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Early sowing increases nitrogen uptake and yields of winter wheat grown with cattle slurry or mineral fertilizers

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Abstract

The current study evaluated the effect of sowing date (early, mid-August or timely, mid-September) on two winter wheat (*Triticum aestivum* L.) cultivars (Hereford, Mariboss) with different rates of nitrogen (N) (0–225 kg total N/ha) applied as animal manure (AM; cattle slurry) or mineral fertilizers (N: phosphorus: potassium; NPK). Overwinter plant N uptake and soil mineral N content were determined during 2014/15, while harvest yields (grain, straw, N content) were determined during 2014/15 and 2015/16. Overwinter uptake of N was 14 kg N/ha higher in early than in timely-sown wheat. Despite very different yield levels in 2015 and 2016 harvests, the advantage of early sowing on grain yields was similar (1.1 and 0.9 t/ha); straw yield benefits were greater in 2015 (1.7 t/ha more) than in 2016 (0.4 t/ha more). In 2015 and 2016, N offtake was 35 and 17 kg N/ha higher in early than in timely-sown wheat, respectively. The mineral N fertilizer value of cattle slurry averaged 50%. Early sowing increased the apparent N recovery (ANR) for wheat regardless of nutrient source. However, ANR was substantially higher for NPK (82% in 2015; 52% in 2016) than for AM (39% in 2015; 27% in 2016). Performance of the two cultivars did not differ consistently with respect to the effect of early sowing on crop yield, N concentration and offtake, or ANR. Within the north-west European climatic region, moving the sowing time of winter wheat from mid-September to mid-August provides a significant yield and N offtake benefit.

Introduction

In the temperate climate prevailing in north-west Europe, winter wheat (*Triticum aestivum* L.) remains a most important cereal because of its high yield potential. Average grain yields have shown a steady annual increase of 0.1 t/ha from the start of the 1960s until the mid-1990s (Brisson *et al.* 2010; Petersen *et al.* 2010). Subsequently, grain yields have plateaued although progress in cultivar performance does not appear to be a limiting factor. Recent decades have witnessed development of winter wheat cultivars with grain yields exceeding 10 t/ha (Barraclough *et al.* 2010), given an ample supply of nitrogen (N). The stagnation in wheat yields has been ascribed to climate change, declining frequency of legume crops in cereal rotations and increased constraints on N use in plant production (Brisson *et al.* 2010; Petersen *et al.* 2010; Olesen *et al.* 2011).

In response to EU directives on environmental protection, Denmark has implemented a regulatory framework with restrictive use of N in agricultural production. This is because 60% of the land surface is under intensive cultivation and supports high livestock densities, and because substantial net percolation during the autumn and winter periods and short distances from fields to coastal surface waters provide little retention of N in the landscape. The regulations include restrictions on the use of N fertilizer (application times and maximum rates for individual crops) and prescribed use efficiencies for N applied with animal manures (AMs) (Dalgaard *et al.* 2014). Basically, the prescribed N use efficiency for different animal categories and types of manure implies that ammoniacal N, present in manure at the time of application, is as efficient as N added in mineral fertilizer. Moreover, AMs are ascribed mandatory residual N values for subsequent crops.

To compensate for restrictions on fertilizer N use while still harvesting the benefits of high-yielding wheat cultivars, other management options are scrutinized to optimize overall N use efficiency (Christensen 2004). Autumn-sown wheat accounts for 42% of the present cereal area in Denmark and wheat is also the preferred cereal on farms specializing in livestock production. Alternative management options for winter wheat include better estimates of the residual value of previously added manure-N (Petersen *et al.* 2012; Sørensen *et al.* 2017), the use of nitrate catch crops in between main crops (Hansen *et al.* 2000) and improved management of AMs during storage and application in the field (Webb *et al.* 2013).

Another alternative could be an earlier sowing date. While recent studies under north-west European conditions show marginal yield benefits of early sowing (Sieling *et al.* 2005; Myrbeck *et al.* 2012; Rasmussen & Thorup-Kristensen 2016; Munkholm *et al.* 2017), early studies based on field trials with winter wheat in southeast England showed that wheat developed a greater root system, recovered more soil N and produced greater grain yields when the seeding date was moved from October to September (Barraclough & Leigh 1984; Widdowson *et al.* 1987; Milford *et al.* 1993). These studies relied on N added with mineral fertilizers. When mineral N fertilizer is substituted by ammoniacal N in AM, more total N is added to the soil and a greater N residual value is expected due to subsequent mineralization of organically bound manure N (Webb *et al.* 2013). For autumn-sown wheat grown in crop rotations with grass-clover and frequent use of AM, an earlier sowing date may therefore be beneficial to wheat growth and improve the recovery of soil N, thereby reducing N losses from soil.

The current study evaluated the effect of sowing date (early, mid-August; timely, mid-September) on two contemporary winter wheat cultivars (Hereford and Mariboss) grown with different rates of nutrients added as AM (cattle slurry) or mineral fertilizers. Overwinter plant N uptake and soil mineral N concentrations were determined in the cropping year 2014/15, while harvest yields (grain, straw, N content) were determined over two cropping years (2014/15 and 2015/16). The study was embedded in the Askov Long-Term Experiment on Animal Manure and Mineral Fertilizers (Askov-LTE).

Materials and methods

Askov-LTE: site characteristics and experimental layout

The Askov-LTE is located on the Lermarken site at Askov Experimental Station, South Jutland, Denmark (55°28′N, 09°07′E, 63 m a.s.l.). The soil is classified as Ultic Hapludalf (Soil Survey Staff 1999) and Aric Haplic Luvisol (IUSS Working Group WRB 2015). During the present study (August 2014–July 2015 and August 2015–July 2016), mean precipitation and temperature was 1115 and 1140 mm, and 9.5 and 9.8 °C, respectively (Fig. 1). The soil is a light sandy loam with 10% clay (<2 µm), 12% silt (2–20 µm), 43% fine sand (20–200 µm) and 35% coarse sand (200–2000 µm) in the 0–20 cm layer.

