differed by 10 to 20 cm. Cultivars included were Kymppi and Saana for barley, Veli and Pal for oat, and Mahti and Tjalve for wheat. Gibberellin biosynthesis inhibitors chlormequat [CCC, a.i. chlormequat (2-chloroethyl)-trimethylammonium chloride at 750 g l^{-1}] and trinexapac-ethyl [Moddus, a.i. ethyl-(3-oxido-4-cycloprpionyl-5-oxo] oxo-3-cyclohexene-carboxylate at 250 g l^{-1}] and ethylene-releasing ethephon [Cerone, a.i. 2-chloroethyl phosphonic acid at 480 g l^{-1}] application rates were similar to those used in commercial farming in Finland, i.e., CCC 1 l ha^{-1} for oat and 0.5 l ha^{-1} for barley and wheat, trinexapac-ethyl 0.3 l ha^{-1} for all species, and ethephon 0.5 l ha^{-1} for all species. All PGRs were applied at early growth stages (Zadoks growth scale ZGS 13–14, Zadoks et al. 1974) and at the recommended time [CCC at ZGS (31–32) and trinexapac-ethyl and ethephon at flag leaf stage ZGS (39–40)]. PGRs were applied to the canopy using a tractor-mounted plot-sprayer at 300 l ha^{-1}. Sowing rate was 500 viable seeds m^{-2} for barley and oat, and 600 viable seeds m^{-2} for wheat.

In 2000, similar field trials were arranged in Helsinki and Jokioinen (exp 2). Barley cv. Saana was sown at 200, 300, 400, and 500 viable seeds m^{-2}. The experiments were arranged as split-plot designs, with seeding rate was the main plot and PGR treatments split across them. Chlormequat chloride was applied at an early growth stage (ZGS 13–14) and at the recommended time (CCC at ZGS 31–32) at rates as described above. PGR was applied to the canopy with a tractor-mounted plot-sprayer in Helsinki and with a hand-held sprayer in Jokioinen at 300 l ha^{-1}. Due to windy conditions during the day all PGR applications were conducted during evening (1900–2400 hours). The plot size was 10 m^2 (1.25 × 8 m with 12.5 cm between rows) in all experiments. All plots were fertilized at sowing with NH_4NO_3 at 80 kg N ha^{-1}. A mixture of MCPA and diklorpropp (DIPRO) at 2 l ha^{-1} was used to control weeds at ZGS 12.

Plant height (cm), to uppermost leaf ligule of 10 plants plot^{-1}, was measured 14 days after early PGR application. Days from sowing to heading and to maturity were recorded. Close to maturity numbers of heads m^{-2} were measured (3 × 0.5 m plot^{-1}), plant height (cm) to the top of the head was measured and if lodging (%) occurred it was noted. When cereal stands were yellow ripened, plant samples were collected (3 × 0.5 m plot^{-1}) in both experiments to determine main shoot and tiller phytomass (mg plant^{-1}), tiller number per main shoot, tiller weight (mg plant^{-1}), head weight (mg grains plant^{-1}), number of grains per main shoot and HI (%), and single grain weight (SGW, mg). In addition, in 1998 20 plants plot^{1} were collected three times at 7-day intervals (first 7 days after early PGR application) to determine main shoot and tiller weight (mg plant^{-1}) and tiller number. In exp 2, at Jokioinen, 20 plants plot^{-1} were collected 8 times at 7-day intervals to determine main shoot, tiller and head weight (mg plant^{-1}) and tiller number. When matured, plots were combine-harvested and grain yield (g m^{-2}) and hectoliter-weight (kg) were measured.

Statistical analyses were carried out with the Statistical Analysis System (SAS) (Littell et al. 1996). LSMEANS and differences among LSMEANS were estimated using PROC MIXED, where year and cultivar were considered as a random effect in exp 1 and location and sowing rate as random effects in exp 2. A repeated measures method was employed to analyse results from the plant samples collected repeatedly after PGR application in 1998 and 2000.

