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Cultivar improvement and environmental variability in yield removed nitrogen of spring cereals and rapeseed in northern growing conditions according to a long-term dataset

Pirjo Peltonen-Sainio* and Lauri Jauhiainen

MTT Agrifood Research Finland, Plant Production Research, FI-31600 Jokioinen, Finland

**email pirjo.peltonen-sainio@mtt.fi*

The balance between applied and harvested nitrogen (yield removed nitrogen, YRN %) is a recognized indicator of the risk of N leaching. In this study we monitored the genetic improvements and environmental variability as well as differences among crop species (spring cereals and rapeseed) in YRN in order to characterize changes that have occurred and environmental constraints associated with reducing N leaching into the environment. MTT long-term multi-location field experiments for spring cereals (*Hordeum vulgare* L., *Avena sativa* L. and *Triticum aestivum* L.), turnip rape (*Brassica rapa* L.), and oilseed rape (*B. napus* L.) were conducted in 1988–2008, covering each crop's main production regions. Yield (kg ha^{-1}) was recorded and grain/seed nitrogen content (N_{grain}, g kg^{-1}) analyzed. Total yield N (N_{yield}, kg ha^{-1}) was determined and YRN (%) was calculated as a ratio between applied and harvested N. A mixed model was used to separate genetic and environmental effects. Year and location had marked effects on YRN and N_{yield}. Average early and/or late season precipitation was often most advantageous for N_{yield} in cereals, while in dry seasons N uptake is likely restricted and in rainy seasons N leaching is often severe. Elevated temperatures during early and/or late growth phases had more consistent, negative impacts on YRN and/or N_{yield} for all crops, except oilseed rape. In addition to substantial variability caused by the environment, it was evident that genetic improvements in YRN have taken place. Hence, YRN can be improved by cultivar selection and through favouring crops with high YRN such as oat in crop rotations.

Key-words: nitrogen, growing conditions, cultivar, barley, oat, wheat, oilseed rape, turnip rape, yield, protein content

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Introduction

Risks associated with nitrogen leaching into natural water systems is high in northern Europe and especially in Finland with its more than 100000 lakes, 14000 km of Baltic coastline (Peltonen-Sainio et al. 2009d), and substantial annual precipitation averaging 500–650 mm for 1970–2000 (Finnish Meteorological Institute). While grasslands ensure continuous ground cover in the central and northern parts of Finland, spring-sown crops provide only partial ground cover in the main production areas in the south of the country. The capacity of spring sown crops to utilize nitrogen (N) determines the potential risk for N leaching in the major production areas of Finland, with typical peaks in autumn and winter (Syväsalo et al. 2006). Nitrogen surplus is evident when the quantity of N applied is greater than that used for production of crop biomass (Rankinen et al. 2007). For this and economic reasons it is essential that N application occurs when the crop needs it, when it can be used for biomass production and is harvested instead of remaining unused in the soil (Peltonen-Sainio et al. 2009d). Yield removed nitrogen (YRN, %) represents the ratio between applied and harvested N.

Most N in harvested grains derives from N translocated from senescing vegetative plant parts (Cox et al. 1985, Papakosta and Gagianas 1991, Bulman and Smith 1994). When available, N can also be taken up from the soil during grain filling (Cox et al. 1985). In northern Europe this occurs, for example, when N is not taken up adequately at pre-heading because of typical early summer drought (Peltonen-Sainio et al. 2010), manure is used or elevated late summer temperatures stimulate excess N mobilization from soil (Rajala et al. 2007). Typically N uptake values for fertilized wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) range from 20% to 100% of fertiliser applied in temperate regions (Gauer et al. 1992, Le Gouis et al. 2000, Sinebo et al. 2003, Noulas et al. 2004). This indicates considerable induced variability in N uptake according to growing conditions and challenges sustainable and economic fertilizer use.

Genetic variation in N uptake was reported for cereals (Kelly et al. 1995, Singh and Arora 2001). However, in wheat no consistent correlations between N uptake and year of cultivar release were recorded (Slafer et al. 1990, Calderini et al. 1995, Foulkes et al., 1998) in contrast to six-row barley (Bulman et al. 1993) and oat (*Avena sativa* L.) (Wych and Stuthman 1983, Welch and Leggett 1997). Modern cultivars have high yield potentials (Peltonen-Sainio et al. 2009b) associated with improvements in many N-related traits (Muurinen 2007). Early vigorous growth can also enhance N uptake as shown in modern wheat lines (Liao et al. 2004 and 2006). Genetic variation and gains were reported for other N traits that are important for efficient N use (Woodend et al. 1986, Papakosta 1994, Singh and Arora 2001). Improvements in key N traits are essential for efficient N uptake and use.

In this study, using 20-year multi-location trial datasets, we monitored the balance between genetic improvements and environmental variability for applied and harvested N in spring barley, oat and wheat as well as turnip rape (*Brassica rapa* L.) and oilseed rape (*B. napus* L.) in order to characterize current position but also past changes in YRN. We also assessed environmental constraints associated with reducing N leaching into the environment for spring cereal and rapeseed production systems.