The Askov-LTE was initiated in 1894 and includes four separate fields (termed B2, B3, B4 and B5). The experiment carries a four-course rotation of winter wheat (*T. aestivum* L.), silage maize (*Zea mays* L.) and spring barley (*Hordeum vulgare* L.), undersown with a grass-clover mixture that is cut twice in the subsequent production year. The B2 field is divided into a west (B2w) and an east (B2e) section. The crops are rotated across the fields in a fixed sequence whereby a given field grows only one crop a given year. Above-ground biomass is removed from all plots at harvest. Magnesium-enriched lime is added every 4 years to maintain soil pH in the range 5.5–6.5, and sulphur (S) is added annually at a rate of 12.5 kg S/ha. Chemical crop protection measures are applied when needed.

The main nutrient treatments are different rates (0, ½, 1 and 1½ times the standard rate for a given crop; grass-clover remains without nutrient additions) of total N, phosphorus (P) and potassium (K) in AM (cattle slurry since 1973) or mineral fertilizers (NPK). The size of the nutrient-treated plots is 11.7 × 9.4 m (B3, B4 and B5 fields) and 7.3 × 9.4 m (B2 field). Averaged across the rotation, 1 AM and 1 NPK represent an annual input of 100 kg total N, 20 kg P and 80 kg K/ha. The cattle slurry has 5% dry matter (DM) and 60–70% of its total N content as ammoniacal N. Treatment 1 AM corresponds to 25 t slurry/ha (w/w). Further details are given by Christensen *et al.* (2006).

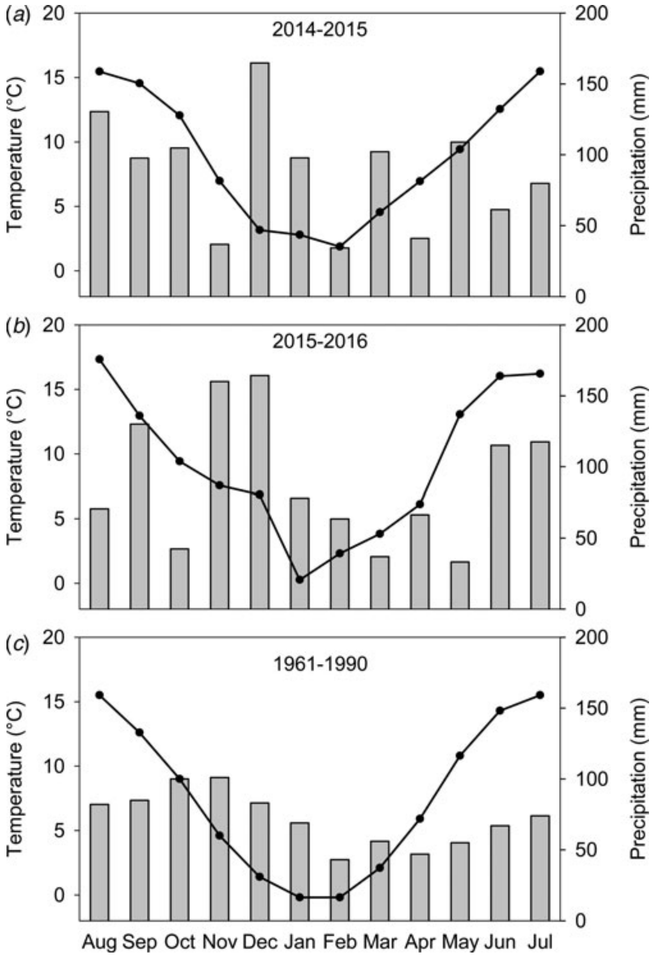

Fig. 1. Monthly mean temperature (lines) and precipitation (bars) during (*a*) August 2014–July 2015 and (*b*) August 2015–July 2016 at Askov Experimental Station; (*c*) shows long-term mean values (1961–1990).

Experiments with wheat sowing dates

The present study was based on a split–split plot design and accommodated into the B3 field during 2014/15 (2015 harvest) and the B2e field during 2015/16 (2016 harvest). The study employed three field replicates of the nutrient treatments: 0 (unmanured), 1 AM, 1½ AM, 1 NPK and 1½ NPK (Table 1). For winter wheat, nutrient level 1 corresponds to 150 kg total N, 30 kg P and 120 kg K/ha. All nutrients were surface-applied in the spring (Table 2). The grass-clover crop that preceded winter wheat was terminated after the second cut by spraying with glyphosate and ploughing. Each nutrient plot was then divided into four sub-plots to accommodate the wheat cultivars Mariboss (Nordic Seeds, Denmark) and Hereford (Syngenta, Switzerland) and two sowing dates: early (mid-August) and timely (mid-September). For early-sown wheat, the seedbed in two sub-plots was prepared in August by harrowing and seeds of Hereford and Mariboss (treated with Latitude™ to prevent attacks of take-all (*Gaeumannomyces graminis*)) were sown in separate sub-plots at a rate of 225 seeds/m^2. For timely-sown wheat, the seedbed in the remaining two sub-plots (left undisturbed after ploughing) was prepared in September and the

Table 1. Animal manure (AM) and mineral fertilizer (NPK) treatments in the B3 and B2e fields involved in the present study

Nutrient treatment		B3		B2e	
		C	N	C	N
Code	kg total-N/ha	mg/g soil		mg/g soil	
Unmanured	0	11.1	0.9	10.2	1.0
1 AM	150	13.4	1.2	13.2	1.2
1½ AM	225	14.9	1.3	14.0	1.3
1 NPK	150	12.9	1.0	12.1	1.1
1½ NPK	225	13.1	1.1	11.3	1.1

For winter wheat, the treatments 1 NPK and 1 AM correspond to 150 kg total N, 30 kg P and 120 kg K/ha. Concentrations of C and N in the soil were determined in autumn 2016.

wheat cultivars sown at a rate of 350 seeds/m^2. The distance between wheat rows was 12 cm. Reduced seeding rates are recommended for early sowing of winter wheat to reduce fungal attacks during autumn and crop lodging in the subsequent production season. Table 2 includes dates for main field operations and measurements.

Measurements during crop growth

The concentration of mineral N (ammonium and nitrate) in 0–20 cm soil was determined on samples collected in the B3 field from each replicate plot on 18 August, 17 September and 20 November 2014, and on 18 March 2015. The soils were sieved to <2 mm and a 15 g sub-sample shaken for 1 h with 30 ml of 1 M potassium chloride. Ammonium-N and nitrate-N in the filtrate (0.7 µm fiberglass filter) was determined colorimetrically using a Bran + Lübbe AutoAnalyser 3 (Seal Analytical, Norderstedt, Germany). Another soil sub-sample was oven-dried at 105 °C for 24 h to determine soil moisture content at sampling. The concentration of mineral N in the soil is reported as mg N/kg dry soil.

