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RESEARCH ARTICLE



Differences in N use efficiency, N translocation and N immobilization capacity of their residues of oilseed rape varieties due to N fertilization

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ABSTRACT

Winter oilseed rape (OSR) is known to poorly utilize nitrogen (N), thus increasing the risk of N losses. In five environments in Germany, eight OSR varieties were grown in combination with five fertilizer N treatments enabling to fit N response curves for each variety separately. At Hohenschulen, additional plant sampling after flowering and at harvest allowed to calculate N translocation from the vegetative plant parts into the seeds and to estimate the potential of the residues to immobilize N after harvest. Nitrogen fertilization increased seed and N yield. Varieties differed significantly in their yields and consequently in their NUE, however, without any significant interaction with the N supply. Total N accumulation at harvest, (N) harvest index and N translocation after flowering into the seeds as well as the N immobilization potential (I_{pot}) of the residues followed a similar pattern. Without N, the low amount of residues reduced I_{pot} despite the wide C/N ratio, while a high N fertilization only slightly increased the amount of residues, but clearly decreased their C/N ratio resulting in a lower I_{pot} . Our results support the approach that breeding for increased seed yields seems to be the most promising way to also improve NUE.

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Introduction

Winter oilseed rape (OSR) is a favorable preceding crop for cereals, mainly winter wheat, since it reduces the inoculum of root pathogens and leaves considerable amounts of nitrogen (N) after harvest in the soil (Henke et al. 2008; Sieling and Christen 2015). However, winter wheat can only partially use this nitrogen before winter; consequently, the risk of N leaching losses during the subsequent percolation period is increased under the climatic conditions of Northern Germany (Sieling and Kage 2006).

In order to reduce the negative environmental impact, the generally low N use efficiency (NUE) of OSR has to be improved. In the literature, the definition of NUE proposed by Moll et al. (1982) is widely used, where the seed yield is related to the total N supply (from fertilizers and/or soil). NUE can be further subdivided into N uptake efficiency (NUpE; N uptake related to N supply) and N utilization efficiency (NUE; seed yield related to N uptake (at flowering or

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harvest)) (Hawkesford and Griffiths 2019; Williams et al. 2021). The efficiency of the N fertilization can also be estimated by the 'Apparent Fertilizer N Recovery' (AFR) indicating that the N yield (N offtake by the seeds) increases due to the N fertilization and additionally taking the N supply from the soil and deposition (estimated by the N yield of the unfertilized control) into account (Hawkesford and Griffiths 2019). Storer et al. (2018) pointed out the relevance of testing more than two fertilizer N levels out to allow for a NUE estimate at the economic optimum N fertilization.

Besides an optimized N fertilization, choosing N-efficient varieties is frequently discussed. Several authors have found genotypic differences and tried to identify physiological traits (e.g. Kessel et al. 2012; Stahl et al. 2016, 2017, 2019, He et al. 2017; Storer et al. 2018; He et al. 2021). Most of the experiments suggested that N uptake during the vegetative growth until flowering as well as between flowering and harvest was more important under low N availability, indicating a high NUPE (Berry et al. 2010; Nyikako et al. 2014; Stahl et al. 2019; Zhang et al. 2020). In contrast, under adequate N supply, N remobilization from vegetative plant parts (stem, leaves) and its translocation into the seeds seemed to be more relevant, thus increasing NUTE (Schulte Auf'm Erley et al. 2007, 2011; Kessel et al. 2012; Ulas et al. 2012). However, Vazquez-Carrasquer et al. (2021) highlighted the relevance of N uptake after flowering under high N fertilization. Other authors found that genotypic variation in post-flowering N uptake better correlated with seed yield than N remobilization from vegetative biomass (Ulas et al. 2013; Guo et al. 2021; He et al. 2021). An increased NUTE requires especially an efficient N remobilization from leaves becoming senescent and before being shed, thus minimizing the N concentration of fallen leaves which correlated with a delayed senescence (Schulte Auf'm Erley et al. 2007; Girondé et al. 2015; Bouchet et al. 2016; Wang et al. 2016; He et al. 2021). N losses from the plants by leaf drop of 20–45 kg N ha⁻¹ have been observed (Schjoerring et al. 1995; Malagoli et al. 2005). Besides the total N amount in the vegetative plant part as source size, the number of seeds per pod (He et al. 2017) or per m² (Berry et al. 2010; Stahl et al. 2019) as sink size has to be considered as a relevant determinant for NUTE.

