*Journal of Agricultural Science, Cambridge* (1997), **128**, 143–154. © 1997 *Cambridge University Press* 

# Effect of a plant growth regulator regime on internode length and weight of tillers in conventional and hybrid rye and the impact of nitrogen on crop performance

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(*Revised MS received 12 June 1996*)

## SUMMARY

The effect of nitrogen and a plant growth regulator regime (chlormequat chloride followed by 2-chloroethylphosphonic acid) on the crop performance of a hybrid (cv. Luchs) and a conventionally bred winter rye (cv. Sentinel) were investigated in two field experiments each year between 1993 and 1995 at Winchester, UK. Internode length and dry weight/unit length of internodes was measured in order to assess the effect of the growth regulator regime on stem structure. Grain yields were 15% higher in the hybrid Luchs than in Sentinel. With high levels of applied nitrogen, both cultivars lodged in all seasons and this was most severe in 1994 when 88% of the crop lodged in Sentinel and 52% in Luchs. Plant growth regulator treatment consistently reduced lodging but did not eliminate it. Reductions in lodging were not always associated with an increase in grain yield. In the hybrid cultivar, the growth regulator treatment reduced yield in 1993 and 1995 when 2-chloroethylphosphonic acid was applied at GS49 and GS39 respectively, but increased yield in 1994 when applied at GS37. Growth regulator consistently reduced stem length, and the percentage reduction in length of the individual internodes within the stem was strongly influenced by the timing of the 2-chloroethylphosphonic acid component of the PGR treatment. Growth regulator reduced internode lengths by up to 25% in Sentinel and 35% in Luchs, and this was associated with reductions in the dry weight of internodes by up to 32% in Sentinel and 38% in Luchs. Consequently, dry weight/unit length of the stem was not increased by growth regulator treatment. Yield reductions in Luchs following growth regulator treatment may have been due to reduced stem reserves which have been associated with tolerance of stress in rye. Both cultivars were highly responsive to nitrogen. Economic optima varied from season to season, but they ranged over three years, from 175–273 kg/ha nitrogen, and were greater than the currently recommended application rates. Crop lodging increased with increasing nitrogen rate even when plant growth regulator was applied and yield penalties from lodging would have been high, if weather conditions during grain maturity had been unfavourable.

## INTRODUCTION

Winter rye (*Secale cereale*) is tall and relatively weak strawed compared with wheat and barley (McDonald 1991). Crop height in rye can exceed 1·5 m, making it susceptible to lodging, which often results in loss of both yield and quality, particularly Hagberg falling number (HFN). To minimize the risks from lodging, growers use lower nitrogen (N) rates than in wheat and barley, choose sites of lower fertility, and routinely apply plant growth regulators (PGR). Traditionally, the rye crop has been grown on poorer soils, due to its claimed ability to tolerate drought and to produce acceptable yields under adverse conditions. This tolerance to stress has been attributed to reserves of stem assimilates which can be mobilized in late season (Bushuk 1976).

In recent years, hybrid cultivars of rye have been introduced into the UK. Whilst hybrids are higher yielding than conventional cultivars, crop height and lodging resistance are similar to existing conventionally bred cultivars (Anon. 1994*a*).

Lodging in wheat and barley is known to be affected by many factors such as cultivar, PGR, N rate, sowing rate, weather pattern and soil type, and whilst it is likely that these factors also influence the rye crop, there have been comparatively few studies on this crop in the UK. Whilst PGRs remain an important agronomic tool for growers of rye, straw strength in terms of dry weight/unit length, such as that proposed for barley by White (1991), could provide a valuable indicator of the value of differing PGR strategies in rye cultivars. By comparing the effect of a PGR regime on internode length and weight in both a hybrid and conventional rye, this study sought to improve understanding of growth regulator effects on tiller structure and crop performance.

## MATERIALS AND METHODS

Two cultivars of winter rye: Sentinel, a conventionally bred cultivar, and Luchs, a hybrid cultivar, were sown in adjacent field experiments in the 1993, 1994 and 1995 seasons at ADAS Bridgets Research Centre, Winchester, Hampshire. Different fields were used each year and all rye crops followed winter wheat. In each year two experiments were sown; in the first, Sentinel and Luchs were grown with and without a PGR regime at 100 kg/ha N. This experiment was used for destructive sampling of rye plants and was not taken to yield. In a second experiment, located adjacent to the first, both cultivars were grown with and without a PGR regime and with 0, 50, 100, 150, 200 and 250 kg/ha N. In both experiments, the PGR regime consisted of chlormequat chloride (New 5C Cycocel; 57% s.c.; BASF) at crop GS31 (Tottman 1987) at 1600 g a.i. ha, followed by 2-chloroethylphosphonic acid (Cerone; 39·6% s.c.; Rhône-Poulenc) at GS37-49 at 480 g a.i. ha. Growth regulator treatments were applied using an Oxford precision sprayer fitted with flat fan 110° nozzles, at 2 bar in 200 l of water/ha. All N treatments were applied as a split dressing (ammonium nitrate; 34·5% N; ICI) with 40 kg N/ha at GS24 and the remainder at crop GS31. In both experiments, all treatments were fully randomized, with three replications of each treatment, one per block. Experiment 1 was a two-way factorial with PGR and cultivar as the factors and Expt 2 was a three-way factorial with PGR, cultivar and N as the factors. Individual experimental plots were 24 × 3 m. Cultivars were sown at a uniform seed rate of 400 seeds/m² and all experiments received a standard agrochemical programme to control any pest, weed or disease problems (Table 1). Experiments were sited on infertile silty clay loam soils overlying chalk and followed continuous wheat.

### *Pre-harvest assessment of internodes to determine weight/unit length*

In Expt 1, plant samples from two adjacent 0·5 m lengths of row were taken at crop GS91–92 from ten sampling points per plot, using the same grid pattern within the whole plot. The total number of tillers per sampling point was counted. Individual tillers were divided into sets having either four, five or six internodes. In 1993, from five of the ten sampling points, ten tillers were selected at random from each internode set, or the entire number of tillers within the internode set if this was less than ten, and separately assessed. In 1994 and 1995, ten tillers were also selected at random from the sets with five internodes, but only one tiller per sampling point was selected from the sets with four or six internodes and these were bulked to provide ten tillers/plot. Individual tillers were dissected with a scalpel. Leaves, leaf sheaths and ears were removed from individual tillers prior to the assessment of internode length. Internodes were numbered from the ear downwards to the base of the stem. Roots were discarded. Bulked samples of plant tissue were oven dried prior to weighing. Ears were threshed, weighed and the number of grains per ear were counted. Using this information, mean tiller length, mean tiller weight, grain number/tiller, 1000-grain weight and harvest index were calculated.