Table 2. Plot sizes and dates for main field operations and measurements in the B3 and B2e fields for the 2014/15 (harvest year 2015) and 2015/16 (harvest year 2016) growing seasons

	2014/15	2015/16
Field	B3	B2e
Size of nutrient plot (m^2)	110	69
Size of sub-plot (m^2)	11	6
Herbicide application	08 August 2014	08 August 2015
Ploughing	20 August 2014	19 August 2015
Early sowing	20 August 2014	21 August 2015
Timely sowing	18 September 2014	21 September 2015
Tiller counts	25 February 2015	16 March 2016
Slurry application	25 March 2015	13 Apr 2016
Mineral fertilizer application	23 March 2015	11 April 2016
Chlorophyll readings	25 June 2015	7 June 2016
Head counts	12 August 2015	28 July 2016
Wheat harvest	20 August 2015	15 August 2016

The nutrient plot is the area receiving the nutrient treatment while the sub-plot is the area of the nutrient plot allocated to each combination of sowing date and cultivar.

Six times during the period 25 October 2014 to 17 March 2015 (see Fig. 2 for sampling dates), above-ground N uptake was determined in the B3 field by collecting biomass from 0.9 m of a single plant row (corresponding to 0.11 m^2) not included in the final harvest plot. The wheat plants were cut at the soil surface. After drying for 18 h at 80 °C, the milled (<0.5 mm) biomass was analysed for total N concentration using a Flash 2000 Organic Elemental Analyser (Thermo Fisher Scientific, USA). The N uptake in above-ground biomass is reported as kg N/ha after DM yields had been corrected for soil contamination by ashing a separate sub-sample.

The number of tillers was assessed on 25 February 2015 (B3 field) and 16 March 2016 (B2e field) at the end of winter dormancy. Within each plot, tillers were counted for plants collected from two randomly chosen areas of 0.06 m^2 and expressed as tillers/m^2.

To evaluate the N status of wheat, chlorophyll concentrations at anthesis was determined on 25 June 2015 (B3 field) and 7 June 2016 (B2e field) using a portable chlorophyll metre (CM-500; Sofranc Technologies, Spain). This device applies a closed chamber technique and measures light transmittance/absorbance to monitor leaf ‘greenness’ as an approximation of chlorophyll content (Ladha *et al.* 2005); readings are given in SPAD units (Soil

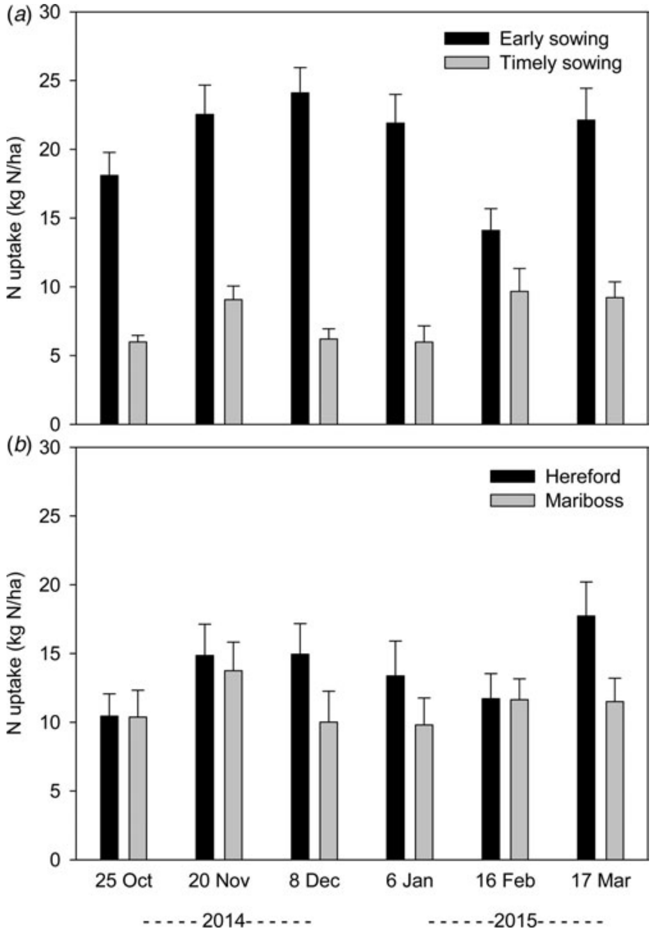

Fig. 2. Effect of (*a*) sowing date and (*b*) cultivar on N uptake in aboveground biomass of wheat grown in the B3 field during the 2014/15 autumn/winter period. Bars show means ± S.E. (*n* = 30).

Plant Analysis Development units). The present study reports average readings taken on the upper fully expanded leaf of ten randomly selected plants within each subplot.

Finally, the number of heads present in a plant row of 0.6 m (representing 0.07 m^2) was counted just before wheat ripeness. This measurement was non-destructive, and results are reported as heads/m^2.

Measurements at crop harvest

At physiological maturity, the wheat was harvested with a plot combine harvester that allows separate determination of grain and straw yields and leaves 5 cm of stubble. Sub-samples of grain and straw were oven-dried at 80 °C for 18 h. Grain yields are reported with 85% DM, while straw yields are reported as 100% DM. Thousand kernel weight (TKW) is expressed as the weight in g of 1000 grains using a seed counter (Contador, Pfeuffer, Germany). The N concentration in grain and straw was determined using a Flash 2000 Organic Elemental Analyser and reported as mg N/kg DM. The N offtake is reported as kg N/ha.

