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Impact of Early Sowing on Winter Wheat Receiving Manure or Mineral Fertilizers

Bent T. Christensen, Johannes L. Jensen, Ingrid K. Thomsen*

Aarhus University, Department of Agroecology, Blichers Allé 20, DK-8830 Tjele, Denmark

*Corresponding author (Ingrid.thomsen@agro.au.dk)

ABSTRACT

To reduce over-winter nitrate leaching from temperate soil under cereal cropping, nitrate catch crops can be grown between main crops. We hypothesize that earlier sowing can replace catch crops sown before winter wheat (*Triticum aestivum* L.) and improve wheat yields and N uptake. Early sown (late August) and timely sown (late September) wheat were tested over two cropping seasons (2011-12 and 2013-14) using two contemporary cultivars (Hereford and Mariboss) and increasing rates of N (0 to 300 kg total-N ha⁻¹) with animal manure (AM; cattle slurry) or mineral fertilizers (NPK), surface-applied in late March. We measured over-winter N uptake in wheat, harvest yields and N concentrations in grain and straw. Over-winter N uptake was 11 kg ha⁻¹ higher for early than for timely sown wheat; at harvest this benefit increased to 19 kg N ha⁻¹. Mariboss yielded more straw than Hereford whereas grain yields did not differ. Early sowing increased grain yields by 0.5 and 1.0 Mg ha⁻¹ for NPK and AM, respectively, regardless of N rate. Grain and straw N concentrations were higher with NPK than with AM, and NPK showed higher N use efficiency (0.48-0.53) than AM (0.15-0.22). Moving sowing of winter wheat from late September to late August provided higher grain and straw yields; the increased over-winter N uptake suggests that the beneficial effect of earlier sowing may surpass that of a catch crop. Cattle slurry surface applied in late March gave poor N use efficiency and low grain protein content.

24 **Abbreviations:** AM, animal manure (cattle slurry); DM, dry matter; NPK, mineral fertilizers; NUE,
25 nitrogen use efficiency; SEM, standard error of the mean

26

27 **Introduction**

28 Wheat remains a most important cereal crop within the European Union. In 2013 wheat accounted
29 for 62 % of the production of small grain cereals, the largest European producers being France,
30 Germany, and United Kingdom (Eurostat, 2015). In 2015, winter wheat (*Triticum aestivum* L.)
31 occupied 42 % of the area used in Denmark for cereals, corresponding to 23 % of the arable land
32 (Statistikbanken, 2016). On farms specialized in livestock production, autumn sown wheat is a
33 preferred cereal and is often grown with application of animal slurry in the spring. To reduce over-
34 winter leaching losses of nitrogen (N), cereal production in Denmark has become subject to
35 environmental regulations. These involve restrictions on use of N fertilizer (application times and
36 rates), prescribed use efficiencies for N in animal manure (depending on type of manure), and
37 compulsory nitrate catch crops in breaks between main crops (Dalgaard et al., 2014). Up to 14% of
38 the arable land may carry catch crops on farms with intense cereal production. However, national
39 regulations of N use and nitrate catch crops may differ even within regions with comparable climate
40 and production systems (Aronsson et al., 2016).

41 Fodder radish (*Raphanus sativus* L.) has been introduced as a nitrate catch crop in
42 breaks between cereal crops: seeds can be applied pre-harvest and subsequently the radish grows
43 vigorously and may accomplish a significant reduction in nitrate leaching losses (Hansen et al.,
44 2015; Li et al., 2015). However, when incorporated before planting of winter wheat, much of the N
45 captured by the radish may become re-mineralized, nitrified and leached even at the low soil
46 temperatures prevailing during autumn and winter (Thomsen et al., 2016). Losses of mineralized N

47 reduce the effect of the catch crop (Thomsen and Hansen, 2014) and call for alternatives. For winter
48 wheat one such alternative could be an earlier sowing date.