### *Assessments of yield and lodging*

In Expt 2, crop lodging was assessed at GS75 and immediately prior to harvest using the method of Caldicott & Nuttall (1979). All plots were harvested using plot combine harvesters, a Class Dominator 38 in 1993 and 1994 and a Sampo Rosenlew 20/25 in 1995. A sample of the harvested grain was taken for the determination of moisture content using a Sinar Datatec P25 electronic moisture meter and final grain yield was adjusted to 85% dry matter. Grain was also assessed for grain specific weight (kg/hl) using a chondrometer, and for percentage nitrogen by Near Infrared Reflectance (Osborne *et al*. 1982).

### *Meteorological data*

Data on daily precipitation was recorded at a weather station *c*. 1 km from the field sites.

### *Statistical analysis*

Data from Expts 1 and 2 were statistically analysed using analysis of variance conducted by GENSTAT (Anon. 1987). In 1993, data on internode length for internodes 1 and 5, in both cultivars, was transformed prior to analysis using a negative reciprocal transformation. Yield data from Expt 2 were used to estimate the economic optimum rate of applied N for yield using a linear plus exponential curve with 'fixed' estimates of the *r parameter*, and a grain:nitrogen price ratio of 3:1 (George 1984). In Expt 1, the data for percentage reduction of weight and length for internode set 5 were analysed using linear regression using the EXCEL software package (Person 1993).

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Table 1. *Soil and husbandry details for the experimental site at ADAS Bridgets, 1993–95*

| | 1993 harvest | 1994 harvest | 1995 harvest |
|---|---|---|---|
| Soil type | Silty clay loam | Silty clay loam | Silty clay loam |
| Previous crop | Winter wheat | Winter wheat | Winter wheat |
| Sowing date | 21 October | 26 October | 17 October |
| Herbicide | Pendimethalin 2000 g a.i./ha 30 October<br>Diclofop-methyl 1134 g a.i./ha 15 April | Pendimethalin 2000 g a.i./ha 29 September<br>Metsulfuron-methyl 30 g a.i./ha 21 March | Pendimethalin 2000 g a.i./ha 17 October |
| Insecticide | Cypermethrin 25 g a.i./ha 9 November | | |
| Fungicide | Prochloraz 405 g a.i./ha + fenpropimorph 750 g a.i./ha 20 April<br>Propiconazole 125 g a.i./ha + fenpropimorph 750 g a.i./ha 10 May | Prochloraz 405 g a.i./ha + carbendazim 150 g a.i./ha + fenpropimorph 563 g a.i./ha 28 April<br>Propiconazole 125 g a.i./ha + fenpropimorph 750 g a.i./ha 10 May | Prochloraz 405 g a.i./ha + fenpropimorph 750 g a.i./ha 13 April<br>Propiconazole 125 g a.i./ha + fenpropimorph 750 g a.i./ha 1 May |
| Plant growth regulator | Chlormequat chloride 1612 g a.i./ha 29 April<br>2-chloroethylphosphonic acid 480 g a.i./ha 6 May | Chlormequat chloride 1612 g a.i./ha 18 April<br>2-chloroethylphosphonic acid 480 g a.i./ha 2 May | Chlormequat chloride 1612 g a.i./ha 10 April<br>2-chloroethylphosphonic acid 480 g a.i./ha 28 April |
| Harvest date | 13 August | 16 August | 8 August |

## RESULTS

### *Meteorological data and timing of growth regulator treatments*

Precipitation in 1993, 1994 and 1995 was 835, 929 and 789 mm, slightly above the 30-year mean at the Bridgets site of 797 mm. However, rainfall from April to harvest varied significantly at 308, 198 and 89 mm respectively in 1993, 1994 and 1995.

In 1993, the timing of the first growth regulator treatment of New 5C Cycocel was delayed due to poor weather and the following Cerone treatment was applied at GS49, the end of the commercially recommended spray window for the product which is GS37–49 (Table 1). In 1994, the Cerone treatment was applied at GS37 and in 1995 at GS39.

### *Experiment 1*

#### *Number of internodes/tiller*

Tillers with four, five and six internodes were identified from both Sentinel and Luchs. Tillers with five internodes occurred most frequently, representing > 81% of tillers in 1993, and 78% in 1995, but only 66% in 1994 when there was an increase in the frequency of tillers with six internodes (Table 2). Overall, there was a greater frequency of tillers with six internodes in Luchs and a greater frequency with four internodes in Sentinel. PGR treatment increased the percentage of tillers with four internodes in both cultivars.

#### *Effect of PGR regime on tillers with 4, 5 or 6 internodes*

In 1993, tiller length increased with increasing number of internodes, and PGR treatment reduced the lengths of tillers with four, five and six internodes in both Sentinel and Luchs (Fig. 1). In 1993, tiller length in Sentinel was reduced by 11, 9 and 9%, respectively, in the tiller sets with four, five and six internodes and by 8% for all three sets, in Luchs. Dry weight/tiller increased with increasing number of internodes and was reduced by PGR treatment. Overall, PGR treatment had a consistent effect in reducing tiller dry weight.

#### *Internode length and dry weight in tillers with five internodes*

In all years, internode length and internode weight, in both Sentinel and Luchs, were reduced by PGR treatment (Table 3). Internode lengths were greatest for internodes 1 and 2, nearest the ear. The timing of the PGR treatment affected the percentage reduction in internode length (Fig. 2). In 1993 and 1995, when the PGR was applied at GS49 and GS39 respectively, it reduced the length of all internodes by between 5 and 35%. However, in 1994, when applied at the earlier timing of crop GS37, only the length of the lower internodes 3, 4 and 5 were reduced. In 1994, there was a reduction in the length of internode 2 and in Luchs a small increase in length of internode 1, but these were not statistically significant. Internode weight was greatest for internode 2 in all seasons in both cultivars and declined towards the base of the tiller (Table 3). Dry weight/unit length for internodes 1–5 are shown in Fig. 3. Dry weight/unit length was greatest for internode 5, at the base of the tiller, and least for internode 1, nearest to the ear. There was a straight-line relationship between the percentage reduction in internode length and dry weight following growth regulator treatment in both Sentinel $y = 4{\cdot}35 + 0{\cdot}78$; S.E. $\pm 6{\cdot}30$ ($r^2 = 0{\cdot}75$, D.F. 14) and Luchs $y = -2{\cdot}89 + 1{\cdot}07$; S.E. $\pm 4{\cdot}03$ ($r^2 = 0{\cdot}94$, D.F. 14) (Fig. 4).