In general, consideration of NUE is restricted to a single crop; however, Dresbøll and Thorup-Kristensen (2014) highlighted the need to broaden the sight to the whole crop rotation since a subsequently grown crop may be able to utilize N not used by the preceding crop. This requires that N not exported with the harvest products, but left in the system, must not be lost via leaching or volatilization during autumn and winter when none or only small plant N demand exists. One approach could be the short-term immobilization of nitrate being present in the soil after harvest by crop residues with a large C/N ratio, thus preventing it from being lost during winter, but remineralized during the subsequent growth period. Several authors reported that incorporation of rapeseed residues decreased soil mineral N (SMN) content in autumn, thus reducing the risk of N losses via leaching (Justes et al. 1999; Trinsoutrot et al. 2000; Coppens et al. 2006; Engström and Lindén 2012) or as N₂O volatilization (Kesenheimer et al. 2019; Rothardt et al. 2021).

Based on the results of a field trial conducted in five environments with eight varieties and five N treatments, this paper aims to estimate N response curves for each variety separately and to derive NUE. The NUE defined by Moll et al. (1982) does not take the seed protein (resp. seed N) concentration into account. Therefore, NUE used here was modified and relates the N yield (N offtake by the seeds instead of the seed yield alone) to the applied fertilizer amount. In addition, detailed analysis of N uptake after flowering and at harvest at two environments allowed to assess the N uptake until flowering and harvest and the N translocation from vegetative plant parts into the seeds. Furthermore, the potential of the residues to immobilize soil N was estimated. We hypothesize that, depending on the level of N supply, the varieties differ in a) their N response and their economic optimum N rate, b) their capability to take up and translocation N into the seeds and c) the amount and composition of their residues, thus affecting the potential of immobilization of soil N after harvest. Therefore, the objectives were a) to estimate variety-specific N response curves, b) to determine the total above-ground N accumulation and the extent of its translocation into the seeds and c) to estimate the potential of the residues to immobilize soil N.

Materials and methods

Sites and soils

The experiment was carried out in 2 years (2019, 2020) at three sites: Groß-Gerau (only 2019), Hohenschulen and Rauischholzhausen. Details of the sites are given in Table S1, those of the weather (rainfall and average air temperature) in Table S2, both in the supplement.

Treatments and measurements

In all five sites \times year combinations (environments), eight OSR varieties (V1–V8) were grown under five N treatments (N1–0/0, N2–30/30, N3–60/60, N4–90/90, N5–120/120 kg N ha⁻¹ (beginning of spring growth/stem elongation)) in two (Groß-Gerau, Rauischholzhausen 2020), three (Rauischholzhausen 2019) and four replicates (Hohenschulen 2019 + 2020) (Table 1; for dates, see Table S3 in the supplement). The cultivars are anonymized in the result section upon request of the supporting breeding companies.

Straw of the preceding crops (mainly winter barley) remained on the plots. Crop management not involving the treatments (e.g. soil tillage, sowing date, application of pesticides and plant regulators) was the same in all plots and according to standard farm practice.

Combine-harvested seed yield was standardized to t ha⁻¹ with 91% dry matter (DM) based on the moisture content of a seed subsample. Seed oil concentration (given at 100% DM) was determined by NIRS (Near-InfraRed-Spectroscopy). Seed protein concentration (given at 100% DM) was calculated by multiplying the respective N concentration of the subsample (determined by NIRS) with a conversion factor of 6.25. Nitrogen yield (N offtake by the seeds) was obtained by multiplying the seed DM with the N concentration of the combine-harvested seed. The difference between N fertilization and N yield gave the N balance.

Nitrogen use efficiency (NUE; %) (eq. 1) was determined by relating N yield of the fertilized plots (N yield_{fertilized}, kg N ha⁻¹) to the N amount applied [kg N ha⁻¹].

$$NUE = \frac{N \text{ yield}_{\text{fertilized}}}{N \text{ amount applied}} \times 100 \quad (1)$$

Apparent fertilizer N recovery (AFR; %) (eq. 2) was calculated by comparing N yield [kg N ha⁻¹] of the fertilized plots with that of the corresponding unfertilized plot in relation to the N amount applied [kg N ha⁻¹]. This approach assumes the same soil N mineralization in both fertilized and unfertilized plots (Jenkinson et al. 1985).

$$AFR = \frac{N \text{ yield}_{\text{fertilized}} - N \text{ yield}_{\text{unfertilized}}}{N \text{ amount applied}} \times 100 \quad (2)$$

Soil mineral N content (SMN) was only determined at Hohenschulen at four dates (sowing, end of autumn growth, beginning of spring growth, harvest). Since SMN before the first N fertilizer application was similar in all plots sampled (around 20 kg N ha⁻¹ in 0–90 cm in both years) and in order to

Table 1. Varieties tested in the trials.

