Research Article • DOI: 10.2478/ijafr-2019-0005 IJAFR • 58 • 2019 • 34-43

Irish Journal of Agricultural and Food Research

Effect of nitrogen fertiliser application timing on grain yield and grain protein concentration of spring barley

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Abstract

There is relatively little recent information regarding the effect of timing of fertiliser N application to spring barley on grain yield and grain protein concentration (GPC) under Irish conditions. The objectives of this work were to examine the effects of a) timing of the first N application to spring barley (at sowing or at crop emergence), b) altering the proportion of the total N allocation that is applied in the first of two applications and c) delaying a portion of the total N dose until after the tillering phase on grain yield and GPC of spring barley. Twenty experiments were carried out over four seasons (2011–2014) in the south and south-east of Ireland. Results indicated that there was little consistent difference, in terms of grain yield or GPC between applying the first N at sowing compared to where the initial N application was made at crop emergence. Similarly, altering the proportion of N applied in the first application, irrespective of whether the first application was at sowing or at crop emergence, had little effect on either yield or GPC. Delaying the application of a portion (0.2) of the total N until after the tillering stage also had little consistent effect on either yield or GPC. It is concluded that where the majority of N is applied to spring barley before the end of the tillering stage, altering the timing of applications or the proportion of the total applied in each application will have limited effect on grain yield or GPC.

Keywords

Grain protein • nitrogen • spring barley • timing • yield

Introduction

Spring barley is the main cereal crop in Ireland accounting for 41% of the area sown with cereals in 2016 (CSO, 2016). The barley produced is used mainly for animal feed but an increasing proportion is used for the production of malt. Fertiliser N is a key input in the production of barley, which affects both grain yield and grain quality. The effects of fertiliser N rate on both grain yield and the grain quality of spring barley have received considerable attention under Irish conditions (Conry, 1994; 1995a; 1997), but the effects of altering the timing, size and number of applications have received less attention.

Grain protein concentration (GPC) is a key quality criterion in malting barley production, and failure to meet the required GPC specifications leads to rejection of the crop for malting. Managing GPC is therefore a key requirement in the successful production of malting barley. GPC is a function of grain yield and grain N accumulation, both of which are strongly influenced by fertiliser N application. Although the total amount of fertiliser N applied often has the largest effect on both yield and GPC, the number of applications used to apply the N and the timing of those applications can have significant effects also (Needham, 1983; Easson, 1984; Conry, 1994; McTaggart and Smith, 1995).

Typically, in Ireland, N is applied to spring barley two or three times, with the first applied to the seedbed and the remainder during the tillering stage (Wall and Plunkett, 2016). However, the N requirement of the emerging seedling is small and will be satisfied to a significant extent by N derived from the seed and soil (Andrews *et al.*, 1991). Therefore, it may not be necessary to apply N to the seedbed and instead apply the first N at crop emergence. This could be particularly important for very early sown crops under Irish conditions (e.g., February sown) where growth, and hence N uptake, will be slow and rainfall can be high exposing N applied at sowing to leaching risk. However, there is relatively little work comparing the application of the first N at sowing with its application at crop emergence.

Effects of altering the number of applications used to apply the total dose of fertiliser N have received a greater level of attention. It has been reported that there is no effect on grain yield or GPC by using split applications compared to applying all the N in one application at sowing, particularly when the topdressing was applied before the crop entered the stem elongation phase (Easson, 1984). However, in situations where high rainfall occurs soon after sowing, and before significant crop uptake, applying all the N to the seedbed can increase the risk of N loss by leaching, and in these situations, split applications can

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be advantageous (Widdowson *et al*., 1961; Easson, 1984). Where application of majority of the N dose is delayed until the crop has entered the stem elongation phase, the yield can be reduced and GPC increased (Easson, 1984). Although two applications, where the final application is completed before the stem elongation phase of growth, are normally used for spring barley in Ireland, the use of a third application later in the growing season is sometimes practised. The effects of these later applications on yield or GPC have received little attention under Irish conditions.

In addition to altering the number of applications, the proportion of N applied in each application can also be altered. Conry (1995b) compared the application of different proportions of the same total amount of fertiliser N at sowing with the remainder applied at the tillering stage and found little consistent effect on either grain yield or GPC, although GPC tended to be lower when all the N was applied at sowing for early sowing dates.

There has been relatively little recent work examining the effect of different fertiliser N strategies on grain yield and GPC of spring barley under Irish conditions. The objectives of this work were to determine the effects on grain yield and GPC of a) applying the first N at crop emergence rather than to the seedbed, b) altering the proportion of the total N amount applied in the first of the two applications and c) applying a portion of the total N in a third application after the tillering stage.

Materials and methods

A total of 20 field experiments were established at a range of sites over four seasons (2011–2014). Details of the locations of the experiments are given in Table 1. Rainfall data were obtained from the nearest recording station, which was generally within 5 km of the respective sites. Data from the Oak Park site were used for the Athy and Leighlinbridge sites in 2011. All data were obtained from the Irish Meteorological Service, Met Éireann.