Material and methods

Plant material, experimental design, measurements and estimations

MTT long-term field experiments for spring cereals (barley, oat, and wheat), turnip rape, and oilseed rape were conducted in 1988–2008 at 12–19 different locations in Finland according to crop and production area. The experiments were part of the MTT Official Variety Trials and all followed procedures specified for that purpose (Kangas et al. 2005). In addition to MTT Agrifood Research

Finland, which has numerous regional research units in Finland, some of the experiments were organized by plant breeding companies and private agricultural research stations.

All experiments were arranged as randomized complete block designs or incomplete block designs. Three to four replicates were used. Each year the tested set of cultivars and breeding lines changed, but long term-check cultivars were used. Annual turnover of cultivars and breeding lines was usually less than 20%, which made it possible to separate effects of environment and genotype. Plots were 7–10 m × 1.25 m, depending on location and year. Seeding rate depended on crop, conforming to the commonly used seeding rates in Finland. Weeds were chemically controlled with commonly used agents. Diseases were not routinely controlled with fungicides to allow differences among entries in disease resistance to be recorded. Fertilizer use depended on cropping history, soil type and fertility and was comparable with standard practices in Finland. There was, however, no systematic reduction or increase in N fertilizer use during the 20-year study period.

Cereals and rapeseed were combine-harvested and the grain/seed weighed (kg ha^{-1}) after removing straw, weed seeds, and other particles. Grain/seed moisture content was determined by weighing samples before and after oven drying, or more recently by using a GAC II grain analysis computer (DICKEY-john corporation, USA). Grain and seed nitrogen content (N_{grain}, g kg^{-1}) were analyzed using the Kjeldahl-method. Yield and N content were both adjusted to 0% moisture content. Total yield N (N_{yield}, kg ha^{-1}) was calculated by multiplying yield (kg ha^{-1}) by N_{grain} (%) and dividing by one hundred.

Yield removed N (YRN, %) was calculated by dividing N_{yield} (kg ha^{-1}) by applied N fertilizer rate (kg ha^{-1}) and multiplying by one hundred. As no unfertilised plots were included in these long-term experiments, contribution of soil derived N to YRN could not be distinguished. In addition to YRN, we approximated the likely minimum to maximum range of N use efficiency (NUE_{range}, kg kg N^{-1}) and N harvest index (NHI_{range}, %). Due to absence of actual measurements of harvest index (HI) for these long-term datasets, for above-ground vegetative biomass (VEGE, kg ha^{-1}) we estimated ranges of HI documented for Finnish conditions (Peltonen-Sainio et al. 2008, Hakala et al. 2009, Pahkala et al. 2009). These were 0.44–0.60 for two-row barley, 0.47–0.63 for six-row barley, 0.40–0.56 for oat, 0.35–0.48 for wheat, and 0.28–0.38 for turnip rape and oilseed rape. Furthermore, due to lack of information on N content of vegetative above-ground biomass (N_{vege}, g kg^{-1}) in these experiments, we used mean estimates of 0.58%, 0.43%, 0.41%, 0.42%, 0.90% and 0.90% for two- and six-row barley, oat, wheat, turnip rape and rapeseed, respectively. These estimates were based on results from e.g. Muurinen et al. (2007), Peltonen-Sainio et al. (2009c and unpublished crude data), and Hocking et al. (1997). By this means, NUE_{range} was estimated as yield divided by (N_{grain}+N_{vege}), having minimum and maximum estimates for N_{vege} according to HI range typical for each crop. Similarly, NHI_{range} was estimated as N_{grain} divided by (N_{grain}+N_{vege}) and multiplied by one hundred. As NUE_{range} and NHI_{range} were only rough estimates, they were not necessarily included in statistical analyses. Benchmarking with documented cereal NHI values, showed our NHI_{range} estimates to be close to or even exceeding 80% (Spiertz and de Vos 1983, Feil 1997, Noulas et al. 2004), though NHI is strongly affected by e.g. weather conditions (Feil, 1997).

Statistical analyses

The main purpose of the statistical analysis of yield and nitrogen content was to estimate two effects: genetic and environmental effects. A mixed model technique was applied for this purpose using the following statistical model for each individual crop:

$$y_{ijk} = \mu + \alpha_i + \beta_{jk} + \varepsilon_{ijk}$$

where y_{ij} is the observed seed yield or nitrogen content of the ith cultivar in the jth location and kth year,

μ is the intercept, α_i is the effect of the ith cultivar, β_{jk} is the effect of the jkth experiment and ε_{ijk} is the normally distributed residual error.

Nitrogen traits of cultivars were compared using the estimated cultivar effects, $\hat{\alpha}_i$. Cultivars included in 20 or more experiments contributed to the comparison. For oilseed rape, limitation was decreased to 10 experiments because the annual number of trials was smaller than for other crops. By this means, 60 two-row barley, 51 six-row barley, 65 oat, 44 wheat, 33 turnip rape and 22 oilseed rape cultivars were compared.