#### *Crop components, harvest index and tiller height*

The effects of PGR treatment and choice of cultivar on the mean dry weight in ears, internode and leaf sheath, together with grain number/tiller, 1000-grain weight, harvest index and tiller height for 1993–95 are shown in Table 4. There were significant interactions between PGR and cultivar for many of the variables

Table 2. *Percentage of tillers in internode 'sets' in Sentinel and Luchs, 1993–95*

| Year | Internode set | Sentinel −PGR | Sentinel +PGR | Sentinel Mean | Luchs −PGR | Luchs +PGR | Luchs Mean |
|---|---|---|---|---|---|---|---|
| 1993 | 4 | 13 | 18 | 15 | 7 | 7 | 7 |
| | 5 | 81 | 79 | 80 | 84 | 82 | 83 |
| | 6 | 6 | 3 | 5 | 9 | 11 | 10 |
| 1994 | 4 | 1 | 2 | 1 | 1 | 3 | 2 |
| | 5 | 64 | 66 | 65 | 66 | 67 | 67 |
| | 6 | 34 | 32 | 33 | 33 | 30 | 31 |
| 1995 | 4 | 10 | 16 | 13 | 6 | 10 | 8 |
| | 5 | 80 | 75 | 77 | 83 | 76 | 79 |
| | 6 | 10 | 9 | 9 | 11 | 14 | 13 |

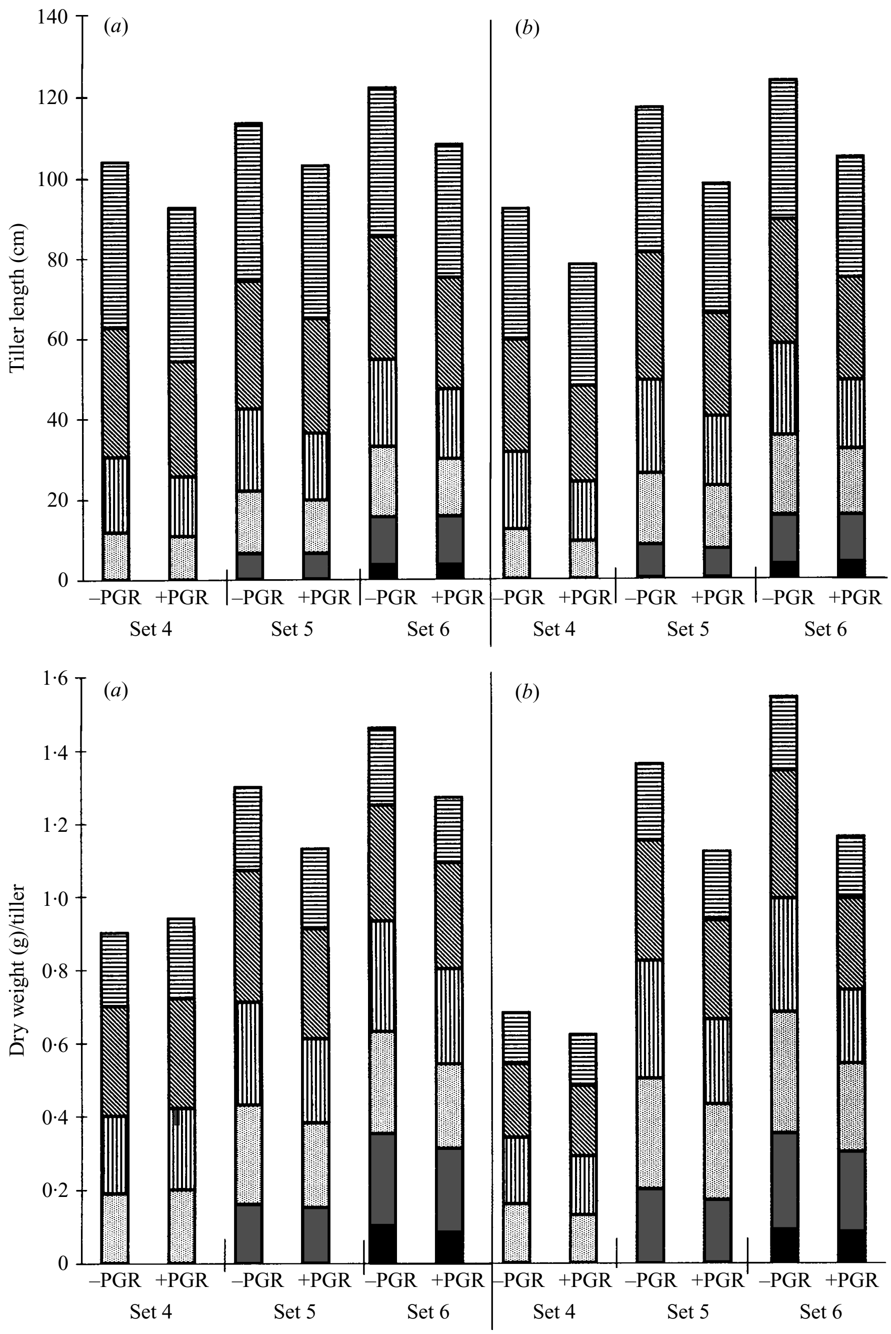


Fig. 1. Effect of PGR regime in winter rye cultivars (*a*) Sentinel and (*b*) Luchs on mean tiller length (cm) and mean dry weight (g)/tiller in internodes: 1 (▤), 2 (▧), 3 (▥), 4 (▨), 5 (▩) and 6 (■) for internode sets 4, 5 and 6 in 1993.

measured. However, in all seasons, the addition of PGR reduced ear and internode dry weight, although leaf sheath dry weight was unaffected. Ear dry weight was greater in Luchs than Sentinel in 1993 and 1994, whilst in 1995, ear weight was similar in the two cultivars. In all seasons, total tiller weight was reduced by PGR treatment. Grain number/tiller was greater in Luchs than in Sentinel but declined following PGR

https://doi.org/10.1017/S0021859696004029 Published online by Cambridge University Press