Results

Yield and yield components

CCC applied at ZGS 13–14 increased and ethephon (ETH) applied at ZGS 39–40 reduced oat yield by 7 and 5%, respectively. CCC applied at ZGS 31–32 reduced wheat yield by 8%. Other treatments did not affect grain yield of oat or wheat. Neither PGR by cultivar nor PGR by cultivar by year interaction occurred for grain yield in oat and wheat (Table 1). No PGR main effect was noted in barley, though barley cultivars responded differently to PGR treatments. PGR treatments tended to increase grain yield in cv. Kymppi, whereas in cv. Saana, when applied at the recommended time, trinexapac-ethyl (TE) reduced yield (Table 1).

Grain yield components of main shoot and tillers were unaltered by PGRs in oat. Neither PGR X cultivar nor PGR X cultivar X year interaction occurred in oat or wheat for main and tiller head weight or grain number in main and tiller heads (Table 2). CCC applied at ZGS 31–32 and ETH applied at ZGS 39–40 reduced main head weight of wheat by 6 and 4%, respectively. Single grain weight was reduced in wheat by CCC treatments in 1996 and 1998 and by ETH and TE when applied at recommended times in

Table 1. ANOVA table (a) and LSMEANS (b) for grain yield g m^{-2}. Difference of the LSMEANS was estimated between untreated control and PGR treatments. Level of the significance of the difference is shown next to the LSMEAN value (exp. 1).

(a) ANOVA		Barley	Oat	Wheat
	DF	P	P	P
Y	2	< 0.001	0.003	0.004
CV	1	< 0.001	0.002	0.04
PGR	6	0.33	< 0.001	< 0.001
Y × CV	2	0.01	< 0.001	0.45
Y × PGR	12	0.08	0.44	0.18
CV × PGR	6	0.005	0.42	0.23
Y × CV × PGR	12	0.21	0.26	0.56

(b) LSMEANS for grain yield, g m^{-2}

	Barley				Oat		Wheat	
PGR	cv. Kymppi		cv. Saana					
CONT	616		710		528		598	
CCC1	635	ns	725	ns	565	*	594	ns
CCC2	639	ns	706	ns	528	ns	550	***
ETH1	652	**	697	ns	531	ns	597	ns
ETH2	644	*	691	ns	501	*	579	ns
TE1	644	*	696	ns	533	ns	604	ns
TE2	644	*	671	**	534	ns	585	ns

Y, year; CV, cultivar; PGR, plant growth regulator treatment
CONT, control
CCC1, ETH1 and TE1 treatment at ZGS 13–14
CCC2 treatment at ZGS 31-32, ETH2 and TE2 treatment at ZGS 39–40
ns = non significant, * P < 0.05, ** P < 0.01, *** P < 0.001

1998 (Table 3). In barley, tiller head weight was decreased by ETH applied at the recommended time. In 1998, SGW was reduced by all PGR treatments except TE applied at ZGS 39 (Table 4). No PGR X cultivar interaction was recorded for main head weight and grain number or for tiller head weight of barley (Table 4). CCC applied at ZGS 13–14 increased tiller head grain number by two grains in cv. Kymppi, whereas TE applied at ZGS 39–40 reduced it by two grains in cv. Saana (Table 4).

In 1998, when the effect of early application of PGR on main shoot and tiller growth was monitored at 7-day intervals, CCC, ETH and TE treatments enhanced tiller number at first measurements by 10 to 15% in wheat. However, the only change in tiller weight (+35%) followed ETH treatment. In barley and oat, PGR treatments did not improve tillering or tiller growth. When tiller and head bearing tiller number were determined from the mature plant samples, no PGR effect was noted in any of the studied species. Similarly, main shoot and tiller weight in oat and barley were unchanged at maturity, whereas in wheat, CCC treatments slightly reduced (–4 to –5%) main shoot weight (data not shown). In 2000, main shoot, and to a greater extent tiller growth and tiller number, were enhanced at reduced sowing rates. No PGR effect was detected, nor was a PGR X seeding rate interaction present for tiller number or weight per main shoot (data not shown).

In exp 2 (2000), sowing rate and PGR treatment effected grain yield of barley cv. Saana (Table 5). Average grain yields were 592, 623, 663, and 663 g m^{-2} at sowing rates of 200, 300, 400, and 500 seeds m^{-2}, respectively. CCC applied early or at the recommended time improved

Table 2. ANOVA table for grain weight and grain number in main and tiller head and single grain weight (SGW) in barley, oat and wheat (exp. 1).