During the next stage the estimated environmental effects, $\hat{\beta}_{jk}$, were examined graphically by drawing box-plots for all experimental sites and years. Correlation analysis was performed to measure relationships between studied traits and variables. Correlation analysis was applied using the estimated environmental effects.
Subsequently $\hat{\beta}_{jk}$ values were used to compare different crops using the following mixed model and the REML (Restricted Maximum Likelihood) estimation method:

$$\hat{\beta}_{jkl} = \mu + \phi_l + \gamma_j + \eta_k + \iota_{jk} + \varphi_{jl} + \kappa_{kl} + \varepsilon_{jkl}$$

where $\hat{\beta}_{jkl}$ is the previously estimated environmental effect or derivative of these estimates (N_{yield}, N rate, YRN, NUE estimate, NHI estimate) for the lth crop, μ is the intercept, ϕ_l is the effect of the lth crop while γ_j, η_k, ι_{jk}, φ_{jl}, κ_{kl}, and ε_{jkl} are random effects of location, year, location x year, crop x location, crop x year, and residual, respectively. The model assumes that all the random effects are mutually independent. This model can estimate the mutually comparable crop means despite not testing the complete set of crops every year at all the locations.

The precipitation during early (15 May to 31 June) and late growing seasons (1 July to 15 Aug.) was calculated for each experiment from the data of the Finnish Meteorological Institute. According to precipitation, experiments were classified into three categories: dry, average or rainy. Early seasons with precipitation ≤55 mm, 56–104 mm and ≥105 mm were considered to be dry, average and rainy (±5 mm depending on crop species), while in late season ≤82 mm, 83–144 mm and ≥145 mm, respectively (±10 mm depending on crop species). The average condition contained 50% of experiments, while dry and rainy only 25%. This classification was done for both seasons and relationships between precipitation, YRN, and N_{yield} were examined using following model:

$$y_{ijk} = \mu + \omega_i + \upsilon_j + \tau_{ij} + \varepsilon_{ijk}$$

where y_{ijk} is the observed YRN or N_{yield}, μ is the intercept, ω_i is the effect of precipitation in the early season (i=dry, average, or rainy), υ_j is the effect of precipitation late in the season (j=dry, average, or rainy), τ_{ij} is the interaction between two seasons, and ε_{ijk} is the residual error. The relationships between mean temperature and YRN and N_{yield} were examined using the same procedure. All the statistical analyses were done using SAS/MIXED and SAS/CORR software (SAS 1999).

Results

Crop species differed significantly in yield, N_{grain}, N_{yield}, and YRN as well as in N fertilizer used (Table 1). Oat had superior yield, N_{yield} and YRN despite receiving less N fertilizer than two- and six-row barley. Turnip rape and oilseed rape contrasted with oat. Their YRN was only close to half of that in oat, although the N content in seeds clearly exceeded that of cereals. Of the cereals wheat had the lowest YRN. All crop yields were strongly and positively associated with N_{yield} and YRN, but were negatively associated with grain or seed N content (Table 2). Depending on crop, a 100 kg ha^{-1} increase in yield resulted in 1.5–2.7 percentage unit increase in YRN and 1.5–3.0 kg ha^{-1} increase in N_{yield}. In contrast, YRN was positively and significantly associated with N_{grain} ($p < 0.001$, r = 0.25) only for oat. Approximating the range for NUE and NHI suggested that cereals clearly out-perform turnip rape and oilseed rape: even the estimated maxima for NUE and NHI of oil crops were lower than estimated minima for NUE and NHI for any of the spring cereals (Table 1).

In general, location x year was the dominant source of variation associated with yield, N_{grain}, N_{yield}, and YRN (Table 3). Depending on the year, the yield ranged from –799 to 533 kg ha^{-1} compared with the mean yield over all years. Similarly N_{grain} ranged from –0.3 to 0.3 % units, N_{yield} from –7.8 to 7.2 kg ha^{-1}, and YRN from –9 to 11% units. Variation due to location exceeded that for year only for YRN, where it was –15 to 25% units. High within year and inter-annual variation for N_{yield} and YRN (Fig. 1 and 2) emphasized comprehensive instability in both N traits and in all crops. The slight differences in favour of wheat and rapeseed, which seemed to be more stable than the other cereals, is probably an artefact resulting from later maturing species grown in more southerly regions than oat and six- and two-row barley. Although total range of variability between the lowest and highest recorded N_{yield} and YRN did not show any clear and consistent trend of reduced within year variability, for oat and two- and six-row barley, the recorded values were more concentrated around their mean and/or median in the latter than the former part of the 20 year study period, especially regarding N_{yield}. There was no consistent tendency for improved mean N_{yield} and YRN over time. On the other hand, despite marked variability in N traits of cereals, years with exceptionally low YRN and N_{yield} were rare. Such years were 1998 and 1999 for

Table 1. Comparable crop means (standard errors of means in parentheses) for grain or seed yield, grain or seed N content (N_{grain}), N yield, N fertilizer application rate, yield removed N (YRN), and estimated ranges of N use efficiency (NUE) and N harvest index (NHI).