Calculations and statistical analysis

Apparent N recovery (ANR) was calculated as:

$$\mathrm{ANR} = \frac{U_{\mathrm{T}} \; - U0}{F_{\mathrm{N}}} \times 100 \tag{1}$$

where U_{T} is N offtake (kg N/ha) in wheat grain or straw in plots receiving AM or mineral fertilizer, U_0 is corresponding N offtakes in unmanured plots and F_{N} is N applied (kg N/ha) in AM or mineral fertilizer,

The recovery of N added with AM (*ANR man*) was related to the recovery of N added with mineral fertilizers (*ANR min*) by calculating the manure fertilizer value (MFV):

$$\mathrm{MFV} = \frac{\mathrm{ANR\ man}}{\mathrm{ANR\ min}} \tag{2}$$

The experimental layout was a split–split–block design with three replicates and for the statistical analyses the following linear model was applied:

$$\begin{aligned} y_{\mathrm{ijkl}} = {} & \mu + B_{\mathrm{i}} + Tj + \mathrm{BT}_{\mathrm{ij}} + P_{\mathrm{k}} + \ \mathrm{BP}_{\mathrm{ik}} + \mathrm{TP}_{\mathrm{jk}} \\ & + \mathrm{BTP}_{\mathrm{ijk}} + V_{\mathrm{l}} + \mathrm{BV}_{\mathrm{il}} + \mathrm{PV}_{\mathrm{kl}} + \mathrm{TPV}_{\mathrm{jkl}} \\ & + \mathrm{TV}_{\mathrm{jl}} + \mathrm{BTV}_{\mathrm{ijl}} + \mathrm{BPV}_{\mathrm{ikl}} + \mathrm{BTPV}_{\mathrm{ijkl}} + \varepsilon_{(\mathrm{ijklm})} \end{aligned}$$

where i is block (three replicates); j is treatment (five replicates); k is sowing date (two replicates); l is wheat cultivar (two replicates); y_{ijk} is observation of the l^{th} wheat cultivar at k^{th} sowing date and j^{th} nutrient treatment; μ is grand mean; B_{i} is random effect of the i^{th} block NID (0, σ_{b}^2); T_{j} is fixed effect of the j^{th} nutrient treatment; P_{k} is fixed effect of the k^{th} sowing date; $\mathrm{TP}_{\mathrm{jk}}$ is interaction between the j^{th} nutrient treatment and the k^{th} sowing date; V_{l} is fixed effect of the l^{th} cultivar; $\mathrm{PV}_{\mathrm{kl}}$ is interaction between the k^{th} sowing date and the l^{th} cultivar; $\mathrm{TPV}_{\mathrm{jkl}}$ is interaction between the j^{th} treatment, the k^{th} sowing date and the l^{th} cultivar; $\mathrm{TV}_{\mathrm{jl}}$ is interaction between the j^{th} sowing date and the l^{th} cultivar, and $\varepsilon_{(\mathrm{ijklm})}$ is the random experimental error (0, σ_{e}^2)

The data were analysed using SAS 9.3 mixed-model procedure (SAS Institute 2013). Interactions and main effects were declared significant at $P < 0.05$. Variables were checked for assumptions of normality and homogeneity of variances based on the plot of residuals *v.* predicted values. Log transformations were performed where necessary based on the Box–Cox power transformation series (Box & Cox 1964). Back-transformed means are presented for ease of interpretation. Least-square means were separated using the PDIFF option of LSMEANS in SAS proc mixed. Pair-wise comparisons were based on the ESTIMATE statement in SAS. The least significant differences are reported at $P < 0.05$ significance level. All analyses refer to individual years/fields.

Results

Soil mineral nitrogen content and wheat nitrogen uptake in B3 field during the autumn/winter period

The concentration of mineral N in the 0–20 cm soil horizon differed significantly between nutrient treatments ($P \leqslant 0.001$), sowing date ($P \leqslant 0.01$) and soil sampling date ($P \leqslant 0.001$), but not between cultivars (Table 3). Generally, more mineral N was present in AM plots than in unmanured and NPK plots, although differences between plots with different nutrient treatments were small for soil sampled in spring (Fig. 3). Soil sampled 17 September 2014 under early-sown wheat was higher in mineral N than soil under timely-sown wheat; the opposite was true for subsequently sampled soil. The concentration of mineral N in soil showed a general decline during the autumn/winter period (Fig. 3) with a tendency for an interaction between soil sampling date and nutrient treatment ($P = 0.06$; Table 3).

The overwinter N uptake in wheat differed significantly ($P \leqslant 0.001$) between nutrient treatments, sowing date, cultivar and plant sampling date (Table 3). At all plant samplings, the N uptake of early-sown wheat was significantly ($P \leqslant 0.001$) higher

Table 3. Main effects and interactions for soil mineral N (nitrate N and ammonium N) and N uptake in above ground biomass measured in the B3 field during the 2014/15 autumn/winter period

	Mineral N mg N/kg soil	N uptake kg N/ha
Nutrient treatment (T)	$P \leqslant 0.001$	$P \leqslant 0.001$
Sowing date (D)	$P \leqslant 0.01$	$P \leqslant 0.001$
Cultivar (C)	NS	$P \leqslant 0.001$
Sampling date (S)	$P \leqslant 0.001$	$P \leqslant 0.001$
T × D	NS	NS
T × C	NS	$P \leqslant 0.001$
D × C	NS	NS
T × D × C	NS	NS
T × S	NS	$P \leqslant 0.001$
D × S	$P \leqslant 0.001$	$P \leqslant 0.001$
T × D × S	NS	NS
C × S	NS	$P \leqslant 0.01$
T × C × S	NS	NS
D × C × S	NS	NS
T × D × C × S	NS	NS

NS, not significant.