The experiments were designed to determine the effect of different fertiliser N regimes (rate, times of application, number of applications and proportion of the total dose applied in each application) on grain yield and GPC of spring barley and comprised a range of treatments, the number and composition of which varied between experiments, depending on the objectives of the individual experiments. The results presented here relate to two subsets of the treatments from the experiments that examined a) the effect of timing and size of the initial application of N and b) the effect of applying a portion of the total N allocation as a third application compared to applying the total N dose in two applications. A total of 150 kg N/ha was applied to all the treatments in this subset as calcium ammonium nitrate.

The effect of timing and size of the initial application of N was evaluated using a factorial arrangement of timing of the first N application (at sowing or at emergence) and proportion of total applied in the first application (0.2–30 kg N/ha, 0.4–60 kg N/ha and 0.6–90 kg N/ha). These treatments were included in each of the experiments in the first three seasons. In the fourth season, the treatments at crop emergence were not included, therefore only the effect of proportion of the total N applied in the first application was examined in the fourth season. Where N was applied at sowing, either 30 or 60 kg N/ha was combine drilled with the seed using a Fiona combined fertiliser and seed drill (Fiona Maskinfabrik A/S, Bogense, Denmark). For the 90 kg N/ha treatment, 60 kg N/ha was combine drilled with the seed and the remaining 30 kg N/ha was surface applied by hand immediately after sowing. This was done to avoid possible adverse effects of high amounts of fertiliser N combine drilled with the seed on crop emergence. Treatments applied at crop emergence were applied at GS11/12. In all the experiments, the total allocation of N was applied in two applications. The second application was made to all treatments in an experiment on the same day, when the crop was at the tillering stage (GS22-25). Treatments after crop emergence were applied using a carefully calibrated drop spreader (Fiona Maskinfabrik A/S), when the crop was at the respective growth stage.

The effect of retaining a portion of the total N allocation for use as a third application compared to applying the total N dose in two applications was examined by retaining 30 kg N/ha for application at GS31, GS32 GS37 or GS61. For these treatments, 30 kg N/ha, from a total allocation of 150 kg N/ha, was combine drilled with the seed at sowing and the remaining 120 kg N/ha was either applied in full at the tillering stage (GS22-25) or alternatively 90 kg N/ha was applied at the tillering stage and the remaining 30 kg N/ha was applied at GS31, GS32, GS37 or GS61. The GS32 treatment was not included at sites 1, 2, 7, 8, 12 and 13, and the GS61 treatment was not included at sites 1 and 2.

A randomised complete block (RCB) design or alpha design with four or five replicates was used, depending on location (Table 1). Plot width was 2.3 m in all cases; plot length ranged from 12 m to 15 m. Phosphorus and potassium fertilisers were broadcast to all experiments to match or exceed the recommended amounts (Wall and Plunkett, 2016). An application of at least 15 kg S/ha was applied to all the experiments as kieserite. All other inputs were applied according to standard farm practice.

Grain yield (adjusted to 85% DM) was determined using a small plot combine harvester with onboard weighing equipment. GPC, moisture content and specific weights were determined using a whole grain analyser (Infratec 1241 grain analyser – Foss, Hillerod, Denmark) on sub-samples of approximately 2 kg obtained from each plot during combine harvest. GPC was expressed at 100% DM. Grain N accumulation (on a per hectare basis) was calculated as the product of grain yield and grain N concentration. Grain N concentration was calculated by dividing GPC by 6.25.

Data from each site were analysed with the Proc Mixed procedure of SAS (SAS 9.4, SAS Institute Inc. Cary, NC, USA). Treatments were included as fixed effects and replicates, and incomplete blocks in the case of alpha designs were included as random effects. Data from all treatments including those not reported in this paper were used to estimate the experimental error and the factorial structure of the treatments examining the timing of the first N application and proportion of the total N allocation applied in the first application was taken into account using methods outlined by Piepho *et al*. (2006). Treatment mean values were separated using Fisher's protected least significant difference with a = 0.05. Due to the use of two experimental design types and the absence of some treatments in some experiments, a combined analysis over sites and seasons was not carried out.

Results

Rainfall at the locations where the experiments were conducted varied between seasons (the Oak Park data were taken as being representative of both the Leighlinbridge and Athy sites in 2011). Cumulative rainfall for January and February was above the 30-year mean at Oak Park, the only site for which 30-year mean data were available, in three of the four seasons and were particularly high at all sites in 2014. The pattern of rainfall within a growing season was similar across sites. March had lower rainfall in 2011 and 2012 compared to the following two seasons. April rainfall was lower in the first season at Oak Park and Castledockrell than in the following three seasons, which had similar rainfall levels. Rainfall in May was similar between seasons. June rainfall in 2012 was higher than the other three seasons at Oak Park and Castledockrell and higher than in 2013 and 2014 at the Ardfinnan site. June rainfall at the Ardfinnan site in 2011 was higher than at the other sites.