Table 3. *Effect of plant growth regulator regime on internode length (cm) and weight (g) in Sentinel and Luchs for internode set 5, 1993–95*

| | | Length (cm) | | | | | | | | Weight (g) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Sentinel | | | Luchs | | | S.E. (D.F. 6) | | Sentinel | | | Luchs | | | S.E. (D.F. 6) | |
| Year | Internode | −PGR | +PGR | Mean | −PGR | +PGR | Mean | PGR × cultivar | Cultivar | −PGR | +PGR | Mean | −PGR | +PGR | Mean | PGR × cultivar | Cultivar |
| 1993 | 1 | −0·03* | −0·03* | −0·03* | −0·03* | −0·03* | −0·03* | 0·0004* | 0·0003* | 0·23 | 0·22 | 0·23 | 0·21 | 0·19 | 0·20 | 0·010 | 0·007 |
| | 2 | 31·9 | 28·6 | 30·2 | 31·9 | 25·7 | 28·8 | 0·46 | 0·32 | 0·36 | 0·30 | 0·33 | 0·33 | 0·27 | 0·30 | 0·016 | 0·011 |
| | 3 | 20·4 | 16·5 | 18·4 | 23·0 | 17·1 | 20·1 | 0·26 | 0·18 | 0·28 | 0·23 | 0·26 | 0·32 | 0·23 | 0·28 | 0·010 | 0·007 |
| | 4 | 15·5 | 13·3 | 14·4 | 17·7 | 15·7 | 16·7 | 0·37 | 0·26 | 0·27 | 0·23 | 0·25 | 0·30 | 0·26 | 0·28 | 0·008 | 0·006 |
| | 5 | −0·16* | −0·16* | −0·16* | −0·12* | −0·14* | −0·13* | 0·0076* | 0·0054* | 0·16 | 0·15 | 0·16 | 0·20 | 0·17 | 0·19 | 0·009 | 0·006 |
| | Total | 67·6 | 58·2 | 63·2 | 72·5 | 58·7 | 65·8 | | | 1·30 | 1·13 | 1·22 | 1·36 | 1·12 | 1·24 | | |
| 1994 | 1 | 40·9 | 40·8 | 40·8 | 36·5 | 37·3 | 36·9 | 2·92 | 2·07 | 0·23 | 0·22 | 0·23 | 0·21 | 0·21 | 0·21 | 0·025 | 0·016 |
| | 2 | 33·0 | 32·2 | 32·6 | 31·9 | 31·3 | 31·5 | 2·06 | 1·46 | 0·32 | 0·33 | 0·28 | 0·31 | 0·32 | 0·32 | 0·029 | 0·021 |
| | 3 | 21·3 | 18·8 | 20·1 | 22·8 | 19·7 | 21·2 | 1·47 | 1·04 | 0·26 | 0·23 | 0·25 | 0·27 | 0·24 | 0·26 | 0·019 | 0·014 |
| | 4 | 16·4 | 13·2 | 14·8 | 18·8 | 14·2 | 16·5 | 1·27 | 0·90 | 0·25 | 0·19 | 0·22 | 0·27 | 0·21 | 0·24 | 0·019 | 0·014 |
| | 5 | 8·7 | 7·5 | 8·1 | 9·5 | 7·4 | 8·5 | 0·55 | 0·39 | 0·18 | 0·15 | 0·17 | 0·20 | 0·15 | 0·18 | 0·020 | 0·014 |
| | Total | 120·3 | 112·5 | 116·4 | 119·6 | 109·9 | 117·7 | | | 1·24 | 1·12 | 1·18 | 1·26 | 1·13 | 1·20 | | |
| 1995 | 1 | 42·0 | 34·0 | 38·0 | 33·2 | 29·4 | 31·3 | 1·07 | 0·76 | 0·24 | 0·21 | 0·23 | 0·17 | 0·15 | 0·16 | 0·0300 | 0·0213 |
| | 2 | 35·6 | 29·8 | 32·7 | 31·5 | 26·7 | 29·1 | 0·66 | 0·46 | 0·37 | 0·32 | 0·35 | 0·29 | 0·26 | 0·28 | 0·0540 | 0·0382 |
| | 3 | 19·0 | 15·2 | 17·1 | 20·2 | 16·7 | 18·5 | 0·57 | 0·39 | 0·23 | 0·20 | 0·22 | 0·22 | 0·19 | 0·21 | 0·0280 | 0·0198 |
| | 4 | 12·9 | 10·9 | 11·9 | 14·6 | 12·4 | 13·5 | 0·61 | 0·43 | 0·20 | 0·15 | 0·16 | 0·19 | 0·18 | 0·19 | 0·0329 | 0·0232 |
| | 5 | 5·7 | 5·3 | 5·5 | 6·7 | 6·2 | 6·5 | 0·93 | 0·66 | 0·12 | 0·10 | 0·11 | 0·12 | 0·12 | 0·12 | 0·0223 | 0·0157 |
| | Total | 115·2 | 95·3 | 105·3 | 106·1 | 91·4 | 98·8 | | | 1·16 | 0·98 | 1·07 | 0·99 | 0·90 | 0·96 | | |

* Negative reciprocal transformations used on data.