Crop	Yield (kg ha^{-1})	N_{grain} (%)	N_{yield} (kg ha^{-1})	N rate (kg ha^{-1})	YRN (%)	NUE estimate (kg kg^{-1} N)		NHI estimate (%)	
						Min	Max	Min	Max
Two-row barley	4990 (128)	1.9 (0.05)	81 (2.4)	89 (2.7)	95 (4.6)	42	50	69	81
Six-row barley	4740 (125)	2.0 (0.05)	80 (2.4)	89 (2.7)	93 (4.5)	46	52	78	87
Oat	5270 (127)	2.1 (0.05)	93 (2.4)	88 (2.7)	110 (4.5)	42	49	74	84
Wheat	4450 (139)	2.2 (0.05)	82 (2.6)	102 (2.9)	83 (5.0)	38	44	70	80
Turnip rape	1940 (138)	3.6 (0.05)	58 (2.6)	101 (2.9)	58 (4.9)	19	22	57	67
Oilseed rape	2020 (156)	3.7 (0.05)	63 (3.0)	105 (3.2)	61 (5.5)	19	22	58	68
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Table 2. Correlations of grain or seed yield (kg ha^{-1}) with grain N content (N_{grain}, %), N yield (kg ha^{-1}) and yield removed N (YRN, %), and the effect of increase in yield by 100 kg ha^{-1} on N traits for spring cereals and rapeseed according to 20 years multi-location Official Variety Trials (1988–2008).

Crop	Yield and N_{grain}			Yield and N_{yield}			Yield and YRN		
	Correlation coefficient	*p*-value	Change (% units)	Correlation coefficient	*p*-value	Change (kg ha^{-1})	Correlation coefficient	*p*-value	Change (% units)
Two-row barley	–0.26	<0.001	–0.005	0.90	<0.001	1.5	0.70	<0.001	1.9
Six-row barley	–0.25	<0.001	–0.005	0.89	<0.001	1.6	0.71	<0.001	2.0
Oat	–0.14	0.02	–0.003	0.86	<0.001	1.7	0.63	<0.001	2.3
Wheat	–0.35	<0.001	–0.009	0.87	<0.001	1.6	0.59	<0.001	1.5
Turnip rape	–0.17	0.03	–0.011	0.95	<0.001	2.9	0.80	<0.001	2.7
Rapeseed	–0.33	<0.01	–0.020	0.96	<0.001	3.0	0.79	<0.001	2.5

all cereals and for cereals other than wheat 1988 also. In contrast, such failures were more frequent for turnip rape and oilseed rape (Fig. 1 and 2).

Many significant effects were associated with growing conditions through responses of YRN and N_{yield} to precipitation and temperature. Precipitation effects at early and/or late season were frequently recorded for N_{yield}, though not in two-row barley and turnip rape (Table 4). In the case of significant effects, the trend was that rainy early or late seasons resulted in lower N_{yield} compared with below average precipitation conditions, while there were

Table 3. Sources of variation for grain or seed yield, grain or seed N content (N_{grain}), N yield, N fertilizer application rate, and yield removed N (YRN).

Trait and source of variation	Variance	Ratio[a]	Range of variation compared to mean caused by year and location (*p*-value)
Yield (kg ha^{-1}):			
Year	141579	0.19	–799 (<0.001) – 533 (<0.01)
Location	32474	0.04	–
Location × year	303299	0.40	
Year × crop	25076	0.03	
Location × crop	33829	0.04	
Residual	760948	1.00	
N_{grain} (%):			
Year	0.021	0.72	–0.3 (<0.001) – 0.3 (<0.001)
Location	0.012	0.39	–0.2 (0.01) – 0.2 (0.03)
Location × year	0.023	0.78	
Year × crop	0.004	0.14	
Location × crop	0.002	0.05	
Residual	0.030	1.00	
N_{yield} (kg ha^{-1}):			
Year	26.9	0.10	–7.8 (0.01) – 7.2 (0.03)
Location	29.5	0.11	0.0 – 7.0 (0.05)
Location × year	133.6	0.50	
Year × crop	7.8	0.03	
Location × crop	14.5	0.05	
Residual	265.4	1.00	
N rate (kg ha^{-1}):			
Year	0.0	0.00	–
Location	85.9	0.50	–16.9 (<0.001) – 18.9 (<0.001)
Location × year	25.4	0.15	
Year × crop	0.0	0.00	
Location × crop	38.5	0.22	
Residual	172.6	1.00	
YRN (%):			
Year	0.4	0.06	–9 (0.03) – 11 (<0.01)
Location	1.8	0.26	–15 (0.08) – 25 (<0.001)
Location × year	1.9	0.28	
Year × crop	0.0	0.00	
Location × crop	1.0	0.14	
Residual	7.0	1.00	