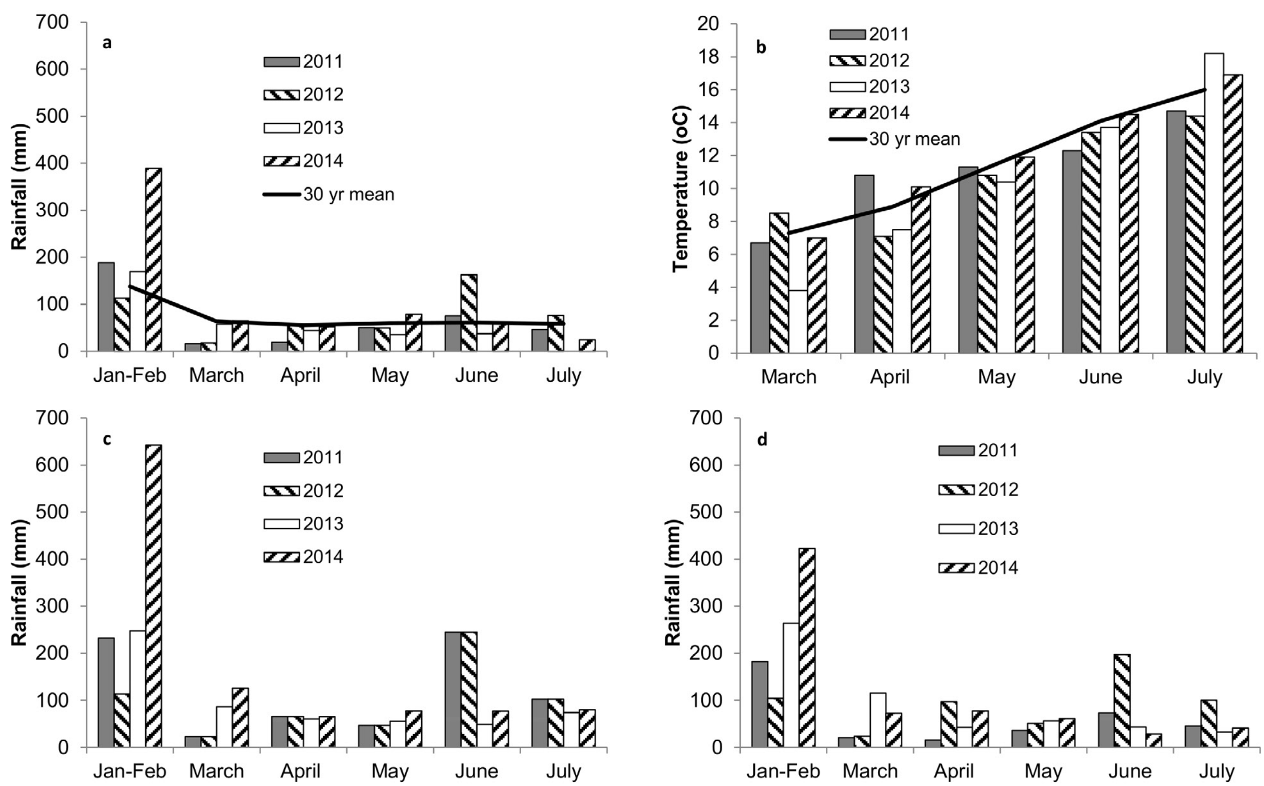

Figure 1. Rainfall before and during the growing season at (a) Oak Park, (c) Ardfinnan and (d) Castledockerell in 2011 to 2014. Mean monthly air temperature is given for Oak Park (b). 30 year mean rainfall and air temperature data (1981-2010) is given for Oak Park.

A wide range of both grain yield and GPC values were recorded. Yield ranged from a low of 5.3 t/ha at site 16 to a high of 8.5 t/ha at site 17. GPC ranged from 13.7 g/100 g at site 8 to 7.5 g/100 g at site 9.

An interaction between timing of the first N application and the proportion of the total N applied in the first application on grain yield was not detected at any of the 17 sites where the interaction was examined (Table 2). Grain yield differences between applying the first N at emergence rather than at sowing were generally not significant; no significant difference was detected in 13 of the 17 experiments (Table 2). In three of the four experiments where a significant difference was detected, application of the first N at sowing gave a significantly higher yield compared to when the first N was applied at emergence; the yield benefit ranged between 0.18 and 0.24 t/ha. In one experiment (site 13), the yield was significantly lower by 0.25 t/ha, where the first N was applied at sowing compared to when the first N was applied at emergence.

Effects of timing of the first N on GPC were variable (Table 3). In nine of the 17 experiments, there was no effect of timing of the first N application on GPC. In four of the eight experiments where there was a significant effect, application at sowing gave a significantly higher GPC than application at emergence with the increase in GPC ranging from 0.17 to 0.50 g/100 g. In the remaining four experiments, this effect was reversed; application at sowing gave a significantly lower GPC with the decrease in GPC ranging from 0.14 to 0.37 g/100 g.

The effect of varying the proportion of the total applied in the first application between 0.2 and 0.6 of the total was not significant in the majority of the 20 experiments where the comparison was made for both grain yield and GPC (Tables 2 and 3). A significant effect on yield of altering the amount applied in the first application was detected at only four of the 17 sites; for GPC, a significant effect was detected at only five of the sites. Where significant differences were detected, there was no consistent ranking of the three proportions used. For yield, the treatment receiving 0.2 of the total N in the first application had significantly lower yield than both the 0.4 and 0.6 treatment in two of the experiments but had significantly higher yield than both 0.4 and 0.6 at a third site. In the fourth site where a significant difference was detected, the 0.4 treatment had a significantly higher yield than both the 0.2 and 0.6 treatments. Similarly, for GPC, at the sites where significant effects of altering the proportion were detected, there was no consistent ranking of the treatments; at one site, the 0.6 treatment had significantly higher GPC than both the

Table 1. Details of sites and experimental designs used for experiments.