Variety	Breeder	Year of release
Advocat	Limagrain	2017
Architect	Limagrain	2017
Arsenal	Limagrain	2012
DK Expansion	Monsanto	2015
Fossil	Norddeutsche Pflanzenzucht	2018
Patron	BASF	2012
Puzzle	Norddeutsche Pflanzenzucht	2017
Violin	Norddeutsche Pflanzenzucht	2018

allow the use of the data from all environments, only the fertilizer N amount was used to characterize the N supply when calculating NUE and AFR.

At Hohenschulen, plants (only from V2, V5 and V8 in combination with the 0, 120 and 240 kg N ha⁻¹ treatments) from 1 m² were sampled at the same date (05/06/2019, 03/06/2020), but at different growth stages (beginning of ripening (GS 80) in 2019; end of flowering (GS 69) in 2020) and additionally at maturity. Plants were fractionated into leaves, stems and pods (if existing). At harvest, additionally the seed yield and the thousand seed weight were measured and used to calculate the number of seeds m⁻². Dry matter was determined, and N and C concentrations of all fractions obtained were estimated using a CN analyzer (Vario Max CN, Elementar Analysensysteme, Hanau, Germany).

Nitrogen translocation into the seeds after anthesis (N_{trans}) was calculated as follows:

$$N_{trans} = N_{GS80 \text{ or } GS69} - N_{stems \text{ and } pod \text{ walls}} - 0.5 \times N_{leaves} \quad (3)$$

$N_{GS80 \text{ or } GS69}$ represents the total N amount in the plant at the beginning of ripening (GS 80) in 2019 and the end of flowering (GS 69) in 2020, respectively, $N_{stems \text{ and } pod \text{ walls}}$ the N amount of the stems and pod walls at harvest, and N_{leaves} the N amount of the leaves at GS80 and GS69, respectively. Based on the results of Malagoli et al. (2005), it was assumed that only 50% of the total leaf N being present at GS80 and GS69, respectively, were translocated, while the other 50% were lost by the fallen leaves until harvest.

The potential of the residues to immobilize soil N after harvest (I_{pot}) was estimated according Verberne et al. (1990):

$$I_{pot} = - \left(C_R \times \left(\frac{1}{C_R/N_R} - \frac{E}{C_B/N_B} \right) \right) \quad (4)$$

C_R represents the C amount added by the residues, C_R/N_R the C:N ratio of the residues, E the efficiency factor (assumed to be 0.4) and C_B/N_B the C:N ratio of the microbial biomass (assumed to be 8:1).

Unfortunately, no fractionation of the plants and no sampling at harvest were done at Groß-Gerau and Rauschholzhausen; therefore, data from both sites had to be excluded from the analysis.

Statistical analysis

Analysis of seed yield, N yield, N surplus, NUE and AFR was done with data from all five environments (Groß-Gerau 2019, Hohenschulen 2019 + 2020, Rauschholzhausen 2019 + 2020), all eight varieties and all five N treatments. On the contrary, data from plant sampling (e.g. yield components, total DM, N uptake, residue DM and N uptake, immobilization potential, etc.) were only analyzed for two environments (Hohenschulen 2019 + 2020) in three varieties (V2, V5, V8) and three N treatments (0, 120, 240 kg N ha⁻¹).

This project focused mainly on the effects of the varieties, the N treatments and their interaction rather than on the environments; therefore, the statistical analysis was done using the MIXED procedure of SAS statistical package (version 9.4, SAS Institute 2002–2012) with the environments and replicates as random terms.

Quadratic N response curves for different parameters (seed yield [SY, t ha⁻¹], N yield [kg N ha⁻¹], N surplus [kg N ha⁻¹]) were fitted to the crop data:

$$Y = a + b \times N + c \times N^2 + d \times var + e \times var \times N \quad (5)$$

where Y stands for the different traits (seed yield, N yield, N surplus). N denotes the amount of fertilizer N [kg N ha⁻¹] applied throughout the growing period, var is the variety and a , b , c , d and e are constants (Table S4). In this analysis of covariance, var describes the effect of the non-metric variable 'variety' and $var \times N$ that of the interaction between the variety and the N amount.