		Head weight		Grain number		SGW
		Main head	Tiller head	Main head	Tiller head	
	DF	P	P	P	P	P
Barley						
Y	2	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
CV	1	< 0.001	0.04	0.02	< 0.001	< 0.001
PGR	6	0.34	0.03	0.38	0.007	0.01
Y × CV	2	0.34	0.16	0.05	0.03	0.02
Y × PGR	12	0.27	0.09	0.72	0.07	0.01
CV × PGR	6	0.54	0.19	0.25	0.05	0.62
Y × CV × PGR	12	0.44	0.79	0.39	0.67	0.91
Oat						
Y	1	< 0.001	0.05	< 0.001	0.29	0.91
CV	1	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
PGR	6	0.35	0.89	0.70	0.85	0.65
Y × CV	1	< 0.001	0.33	0.24	0.02	< 0.001
Y × PGR	6	0.25	0.35	0.47	0.53	0.29
CV × PGR	6	0.32	0.63	0.72	0.60	0.63
Y × CV × PGR	6	0.88	0.23	0.73	0.24	0.88
Wheat						
Y	2	< 0.001	0.004	< 0.001	< 0.001	< 0.001
CV	1	< 0.001	0.30	< 0.001	0.38	< 0.001
PGR	6	0.006	0.91	0.47	0.75	< 0.001
Y × CV	2	0.01	0.29	0.007	0.27	< 0.001
Y × PGR	12	0.05	0.95	0.92	0.96	< 0.001
CV × PGR	6	0.73	0.51	0.41	0.55	0.43
Y × CV × PGR	12	0.64	0.35	0.97	0.29	0.24

Y, year; CV, cultivar; PGR, plant growth regulator treatment

Table 3. LSMEANS of main head weight and single grain weight (SGW) in wheat. Difference of the LSMEANS was estimated between untreated control and PGR treatments. Level of the significance of the difference is shown next to the LSMEAN value (exp 1).

	Head weight, mg main head		SGW, mg					
			1996		1997		1998	
CONT	1115		36.9		39.6		31.2	
CCC1	1070	*	35.5	*	39.0	ns	28.7	***
CCC2	1048	**	33.2	***	38.7	ns	27.3	***
ETH1	1123	ns	36.2	ns	38.9	ns	30.7	ns
ETH2	1070	*	36.5	ns	38.5	ns	29.3	**
TE1	1099	ns	35.8	ns	38.4	ns	30.5	ns
TE2	1088	ns	37.3	ns	38.6	ns	29.4	**

CONT, control
CCC1, ETH1 and TE1 treatment at ZGS 13–14
CCC2 treatment at ZGS 31-32, ETH2 and TE2 treatment at ZGS 39–40
ns = non significant, * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$

Table 4. LSMEANS for head weight, grain number and single grain weight (SGW) in barley. Differences among the LSMEANS were estimated between untreated control and PGR treatments. Level of the significance of the difference is shown next to the LSMEAN value (exp. 1).

	Head weight, mg in tiller head		Grain number in tiller head				SGW, mg					
			cv. Kymppi		cv. Saana		1996		1997		1998	
CONT	573		13.5		12.0		45.5		50.4		41.5	
CCC1	565	ns	15.5	*	10.7	ns	44.9	ns	50.7	ns	39.2	**
CCC2	582	ns	14.0	ns	12.2	ns	45.9	ns	50.9	ns	38.5	***
ETH1	606	ns	14.9	ns	12.7	ns	44.7	ns	51.4	ns	38	***
ETH2	501	*	11.7	ns	11.0	ns	45.5	ns	51.5	ns	39	***
TE1	531	ns	13.9	ns	10.4	ns	45.2	ns	50.7	ns	37.6	***
TE2	534	ns	13.6	ns	10.0	*	45.9	ns	51.7	ns	40.4	ns

Y, year; CV, cultivar; PGR, plant growth regulator treatment
CONT, control
CCC1, ETH1 and TE1 treatment at ZGS 13–14
CCC2 treatment at ZGS 31–32, ETH2 and TE2 treatment at ZGS 39–40
ns = non significant, * P < 0.05, ** P < 0.01, *** P < 0.001

Table 5. ANOVA table for grain yield, head weight, grain number and single grain weight (SGW) in barley cv. Saana (exp. 2).