49 Field trials established in southeast England during the 1980'ies showed that
50 compared to winter wheat sown in October, wheat sown in September recovered more soil N,
51 produced greater yields of grain and straw, and developed a greater root system (Barracclough and
52 Leigh, 1984; Widdowson et al., 1987; Milford et al., 1993). In more recent studies on winter wheat
53 grown in southern Sweden (Myrbeck et al., 2012), northwest Germany (Sieling et al., 2005) and
54 eastern Denmark (Rasmussen and Thorup-Kristensen, 2016) grain yields appear to be only
55 marginally improved by early sowing. Even if earlier sowing of winter wheat may reduce nitrate
56 leaching and thereby substitute the effect of a dedicated nitrate catch crop, implementation of early
57 sowing will only become widespread if wheat yields and N use efficiencies are improved.

58 Previous studies on the effect of early sowing have relied on N added in mineral
59 fertilizers while studies testing the interaction between sowing date, use of animal manure and
60 wheat cultivar could not be traced. Our objective was to examine the effect of sowing date for two
61 contemporary winter wheat cultivars dressed with increasing rates of N in cattle slurry or mineral
62 fertilizers. Over-winter N uptake, harvest yields, and concentrations of N in grain and straw were
63 tested over two cropping seasons in the Askov Long-Term Experiment on Animal Manure and
64 Mineral Fertilizers (Askov-LTE).

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MATERIALS AND METHODS

Askov-LTE: Site and Experimental Layout

The Askov-LTE was established in 1894 on the Lermarken site at Askov Experimental Station, Denmark (55°28'N, 09°07'E). Annual precipitation, potential evapotranspiration and temperature are 862 mm, 543 mm and 7.7°C, respectively (1961-1990 averages). The soil is a light sandy loam derived from Weichselian glacial deposits (Nielsen and Møberg, 1984) and classifies as Ultic Hapludalf (Soil Survey Staff, 2014). The topsoil (0-20 cm) has 10% clay (<2 µm), 12% silt (2-20 µm), 43% fine sand (20-200 µm) and 35% coarse sand (200-2000 µm). Soil pH is maintained in the range 5.5-6.5 by addition of magnesium-enriched lime every four years. Sulphur is applied annually at a rate of 12.5 kg ha⁻¹.

The Askov-LTE includes four separate fields (termed B2-, B3-, B4- and B5-field) with a four course rotation of winter wheat (*Triticum aestivum* L.), silage maize (*Zea maize* L.), and spring barley (*Hordeum vulgare* L.) undersown with a grass-clover mixture that is used for cutting in the subsequent production year. The grass-clover crop includes lucerne (*Medicago sativa* L.), alsike clover (*Trifolium hybridum* L.), birdsfoot trefoil (*Lotus corniculatus* L.), perennial ryegrass (*Lolium perenne* L.), fescue (*Festuca pratensis* Huds.), and timothy (*Phleum pratense* L.). The four crops in the rotation are grown in a fixed sequence across the four fields; thus a given field grows only one crop in a given year. Crop protection measures (e.g. pesticides and weed killers) are applied when needed.

The main treatments of the Askov-LTE are unfertilized plots and plots receiving different rates (½, 1, 1½, 2 times the standard rate for a given crop) of nitrogen (total-N), phosphorus (P) and potassium (K) in animal manure (AM) or mineral fertilizer (NPK). One subsidiary treatment (1 PK) takes only P and K in mineral fertilizers. Averaged across the rotation (no additions to the grass-clover crop), 1 AM and 1 NPK corresponds to an annual input of 100 kg

95 total-N ha⁻¹, 20 kg P ha⁻¹, and 80 kg K ha⁻¹. Mineral fertilizer N, P and K are given in calcium-
96 ammonium-nitrate, triple-super-phosphate and potassium-chloride, respectively. Since 1973, AM
97 has been cattle slurry with approximately 5 % dry matter and 60-70 % of its total N on ammoniacal
98 form. The treatment 1 AM receives 25 Mg ha⁻¹ (wet weight). Not all nutrient treatments are present
99 in all fields and the number of treatment replicates within a field differs. Within each field, the
100 nutrient treatments (different nutrient source and different nutrient rates) and their replicates are
101 randomized. Christensen and Johnston (1997) and Christensen et al. (2006) provide further details.
102