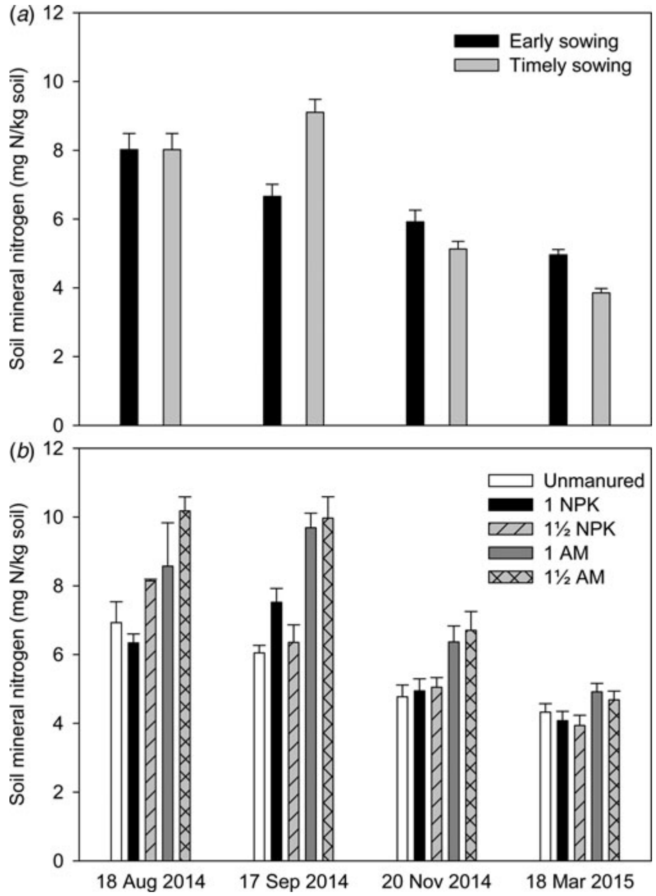

Fig. 3. Concentrations of mineral N (nitrate-N and ammonium-N in 0–20 cm soil) sampled at four dates in the B3 field during the 2014/15 autumn/winter period. (*a*) The effect of sowing date; bars show means ± S.E. ($n = 15$ for 18 August; $n = 30$ for other dates). (*b*) The effect of nutrient treatment; bars show means ± S.E. ($n = 3$ for 18 August; $n = 12$ for other dates). Early and timely sowing was on 20 August and 18 September 2014, respectively.

(average 22 kg N/ha) than that of timely-sown wheat (average 8 kg N/ha), with the largest differences (18 kg N/ha) appearing for plants sampled 8 December 2014 and 6 January 2015 (Fig. 2). The N uptake differed significantly between cultivars and sampling dates ($P < 0.01$), but differences between cultivars were not consistent at all sampling dates. There was an interaction between nutrient treatment and sampling date, and plant uptake decreased in the order: 1½ AM>1½ NPK>1 NPK>1 AM>unmanured.

Number of tillers

Early sowing increased the number of tillers counted after winter dormancy (Table 4). In 2015, early-sown wheat had 933 tillers/m^2 while timely-sown wheat had 754 tillers/m^2, the corresponding numbers in 2016 were 888 and 730 tillers/m^2. In 2015, but not in 2016, Mariboss grew more tillers than Hereford. Wheat on unmanured plots had fewer tillers/m^2 than wheat grown with AM or NPK (not including 1 NPK in 2016); differences between nutrient treatment were absent. Significant interactions were observed in 2015 for sowing date and cultivar ($P \leqslant 0.05$), and for nutrient treatment, sowing date and cultivar ($P \leqslant 0.01$) (Table 5) but none of these interactions were significant in 2016.

Chlorophyll metre readings

Chlorophyll metre readings (CMR) at anthesis showed a significant ($P \leqslant 0.001$) effect of nutrient treatment in both years (Tables 4 and 5). The NPK treatments showed higher readings than AM treatments, while unmanured treatments showed the lowest CMR. There was a significant ($P \leqslant 0.001$) effect of sowing date for both years of the experiment. Early-sown wheat showed higher SPAD reading than timely-sown wheat. Cultivars differed only in 2016 with Hereford showing higher values than Mariboss.

Number of heads

Nutrient treatment ($P \leqslant 0.001$) and sowing date ($P \leqslant 0.05$) had significant effects on the number of heads (Tables 4 and 5). The smallest number of heads/m^2 were registered for wheat grown on unmanured plots. Early sowing resulted in a larger number of heads compared with timely sowing, the average difference being 63 heads/m^2 in favour of early sowing ($P < 0.05$). Mariboss developed a trend for a higher number of heads compared with Hereford with 60 heads/m^2 in favour of Mariboss ($P \leqslant 0.01$).

Yields of grain and straw

The winter wheat yielded considerably more grain and straw in 2015 than in 2016 (Table 6). The mean grain yield was 8.5 t/ha in 2015 and 4.7 t/ha in 2016; the corresponding straw yields were 6.7 and 3.0 t DM/ha. Yields peaked in 2015 for wheat grown with 1½ NPK; for this treatment, grain yield passed 11 t/ha. The grain yield decreased in the order: 1½ NPK>1 NPK>1½ AM>1 AM>unmanured. In 2016, grain yields were similar for 1½ AM and 1½ NPK, and for 1 AM and 1 NPK (Table 6).

Early-sown wheat yielded significantly ($P \leqslant 0.001$) more grain than timely-sown wheat (Fig. 4; Table 6). The effect of cultivar was significant in 2015 ($P < 0.001$) but not in 2016, and the effect of cultivar depended on nutrient treatment ($P < 0.05$). Hereford was more productive than Mariboss in plots given 1½ NPK and 1 NPK, whereas there was no difference between cultivars in plots dressed with 1 AM. On average, Hereford yielded 0.7 t/ha more grain than Mariboss (Fig. 4). Early-sown wheat produced more straw than timely-sown wheat in 2015 ($P < 0.001$) and in 2016 ($P < 0.05$). The two cultivars gave similar yields of straw.

Thousand kernel weight

The greatest kernel weight was obtained for wheat grown with AM, whereas grains harvested in NPK-treated plots and unmanured plots did not differ consistently in TKW (Table 6). Early sowing gave significantly ($P \leqslant 0.001$) higher TKW compared with timely sowing in 2015, although the difference was numerically small. Hereford provided significantly higher TKW than Mariboss in both 2015 ($P \leqslant 0.05$) and 2016 ($P \leqslant 0.01$). Seen across the two harvest years, the average grain of Hereford was 4.5 mg heavier than grains produced by Mariboss.

Crop nitrogen concentrations and nitrogen offtake

Nutrient treatments had a significant impact ($P < 0.001$) on the N concentration in grains and straw harvested in 2015 and 2016. The N concentrations differed between cropping years with smaller concentrations in 2015 than in 2016 (Table 7). However, for both years, wheat grown with mineral fertilizer (1 NPK and 1½

Table 4. Mean values for tiller counts, chlorophyll metre readings and number of heads as influenced by nutrient treatment, cultivar and sowing date

	Number of tillers		Chlorophyll metre readings		Number of heads	
	2015	2016	2015	2016	2015	2016
Factor	Tillers/m^2		SPAD units		Head/m^2	
Nutrient treatment						
Unmanured	518	587	16	23	278	282
1 NPK	899	864	26	39	403	426
1½ NPK	933	855	30	40	478	499
1 AM	930	785	20	28	385	378
1½ AM	939	953	22	27	406	469
Cultivar						
Hereford	686	685	23	32	349	383
Mariboss	1002	932	23	29	422	432
Sowing date						
Early	933	888	24	32	416	440
Timely	754	730	22	29	354	376

NPK) reached significantly ($P \leqslant 0.001$) higher N concentrations compared with wheat grown with AM (1 AM and 1½ AM). The concentration of N in wheat grains from animal manured plots was similar to grains from unmanured plots. In 2015, early sowing increased N concentrations in grain and straw compared with timely sowing while early and timely sowing did not differ for wheat harvested in 2016.