		Grain yield	Head weight		Grain number		SGW
			Main head	Tiller head	Main head	Tiller head	
	DF	P	P	P	P	P	P
SR	3	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.003
PGR	2	0.004	0.27	0.06	0.33	0.19	< 0.001
TRIAL	1	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
SR × PGR	6	0.59	0.58	0.92	0.47	0.90	0.84
SR × TRIAL	3	0.46	0.01	0.11	0.07	0.09	0.86
PGR × TRIAL	2	0.73	0.86	0.17	0.99	0.29	0.42
SR × PGR × TRIAL	6	0.84	0.46	0.12	0.73	0.30	0.12

SR, seeding rate; PGR, plant growth regulator treatment

grain yield by 100 and 150 g m^{-2}, respectively when compared with untreated controls. There was no PGR treatment by sowing rate interaction for any of the measured traits. No PGR effect was noted for yield components, except for single grain weight (Table 5), which was slightly reduced by CCC treatment (data not shown).

Shoot growth and lodging

Early application (ZGS 13–14) of PGRs reduced shoot elongation in barley and oat when measured 14 days after treatment (DAT). In wheat, the height reduction occurred only in 1998. Tall and short stature cultivars responded similarly to early PGR treatments and no PGR by cultivar interaction was detected for shoot growth 14 DAT for any of the studied species (Table 6). At maturity, an early PGR treatment effect was noted in TE treated barley and CCC treated wheat in two out of the three years. In 1998, wheat also responded to early ETH and TE treatments. Early application of CCC enhanced stem elongation of oat cv. Veli in 1997 (Table 7).

Table 6. ANOVA table (a) and LSMEANS (b) for plant height 14 d after early PGR treatment. Difference of the LSMEANS was estimated between untreated control and PGR treatments. Level of the significance of the difference is shown next to the LSMEAN value (exp. 1).

(a) ANOVA

	DF	Barley P	Oat P	Wheat P
Y	2	< 0.001	< 0.001	< 0.001
CV	1	< 0.001	< 0.001	< 0.001
PGR	6	< 0.001	0.04	< 0.001
Y × CV	2	< 0.001	0.02	< 0.001
Y × PGR	12	0.06	0.56	< 0.001
CV × PGR	6	0.40	0.60	0.39
Y × CV × PGR	12	0.30	0.77	0.17

(b) LSMEANS for plant height 14 DAT, cm

	Barley		Oat		Wheat					
					1996		1997		1998	
CONT	31.6		26.0		20.3		27.7		22.6	
CCC1	29.2	***	24.9	*	19.6	ns	26.6	ns	17.9	***
ETH1	29.0	***	25.1	*	20.7	ns	27.1	ns	19.8	***
TE1	29.4	***	25.0	*	19.7	ns	27.3	ns	19.9	***

Y, year; CV, cultivar; PGR, plant growth regulator treatment; DAT, days after treatment
CONT, control
CCC1, ETH1 and TE1 treatment at ZGS 13–14
CCC2 treatment at ZGS 31-32, ETH2 and TE2 treatment at ZGS 39–40
ns = non significant, * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$

When applied at the recommended time, PGRs reduced stem length in the species studied. The exception was dwarf oat cv. Pal, possessing the *DW6* dwarfing gene, which responded poorly to all PGR treatments. A slight increase in stem elongation was noted after treating cv. Pal with CCC. Similarly, in 1997 early-applied PGRs tended to enhance stem elongation in oat cv. Veli. CCC treatment was largely ineffective in barley. A strong year X PGR interaction occurred for plant height for all species (Table 7). Lodging occurred only in 1998 in oat cv. Veli and barley cv. Kymppi. ETH and TE reduced lodging in barley cv. Kymppi by 65 and 95%, respectively, when applied at the recommended time, whereas in oat cv. Veli there was no treatment effect (data not shown). PGR treatments prolonged the period from sowing to heading and maturity by up to one day (data not shown).