103 **Experiments with Early and Timely Sown Wheat**

104 The present study was embedded in the B2-field (2011-2012) and the B5-field (2013-2014) using
105 the nutrient treatments (Table 1): 1 PK (no N input), ½ NPK, 1 NPK, 1½ NPK, 2 NPK (2 NPK not
106 present in B5-field), ½ AM, 1 AM, 1½ AM, and 2 AM (2 AM not present in B5-field). For winter
107 wheat, nutrient level 1 corresponds to 150 kg total-N, 30 kg P and 120 kg K ha⁻¹. Mineral fertilizers
108 and cattle slurry were surface applied onto the growing crop in late March (Table 2). The grass-
109 clover crop that precedes winter wheat in the rotation was sprayed with glyphosate after the final
110 cut in August and the grass sward ploughed under one week later.

111 Each plot was then split into four subplots to accommodate two wheat cultivars
112 (Hereford and Mariboss) and two sowing dates. A seedbed was prepared in August in two of the
113 four subplots by harrowing and seeds of Hereford and Mariboss treated with Latitude[®] (Monsanto,
114 UK) against take-all (*Gaeumannomyces graminis*) were sown in separate subplots (termed early
115 sowing). The remaining two subplots were left undisturbed from ploughing until September. Then
116 seedbeds were prepared as for early sowing and Hereford and Mariboss planted in separate subplots
117 (termed timely sowing). The seeding rate targeted 225 and 350 seeds m⁻² for early and timely sown
118 wheat, respectively, and the distance between wheat rows was 12 cm. Table 2 shows the size of the

119 nutrient treated plots and the subplots subjected to different sowing date and wheat cultivars
120 together with dates for main field operations. Altogether, we employed 144 subplots in the B2-field
121 and 92 in the B5-field. Air temperature and monthly precipitation during the two experimental
122 periods are shown in Fig. 1.

123 The wheat was harvested at physiological maturity in August using a plot combine
124 harvester that allowed separate determination of grain and straw yields and left 5 cm of wheat
125 stubble.

126 127 **Over-Winter Sampling of Wheat Biomass**

128 To determine wheat N uptake during the autumn and winter periods, aboveground wheat biomass
129 (divided into green and wilted plant parts) of early and timely sown Hereford was sampled
130 sequentially at eight dates from late October to mid-March (Fig. 2) in three randomly selected
131 replicates of 1 NPK and 1½ NPK (only two replicates of 1½ NPK present in B5-field; Table 1).
132 Each sampling area was defined by a metal frame (610 x 65.4 cm) that was divided into eight
133 rectangles (50 x 60 cm). Shortly after wheat germination, one frame was placed on the soil surface
134 just outside the net area of each subplot. The frame covered four wheat rows. At eight dates during
135 autumn, winter and spring all green plant parts were cut in one randomly selected rectangle of each
136 frame. At the first sampling all wilted plant parts were removed. At the second sampling wilted
137 plant parts were removed from the seven rectangles leaving out the one where green plant parts had
138 been collected at the first sampling. This procedure continued until all eight rectangles had been
139 sampled. The wilted plant parts from each rectangle were bulked to one composite sample.

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Chemical Analyses

Green and wilted plant parts collected over-winter and grain and straw samples obtained at harvest were dried at 80°C for dry matter (DM) determination and ball-milled subsamples were analysed for N on a Flash 2000 Organic Elemental Analyzer. Soil contamination of plant samples collected over-winter was determined as acid-insoluble ash after igniting subsamples at 550°C for 4 h. The ash was subtracted from the measured biomass yield and the N concentration adjusted accordingly.