Table 5. Main effects and interactions for tiller counts, chlorophyll metre readings and number of heads

	Number of tillers	Chlorophyll metre readings	Number of heads
	Tillers/m^2	SPAD units	Heads/m^2
2015			
Nutrient treatment (T)	$P \leqslant 0.001$	$P \leqslant 0.001$	$P \leqslant 0.001$
Sowing date (D)	$P \leqslant 0.001$	$P \leqslant 0.01$	$P \leqslant 0.05$
Cultivar (C)	$P \leqslant 0.001$	NS	$P \leqslant 0.05$
T × D	NS	NS	NS
T × C	NS	NS	NS
D × C	$P \leqslant 0.05$	NS	NS
T × D × C	$P \leqslant 0.01$	NS	NS
2016			
Nutrient treatment (T)	$P \leqslant 0.01$	$P \leqslant 0.001$	$P \leqslant 0.001$
Sowing date (D)	$P \leqslant 0.01$	NS	$P \leqslant 0.05$
Cultivar (C)	$P \leqslant 0.001$	$P \leqslant 0.001$	NS
T × D	NS	NS	NS
T × C	NS	NS	NS
D × C	NS	NS	NS
T × D × C	NS	NS	$P \leqslant 0.05$

NS = not significant

The N offtake in harvested grain and straw was affected significantly by nutrient treatment ($P \leqslant 0.001$), cultivar ($P \leqslant 0.05$) and sowing time ($P \leqslant 0.001$) in 2015 but only by nutrient treatment ($P \leqslant 0.001$) and sowing time ($P \leqslant 0.01$) in 2016. Crop N offtake increased in the order: unmanured<1 AM<1½ AM<1 NPK<1½ NPK (Table 7). Early-sown wheat removed 35 kg N/ha more than timely-sown wheat in 2015; in 2016 the difference was 17 kg N/ha. The difference between cultivars in N offtake was significant in 2015 but accounted for only 6 kg N/ha in favour of Hereford. The ANR was substantially smaller in 2016 than in 2015 (Table 7). The ANR was higher for NPK-treated wheat than for wheat grown on AM plots ($P < 0.001$), and ANR was 12% higher for early-sown than for timely-sown wheat ($P < 0.001$). The cultivars did not differ in ANR and showed an average of 61% in 2015 and 41% in 2016. The MFV did not differ between nutrient treatments, cultivars and sowing date, except for sowing date in 2015, where early sowing showed higher MFV than timely sowing.

Table 8 summarizes main effects and interactions for grain and straw yields, TKW and N concentrations and N offtake at harvest in response to nutrient treatment, sowing date and cultivar. For main effects, the most consistent parameter was nutrient treatment and sowing date. In 2015, cultivar affected grain yield, grain N offtake and TKW in 2015; in 2016, effects of cultivar were only seen for straw N offtake and TKW. Most interactions were not significant.

Discussion

The winter wheat harvested in 2015 yielded considerably more grain and straw and showed a higher total N offtake than wheat harvested in 2016. Several factors contributed to these differences. In 2016, May was characterized by low precipitation (33 mm), whereas precipitation in May 2015 reached 109 mm. Lack of water at the beginning of the critical reproductive stages may induce periodic stress in wheat plants (Musick & Dusek 1980) and this may have compromised 2016 harvest yields. Another

Table 6. Mean values for grain (85% DM) and straw (100% DM) yields, and thousand kernel weight (TKW) as influenced by nutrient treatment, cultivar and sowing date

Factor	Grain yield		Straw yield		TKW	
	2015	2016	2015	2016	2015	2016
	t/ha		t/ha		g	
Nutrient treatment						
Unmanured	3.6	2.2	2.7	1.3	44.7	40.4
1 NPK	10.7	5.1	7.7	3.3	47.5	40.1
1½ NPK	11.4	5.6	8.9	3.8	44.9	39.2
1 AM	7.8	4.9	6.7	2.9	50.3	43.8
1½ AM	8.8	5.8	7.2	3.6	49.6	43.8
Cultivar						
Hereford	8.8	4.8	6.7	2.9	50.1	43.1
Mariboss	8.1	4.6	6.6	3.1	44.7	39.5
Sowing date						
Early	9.0	5.2	7.5	3.2	48	42
Timely	7.9	4.3	5.8	2.8	47	40