[a] compared to residual

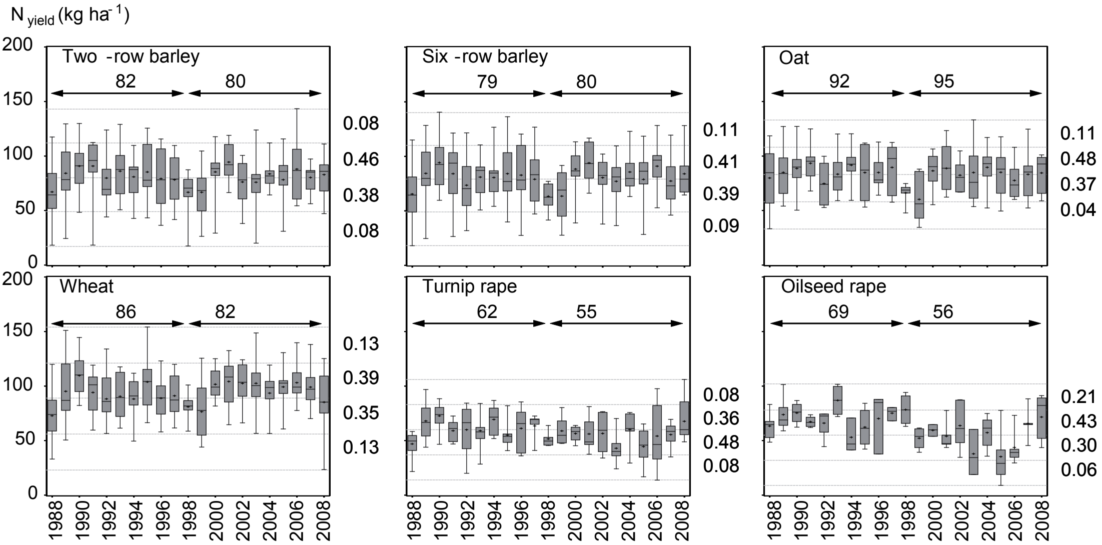

Fig. 1. Within year and between years variation in mean (asterisk), median (line within each box), standard deviation (the lowest and highest limit of the box), minimum, and maximum (bottom and top segment of the line, respectively) for N yield (kg ha^{-1}) of spring cereals and rapeseed. Also frequencies (in right-hand side) for each of the four groups having regular intervals between minimum and maximum N yield (shown with dash lines) are indicated as well as mean N yields above an arrow for early (1988–1998) and late study years (1999–2008). Mean N fertilizer application rates were 89 kg ha^{-1} for two- and six-row barley, 88 kg ha^{-1} for oat, 102 kg ha^{-1} for wheat, 101 kg ha^{-1} for turnip rape, and 105 kg ha^{-1} for oilseed rape.

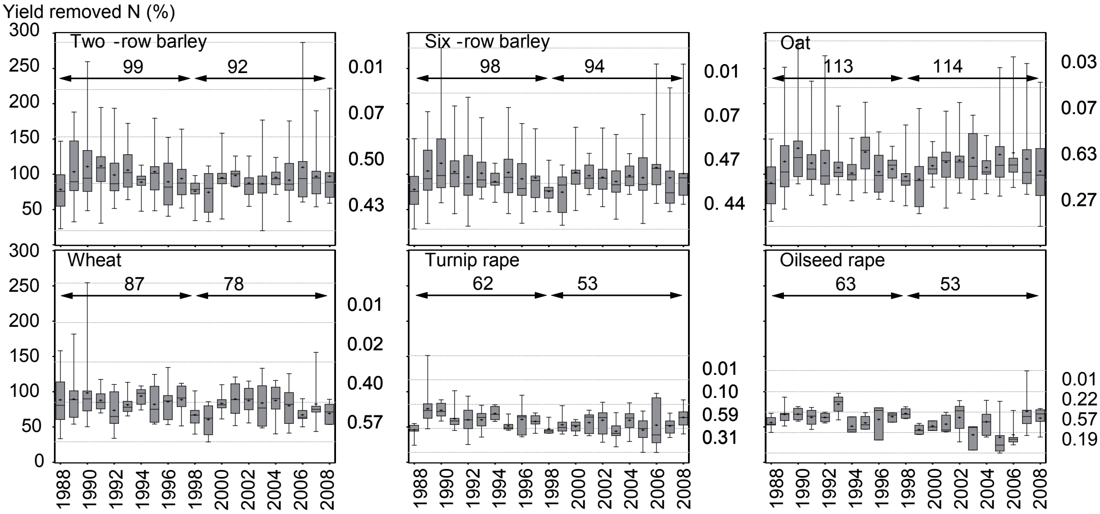

Fig. 2. Within year and between years variation in mean (asterisk), median (line within each box), standard deviation (the lowest and highest limit of the box), minimum, and maximum (bottom and top segment of the line, respectively) for yield removed N (YRN, %) of spring cereals and rapeseed. Also frequencies (in right-hand side) for each of the four groups having regular intervals between minimum and maximum YRN (shown with dash lines) are indicated as well as mean YRN above an arrow for early (1988–1998) and late study years (1999–2008). Mean N fertilizer application rates were 89 kg ha^{-1} for two- and six-row barley, 88 kg ha^{-1} for oat, 102 kg ha^{-1} for wheat, 101 kg ha^{-1} for turnip rape, and 105 kg ha^{-1-} for oilseed rape.

no consistent differences in effect between dry and average precipitation conditions for N_{yield}. For YRN late season precipitation was close to significant, but only for six-row barley and oilseed rape (Table 4). For six-row barley, high precipitation markedly reduced YRN compared with average conditions while for oilseed rape dry conditions resulted in low YRN. No significant interactions between early or late season precipitation were recorded for any of the crops or for YRN or N_{yield}. Temperature had very consistent and significant or close to significant effect on YRN of two-row barley (at late season), six-row barley (early and late), oat (late), and turnip rape (early). YRN was increased at low to average temperatures and at average to high temperatures (Table 5). Temperature effects on N_{yield} were, however, dependent on crop and time of season. Above average temperatures

Table 4. Significant precipitation effects at early and late growing season on N yield and yield removed N (YRN) of spring cereals and rapeseed. Seasons are grouped to be average, dry, or rainy and mean estimates of N trait for each condition are shown with standard errors of the means in parentheses.