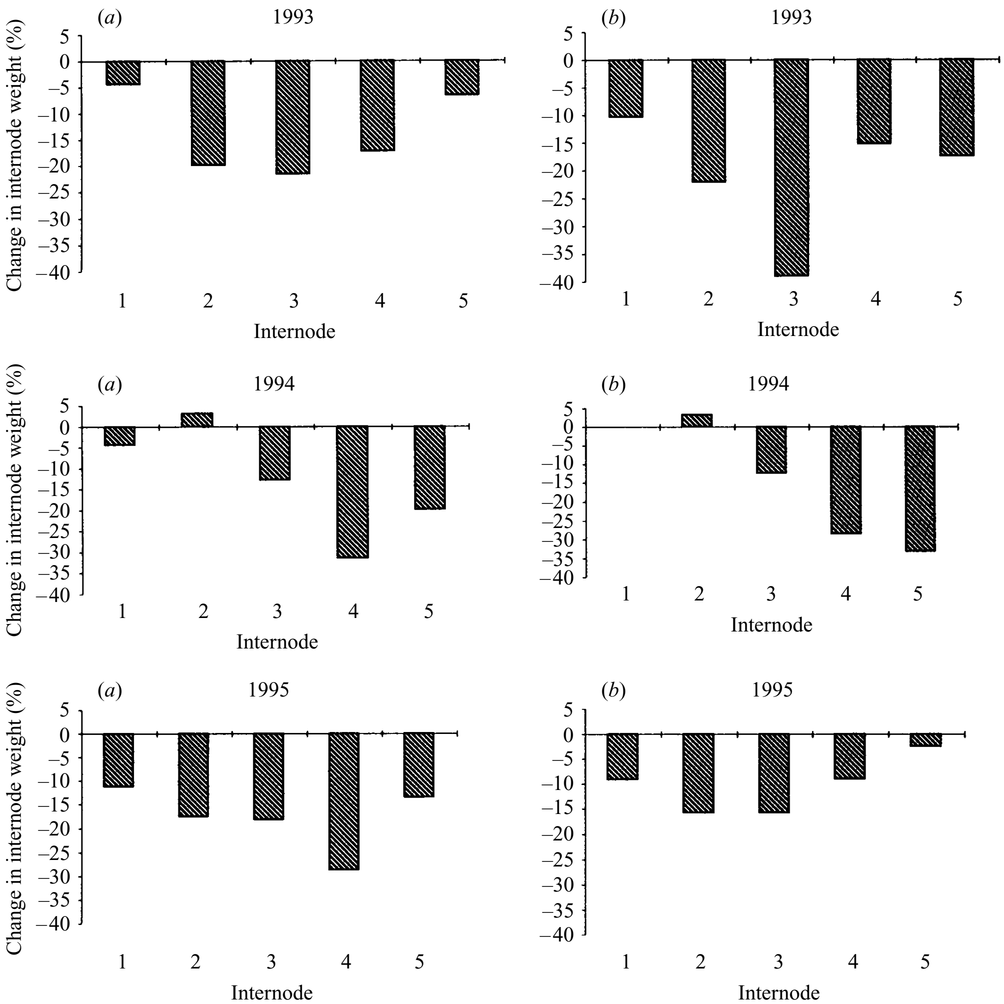


Fig. 2. Percentage reduction in internode weight of winter rye cultivars (*a*) Sentinel and (*b*) Luchs following PGR regime for internode set 5, 1993–95.

treatment in Sentinel in all seasons and in 1994 and 1995 in Luchs. Thousand-grain weight was greater in Luchs than Sentinel in both 1993 and 1994, however, in 1995, it was greater in Sentinel. Harvest index was unaffected by PGR treatment, but was greater in Luchs than in Sentinel.

### *Experiment 2*

#### *Grain yield*

The hybrid cultivar Luchs outyielded the conventional cultivar Sentinel ($P < 0{\cdot}001$) in all years and overall by 15% (Table 5). Both cultivars were highly responsive to increasing rate of applied nitrogen ($P < 0{\cdot}001$). PGR treatment gave a yield benefit ($P < 0{\cdot}05$) in both Sentinel and Luchs in 1994 of 0·23 and 0·18 t/ha, respectively.

In Sentinel in 1994, PGR treatment gave a small yield benefit at all nitrogen rates up to 200 kg/ha, whilst in Luchs the greatest benefit from PGR treatment was seen at nitrogen rates of 200 and 250 kg/ha. In both 1993 ($P < 0{\cdot}05$) and 1995 ($P < 0{\cdot}001$), PGR treatment gave a yield reduction in Luchs of 0·29 and 0·28 t/ha, respectively. In Luchs, there were only small yield differences resulting from PGR treatment at nitrogen rates up to 150 kg/ha, with larger reductions at the higher rates tested. Overall, yields were highest in 1994 for both Sentinel and Luchs, being 0·91 t/ha and 1·05 t/ha greater than the mean yield of the 1993 and 1995 seasons.

#### *Lodging*

There was crop lodging in both cultivars in all seasons, but lodging was most severe in 1994, when

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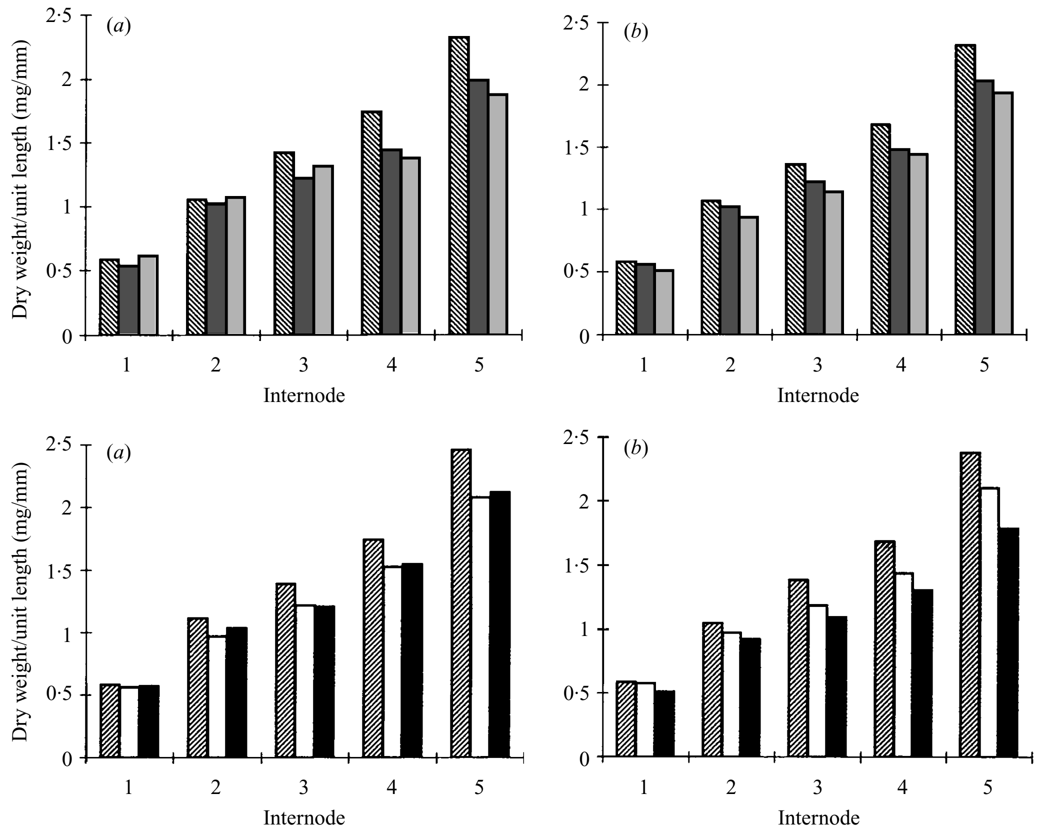


Fig. 3. Effect of PGR regime on winter rye cultivars (*a*) Sentinel and (*b*) Luchs on internode dry weight/unit length (mg/mm) for internode set 5, −PGR 1993 (▧), 1994 (■), 1995 (▩); +PGR 1993 (▨), 1994 (□), 1995 (■).