Site no.	Location	Prior crop[1]	No. trts	Reps	Design	Year	Sow date	Cultivar	Soil[2]
1	Ardfinnan, Tipperary	SB	15	4	RCB	2011	7/3	Snakebite	Loam
2	Ardfinnan, Tipperary	BE	15	4	RCB	2011	7/3	Snakebite	Loam
3	Athy, Kildare	SB	25	5	alpha	2011	8/3	Sebastian	Clay loam
4	Leighlinbridge, Carlow[3]	SB	25	5	alpha	2011	2/3	Sebastian	Sandy loam
5	Oak Park, Carlow	SB	26	5	alpha	2011	9/3	Snakebite	Clay loam
6	Castledockrell, Wexford	SB	25	5	alpha	2011	4/3	Sebastian	Loam
7	Ardfinnan, Tipperary	SB	18	4	RCB	2012	10/3	Snakebite	Loam
8	Ardfinnan, Tipperary	BE	18	4	RCB	2012	10/3	Snakebite	Loam
9	Knockbeg, Laois	SB	24	5	alpha	2012	1/3	Taberna	Clay loam
10	Oak Park, Carlow	WB	24	4	alpha	2012	21/2	Taberna	Sandy loam
11	Castledockrell, Wexford	SB	25	4	alpha	2012	12/3	Sebastian	Loam
12	Ardfinnan, Tipperary	SB	20	4	RCB	2013	3/4	Snakebite	Loam
13	Ardfinnan, Tipperary	BE	18	4	RCB	2013	3/4	Snakebite	Loam
14	Knockbeg, Laois	WW	24	4	alpha	2013	28/3	Taberna	Clay loam
15	Oak Park, Carlow	WW	26	5	alpha	2013	2/4	Taberna	Clay loam
16	Oak Park, Carlow	WB	24	5	alpha	2013	4/3	Taberna	Sandy loam
17	Castledockrell, Wexford	SB	24	4	alpha	2013	4/4	Propino	Loam
18	Ardfinnan, Tipperary	SB	18	4	alpha	2014	16/4	Taberna	Loam
19	Knockbeg, Laois	WB	18	4	alpha	2014	19/3	Taberna	Clay loam
20	Oak Park, Carlow	WB	16	4	alpha	2014	10/4	Taberna	Sandy loam

[1]SB = spring barley BE = beet FR=forage rape WB = winter barley WW = winter wheat.
[2]Soil texture as defined by Shirazi and Boersma (1984).
[3]A short term crop of forage rape was grown after harvest of previous spring barley.

Table 2. Effect of timing of first N and proportion of total N applied in the first application on spring barley grain yield (t/ha @ 85% DM)

	Timing (T)			Proportion (P)				TxP
Site	Sig.[1]	Sowing	Emerge	Sig.[1]	0.2	0.4	0.6	Sig.[1]
1	**	7.87 a	7.63 b	ns	7.69	7.84	7.72	ns
2	*	7.96 a	7.78 b	ns	7.87	7.99	7.75	ns
3	ns	6.35	6.39	***	6.62 a	6.30 b	6.21 b	ns
4	ns	7.41	7.20	*	7.56 a	7.18 b	7.19 b	ns
5	ns	7.87	7.75	ns	7.81	7.78	7.85	ns
6	ns	7.22	7.34	ns	7.27	7.43	7.14	ns
7	ns	6.13	6.20	ns	6.20	6.18	6.11	ns
8	ns	5.84	5.73	ns	5.92	5.70	5.74	ns
9	ns	7.91	7.80	ns	7.81	7.87	7.89	ns
10	*	7.74 a	7.54 b	***	7.43 b	7.92 a	7.57 b	ns
11	ns	6.67	6.69	ns	6.68	6.72	6.63	ns
12	ns	7.17	7.24	*	7.02 b	7.31 a	7.30 a	ns
13	**	7.41 b	7.66 a	ns	7.59	7.55	7.46	ns
14	ns	6.35	6.32	ns	6.31	6.22	6.52	ns
15	ns	6.93	7.01	ns	7.01	6.91	7.00	ns
16	ns	5.41	5.55	ns	5.58	5.53	5.31	ns
17	ns	8.33	8.50	ns	8.38	8.47	8.41	ns
18	-	-	-	ns	7.81	7.91	7.52	-
19	-	-	-	ns	7.44	7.32	7.34	-
20	-	-	-	ns	6.81	6.66	-	-

[1]Sig. indicates the significance of the effect in the analysis of variance. Values for a factor within a row followed by the same letter are not significantly different according to Fisher's PLSD test (P = 0.05).