Statistical Analyses and Calculations

The experimental design in both fields (B2 and B5) was a split-block design with plot (nutrient source and rate) and sowing date as main factors and wheat cultivar as sub-factor. The statistical analysis applied the R-Project software package Version 3.1.1 (R Development Core Team, 2014). All data analyses refer to individual year/field. Linear mixed effect models were used to test the significance of sowing date (early and timely), nutrient source (AM and NPK), nutrient rate (½, 1, 1½ and 2), wheat cultivar (Hereford and Mariboss), and their interactions on wheat grain and straw dry matter yields, N concentrations and N uptake using the *lmer* function of the *lme4* package. Management parameters were fixed effects while field strip (position in the field) and interactions between field strip and plot, between field strip and sowing date, and between field strip, sowing date and plot were set as random effects. This allowed us to account for the unbalanced design of the B2- and B5-fields with different nutrient treatments having different number of replicates. The significance of management parameters was assessed by ANOVA type III applying the Kenward and Roger (1997) method for calculating degrees of freedom.

For plots dressed with NPK, a quadratic N response model was fitted to the grain yield data:

$$Y = aX^2 + bX + c$$

167 where Y is the yield of field replicates (Mg grain ha^{-1}), X is the amount of N applied (kg N ha^{-1}), and
168 a , b and c are model parameters. Potential grain yield was estimated as the maximum of the
169 function:

$$170 \quad Y_{\max} = -b/2a$$

171 For treatments with AM, a linear function was fitted to the wheat yield data as no yield maximum
172 was reached. Nitrogen use efficiency (NUE) was calculated as $\text{kg grain N removed per kg total-N}$
173 applied. For NPK treatments, NUE was calculated as the slope of a linear regression of average
174 grain N yield against rate of N (up to 150 kg N ha^{-1}) due to non-linearity at higher N rates. For AM
175 treatments, NUE was based on all N rates.

176

177 RESULTS

178 Over-Winter Nitrogen Uptake

179 In 2011-12, the N uptake in early sown Hereford grown in plots receiving 1 and $1\frac{1}{2}$ NPK increased
180 from around 10 kg N ha^{-1} in late October to above 30 kg N ha^{-1} in mid-March (Fig. 2). For timely
181 sown wheat, the N uptake during the same period increased from 4 to 20 kg N ha^{-1} . The greater N
182 uptake in early than in timely sown wheat accounted for 11 kg N ha^{-1} at most samplings as an
183 average of plots receiving 1 NPK and $1\frac{1}{2}$ NPK. In 2013-14, over-winter N uptake was generally
184 smaller but at most samplings the difference between early and timely sown wheat were as in 2011-
185 12 (Fig. 2). The proportion of N found in wilted plant parts increased over-winter but differed
186 between the two cropping years. In 2011-12, almost equal amounts of N were present in wilted and
187 green plant parts (Fig. 2). The increased proportion of N in wilted plant parts is ascribed a cold spell
188 in January and February 2012 when air temperature over a short period dropped to -12°C (Fig. 1).
189 The early sown wheat appeared to be more vulnerable to freezing than timely sown wheat. A

190 similar temperature drop did not occur in 2013-14 and the ratio between N in wilted and green plant
191 parts was generally smaller and differed less between sowing dates.

192

193 **Yields of Grain and Straw Dry Matter**

194 The grain yield did not differ between the two cultivars and no interaction was found between
195 sowing time and cultivar (Table 3). The potential grain yields for early sown wheat dressed with
196 NPK and harvested in 2012 and 2014 were 7.7 and 7.6 Mg ha⁻¹, respectively; the corresponding
197 yields for timely sown wheat were 7.3 and 7.2 Mg ha⁻¹. Grain yield responded very differently to N
198 given in AM and in NPK (Fig. 3). While an optimum grain yield was found for NPK, grain yield
199 increased linearly and no optimum was obtained with AM. Early sowing increased yields of grain
200 and straw for AM as well as NPK treated wheat (Table 3; Figs. 3 and 4). The effect of early sowing
201 was more prominent for wheat dressed with AM than for wheat given NPK and significant
202 interactions between date of sowing and nutrient source was found for grain in both years and for
203 straw also in 2014 (Table 3). The time of sowing did not significantly interact with N application
204 rate neither for grain yield nor for straw yield. Interaction between sowing date, N rate and N source
205 was generally absent (Table 3).