The use of a 'Quadratic-Plateau' approach, which is assumed to be more appropriate when analyzing each variety in each environment separately (Kage et al. 2022), was not possible within the MIXED procedure.

From equation 5, the economic N fertilization optimum (Nopt) and the respective seed yield (SYopt) were estimated separately for each variety, assuming 1 € (kg N)⁻¹ and 500 € t⁻¹ rapeseed resulting in a breakeven ratio of 0.002 which is lower than that used by Storer et al. (2018). Taking additionally the benefit of an increased oil concentration into account when estimating Nopt led to similar values (not shown) and was not further considered. The N amount was restricted to the range used in the field trial.

Analyses of variance of NUE, AFR, N_{trans} and I_{pot} were performed, using the MIXED procedure of SAS, where the environments and replicates were considered as random terms. The Tukey-Kramer-Test was used to identify significant differences between the means.

Results

Seed (N) yield, yield components and N surplus

Nitrogen (N) significantly increased the seed yield of the eight winter oilseed rape (OSR) varieties evaluated on average over all five environments (Figure 1a, Table S4). In the unfertilized control plots, varieties realized between 2.0 (V2) and 2.9 t ha⁻¹ (V5), being the lowest yield. The variety V5 achieved the highest seed yield, whereas V2 yielded the least. Although the interaction 'variety × N treatment' was not significant ($P > 0.05$), yield increase of V1 was less pronounced compared to the other varieties. The economic optimum N fertilization (Nopt) varied between 187 and 204 kg N ha⁻¹ (V1: 187, V2: 189, V3: 193, V4: 203, V5: 195, V6: 199, V7: 204, V8: 194 kg N ha⁻¹), resulting in optimum yields which ranged between 3.79 (V2) and 4.78 t ha⁻¹ (V5).

Nitrogen yield was significantly enhanced by the N supply; however, the increase occurred over the complete range of N treatments, thus showing no levelling off in the N range tested as observed in seed yield. Since varieties having lower yield achieved a higher seed protein (and therefore a higher N) concentration (data not shown), variety variations of N yield were smaller than those for yield itself (Figure 1b). Nevertheless, V5 accumulated most N in the seeds, while V2 showed the lowest values. The other varieties ranged between both without obvious differences. Consequently, N surplus progressively increased with rising N fertilization across all environments and became positive if 85 (V2) and 116 kg N ha⁻¹ (V5) were exceeded. In the N5 treatment, N surplus ranged between 94 and 116 kg N ha⁻¹.

Nitrogen use efficiency (NUE) and apparent fertilizer N recovery (AFR)

The N use efficiency (N yield/N fertilization; %) clearly decreased with increasing N fertilization from 136% in the 60 kg N ha⁻¹ treatment down to 56% in the 240 kg N ha⁻¹ treatment (Table 2). On average of the N treatments, V5 (99%) significantly outyielded V2 (79%), while no other significant differences between the varieties could be observed. At their respective Nopt derived from the N response curves (Figure 1b), NUE ranged between 61% (V2) and 71% (V5). The significant interaction variety × N treatment was mainly due to the fact that the increasing N fertilization reduced the NUE of V5 more than that of V2.

Correcting the NUE by the N yield of the unfertilized control as an indicator for the amount of N derived from the soil results in the apparent fertilizer N recovery (AFR). Although AFR of the varieties differed between 31.4% and 38.0% on average of the N treatments, the effect was not significant ($P > 0.05$) (Table 2). Interestingly, AFR was highest in the 120 kg N ha⁻¹ treatment (40.3%), while those of the 60 kg N ha⁻¹ (31.9%) and 240 kg N ha⁻¹ treatments were lowest; however, also these effects were not significant. At Nopt, AFR differences between the varieties (estimated from the N response curves) diminished, ranging between 34.8% and 37.2%.