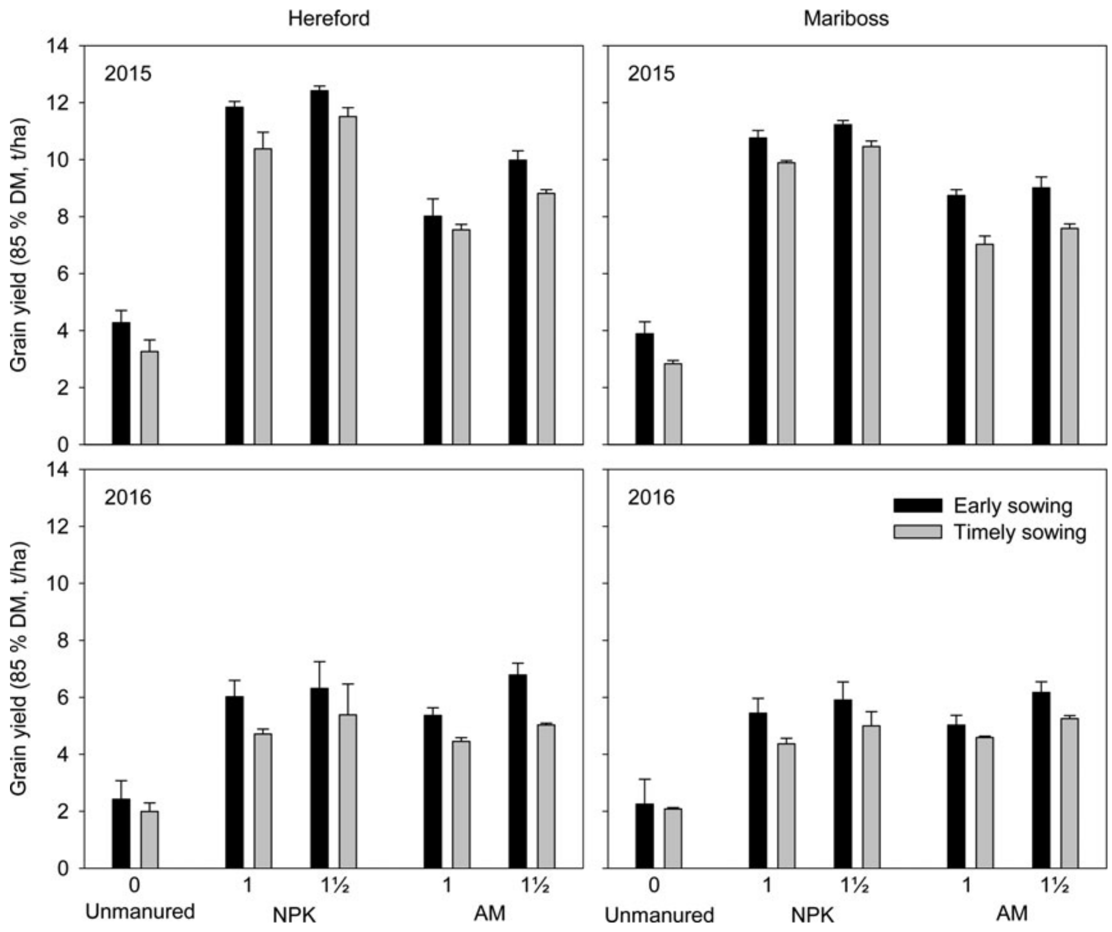

Fig. 4. Effect of nutrient treatment, sowing date and cultivar on grain yields in winter wheat harvested in the B3 field in 2015 and in the B2e field in 2016. Bars show means ± s.e. ($n = 3$).

Table 7. Mean values for concentrations of N in grain and straw, total N offtake at harvest, apparent N recovery (ANR) and mineral fertilizer value (MFV) determined for each factor: nutrient treatment, cultivar and sowing date

Factor	N concentration Grain	Straw	Total N offtake	ANR	MFV
	mg N/kg		kg N/ha	%	
2015					
Nutrient treatment					
Unmanured	1.34	0.33	50		
1 NPK	1.45	0.49	171	80	
1½ NPK	1.84	0.67	240	84	
1 AM	1.24	0.38	109	39	49
1½ AM	1.36	0.46	137	38	45
Cultivar					
Hereford	1.41	0.44	144	61	48
Mariboss	1.43	0.45	138	60	46
Sowing date					
Early	1.47	0.47	159	67	51
Timely	1.37	0.44	124	54	44
2016					
Nutrient treatment					
Unmanured	1.58	0.52	37		
1 NPK	2.17	0.79	121	56	
1½ NPK	2.35	0.98	149	48	
1 AM	1.54	0.59	82	29	53
1½ AM	1.51	0.56	95	25	53
Cultivar					
Hereford	1.78	0.64	97	38	53
Mariboss	1.76	0.66	97	37	53
Sowing date					
Early	1.76	0.66	105	43	56
Timely	1.77	0.64	88	33	50

contributing factor was the timing of nutrient applications in the spring. In 2015, mineral fertilizers and AM were applied on 23–25 March, whereas applications in 2016 were delayed by 3 weeks (11–13 April). However, the positive effects of earlier sowing persisted in spite of the major difference in yield levels.

Early sowing was associated with a number of benefits compared with timely sowing. During the autumn/winter period 2014/15, above-ground biomass of early-sown wheat held more N than timely-sown wheat, with the largest difference (18 kg N/ha) observed for wheat plants sampled in December and January. Similar benefits of earlier sowing on overwinter N uptake in wheat has been demonstrated in previous studies under north-western European growing conditions (Widdowson *et al.* 1987; Milford *et al.* 1993; Rasmussen & Thorup-Kristensen 2016). The higher N uptake is ascribed to be deeper and more developed root systems found in early-sown wheat (Barraclough & Leigh 1984; Rasmussen & Thorup-Kristensen 2016; Munkholm *et al.* 2017). The concentration of mineral N in 0–20 cm soil depth during the autumn/winter period remained relatively low and showed only small differences between early- and timely-sown wheat. Thus, the additional N uptake in early-sown wheat represents an environmental benefit as more N is being conserved in the soil/plant system and less N becomes exposed to loss from the root zone. Previous studies under comparable growth conditions show that earlier sowing dates can reduce the content of mineral N in 0–1 m soil depth by 10–35 kg N/ha during the autumn period (Widdowson *et al.* 1987; Myrbeck *et al.* 2012; Rasmussen & Thorup-Kristensen 2016; Munkholm *et al.* 2017). However, higher overwinter N uptake and reduced soil mineral N contents are not always reflected in larger harvest yields and N offtakes (Sieling *et al.* 2005; Rasmussen & Thorup-Kristensen 2016; Munkholm *et al.* 2017).

In the present study, the advantage of early sowing was similar with regard to grain yields obtained in 2015 (1.1 t/ha) and 2016 (0.9 t/ha), despite the very different yield levels realized for the two cropping seasons. Similar yield benefits of earlier sowing have been reported for winter wheat grown in south-east England, where sowing dates were moved from late October to late September (Widdowson *et al.* 1987; Milford *et al.* 1993). For straw, early sowing also resulted in higher yields but the yield benefit was considerably greater in 2015 (1.7 t/ha) than in 2016 (0.4 t/ha). Apparently, the higher yield obtained by early sowing was derived from a more extensive root system (Barraclough & Leigh 1984), larger numbers of tillers, higher crop N status at anthesis and larger numbers of productive heads. The results of the present study align with the previous studies in which the larger yields associated with early sowing are ascribed to higher numbers of tillers and heads, and a longer vegetative period with earlier onset of stem elongation (Musick & Dusek 1980; Kiss *et al.* 2014).

Early sowing also provided higher N offtake at harvest. This was determined mainly by higher DM yields rather than by N concentration, although grain and straw harvested in 2015 showed slightly higher N concentrations for early-sown wheat. In spring 2015, the difference in N uptake between early- and timely-sown wheat in the B3 field averaged 14 kg N/ha. This difference was increased to 35 kg N/ha at harvest, indicating that early-sown wheat was superior in utilizing N mineralized from the soil N pool and/or N added in the spring 2015. The ANR was higher in 2015 for early-sown wheat (ANR = 67%) than for timely-sown wheat (ANR = 54%). Compared with 2015, the ANR was reduced considerably for early (ANR = 43%) as well as timely-sown wheat (ANR = 33%) and the N offtake benefit associated with early-sown wheat was smaller (17 kg N/ha).