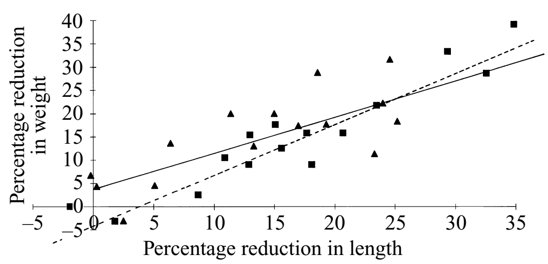


Fig. 4. Linear regression of percentage reduction in weight on percentage reduction in length for winter rye cultivars, Luchs (■), (– – –), and Sentinel (▲), (——), in internode set 5, 1993–95.
Sentinel $y = 4.35 + 0.78$, S.E. $\pm 6.30$ ($r^2 = 0.75$, D.F. 14)
Luchs $y = -2.89 + 1.07$, S.E. $\pm 4.03$ ($r^2 = 0.94$, D.F. 14).

the crop lodged earlier and reached overall 88% lodging in Sentinel and 53% in Luchs at harvest (Fig. 5). There was least lodging in 1995 and in that year no crop lodging was recorded at the first assessment date at GS75. In all seasons, there was more lodging ($P < 0.001$) in Sentinel than in Luchs and percentage lodging increased with increasing rate of applied nitrogen ($P < 0.001$). The plant growth regulator regime reduced lodging ($P < 0.001$) in both cultivars in all seasons, but did not prevent it.

### *Grain quality*

The effect of cultivar, PGR and N on aspects of grain quality is shown in Table 6. In both 1993 and 1995, grain specific weight was less in Luchs than in Sentinel and was reduced by PGR treatment. In 1995, increasing N rate increased grain specific weight and percentage grain nitrogen. HFN was greater in Luchs than in Sentinel in both 1993 and 1995.

### *N optima and yield at N optima*

The economic N optima based upon a grain: nitrogen price ratio of 3:1 varied from 175 to 273 kg/ha N for individual cultivar × growth regulator treatments over the three years of the experiment (Table 7). Mean N optima for the three seasons were 187, 229 and 195 kg/ha N respectively for the 1993, 1994 and 1995 seasons. Yields at N optima were higher in Luchs than in Sentinel in all seasons, yet there was no evidence that the rate of optimum N was higher in the hybrid rye than in the conventional rye.

Table 4. *Distribution of tiller dry weight (g) in ear, internode and leaf sheath, grain number/tiller, 1000-grain weight (g), dry matter harvest index (%) and tiller height (cm) in Sentinel and Luchs for internode set 5, mean 1993–95*

| | Sentinel | | Luchs | | |
|---|---|---|---|---|---|
| Mean | −PGR | +PGR | −PGR | +PGR | S.E. (D.F. 18) |
| Ear (g) | 1·88 | 1·78 | 2·07 | 2·01 | 0·04 |
| Internode (g) | 1·19 | 1·14 | 1·16 | 1·06 | 0·04 |
| Leaf sheath (g) | 0·48 | 0·45 | 0·46 | 0·46 | 0·01 |
| Tiller weight (g) | 3·11 | 2·85 | 3·27 | 3·06 | 0·06 |
| Grain number/tiller | 54·6 | 51·9 | 61·9 | 60·1 | 1·0 |
| TGW (g) 100% DM | 29·3 | 29·1 | 29·2 | 28·7 | 0·4 |
| Dry matter harvest index (%) | 46·3 | 47·0 | 51·6 | 47·9 | 1·4 |
| Tiller height (cm) | 126·3 | 112·8 | 124·2 | 110·0 | 0·7 |

Table 5. *Effect of PGR, nitrogen and cultivar on grain yield (t/ha) in 1993–95*

| Year… | | 1993 | | | 1994 | | | 1995 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Growth regulator | Nitrogen rate (kg/ha) | Sentinel | Luchs | Mean | Sentinel | Luchs | Mean | Sentinel | Luchs | Mean |
| −PGR | N0 | 2·48 | 2·98 | 2·73 | 3·31 | 3·52 | 3·42 | 2·60 | 3·12 | 2·87 |
| | N50 | 4·40 | 5·35 | 4·88 | 4·98 | 5·84 | 5·41 | 4·55 | 5·14 | 4·85 |
| | N100 | 5·83 | 6·98 | 6·41 | 6·58 | 8·14 | 7·36 | 5·96 | 6·96 | 6·46 |
| | N150 | 6·65 | 7·89 | 7·27 | 7·44 | 8·94 | 8·19 | 6·71 | 7·49 | 7·10 |
| | N200 | 6·40 | 8·10 | 7·25 | 7·77 | 8·93 | 8·35 | 6·97 | 8·00 | 7·49 |
| | N250 | 6·97 | 7·83 | 7·40 | 7·80 | 8·99 | 8·40 | 7·11 | 7·89 | 7·50 |
| | Mean | 5·45 | 6·52 | 5·99 | 6·31 | 7·39 | 6·85 | 5·65 | 6·43 | 6·04 |
| +PGR | N0 | 2·61 | 2·85 | 2·73 | 3·56 | 3·36 | 3·46 | 2·61 | 3·18 | 2·89 |
| | N50 | 4·51 | 5·08 | 4·80 | 5·25 | 5·87 | 5·56 | 4·19 | 5·22 | 4·71 |
| | N100 | 5·83 | 6·97 | 6·40 | 6·98 | 7·71 | 7·34 | 6·00 | 6·46 | 6·23 |
| | N150 | 6·70 | 7·74 | 7·22 | 7·75 | 9·23 | 8·49 | 6·74 | 7·44 | 7·09 |
| | N200 | 6·58 | 7·45 | 7·01 | 8·14 | 9·74 | 8·94 | 6·80 | 7·29 | 7·04 |
| | N250 | 6·48 | 7·50 | 6·99 | 7·59 | 9·51 | 8·55 | 6·94 | 7·32 | 7·13 |
| | Mean | 5·45 | 6·23 | 5·84 | 6·54 | 7·57 | 7·02 | 5·55 | 6·15 | 5·85 |
| (D.F. 46) | | | | | | | | | | |
| S.E. Cultivar Mean | | | | 0·043 | | | 0·057 | | | 0·024 |
| S.E. PGR Mean | | | | 0·043 | | | 0·057 | | | 0·024 |
| S.E. N Mean | | | | 0·075 | | | 0·098 | | | 0·041 |
| S.E. PGR × N | | | | 0·106 | | | 0·140 | | | 0·058 |
| S.E. Cultivar × PGR | | | | 0·061 | | | 0·081 | | | 0·034 |
| S.E. Cultivar × N | | | | 0·106 | | | 0·140 | | | 0·058 |
| S.E. Cultivar × PGR × N | | | | 0·151 | | | 0·198 | | | 0·082 |
| C.V. % | | | | 4·4 | | | 4·9 | | | 2·4 |