206 In both cropping years, the cultivar Mariboss yielded significantly more straw than
207 Hereford (Fig. 4). For straw yields obtained in 2012, we found an interaction between cultivar and
208 nutrient source (Table 3). Thus, Mariboss responded more to NPK addition than Hereford. The
209 harvest index (grain yield divided by grain + straw yield) calculated across N application rates
210 appeared higher for Hereford (0.55 in 2012 and 0.58 in 2014) than for Mariboss (0.53 in 2012 and
211 0.55 in 2014) but harvest index was not significantly affected by sowing date or N application rate
212 (data not shown).

213

Nitrogen Concentrations and Uptake

Concentrations of N in grain and straw responded very differently to increasing rates of NPK and AM (Figs. 5 and 6). Increasing rates of NPK increased N concentrations in grain as well as in straw while N concentrations were little affected by rate of N in AM. Accordingly, the interaction between N source and N rate was highly significant for grain and straw N concentrations in both years (Table 3).

The time of sowing had much less influence on N concentrations in grain and straw than the N source (Fig. 5 and 6). Early sowing generally accomplished a slightly higher N concentration than timely sowing but changes were not significant for grain in 2014 (Table 3). While a significant effect of cultivar on concentrations of N in grain and straw was seen for wheat harvested in 2012, no effect was seen for the 2014 harvest.

Harvested grain removed 52 - 165 and 45 - 146 kg N ha⁻¹ in 2012 and 2014, respectively, while straw removed 12 - 99 kg N ha⁻¹ and 8 - 51 kg N ha⁻¹ (Figs. 7 and 8). For wheat dressed with 75 to 225 kg N ha⁻¹, straw accounted for 16 - 34 % of the total N removed at harvest. The N removal in grain and in straw was generally higher after early than after timely sowing (Table 3). Source and rate of N also had a significant influence on the amount of N removed wheat grain and straw at harvest. More N was harvested with NPK than with AM and the N uptake increased with increasing N rate (Fig. 7 and 8). In general, interaction between time of sowing, N source and N rate was not significant (Table 3) indicating that the different response to N rate for AM and NPK was not affected by sowing time.

DISCUSSION

Potential for Reduced Over-Winter Nitrogen Loss

One aim was to evaluate the potential of early sown wheat in reducing nitrate leaching. This was tested by measuring aboveground N uptake in the Hereford cultivar, grown on plots dressed with NPK close to crop-optimum N rate. Differences in plant N accumulation during the autumn and winter period are considered a valid indicator of changes in nitrate leaching losses (Myrbeck and Stenberg, 2014). In early December, we found that wheat sown in late August contained 18 – 22 kg N ha⁻¹ in green and wilted plant parts; this was 11 kg N ha⁻¹ more than held in wheat sown in late September. The increase in N uptake due to early sowing did not differ between the two NPK treatments reflecting the small differences in soil N (Table 1) and confirming that mineralization of soil N derived from previous applications of N in NPK has little impact on cereal yields and N offtake (Thomsen et al., 2003; Petersen et al., 2010, 2012).

Previous field trials in southern Sweden and eastern Denmark comparing winter wheat sown in late August/early September and late September showed comparable benefits of early sowing (6 to 13 kg N ha⁻¹) when plants were sampled in October and November (Myrbeck et al., 2012; Rasmussen and Thorup-Kristensen, 2016), and early sown wheat was found to reduce soil mineral N contents by up to 24 kg N ha⁻¹. Studies in southeast England showed that wheat sown in September held more N (20 to 34 kg ha⁻¹) than wheat sown in October when sampled in early March (Widdowson et al., 1987); this difference was however reduced to 4 -14 kg N ha⁻¹ at crop maturity. A subsequent study on similar sites (Milford et al., 1993) showed differences by early March of 10 – 20 kg N ha⁻¹; this N benefit of early sowing remained until crop harvest. In our study, the N benefit of early sowing was established in the autumn, maintained over-winter and then increased during the subsequent growth period.