It was envisioned that early sowing would be more beneficial to wheat grown with AM than wheat grown with mineral fertilizers. However, higher grain yield was found for 1½ NPK and 1 NPK than for 1½ AM in both years of the experiment. Although the concentration of mineral soil N in autumn was higher for AM plots and more N was taken up in the wheat plants during the autumn/winter period in 1½ AM plots, these benefits of AM were not reflected in higher numbers of tillers in the spring, chlorophyll recordings or number of heads. The only consistent benefit of AM recorded in the present study was a higher grain weight at harvest. Thus, a beneficial effect of AM on grain and straw yields of early-sown wheat could not be confirmed in the present study, as illustrated by a lack of interactions between sowing date and nutrient treatment. The interaction between nutrient treatment and sowing date observed for N concentrations in grain and straw was due to higher concentrations of N in grain

Table 8. Main effects and interactions for grain and straw yield, thousand kernel weight (TKW), concentration of N in grain and straw, N offtake in grain and straw, apparent N recovery (ANR) and mineral fertilizer value (MFV)

	Grain yield	Straw yield	TKW	Grain N	Straw N	Grain offtake	Straw offtake	Total offtake	ANR	MFV
	t/ha		g	mg N/g		kg N/ha			%	%
2015										
Nutrient treatment (T)	$P \leqslant 0.001$	$P \leqslant 0.001$	$P \leqslant 0.001$	$P \leqslant 0.001$	$P \leqslant 0.001$	$P \leqslant 0.001$	$P \leqslant 0.001$	$P \leqslant 0.001$	$P \leqslant 0.001$	NS
Sowing date (D)	$P \leqslant 0.001$	$P \leqslant 0.001$	$P \leqslant 0.001$	$P \leqslant 0.001$	$P \leqslant 0.001$	$P \leqslant 0.001$	$P \leqslant 0.001$	$P \leqslant 0.001$	$P \leqslant 0.001$	$P \leqslant 0.001$
Cultivar (C)	$P \leqslant 0.001$	NS	$P \leqslant 0.05$	NS	NS	$P \leqslant 0.01$	NS	$P \leqslant 0.05$	NS	NS
T × D	NS	NS	NS	$P \leqslant 0.01$	$P \leqslant 0.01$	NS	$P \leqslant 0.05$	$P \leqslant 0.05$	NS	NS
T × C	$P \leqslant 0.05$	NS	$P \leqslant 0.01$	NS	NS	NS	NS	NS	NS	NS
D × C	NS	NS	$P \leqslant 0.01$	NS	NS	NS	NS	NS	NS	NS
T × D × C	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
2016										
Nutrient treatment (T)	$P \leqslant 0.001$	$P \leqslant 0.001$	$P \leqslant 0.01$	$P \leqslant 0.001$	$P \leqslant 0.001$	$P \leqslant 0.001$	$P \leqslant 0.001$	$P \leqslant 0.001$	$P \leqslant 0.001$	NS
Sowing date (D)	$P \leqslant 0.001$	$P \leqslant .05$	NS	NS	NS	$P \leqslant 0.001$	$P \leqslant 0.001$	$P \leqslant 0.01$	$P \leqslant 0.001$	NS
Cultivar (C)	NS	NS	$P \leqslant 0.01$	NS	NS	NS	$P \leqslant 0.01$	NS	NS	NS
T × D	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
T × C	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
D × C	NS	NS	NS	$P \leqslant 0.01$	NS	NS	NS	NS	NS	NS
T × D × C	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

NS, not significant.

and straw from wheat grown with NPK. While grain and straw yields in 2015 were higher for wheat grown with NPK than with corresponding nutrient additions in AM, yield differences between corresponding NPK and AM treatments were not significant for wheat harvested in 2016. Nevertheless, differences in N concentrations in grain and straw caused N offtake and ANR to be higher for wheat given mineral fertilizers than for wheat given AM, regardless of cropping year.

By using the Askov-LTE, the present study included the residual N value derived from decades of AM and mineral fertilizer additions. Although treatment-induced differences in soil total-N content are relatively small, the plots dressed with AM had higher contrations of soil mineral N in the early autumn. The grass-clover crop preceeding the winter wheat remains unfertilized and the larger N mineralization must be ascribed to a residual N effect. However, this residual N effect did not compensate for the smaller input of plant-available N received by plots with cattle slurry. The ANR was considerably higher for NPK- than for AM-treated soils, and averaged over treatments and years, the mineral fertilizer value of cattle slurry was only 50.

Compared with Mariboss, the cultivar Hereford showed higher N uptake in the early spring, larger numbers of heads, heavier grains at harvest, and larger grain and total N offtake in 2015 (but not in 2016). Rasmussen *et al.* (2015) also found higher yields for Hereford compared with three other contemporary wheat cultivars and attributed this to a deeper root system. For ANR, Gaju *et al.* (2011) observed significant interactions between N fertilization and cultivar when testing a range of UK and French winter wheat cultivars. In the present study, the general performance of the two cultivars did not differ consistently with respect to the yields of grain and straw, grain and straw N concentrations and offtake, ANR or effect of N added with cattle slurry.

The optimum sowing time for winter wheat differs from region to region, depending primarily on the climatic conditions and soil types, but also on the technological stage of plant production (including the capacity of farm equipment for harvesting, drying and storing of grains, seedbed preparation and crop protection). In the agro-climatic region encompassing Denmark, timely sowing is generally considered to be mid-September. In most years, winter wheat is harvested in mid-August, but the harvest period may stretch into September due to adverse weather conditions. It is recognized that moving the sowing date from mid-September to mid-August has practical implications, including a narrower time window between harvest and sowing, a shorter period to control grass weeds, and an increased risk of early attacks by barley yellow dwarf virus and fungi such as mildew and eyespot (Jørgensen *et al.* 1997). These implications must be considered when evaluating the net benefits of earlier sowing in continuous winter wheat cropping and may call for more diverse cropping sequences leaving room for early sowing of wheat.

Conclusion

It is concluded that in the north-west European climatic region, moving the sowing date of winter wheat from mid-September to mid-August provides significant yield and N offtake benefits if management skills and sufficient equipment capacity is available.

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