Table 3. Effect of timing of first N and proportion of total N applied in the first application on spring barley GPC (g/100g @ 100% dry matter)

	Timing (T)			Proportion (P)				TxP
Site	Sig.[1]	Sowing	Emerge	Sig.[1]	0.2	0.4	0.6	Sig.[1]
1	ns	7.52	7.53	ns	7.61	7.49	7.48	ns
2	*	7.74 a	7.57 b	ns	7.65	7.68	7.63	ns
3	***	9.27 a	8.81 b	ns	9.03	9.05	9.05	ns
4	***	9.38 a	8.88 b	ns	9.00	9.25	9.15	ns
5	ns	10.00	10.10	ns	10.05	10.12	9.97	ns
6	ns	8.72	8.54	ns	8.50	8.62	8.77	ns
7	*	9.89 b	10.23 a	ns	10.04	9.96	10.17	ns
8	ns	10.59	10.86	ns	10.65	10.63	10.89	ns
9	ns	9.62	9.76	ns	9.61	9.76	9.69	ns
10	ns	9.54	9.53	ns	9.39	9.69	9.53	ns
11	ns	12.01	11.81	**	12.20 a	11.70 b	11.83 b	ns
12	***	10.13 b	10.50 a	*	10.44 a	10.37 a	10.13 b	ns
13	*	9.92 b	10.06 a	ns	10.08	9.95	9.95	ns
14	ns	12.80	12.95	ns	12.59	12.91	13.12	ns
15	*	9.80 b	10.10 a	ns	9.96	9.99	9.90	ns
16	ns	13.44	13.40	ns	13.30	13.68	13.28	ns
17	***	10.41 a	10.14 b	ns	10.27	10.38	10.17	**
18	-	-	-	***	8.63 a	8.27 b	8.07 b	-
19	-	-	-	*	8.21 ab	7.98 b	8.36 a	-
20	-	-	-	**	8.96 b	9.73 a	-	-

[1]Sig. indicates the significance of the effect in the analysis of variance. Values for a factor within a row followed by the same letter are not significantly different according to Fisher's PLSD test (P = 0.05).

0.2 and 0.4 treatments; at two sites, the 0.2 treatment was significantly higher than both the 0.4 and 0.6 treatments.

Timing of the first application of N had a significant effect on grain N accumulation in eight of the 17 experiments where the comparison was made (Table 4). At four of these sites, applying the first N at sowing gave significantly higher grain N accumulation compared to where the first N was applied at crop emergence, the opposite was the case at the other four sites. Altering the proportion of N applied in the first application had significant effect on grain N accumulation at four sites. In the experiments, where a significant difference was detected, the highest grain N accumulation was achieved where either 0.2 or 0.4 of the total was applied in the first application; grain N accumulation tended to be lower where 0.6 of the total was applied in the first application.

In 17 of the 20 experiments, there was no significant effect on grain yield of applying 0.2 (30 kg N/ha) of the total nitrogen allocation as a third application at growth stages between GS31 and GS61 compared to having all the nitrogen applied before the end of tillering on grain yield (Table 5). In two of the experiments, which were located at the same site in the same season but with different prior crops, applying a third application of N at GS31 caused a significant increase in the yield, of between 0.33 and 0.46 t/ha, compared to where all the N was applied by the end of tillering. In one of these experiments (site 13), delaying 0.2 of the total dose of N until GS61 gave a significant reduction in yield compared to all other treatments. In other experiments (site 12) where a significant effect was detected, delaying N until GS61 gave a significant reduction in grain yield of 0.37 t/ha compared to where a third application of N was applied at either GS31 or GS37 but not when compared to where all N was applied by the end of tillering.

Effects of retaining 0.2 of the total N allocation for application later in the season on GPC were more common with a significant effect detected in 12 of the 20 experiments (Table 5). Although, in general, GPC tended to increase as N was delayed until progressively later in the season, the increases with each successive delay in N application were often small and not statistically significant. Delaying a portion of the N until GS31 or GS32 had no significant effect in the majority of experiments; a significant effect of delaying N until GS31 was detected in two experiments (sites 6 and 17) and a significant effect of delaying N until GS32 was detected in three experiments (sites 17, 19 and 20). In all instances where a significant effect was detected, delaying N until GS31 or

Table 4. Effect of timing of first N and proportion of total N applied in the first application on spring barley grain N accumulation (kg N/ha)