261 It is well documented that N uptake in fodder radish during the period from seeding in
262 July/August until late November may exceed 50 kg N ha⁻¹ (e.g. Li et al., 2015) but when used as
263 nitrate catch crop before wheat sown in late September, N accumulation in radish range from 13 to
264 24 kg N ha⁻¹ (Thomsen and Hansen, 2014). Thus, the potential benefit of fodder radish in reducing
265 N leaching losses from under subsequent wheat aligns with that obtained by moving the wheat
266 sowing date from late September (normal sowing date in NW Europe) to late August.

267 Any difference in the accumulation and retention of N in wheat and radish roots is not
268 accounted for here, but the beneficial effect of sowing date may surpass that of fodder radish as the
269 extra N recovered by early sown wheat is removed from the field at harvest. Thus, early sown
270 wheat dressed with 150 kg N ha⁻¹ removed 19 kg N ha⁻¹ more in harvested grain and straw than
271 timely sown wheat. In contrast, N retained from leaching by the radish is returned to the soil where
272 the plant biomass becomes exposed to mineralization. Some of the mineralized N may be captured
273 by the emerging wheat or lost by leaching and denitrification. Thomsen and Hansen (2014) found
274 that the reduction in nitrate leaching obtained by catch crops was halved when catch crops were
275 terminated before sowing of winter wheat instead of left until late autumn or early spring.

276

277 **Yield Benefits of Early Sowing**

278 Previous field studies under NW European conditions and using mineral fertilizers report somewhat
279 diverging results on the effect of sowing date on wheat grain yields. Early studies show yield
280 advantages ranging from - 0.1 to + 1.2 Mg ha⁻¹ when wheat sowing is moved from late October to
281 late September (Widdowson et al., 1987; Milford et al., 1993). More recent studies report maximum
282 yield gains of 0.2 Mg grain ha⁻¹ (Sieling et al., 2005; Rasmussen and Thorup-Kristensen, 2016). For
283 a number of Swedish sites, grain yield benefits ranged from - 0.6 to + 0.6 Mg ha⁻¹ when sowing
284 date was moved from mid/late September to late August (Myrbeck et al., 2012).

285 For wheat dressed with NPK, we found that early sowing increased grain yield by 0.5
286 Mg ha⁻¹. For AM the increase was 1.0 Mg ha⁻¹ corresponding to the effect of adding 75 kg total-N
287 ha⁻¹ in AM. The benefit of early sowing remained the same regardless of fertilization rate (in 2012
288 up to 1 NPK). Thus, the foundation for the higher grain yield was established already in the early
289 autumn. The present study cannot single out the mechanisms leading to higher yields but these may
290 include a more extensive root system for early sown wheat (Barracough and Leigh, 1984; Foulkes
291 et al., 2009; Rasmussen and Thorup-Kristensen, 2016). The establishment of an extensive rooting
292 depth before winter dormancy not only provides greater N uptake in the autumn but may also
293 provide the wheat with a superior starting point when active growth commences in the spring.
294 Differences in root length established early in the growth period have been found to be maintained
295 throughout the growing season and to be positively related to grain yields (Barracough and Leigh,
296 1984). An early sowing date may provide a longer vegetative growth phase with a prolonged pre-
297 anthesis period and modifications in wheat N allocation and plant phenology. Thus Ferrise et al.
298 (2010) found that the number of grains per spike was higher for early sown than for late sown
299 durum wheat. We also found that straw yields were higher for early than for timely sown wheat,
300 indicating that early sowing lead to a larger capacity for photosynthesis and storage of
301 photosynthates. However, to provide a mechanistic explanation for the advantages of early sowing,
302 the entire growth cycle from seeding to harvest needs to be examined in greater detail.