Trait and crop	Significance		Mean estimate (s.e.) for N trait and condition		
	Early or late season	*p*-value	Dry	Average	Rainy
YRN (%):					
Six-row barley	Late	0.09	90 (4.8)	99 (2.9)	88 (4.8)
Oilseed rape	Late	0.06	49 (4.7)	63 (3.4)	63 (5.3)
N_{yield} (kg ha^{-1}):					
Six-row barley	Early	0.01	75 (3.0)	83 (1.9)	73 (3.2)
Six-row barley	Late	0.04	77 (3.1)	82 (1.8)	73 (3.1)
Oat	Early	<0.01	88 (3.1)	97 (2.0)	87 (2.9)
Oat	Late	0.03	94 (2.9)	94 (2.0)	84 (3.1)
Wheat	Early	0.03	73 (4.4)	86 (2.5)	85 (4.0)
Oilseed rape	Late	0.09	66 (6.1)	61 (3.3)	60 (5.2)

Table 5. Significant temperature effects at early and late growing season on N yield and yield removed N (YRN) of spring cereals and rapeseed. Seasons are grouped to have average, low, or high temperatures and mean estimates of N trait for each condition are shown with standard errors of means in parentheses.

Trait and crop	Significance		Mean estimate (s.e.) for N trait and temperature condition		
	Early or late season	*p*-value	Low	Average	High
YRN (%):					
Two-row barley	Late	0.06	100 (4.4)	95 (3.1)	85 (4.6)
Six-row barley	Early	0.11	99 (4.3)	96 (3.0)	87 (4.1)
Six-row barley	Late	0.03	100 (4.0)	97 (2.9)	85 (4.5)
Oat	Late	0.11	118 (5.1)	111 (3.6)	102 (5.5)
Turnip rape	Early	0.03	65 (3.4)	57 (2.3)	52 (3.4)
N_{yield} (kg ha^{-1}):					
Two-row barley	Early	0.05	82 (3.0)	82 (2.3)	74 (2.8)
Six-row barley	Early	<0.01	81 (2.8)	83 (1.9)	71 (2.6)
Oat	Early	<0.01	91 (2.9)	96 (2.0)	84 (2.9)
Wheat	Early	<0.001	94 (3.8)	81 (2.5)	73 (4.3)
Turnip rape	Early	0.05	64 (3.1)	57 (2.1)	53 (3.1)
Turnip rape	Late	0.07	54 (3.1)	62 (2.1)	57 (3.1)

early during the season reduced N_{yield} of all cereal species and turnip rape. For turnip rape, average temperatures during late season were most advantageous for N_{yield}.

Comprehensive differences among cultivars were recorded for YRN and N_{yield} (Table 6). We found the highest relative derived differences among cultivars for N traits in oilseed rape, for which the ranges between the weakest and strongest cultivars were 31% units for YRN and 33 kg ha^{-1} for N_{yield}. In contrast to oilseed rape, differences among turnip rape cultivars were more modest: 14% units for YRN and 14 kg ha^{-1} for N_{yield}. For cereals the range was greatest for oats, reaching 35% units for YRN and 29 kg ha^{-1} for N_{yield}. For wheat it was 24% units and 24 kg ha^{-1}, for two-row barley 21% units and 19 kg ha^{-1}, and for six-row barley 26% units and 20 kg ha^{-1}. When comparing year of release for the top five and bottom five cultivars, according to their YRN, it was evident that in general, and for all crops, modern cultivars outperformed the older ones (Table 7). This was particularly striking in six-row barley, wheat, turnip

Table 6. Cultivar differences for N yield and yield removed N (YRN) in spring cereals and rapeseed (n=60 for two-row barley, n=51 for six-row barley, n=65 for oat, n=44 for wheat, n=33 for turnip rape, and n=22 for oilseed rape). Std, standard deviation of mean.

Crop	Mean	Std	Std/ mean	Min	Max
N_{yield} (kg ha^{-1}):					
Two-row barley	81	4.2	5.2	70	89
Six-row barley	80	4.9	6.1	70	90
Oat	93	4.5	4.9	74	103
Wheat	82	6.2	7.6	69	93
Turnip rape	59	3.2	5.4	52	66
Oilseed rape	69	9.7	14.0	52	85
YRN (%):					
Two-row barley	94	4.8	5.1	83	104
Six-row barley	94	6.0	6.4	81	107
Oat	110	5.5	5.0	87	122
Wheat	82	6.4	7.8	69	93
Turnip rape	59	3.2	5.5	51	65
Oilseed rape	66	9.4	14.2	50	81

Table 7. Ranking of the five top- and bottommost cultivars of spring cereals and rapeseed according to their yield removed N (YRN, %) (n=60 for two-row barley, n=51 for six-row barley, n=65 for oat, n=44 for wheat, n=33 for turnip rape, and n=22 for oilseed rape) with year of release in Finland in parentheses.