	Timing (T)			Proportion (P)				TxP
Site	Sig.[1]	Sowing	Emerge	Sig.[1]	0.2	0.4	0.6	Sig.[1]
1	*	80.5 a	78.1 b	ns	79.6	79.8	78.4	ns
2	**	83.8 a	80.1 b	ns	81.9	83.4	80.4	ns
3	**	80.0 a	76.6 b	**	81.1 a	77.5 b	76.4 b	ns
4	***	94.2 a	86.9 b	ns	92.4	90.0	89.2	ns
5	ns	106.8	106.3	ns	106.8	106.8	106.0	ns
6	ns	85.5	85.1	ns	84.2	86.8	84.8	ns
7	*	82.4 b	86.2 a	ns	84.6	83.8	84.6	ns
8	ns	84.2	84.7	ns	85.9	82.4	85.0	ns
9	ns	103.4	103.6	ns	102.0	104.4	104.1	ns
10	*	101.1 a	98.0 b	***	95.3 c	104.0 a	99.5 b	ns
11	ns	109.0	107.3	ns	110.8	106.7	107.0	ns
12	**	98.8 b	103.3 a	ns	99.6	103.0	100.6	*
13	**	100.1 b	104.8 a	ns	104.0	102.3	101.1	ns
14	ns	109.8	110.9	ns	106.6	108.3	116.1	ns
15	ns	92.5	95.7	ns	94.4	93.5	94.3	ns
16	ns	98.6	100.4	*	100.2 ab	103.0 a	95.3 b	ns
17	ns	118.0	117.4	ns	117.0	119.5	116.5	ns
18	-	-	-	*	91.5 a	89.0 ab	82.4 b	ns
19	-	-	-	ns	82.4	79.5	83.2	ns
20	-	-	-	**	82.6 b	91.3 a	-	ns

[1]Sig. indicates the significance of the effect in the analysis of variance. Values for a factor within a row followed by the same letter are not significantly different according to Fisher's PLSD test (P = 0.05).

Table 5. Effect of applying the final N application at different growth stages to spring barley grain yield and GPC

	Grain yield (t/ha @ 85% DM)						Grain protein concentration (g/100g @ 100% DM)					
Site	Sig.[1]	2 split	GS31	GS32	GS37	GS61	Sig.[1]	GS25	GS31	GS32	GS37	GS61
1	ns	7.80	7.90	-	7.91	-	ns	7.69	7.39	-	7.76	-
2	ns	7.91	8.19	-	8.00	-	ns	7.80	7.81	-	7.98	-
3	ns	6.64	6.66	6.52	6.63	6.49	***	9.26b	9.22b	9.40b	9.37b	9.82a
4	ns	7.67	7.38	7.47	7.60	7.43	ns	9.36	9.17	9.34	9.34	9.63
5	ns	7.84	7.76	7.84	7.74	7.74	*	10.14 b	10.18 b	10.37 b	10.32 b	10.82 a
6	ns	7.24	7.64	7.61	7.51	7.28	***	8.46c	8.99 ab	8.40 c	8.68 bc	9.06 a
7	ns	6.12	6.02	-	6.17	5.83	*	9.95 b	10.19 b	-	10.26 b	10.85 a
8	ns	5.94	5.81	-	5.82	5.42	ns	10.53	10.83	-	10.87	11.18
9	ns	7.83	7.88	8.14	7.61	7.83	***	9.53 c	9.67 c	9.80 bc	10.05 ab	10.22 a
10	ns	7.60	7.53	7.73	7.69	7.30	***	9.39 d	9.67 cd	9.72 bd	10.01 bc	10.37 a
11	*	6.52 bc	6.41c	6.67 ac	7.10 a	6.92 ab	ns	12.39	11.84	12.15	11.81	12.04
12	**	7.01 cb	7.47 a	-	7.28 ab	6.85 c	ns	10.30	10.52	-	10.54	10.55
13	***	7.51 b	7.84 a	-	7.54 b	7.14 c	**	10.00 b	10.11 b	-	10.17 b	10.42 a
14	ns	6.40	6.49	6.05	6.82	6.24	ns	12.53	12.54	12.84	12.30	12.54
15	ns	6.95	6.91	7.11	6.90	6.82	ns	9.90	10.07	10.37	10.31	10.33
16	ns	5.59	5.43	5.68	5.39	5.53	**	13.13 b	13.46 b	13.60 b	14.22 a	13.15 b
17	ns	8.32	8.40	8.45	8.66	8.21	*	10.24 c	10.47 ab	10.56 ab	10.64 a	10.42 bc
18	ns	7.81	7.85	8.14	8.00	7.70	***	8.63 b	8.76 b	8.68 b	9.19 a	9.39 a
19	ns	7.44	7.54	7.66	7.41	7.26	***	8.2 1c	8.47 b	8.67b	9.06a	8.96a
20	ns	6.81	6.84	6.82	6.83	7.00	***	8.96 b	9.27 b	10.19 a	10.21 a	10.13 a

[1]Sig. indicates the significance of the effect in the analysis of variance. Values in a row followed by the same letter are not significantly different according to Fisher's PLSD test (P = 0.05).

Table 6. Effect of applying the final N application at different growth stages to spring barley on grain N accumulation and hectolitre weight