## DISCUSSION

### *Number of internodes/tiller*

In this experiment, tillers with five internodes occurred most frequently in all seasons, unlike in barley, where White (1991) found that plants with six internodes occurred most frequently, despite its shorter length compared to rye. The data from the five internode set can, therefore, be taken as representative of the crop's tiller population, which based on measurements in 1993 on the effect of growth regulator, suggested that tillers with four and six internodes were similarly affected. Most tillers with only four internodes appeared to be weaker, and later developing, with correspondingly low yield potential. In contrast, tillers with six internodes were taller and higher yielding than those with five internodes. The greater frequency of tillers with six internodes in Luchs may explain, in part, its higher yields.

### *Effect of PGR on tiller internodes*

Growth regulator treatment had a consistent effect in reducing internode lengths in both the hybrid and

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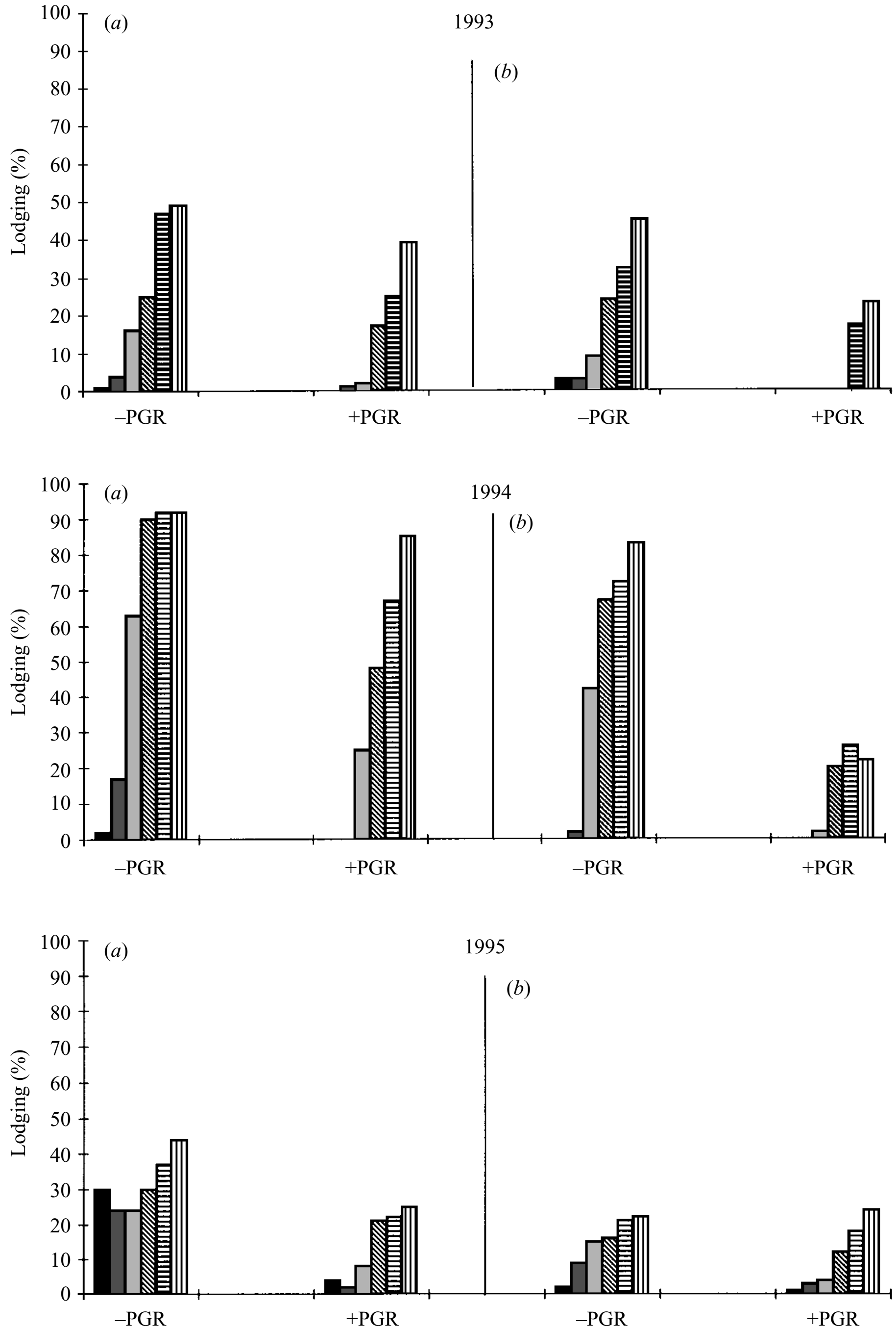


Fig. 5. The effect of PGR regime and nitrogen treatments, N0 (■), N50 (■), N100 (□), N150 (▧), N200 (▤), N250 (▥) on percentage lodging in winter rye cultivars (*a*) Sentinel and (*b*) Luchs, 1993–95.

conventional cultivars. Averaged over the three seasons, tiller length was reduced by 13% in Luchs and 11% in Sentinel, clearly indicating that the hybrid cultivar was as responsive to growth regulator treatment as the conventional cultivar. Seasonal effects related to the timing of growth regulator

https://doi.org/10.1017/S0021859696004029 Published online by Cambridge University Press