Cultivar	Two-row barley		Six-row barley		Oat		Wheat		Turnip rape		Oilseed rape	
ranking	Cultivar	YRN (year)	Cultivar	YRN (year)	Cultivar	YRN (year)	Cultivar	YRN (year)	Cultivar	YRN (year)	Cultivar	YRN (year)
Top:												
1st	Tolar	104 (2003)	Vilde	107 (2005)	Venla	122 (2007)	Anniina	93 (2001)	Cordelia	65 (2009)	Trapper	81 (2009[a])
2nd	Justina	104 (2006)	Tiril	106 (2006)	Roope	120 (1996)	Epos	93 (2007)	Eos	64 (2007)	Sheik	78 (2008)
3rd	Tocada	102 (2006)	Pilvi	103 (2005)	Aslak	119 (1999)	Bombona	93 (2008)	Pouta	63 (2001)	Ilves	77 (2008)
4th	Ingmar	102 (2007)	Einar	103 (2008)	Fiia	116 (2002)	Amaretto	91 (2003)	Apollo	62 (2006)	Merryl	73 (2008)
5th	Xanadu	101 (2007)	Gaute	102 (2003)	Peppi	116 (2006)	Picolo	90 (2006)	Valo	61 (1996)	Wildcat	73 (2002)
Bottom:												
5th	Mentor	92 (1998)	Hjan Potra	87 (1983)	Ivory	107 (2004)	Runar	75 (1987)	Kelta	57 (1991)	Bullet	58 (1996)
4th	Prestige	91 (2007)	Hjan Eero	86 (1975)	Revisor	106 (2001)	Kadett	72 (1981)	Kova	57 (1988)	Ebony	58 (1996)
3rd	Kymppi	90 (1986)	Hjan Pokko	86 (1980)	Salo	106 (1989)	Hjan Tapio	71 (1980)	Valtti	56 (1985)	Bounty	57 (1992)
2nd	Kustaa	85 (1979)	Agneta	85 (1982)	Karhu	103 (1985)	Ruso	70 (1967)	Nopsa	56 (1986)	Topas	53 (1984)
1st	Prisma	83 (1995)	Hankkija-673	85 (1973)	Lisbeth (naked)	87 (1994)	Hjan Ulla	69 (1975)	Ante	51 (1982)	Varma	50 (1985)

[a] expected

rape, and oilseed rape. In two-row barley the only exception to this tendency was for cultivar Prestige, which was only recently included on the National List of Plant Varieties by the Finnish Plant Variety Board. It has very low YRN. This was also true for oat cultivars Ivory and Revisor. Even though top cultivars of most crops were all released in the 2000s, oat differed by having two cultivars (Roope and Aslak) released during the late 1990s in the top YRN ranks, similarly to turnip rape cultivar Valo (Table 7). Substantial genetic gains in YRN were also evident for all crops when comparing the mean YRN among decades based on introduced cultivars (Table 8).

Discussion

Even though the environment had marked effects on YRN and N_{yield} of spring cereals, turnip rape, and oilseed rape, it was also evident that cultivar differences (Table 6) and genetic improvements in N traits were significant. For example, when comparing a large number of cultivars (ranging from 22 to 65, depending on crop), according to their YRN the top five ranked cultivars were all released in Finland in the 2000s, the only exception being two late oat cultivars and a turnip rape cultivar, both released in the 1990s (Table 7). Moreover, only one two-row barley cultivar and two oat cultivars from the 2000s were among the five bottommost cultivars according to YRN comparisons. Results from additional analyses indicated that improvements were consistent and significant over time (Table 8), demonstrating the important role of plant breeding and cultivar selection in improving the balance between applied and harvested N, thereby reducing the N leaching risk. Bertholdsson and Stoy (1995) and Foulkes et al. (1998) also reported that the most recent cultivars were adapted to higher fertilizer application N rates and they took up relatively more N from fertilizer compared with older cultivars.

Improved yields were associated with genetic improvements in YRN and N_{yield}. On the other hand, N_{grain} was associated with YRN only in oat, even though the top ranked (according to YRN) wheat cultivar Anniina had only a moderate yield (4580 kg ha^{-1} compared with 5090–5610 kg ha^{-1} for the other top five cultivars), but exceptionally high N_{grain} (2.42% compared with 1.89–2.09% for other top five cultivars). Furthermore, crops with higher mean yields had higher YRN (Table 1). Consistent genetic gains in yield potential of all these crops have taken place during recent years in the northernmost European growing areas as recently reported: by ca. 26–41 kg ha^{-1} y^{-1} depending on spring cereal and ca. 17 kg ha^{-1} y^{-1} for turnip rape (Peltonen-Sainio et al. 2007 and 2009b). Harvest index has increased substantially through plant breeding, contributing to genetic yield gains, whereas total above-ground biomass has remained virtually unchanged (Austin et al. 1980, Bulman et al. 1993). The impact of yield increase on increase in YRN and N_{yield} was highest for turnip rape and oilseed rape and lowest for wheat, in the case of YRN, although for N_{yield} differences among cereals

Table 8. Mean of yield removed N (YRN, %) for spring cereal and rapeseed cultivars (n indicating their number) introduced into the experiments during different decades.