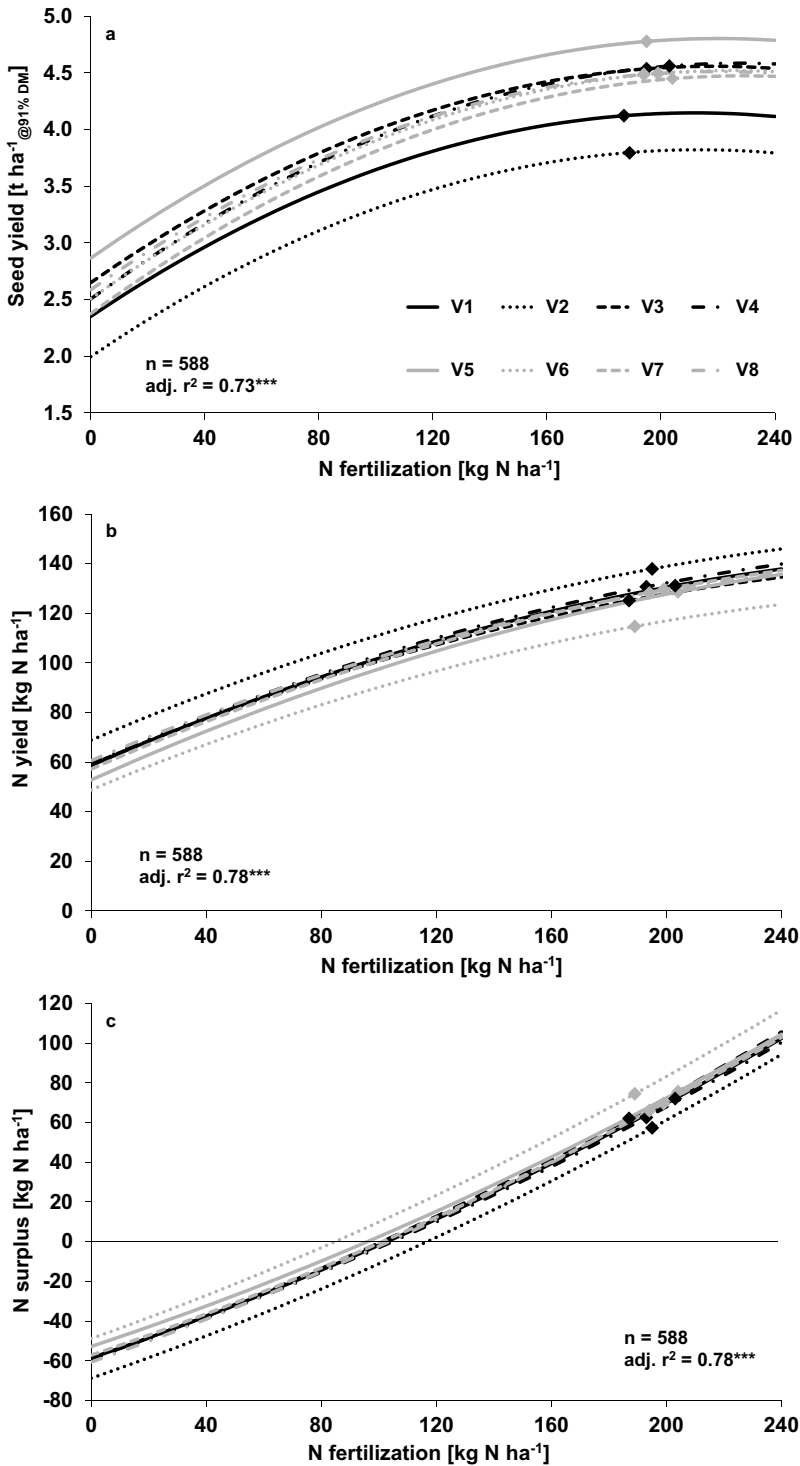


Figure 1. Mineral N fertilizer effects on (a) seed yield [t ha⁻¹], (b) N yield [kg N ha⁻¹] and (c) N surplus [kg N ha⁻¹] of eight oilseed rape varieties (average over five environments, interaction variety × N treatment: not significant). Diamonds indicate the economic optimum N fertilization (500 € t⁻¹ rapeseed, 1 € (kg N)⁻¹).

Table 2. N use efficiency (N yield/N amount applied; %) and apparent fertilizer N recovery ((N yield_{fertilized} – N yield_{unfertilized})/N amount applied; %) of the varieties tested at different N levels on average of all environments. Values for Nopt estimated from the respective N response curves (Fig. 1b).