Table 6. *Effect of cultivar, PGR and nitrogen on grain specific weight (kg/hl), grain nitrogen (%) and Hagberg falling number (HFN) (seconds) in Sentinel and Luchs, mean 1993–95*

| | Year | Sentinel | Luchs | S.E. (D.F. 46) | −PGR | +PGR | S.E. (D.F. 46) | N zero | N 250 | S.E. (D.F. 46) |
|---|---|---|---|---|---|---|---|---|---|---|
| Grain specific weight (kg/hl) | 1993 | 74·2 | 73·9 | 0·10 | 74·3 | 73·7 | 0·10 | 73·9 | 73·7 | 0·18 |
| | 1994 | 76·8 | 76·7 | 0·12 | 76·6 | 76·9 | 0·12 | 76·6 | 77·3 | 0·21 |
| | 1995 | 82·8 | 80·9 | 0·08 | 82·2 | 81·5 | 0·08 | 82·1 | 81·5 | 0·14 |
| Grain N (%) | 1993 | 1·46 | 1·44 | 0·007 | 1·46 | 1·45 | 0·07 | 1·35 | 1·75 | 0·01 |
| | 1994 | 1·59 | 1·57 | 0·02 | 1·58 | 1·58 | 0·02 | 1·40 | 1·93 | 0·03 |
| | 1995 | 1·21 | 1·25 | 0·01 | 1·23 | 1·23 | 0·01 | 1·11 | 1·49 | 0·02 |
| HFN | 1993 | 181 | 204 | 2·55 | 190 | 195 | 2·55 | 197 | 188 | 4·42 |
| | 1994 | 233 | 249 | 2·32 | 243 | 239 | 2·32 | 248 | 228 | 4·01 |
| | 1995 | 252 | 273 | 2·97 | 265 | 261 | 2·97 | 272 | 263 | 4·19 |

Table 7. *Economic N optima and yield (t/ha) at N optima in Sentinel and Luchs, 1993–95*

| Year | Cultivar | Treatment | N optima | Yield at N optima |
|---|---|---|---|---|
| 1993 | Sentinel | −PGR | 211 | 6·78 |
| | | +PGR | 177 | 6·71 |
| | Luchs | −PGR | 184 | 8·11 |
| | | +PGR | 175 | 7·72 |
| 1994 | Sentinel | −PGR | 260 | 7·96 |
| | | +PGR | 194 | 7·82 |
| | Luchs | −PGR | 188 | 9·15 |
| | | +PGR | 273 | 9·87 |
| 1995 | Sentinel | −PGR | 206 | 7·06 |
| | | +PGR | 195 | 6·99 |
| | Luchs | −PGR | 196 | 7·97 |
| | | +PGR | 182 | 7·43 |

treatment had a greater effect on the reduction in tiller length than did choice of cultivar. The smallest reduction in stem length of 6% in Sentinel and 8% in Luchs occurred in the 1994 season when treatments were applied earlier at crop GS37. Whilst the GS37 treatment was effective in reducing internode lengths, this reduction was associated with the lower, shorter internodes of the stem. In 1994, there was also a compensatory effect of internodes lengthening in the penultimate internode nearest to the ear, an effect that was also observed by Boothroyd & Clare (1984) in wheat. Nevertheless, despite the relatively smaller effect on final tiller length, growth regulator treatment in 1994 reduced lodging and gave a yield benefit in both cultivars, unlike in 1993 and 1995. Reductions in internode length were closely correlated with reductions in internode weight, suggesting that growth regulator treatment may not have increased tiller strength. The failure of growth regulator treatment to increase dry weight/unit length suggests that the main benefits from treatment leading to reduced lodging were directly associated with the physical effects of tiller shortening, as suggested by Neenan & Spencer-Smith (1975) in wheat and barley. The failure of growth regulator treatment not only to shorten, but also to increase dry weight/unit length may have other implications in rye. In rye, between heading and anthesis, large amounts of assimilates are found in the stem, which at later stages are withdrawn into the grain (Bushuk 1976). This effect has been linked to the ability of rye to tolerate stress, such as drought, in late season and, therefore, any treatment which reduces the overall level of assimilates within the stem may also reduce tolerance to stress.

### *Effect of growth regulator and nitrogen on crop performance*

In this series of experiments, yield responses to growth regulator treatment were small compared to those of growing a hybrid, rather than a conventional cultivar of rye. Whilst all rye crops lodged, yield penalties from lodging were relatively small, possibly due to the favourable weather conditions, particularly the low rainfall during July and August, in all seasons. However, in 1994, when lodging occurred earlier and when most lodging was observed, significant yield responses were obtained in both cultivars. In 1993 and 1995, there was less crop lodging, but some occurred and was reduced by growth regulator treatment. The lack of a yield response in Sentinel and the small yield reduction in the hybrid cultivar Luchs is surprising and in contrast to wheat and barley, where reduced lodging is invariably associated with yield increases (Thomas 1985). This result may suggest that the penalty from reduced stem reserves following growth regulator treatment was outweighed by any benefits from reduced lodging in seasons of low lodging pressure. Additionally in the 1995 season, there was only 89 mm of rainfall in the 5 months preceding harvest, leading to drought conditions. Application of growth regulator to rye can result in yield loss and this has often been associated with chemical treatment whilst the crop was under physiological stress. Mills (1993) reported on yield losses following growth regulator treatment, in the absence of lodging, in several cultivars of conventional rye. There were differences between the four conventional cultivars compared in their tolerance to growth regulator treatment, with yield reductions in two of the cultivars, including Sentinel. Hybrid rye was not included in the study by Mills (1993), but there may be differences in the tolerance not only between cultivars, but between hybrid and conventional rye. It is possible that Sentinel, with its higher dry weight/unit length, and possibly greater stem reserves than Luchs, had greater tolerance of stress conditions.

Whilst growth regulator treatment had a consistent effect in reducing lodging, it did not eliminate it in either cultivar. In 1994, with growth regulator treatment, there was 20% lodging in Sentinel at 100 kg/ha N and in Luchs, at 150 kg/ha N, demonstrating the susceptibility of rye to lodging even when grown in infertile conditions at low rates of N.

Both cultivars were highly responsive to increasing rate of nitrogen, partly reflecting the low inherent fertility of the experimental sites used in this study. Over three seasons, the differences in the economic N optima when growth regulator was applied were small and N optima were marginally less in Luchs than in Sentinel, despite its higher yield. However, the overall optimum N rate of 200 kg/ha was greater than currently recommended (Anon. 1994*b*). The current recommendation of 125 kg/ha is low, but this recommendation also reflects the risk of substantial yield loss and quality from lodging at higher N rates, which could occur in seasons of adverse weather conditions.

This experiment clearly demonstrated that rye responds to high rates of N and that hybrid rye offers growers an opportunity to significantly increase yields. However, control of crop lodging with growth regulators remains a priority for all rye growers. If growers are to benefit from these higher yields, strategies involving both growth regulators and N, which lead to reduced lodging and increased yield, or yield reliability from season to season, without adversely affecting crop production or the rye crops' tolerance of stress, are required.

Financial support from the (UK) Ministry of Agriculture, Fisheries and Food (MAFF) is gratefully acknowledged. Thanks are also due to F. Seeney for advice on experimental design and statistical analysis and to the staff at ADAS Bridgets.

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