Decade	Two-row barley		Six-row barley		Oat		Wheat		Turnip rape		Oilseed rape	
	n	YRN	n	YRN	n	YRN	n	YRN	n	YRN	n	YRN
1970	2	85	8	89	3	111	6	72	2	54	1	53
1980	7	91	18	91	18	106	15	81	17	57	3	56
1990	29	93	10	96	33	111	16	84	8	60	10	62
2000	23	97	16	99	11	114	7	89	6	62	8	75
p-value		<0.01		<0.001		<0.001		<0.001		<0.001		<0.001

were not significant (Table 2). There was, however, a significant and negative association between yield and grain or seed N content for all crops: i.e. under highly productive conditions crops yielded relatively more per unit available, grain-allocated N.

It is possible that differences in N fertilizer rate of up to 15 kg N ha^{-1}, depending on crop, interfere with crop species comparisons. However, differences in N use for different field crops are very typical of farming in Finland. Furthermore, in these experiments, as is common farming practice, N was applied only at sowing and was expected to sustain growth for the entire period from sowing to maturity (Peltonen-Sainio et al. 2009d). Therefore, our results may represent the prevalent conditions in Finnish fields, except that yields are systematically higher for all crops grown in experiments than when grown on-farm (Peltonen-Sainio et al. 2009b). On the other hand, considering direct comparisons among YRN values is justifiable only in the cases of oat, two-row, and six-row barley, which all received N at 88–89 kg ha^{-1} and for wheat and turnip rape receiving 101–102 kg N ha^{-1}. It was evident that oat was superior regarding YRN, averaging 110 % and exceeding the values for two- and six-row barleys by 15 and 13 percentage units, respectively. Furthermore, the later maturing wheat and turnip rape differed even more. YRN for wheat was 25 percent units higher than that for turnip rape. Because we were only able to compare quantities of applied and harvested N in the long-term datasets, and had no information on N mobilized from soil nor on N content of vegetative biomass, we estimated the likely range (min to max for all experiments and cultivars) for NUE and NHI. Although being only estimates, NUE and NHI ranges were far lower for turnip rape than for wheat or other spring cereals. These comparisons and findings highlight the advantageous role of oat over barley in crop rotations when early maturity is required, and that of wheat over turnip rape when later maturity is possible (in southern regions), solely considering better capacity to transfer applied N to harvested yield and reduce risk of N leaching. Also Granlund et al. (2000) emphasized with modelling the high risks of nitrate leaching in turnip rape under Finnish conditions. Turnip rape has, however, many prominent advantages as a break-crop (Smith et al. 2004; Shahbaz et al., 2006; Kirkegaard et al., 2008) especially in cereal rotations as a sole non-cereal break-crop.

Even though marked differences among crop species and cultivars were recorded, it was obvious that because YRN and N_{yield} were highly variable traits (Fig. 1 and 2), similarly as for grain yield, (Peltonen-Sainio et al. 2009a), genetic improvements were largely masked by variation attributable to growing conditions and because of the large numbers of cultivars included in the annual trials. In fact, for most crops N_{yield} and YRN were higher at early than latter part of the study period when averaged over years. Because year x crop and location x crop interactions were not significant sources of variation for yield, N_{grain}, N_{yield}, and YRN, compared with year, location, and their interaction (Table 3), differences among crop species often remained consistent despite large recorded differences attributable to conditions. Within year variability in YRN and N_{yield} ranged from modest in 2001 and 2004 for two- and six-row barley to substantial in 1989, 1990, and 2006 (Fig. 1 and 2). When considering the risks of an exceptionally low YRN, associated with higher risks of N leaching, we noticed that even though such years were evident, they were rare for cereals, although systematically low YRN was evident for turnip rape and oilseed rape. On the other hand, exceptionally high YRN (even over 150%) were generally more frequent for cereals than exceptionally low values, indicating that soil-remobilized N was particularly significant in some experiments and resulted in excess uptake and N allocation to grains.

Water availability is a principal factor affecting N uptake and utilization by a crop and our study confirmed that N_{yield} depends on precipitation, and occasionally YRN also (Table 4). Average early and/or late season precipitation often benefited N_{yield} in cereals. Under dry conditions N uptake is disrupted, while in rainy seasons N leaching increases (Rankinen et al. 2007). There is thus considerable variability in N losses attributable to changes in weather conditions (Granlund et al. 2007). However, in this study elevated temperatures during early and/or late growth phases had a consistent negative impact on YRN and/or N_{yield} for all crops except oilseed rape (Table 5). Elevated temperatures, often coinciding with drought, are critical for yield determination (Ugarte et al. 2007), as also demonstrated for the northernmost European growing areas, where they result in yield penalties of up to 160 kg ha^{-1} for spring cereals and 140 kg ha^{-1} for oil crops for each degree rise in temperature (Peltonen-Sainio et al. 2010). Therefore, yield penalties caused by elevated temperatures are likely to increase the challenge of climate change regarding N leaching, in addition to the projected increases in annual precipitation, milder winters, higher soil temperatures, and increased N mobilization from soil at northern latitudes (Peltonen-Sainio et al. 2009d).

In conclusion, we found that inter-annual and within year variation in YRN is marked. YRN can, however, be improved through cultivar selection and designing better crop rotations because modern cultivars were generally superior to their predecessors. However, elevated temperatures that cause yield penalties for cereals and *Brassica* crops under long-day conditions due to hastened development, often resulted in reduced YRN.

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