	Grain N accumulation (kg N/ha)						Hectolitre weight (kg/hl)					
Site	Sig.[1]	2 split	GS31	GS32	GS37	GS61	Sig.[1]	GS25	GS31	GS32	GS37	GS61
1	ns	81.5	79.5	-	83.4	-	ns	66.5	66.0	-	66.6	-
2	ns	83.8	87.1	-	86.9	-	ns	66.7	66.5	-	66.6	-
3	ns	83.5	83.5	83.1	84.4	86.4	ns	70.9	70.7	70.9	70.8	71.6
4	ns	97.2	91.6	94.4	96.8	97.0	ns	70.0	69.5	69.8	69.7	70.3
5	ns	108.2	108.0	110.3	108.6	114.0	ns	72.2	72.1	71.7	72.2	72.5
6	ns	83.7c	93.0a	87.5bc	88.1ac	89.5ab	ns	68.6	68.7	68.9	69.1	68.9
7	ns	82.8	83.3	-	86.1	85.9	ns	60.1	61.5	-	60.8	61.8
8	ns	85.2	85.3	-	86.2	82.5	ns	60.0	60.1	-	59.2	58.6
9	ns	101.4d	103.4ad	108.1ab	104.1bcd	109.1ac	***	66.6 a	66.3 a	66.3 a	64.9 b	67.0 a
10	ns	97.3	99.2	102.2	103.8	103.0	**	66.9 a	67.2 a	66.4 ab	65.6 b	67.3 a
11	*	110.0	103.9	110.2	113.9	112.8	ns	57.9	58.2	57.9	57.8	58.6
12	**	98.3b	106.8a	-	104.3a	98.3b	ns	71.6	71.9	-	71.8	72.2
13	***	102.2	107.8	-	104.4	101.3	ns	71.3	71.5	-	71.4	71.9
14	ns	106.6	109.8	105.4	113.0	107.9	ns	70.8	71.2	70.8	71.2	71.1
15	ns	93.5	95.5	101.0	96.4	95.7	ns	72.2	71.6	72.0	72.1	72.5
16	ns	99.1	98.3	104.7	103.7	99.0	ns	72.5	72.7	72.3	72.5	73.0
17	ns	115.9c	119.6cb	121.2ca	125.3ba	116.4c	**	70.6 b	70.4 b	70.5 b	70.7 b	71.3 a
18	ns	91.5	93.2	96.6	100.3	98.0	ns	69.7	70.3	69.9	70.8	70.7
19	ns	82.4d	86.4cd	90.6bc	91.8ab	89.3ac	**	72.9 bc	72.3 c	72.3 c	73.7 ab	74.0 a
20	ns	82.6b	87.6b	95.0a	94.3a	95.5a	ns	68.9	68.3	68.2	69.2	69.4

[1]Sig. indicates the significance of the effect in the analysis of variance. Values in a row followed by the same letter are not significantly different according to Fisher's PLSD test (P = 0.05).

GS32 gave higher GPC compared to where all N was applied by GS25, with the increase ranging from 0.23 g/100 g to 1.23 g/100 g.

Delaying a portion of the N until GS37 gave a significant increase in GPC in seven experiments where the increase ranged from 0.40 g/100 g to 1.25 g/100 g. In 10 of the 12 experiments where a significant effect of delaying a portion of the nitrogen until after the tillering stage was detected, delaying until GS61 gave a significant increase in GPC compared to where all N was applied by the end of tillering, with the increase ranging from 0.42 g/100 g to 1.17 g/100 g.

Significant effects of delaying a portion of N on grain N accumulation were detected in only six of the 20 experiments (Table 6). In general, in those experiments where a significant effect was detected, delaying a portion of N until after the tillering stage increased grain N accumulation. However, the growth stage at which the third application was made that gave the greatest grain N accumulation varied between experiments. The highest grain N accumulation was detected where the final N was applied at GS31 in two experiments, where the final N was applied at GS37 in another two experiments and where the final N was applied at GS61 in another two experiments. Differences in grain N accumulation due to the growth stage at which a third application was made ranged between 7.7 and 12.9 kg N/ha.

Effects of delaying a portion of N on hectolitre weight were generally small, and statistically significant effects were detected in only four of the 20 experiments (Table 6). In the experiments where significant effects were detected, delaying a portion of the N until GS37 or GS61 tended to result in higher hectolitre weight but the effects were not always statistically significant.

Discussion

The effects of altering both the timing and proportion of the total dose applied in each application on both yield and GPC observed in this study were generally small and inconsistent. A number of authors have demonstrated that altering the timing of N inputs to a crop, where the majority of N is applied before the main period of uptake, has a much smaller effect than altering the total amount of fertiliser N applied (Needham, 1983; Banfield *et al*., 1980). In these experiments, both where the timing and proportion of the total N dose applied in the first N application were altered or where a third application was used, the majority of the N was applied before the beginning of stem extension. N accumulation by spring barley during the early stages of growth is low relative to the total N accumulation (Nielsen *et al*., 1988). The majority of nitrogen accumulation by barley occurs between the start of stem extension and anthesis (Carreck and Christian, 1991; McTaggart and Smith, 1995). This is supported by monitoring of commercial crops of spring barley in Ireland, which has indicated that the amount of N accumulated before the start of stem extension is typically less than 30% of the total N accumulated by the crop at maturity with approximately 50% of the total being accumulated between the beginning of stem extension and the beginning of flowering (Anon, 2015). This suggests that where the majority of the total N dose is applied before the onset of stem extension, how the N dose is apportioned between splits is not likely to have a significant effect on N uptake during the period after stem extension.

Conry (1995b) reported a greater effect on yield of altering the proportion of N applied at sowing when barley was sown in March compared to when it was sown in April, but found that the proportion of N at sowing that gave the highest yield varied between sites. This is in line with the results of the current study where the majority of experiments were sown in March and there was no consistent effect of altering the proportion of N applied at sowing on yield.