Discussion

When grown at high latitudes PGR treatments both increased and decreased yield. Varying PGR effect has also been noted by others (Simmons et al. 1988, Moes and Stobbe 1991, Taylor et al. 1991, Ma and Smith 1992, Peltonen-Sainio and Rajala 2001). However, neither PGR by cultivar nor PGR by year interactions occurred for grain yield in oat and wheat, indicating cultivar independent yield responses to PGRs in both species. The most apparent effect was the yield reduction (500 kg ha^{-1}) in CCC treated wheat. This reduction was associated with the main head weight, which was reduced in parallel. Grain number per head was not affected, but single grain weight was considerably reduced by application of CCC at recommended times in two out of three years. There was no obvious reason

Table 7. ANOVA table (a) and LSMEANS (b) for plant height at maturity. Difference of the LSMEANS was estimated between untreated control and PGR treatments. Level of the significance of the difference is shown next to the LSMEAN value (exp. 1).

(a) ANOVA

		Barley	Oat	Wheat
	DF	P	P	P
Y	2	< 0.001	< 0.001	< 0.001
CV	1	< 0.001	< 0.001	< 0.001
PGR	6	< 0.001	< 0.001	< 0.001
Y × CV	2	< 0.001	< 0.001	0.007
Y × PGR	12	0.002	< 0.001	< 0.001
CV × PGR	6	0.31	< 0.001	0.55
Y × CV × PGR	12	0.37	< 0.001	0.95

(b) plant height at maturity, cm

	Barley						Wheat					
	1996		1997		1998		1996		1997		1998	
CONT	82		62		90		89		81		100	
CCC1	83	ns	61	ns	91	ns	85	**	79	ns	91	***
CCC2	80	*	63	ns	91	ns	78	***	75	***	84	***
ETH1	83	ns	63	ns	90	ns	90	ns	80	ns	94	***
ETH2	79	**	55	***	85	***	88	ns	69	***	91	***
TE1	79	***	60	**	88	ns	90	ns	82	ns	93	***
TE2	77	****	56	****	85	****	86	*	75	***	90	***

	Oat							
	1996				1997				1998			
	cv. Pal		cv. Veli		cv. Pal		cv. Veli		cv. Pal		cv. Veli	
CONT	88		127		65		94		97		135	
CCC1	89	ns	128	ns	65	ns	99	**	99	ns	134	ns
CCC2	91	ns	119	***	67	ns	89	***	100	*	132	*
ETH1	89	ns	126	ns	68	ns	96	ns	99	ns	135	ns
ETH2	87	ns	123	*	65	ns	82	***	98	ns	134	ns
TE1	87	ns	124	ns	64	ns	97	ns	99	ns	135	ns
TE2	84	*	121	***	63	ns	77	***	100	ns	134	ns

Y, year; CV, cultivar; PGR, plant growth regulator treatment
CONT, control
CCC1, ETH1 and TE1 treatment at ZGS 13–14
CCC2 treatment at ZGS 31-32, ETH2 and TE2 treatment at ZGS 39–40
ns = non significant, * P < 0.05, ** P < 0.01, *** P < 0.001

for this reduction in single grain weight as the grain number, tiller number and tiller phytomass were unaltered. Hence, increased competition for growth resources was not a probable explanation for reduced single grain weight in the main head. In fact, stem length was shortened from 6 to 16 cm by CCC treatment and according to the literature, stem shortening should redirect more assimilates to alternative sinks, including tillers and grains (Gale and Youssefian 1985, Peltonen-Sainio and Järvinen 1995, Peltonen and Peltonen-Sainio 1997, Gent and Kiyomoto 1998).

However, such changes were not observed in this study. On the contrary, CCC induced stem shortening was associated with less phytomass of the main shoot and lower main head weight. While no PGR induced changes in tiller growth and tiller produced yield were noted, together these resulted in yield loss in CCC treated wheat. Carbon dioxide exchange rate was not measured in this study, but according to a report and our earlier experiment, CCC treatments had little, if any, effect on photosynthesis in wheat (Höfner and Kühn 1982, Rajala and Peltonen-Sainio 2001). CCC application induced stress is also not a likely explanation for reduced growth, as no changes in wheat ethylene production was recorded to follow CCC application (Grossmann 1992, Rajala et al. 2002).