303 Averaged across harvest year, sowing time, source of N and N rate, Mariboss
304 produced 0.5 Mg ha⁻¹ more straw than Hereford. Similarly, Larsen et al. (2012) found straw yields
305 of Mariboss to be higher than those of Hereford. In our study, straw yields were 0.7 Mg ha⁻¹ greater
306 for early than for timely sown wheat (averaged across cultivars, source of N type and N rate). When
307 collected for producing thermal energy or cellulosic ethanol, larger straw yields are beneficial

308 (Kløverpris et al., 2016). Milford et al. (1993) found straw yields to increase by 0.6 Mg ha⁻¹ (range:
309 0.3 to 0.8 Mg ha⁻¹) when sowing of wheat was moved from mid-October to mid-September.

310

311 **Nitrogen Utilization**

312 In the Askov-LTE, the N application rates are based on total-N. Consequently, wheat grown with
313 AM receives less inorganic N than wheat grown with NPK, and AM plots showed lower yields of
314 both grain and straw than corresponding NPK plots. Any background mineralization of soil organic
315 N derived from previous AM additions appears not to fully compensate for reduced rates of plant
316 available N supplied with AM early in the growing season. The N use efficiency (NUE) for wheat
317 dressed with NPK ranged 0.42 - 0.53; for AM the NUE was 0.15 - 0.22 (Table 4). Thus, the mineral
318 fertilizer equivalent of AM (NUE for AM divided by NUE for NPK) surface applied to wheat in
319 late March averaged 0.37 (range: 0.33 to 0.42). This means that it only takes 37 kg N ha⁻¹ in NPK to
320 replace the effect of 100 kg total-N ha⁻¹ applied with AM and indicates that a substantial part of the
321 ammoniacal N present in AM at the time of application has been lost, most likely by ammonia
322 volatilization (Webb et al., 2013).

323 The inferior effect of N in surface applied AM implies that even the highest rate of
324 slurry (2 AM = 300 kg total-N ha⁻¹) only provided a yield corresponding to 111 kg N ha⁻¹ added in
325 NPK. This was reflected in grain and straw N concentrations. Thus, grain N concentration for wheat
326 grown with AM was similar to that obtained for wheat grown on soil receiving only P and K (1 PK
327 plots) and soil receiving 75 kg N ha⁻¹ in NPK. The low N concentration provides poor grain quality
328 in terms of protein (N concentration x 6.25); for AM grain protein contents ranged from 8 to 9 %. In
329 contrast, concentration of N in grain and straw increased almost linearly with increasing addition of
330 N in NPK. When 150 kg N ha⁻¹ was added in NPK, grain N concentrations averaged 16 mg N g⁻¹
331 corresponding to a protein content of 10 %; this increased to 13 % when 225 kg N ha⁻¹ was added.

332 In spring, the additional accumulation of N in early sown wheat averaged 11 kg N ha⁻¹
333 for Hereford dressed with 1 NPK and 1½ NPK. This difference between early and timely sowing
334 increased during the growing season and ranged at harvest from 14 to 26 kg N ha⁻¹ in grain plus
335 straw, suggesting a superior utilization in early sown winter wheat of fertilizer N added in spring
336 and/or of N mineralized from the soil N pool during the growth period.

337 In both years, the amount of N removed in harvested grain and straw was significantly
338 higher for early sown than for timely sown wheat. Early sown wheat removed up to 257 kg N ha⁻¹
339 in 2012 and 196 kg N ha⁻¹ in 2014; the corresponding values for timely sown wheat were 241 and
340 187 kg N ha⁻¹. The N cycle of agroecosystems is more leaky than that of natural ecosystems
341 (Christensen, 2004) and any cropped soil will be subject over-winter leaching losses of N.
342 Considering the amount of N removed in the present study in harvested grain and straw, the overall
343 N balance of the wheat crop at yield optimum most likely becomes negative suggesting a decrease
344 in the soil organic N pool.