The absence of an effect of varying the proportion of total N applied at sowing on GPC in the majority of experiments in the current study contrasts with the results of Conry (1995b) who reported that applying all the N at sowing gave significantly lower GPC in the majority of occasions compared to where a low proportion was applied at sowing, although the effect was more pronounced at earlier sowing dates. The reasons for this are unclear. Lower GPC that occurred when all the N was applied to the seedbed was often associated with lower total accumulation of N in the grain in the experiments of Conry, an effect that was more pronounced for March than for April sowing dates. This could suggest that applying all the N to the seedbed resulted in lower recovery of N by the crop, which may have been due to losses of N as a result of leaching or immobilisation of the N in the soil (Conry, 1995b). In these experiments, increasing the proportion of N applied at the first application generally had no significant effect on grain N accumulation, but treatments where all the N was applied at sowing were not included in this study. The total rate applied in this study (150 kg N/ha) was also higher than that (100 kg N/ha) used by Conry (1995b). Given that grain yields obtained in this earlier study were broadly similar to the yields obtained in this study, the lower application rate may have rendered the crop more likely to experience deficiency if any of the N was lost or became unavailable due to immobilisation in the soil.

In these experiments, the total N dose was applied in at least two applications, in line with standard practice under Irish conditions, where rainfall can be high during the early establishment phase of the crop when N requirement is low. Easson (1984) and McTaggart and Smith (1995) reported that there was little difference between applying all the fertiliser N in one dose at sowing compared to where some of the N was applied in a second application, as a top dressing at mid tillering, except where rainfall was high during the early stages of growth of the crop. Where high rainfall was recorded using split applications generally gave higher yields than single applications.

Delaying a portion of the total N allocation, for a third application, until after the tillering stage, generally had only limited effects on both yield and protein content in these experiments. This is in contrast to Easson (1984) who found that delaying N application until GS31 or later caused a yield reduction. However, where split applications were used in the experiments of Easson (1984), only a small proportion (0.14–0.33) of the total N dose was applied prior to GS31, which may indicate that these crops had received insufficient N during the establishment and tillering phases when compared to the treatments where all N was applied at sowing, which may have compromised yield by reducing tiller production. In the experiments described here, where a portion of the fertiliser N was delayed until after the tillering stage, 0.8 of the total N dose had been applied by the end of the tillering stage with only 0.2 being delayed until GS31 or later. Baethgen *et al*. (1995) indicated that while N application at GS30 was effective at increasing grain yield in spring barley, this was only the case where the crop had access to N during the establishment phase either from N applied at sowing or in situations where soil N was high after a prior grass legume crop.

Some authors have reported that applying N later in the growth cycle of a crop leads to greater recovery of the applied N compared to where the N was applied at earlier growth stages (Limaux *et al*., 1999; Blankenau *et al*., 2002). This might suggest that later applications of N to spring barley could lead to higher GPC, which could impact on the ability to meet the specified GPC levels required for malting barley. While there was often a trend towards greater GPC where a portion of N was delayed until GS37 or GS61, in these experiments, the effects were generally modest and not statistically significant. Bulman and Smith (1993) also reported no effect on GPC where one-third of the total dose of N was applied as the ear emerged compared to where all the N was applied at sowing. De Villiers *et al*. (1998) reported that a number of indicators of malting quality of barley were either unaffected or improved when fertiliser N was applied in five applications between sowing and ear emergence compared to where fewer applications were used and N application was completed earlier in the crop growth cycle.

The fertiliser nitrogen requirement of cereals is dependent on the grain yield obtained (Sylvester-Bradley and Kindred, 2009) and, in Ireland, an estimate of yield potential is taken into account when devising fertiliser N requirements for crops (Wall and Plunkett, 2016). N application to spring barley is often completed by the end of tillering, by which time the crop has only accumulated a small proportion of its final biomass. This means that the final decision regarding the amount of N to be applied to a crop has to be made before the majority of growth occurs, and therefore, little account can be taken of the variation in crop growth due to site or seasonal factors, which will impact the yield that occurs later in the season. Delaying the final decision regarding the total amount of N to apply until the crop has progressed further through its life cycle would allow more account to be taken of actual variation in crop growth, and therefore, potentially allow more precise fertiliser N inputs. The lack of a significant reduction in yield where a portion of the nitrogen was retained until later in the season in the majority of the current experiments suggests that there is potential to delay the decision regarding the total amount of N to apply when account can be taken of actual crop growth.

Conclusions

The results of this work indicate that where the majority of N is applied before the end of tillering stage of crop development, the grain yield and GPC of spring barley are relatively insensitive to the timing of fertiliser N inputs. There is little consistent difference between applying the first N at sowing compared to applying the first N at emergence on either grain yield or GPC. Similarly, altering the proportion of the total N dose that is applied at the first application, where the remaining N is applied before stem extension, has no consistent effect on either grain yield or GPC. The work also indicates that there is potential to delay a portion of N for spring barley until the stem elongation phase without compromising grain yield or grain quality as indicated by GPC.

Acknowledgements

The assistance of Ivan Mitchell in field and laboratory tasks associated with this study is gratefully acknowledged.

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