Response of barley cultivars to PGRs varied in this study. Yield increases were noted in PGR treated cv. Kymppi and decreases in ETH and TE treated cv. Saana. The most evident response was for cv. Saana, in which grain yield was reduced by 400 kg ha^{-1} by TE applied at ZGS 39–40. This was associated with reduced tiller head weight and number of grains in tiller heads. Barley cv. Kymppi seemed to benefit from PGR treatments, though the only yield component improved was grain number in tiller heads when treated with CCC at early growth stages. In exp 2 (2000), CCC treatments slightly increased grain yield in barley cv. Saana. However, when yield components were examined, both CCC treatments tended to slightly decrease yield components, especially single grain weight. High seeding rates suppressed tiller formation in barley up to 40%. CCC had no enhancing effect on tiller formation and growth at any of the seeding rates irrespective of time of application. Thus, CCC was ineffective in promoting tillering in cv. Saana at high latitudes when low sowing rates were used.

In most cases PGRs applied at the recommended time shortened stems of the cultivars studied. The shortening ranged from 3 to 22%, though the responses were not constant across years. Barley did not respond to CCC treatment and no PGRs had substantial effects on dwarf oat cv. Pal. Similarly, dwarf wheat cultivars responded weakly to CCC treatments (Abbo et al. 1987, Evans et al. 1995). CCC may even enhance longitudinal stem growth in dwarf oat, as recorded in this study and in an earlier study (Peltonen-Sainio and Rajala 2001). Also, there was an increase in stem length of barley after CCC treatment (Clark and Fedak 1977, Waddington and Cartwright 1986). When shoot length was measured 14 days after early PGR treatment, cv. Pal and non-dwarf oat cv. Veli responded similarly to PGR treatments. It seems that dwarf and standard oat types responded similarly to CCC treatment, but stem elongation was retarded for a shorter period in the dwarf type and was followed by enhanced elongation, which finally resulted in stems that were similar in length or longer than the untreated control. Also, in cv. Veli, early application of CCC enhanced stem growth in 1997. The reason for this accelerated elongation is, however, not thoroughly understood (Peltonen-Sainio and Rajala 2001). The response of barley to CCC seems to be similar to that observed in dwarf oat. Stem length of barley did not respond to CCC treatment when measured at maturity, but at 14 DAT shoot length was retarded equally following ETH and TE treatments. Due to varying responses in barley cultivars, CCC is not recommended for control of lodging in commercial farming.

With regard to the reduction in early shoot elongation, all cultivars responded rather similarly to PGRs, irrespective of species, stem stature or PGR involved. If the PGRs' capability to modify cereal growth is based on change in availability of photo-assimilates, then the observed reduction in main shoot elongation provides evidence for the hypotheses that all PGRs applied at the early growth stage were equally effective in modifying cereal growth, at least in the short term (Cooke et al. 1983, Knapp et al. 1987, Ma and Smith 1992). In support of this assumption, PGRs were noted to retard main shoot dry matter accumulation in barley, oat and wheat grown in the greenhouse (Rajala and Peltonen-Sainio 2001, Peltonen-Sainio et al. 2002). Contrary to this, PGRs applied prior to the tillering period were unable to modify tillering pattern as none of the PGRs involved had any effect on tiller or head bearing tiller number (when measured at maturity) in the studied species, indicating PGRs' ineffectiveness in promoting tillering under field conditions in the cultivars involved the study.

Use of moderate fertilizer application (80 kg N ha^{-1}) under non-lodging susceptible weather conditions during the experiments reduced the pressure for lodging. However, in 1998, prevailing weather conditions promoted stem elongation in all species. This resulted in moderate lodging in barley cv. Kymppi and oat cv. Veli. In contrast to effects on cv. Kymppi, PGR treatments failed to reduce stem length and degree of lodging in cv. Veli in 1998. Cultivars selected for the trials were modern and not susceptible to lodging, as the main interest lay in possibilities to modify plant stand structure and formation of yield potential rather than to test the ability to prevent lodging. As noted elsewhere, response to PGR treatments may vary from year to year and PGR treatments are often economically feasible only under conditions promoting lodging (Simmons et al. 1988, Ma and Smith 1992, Erviö et al. 1995).