345

346 **Practical Implications for Wheat Production**

347 There are a number of practical implications of early sowing. The seeding rate should be adjusted
348 according to sowing time. A reduced seeding rate at early sowing provides a less dense wheat plant
349 canopy and may reduce early-season attacks by fungi such as mildew and eye spot (Jørgensen et al.,
350 1997). Nevertheless, early sowing may well call for a larger effort in terms of crop protection
351 against weeds, pests and plant diseases. We maximized crop protection by using reduced seeding
352 rate, Latitude treated seeds, relevant wheat cultivars, and by adopting a preventive plant protection
353 scheme.

354 When wheat is sown in late August, the time window between harvest of the previous
355 crop and sowing of the subsequent wheat crop will be narrow. The practical implication is less time

356 to prepare for the establishment of an early sown wheat crop which may call for greater capacity in
357 terms of farm machinery and manpower. This practical implication also has to be factored in when
358 evaluating the benefits of early sowing.

359

360

CONCLUSIONS

361 Our study showed distinct yield and N uptake benefits of moving winter wheat sowing from late
362 September to late August. This was true for grain as well as straw yields. The effect of early sowing
363 in reducing N leaching losses may surpass that obtained by establishing a nitrate catch crop before
364 timely sown wheat. However, we also found that surface application of AM in late March provided
365 poor N use efficiency and reduced grain protein compared to that of N applied in NPK.

366

367

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475 **Figure legends**

476 Fig. 1. Air temperature and monthly precipitation at Askov Experimental Station during the two
477 experimental periods (2011-2012 and 2013-2014).

478

479 Fig. 2. Nitrogen in aboveground plant parts of early and timely sown Hereford wheat sampled
480 during late October to mid-March. The wheat was grown in the B2-field (2011-2012) and the B5-
481 field (2013-2014). N in green = N in green plants parts; total-N = N in green and wilted plant parts.
482 Error bars are +/- 1 SEM (Standard Error of the Mean).

483

484 Fig. 3. Grain yields of early and timely sown wheat grown in the B2-field (2012 harvest) and the
485 B5-field (2014 harvest) with increasing rates of N in mineral fertilizer (NPK) or animal manure
486 (AM). Values are mean of Hereford and Mariboss cultivars and error bars are +/- 1 SEM.

487

488 Fig. 4. Straw yields of early and timely sown Hereford and Mariboss wheat cultivars grown in the
489 B2-field (2012 harvest) and the B5-field (2014 harvest) with increasing rates of N in mineral
490 fertilizers (NPK) or animal manure (AM). Error bars are +/- 1 SEM.

491

492 Fig. 5. Concentrations of N in grains from early and timely sown Hereford and Mariboss wheat
493 cultivars grown in the B2-field (2012 harvest) and the B5-field (2014 harvest) with increasing rates
494 of N in mineral fertilizers (NPK) or animal manure (AM). Error bars are +/- 1 SEM

495

496 Fig. 6. Concentrations of N in straw from early and timely sown Hereford and Mariboss wheat
497 cultivars grown in the B2-field (2012 harvest) and the B5-field (2014 harvest) with increasing rates
498 of N in mineral fertilizers (NPK) or animal manure (AM). Error bars are +/- 1 SEM.

499

500 Fig. 7. Removal of N in grain from early and timely sown Hereford and Mariboss wheat cultivars
501 grown in the B2-field (2012 harvest) and the B5-field (2014 harvest) with increasing rates of N in
502 mineral fertilizers (NPK) or animal manure (AM). Error bars are +/- 1 SEM.

503

504 Fig. 8. Removal of N in straw from early and timely sown Hereford and Mariboss wheat cultivars
505 grown in the B2-field (2012 harvest) and the B5-field (2014 harvest) with increasing rates of N in
506 mineral fertilizers (NPK) or animal manure (AM). Error bars are +/- 1 SEM.