In conclusion, PGR treatments had little effect on plant stand structure other than stem height. There was short-term reduction of shoot elongation following PGR application at ZGS 13–14 in all cultivars, irrespective of stem stature or PGR. CCC also reduced shoot elongation in dwarf oat and barley, which are often considered insensitive to CCC. Both yield increases and decreases were recorded in PGR treated plants, depending on cultivar and species. Barley cv. Kymppi seemed to benefit from PGR treatments. In wheat, CCC applied at ZGS 31–32 and in oat ETH applied at ZGS 39–40, reduced yield. This was associated with reduced single grain weight. Oat benefited from early application of CCC – at a relatively low cost of CCC; this treatment may be feasible for oat. However, in general, under low lodging pressure, PGR applications were not advantageous for yield formation of spring cereals when grown at high latitudes.

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SELOSTUS

Aikaisen ja tavanomaisen kasvunsäädekäsittelyn vaikutus kevätviljojen kasvustoon ja satoon

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Kasvunsääteitä käytetään perinteisesti viljojen laontorjuntaan. Monet, lähinnä ulkomaiset tutkimustulokset antavat kuitenkin viitteitä, että kasvunsäädekäsittelyllä voidaan vaikuttaa korren pituuskasvun lisäksi myös muihin kasvusto-ominaisuuksiin kuten versoutumiseen ja jyvien lukumäärään. Tutkimme aikaisin ja tavanomaiseen aikaan suoritettujen kasvunsäädekäsittelyjen vaikutuksia kauran, ohran ja vehnän kasvustoihin ja sadon muodostumiseen pitkän päivän kasvuoloissa.

Peltokokeet tehtiin Helsingin yliopiston Viikin koetilalla vuosina 1996–1998 ja 2000, sekä Maa- ja elintarviketalouden tutkimuskeskuksessa Jokioisilla vuonna 2000. Kustakin kevätviljalajista oli kokeissa mukana pitkä- ja lyhytkortinen lajike: kaura (Veli ja Pal), ohra (Kymppi ja Saana) ja vehnä (Mahti ja Tjalve). Tutkittuja kasvunsääteitä oli kolme. Näistä kahden, CCC:n ja Modduksen, kortta lyhentävä vaikutus perustuu gibberelliinihapon biosynteesin rajoittamiseen, kun taas Etefoni lisää etyleenin määrää kasvisolussa. Kasvustot käsiteltiin joko kolme–neljä-lehtivaiheesa tai tavanomaisessa kasvuvaiheessa (CCC korren pituuskasvun alussa, Etefoni ja Moddus lippulehtivaiheessa).

Kasvunsäädekäsittelyt vaikuttivat vähän muihin kasvusto-ominaisuuksiin kuin korren pituuteen. Aikaiset kasvunsäädekäsittelyt lyhensivät hetkellisesti kaikkien lajien oraan pituuskasvua, mutta tuleentuneen kasvuston pituuteen niillä ei ollut vaikutusta. Kasvunsäädekäsittelyt vaikuttivat satoon vaihtelevasti. Toisin kuin kauralla ja vehnällä, ohralla kasvunsääteet vaikuttivat satoon lajikkeittain. Ohralajike Kymppi hyötyi kaikista kasvunsäädekäsittelyistä, kun taas Saanan sato oli sama tai pienempi eri käsittelyillä. Kauralla aikainen CCC-käsittely lisäsi satoa 370 kg ha^{-1} ja Etefoni-käsittely tavanomaiseen aikaan laski satoa 270 kg ha^{-1}. Vehnällä tavanomaiseen aikaan annettu CCC laski satoa lähes 500 kg ha^{-1}. Samanaikaisesti tämän voimakkaan sadon alenemisen kanssa pääverson tähkän paino ja tuhannen jyvän paino pienenivät. Tulosten perusteella kasvunsääteiden käytöllä ei saavuteta muita muutoksia kasvustossa kuin korren lyheneminen, ja kasvunsääteet vaikuttavat satoon vaihtelevasti, varsinkin kun lakoa ei esiinny.