Variety	N fertilization [kg N ha ⁻¹]				Average	Nopt
	60	120	180	240		
N use efficiency (%)						
V1	135.4	92.1	69.0	56.0	88.1 ^{ab}	66.9
V2	117.6	83.0	63.8	50.5	78.7 ^b	60.7
V3	139.0	90.4	74.2	56.7	90.1 ^{ab}	67.7
V4	142.9	93.3	68.5	55.9	90.2 ^{ab#}	64.6
V5	158.6	105.0	73.4	60.9	99.5 ^a	70.7
V6	131.3	89.3	71.6	56.1	87.1 ^{ab}	65.1
V7	129.8	89.4	67.8	56.7	85.9 ^{ab}	63.0
V8	136.9	96.9	69.1	56.6	89.9 ^{ab}	66.0
Average	136.4 ^a	92.4 ^b	69.7 ^{bc}	56.2 ^c		
Apparent fertilizer N recovery (%)						
V1	30.4	39.6	34.0	29.8	33.5	35.3
V2	32.3	40.2	35.4	29.2	34.3	34.9
V3	32.2	37.2	38.6	30.1	34.5	37.0
V4	44.8	44.1	35.9	31.5	39.1	35.7
V5	44.1	48.1	35.4	32.3	40.0	35.4
V6	26.8	36.7	36.8	30.0	32.5	36.4
V7	36.8	42.6	36.7	33.3	37.4	37.2
V8	32.3	44.6	34.5	30.7	35.5	34.8
Average	35.0	41.6	35.9	30.9		

Note: [#]Different letters indicate significant differences ($P < 0.05$) within each parameter between the varieties and the N treatments, respectively.

Interaction variety \times N treatment for NUE: significant ($P = 0.0005$); for AFR: not significant.

Yield components and N translocation into the seeds

At Hohenschulen in 2019 and 2020, plants from cvs V2, V5 and V8 in the N1, N3 and N5 treatments were sampled in June and at maturity, allowing a more detailed insight into the yield formation and N translocation into the seeds. Since no significant interaction between both factors occurred, only the main effects are presented.

On average over both years, the varieties and the N treatments evaluated significantly affected seed yield with V2 and the unfertilized control yielding least (Table 3), mainly due to a reduced seed number m⁻². Without N fertilization, the thousand seed weight was increased, probably due to the lower sink capacity (seed number m⁻²). Stem and pod wall DM and seed DM responded similarly, resulting in only small variations of the harvest index (HI; 0.31–0.34). The N harvest index (NHI) showed a larger range, especially between the N treatments, clearly decreasing from 0.74 (N1) to 0.63 (N5). The variety V2 achieved the lowest (N)HI values (0.31 (HI) and 0.66 (NHI), respectively).

As mentioned above, growth stages of the canopy during sampling in June differed between both years; therefore, the analysis was made for each year separately. In both years, no significant variety effects on the parameter evaluated could be observed mainly due to a large variation, except that on the N amount in the above-ground biomass and in the seeds in 2020, when V2 accumulated less N in its seeds than the other varieties (Table 4). In contrast, N treatments significantly affected nearly all parameters. No significant interactions between variety and N treatment occurred.

In 2019, above-ground N accumulation of the varieties ranged between 221 and 251 kg N ha⁻¹. Until harvest, plants additionally took up less than 20 kg N ha⁻¹. At harvest, total N amount (237 kg N ha⁻¹) split up into 150 kg N ha⁻¹ N amount in the seeds and 87 kg N ha⁻¹ in stems and pod walls, resulting in 135 kg N ha⁻¹ being translocated from the vegetative parts into the seeds. Increasing N fertilization increased N amounts and N translocation but decreased N translocation and the ratio of translocated N to total N amount in June.

Compared to 2019, N accumulation in the different fractions and N translocation into the seeds were lower in 2020. However, N uptake between June sampling and harvest was more

Table 3. Yield, yield components, DM and N accumulation at harvest (Hohenschulen, mean of 2019 and 2020). The interaction variety \times N treatment was not significant for all parameters tested ($P > 0.05$).

Parameter	Variety			N treatment [kg N ha ⁻¹]			Average
	V2	V5	V8	0	120	240	
Seed DM [#] [g m ⁻²]	357 ^b	476 ^{a†}	463 ^a	295 ^b	470 ^a	531 ^a	432
No. seeds m ⁻² ($\times 1000$)	77.2 ^b	95.9 ^a	102.0 ^a	60.1 ^b	101.1 ^a	114.0 ^a	91.7
TSW [g]	4.71 ^b	5.01 ^a	4.60 ^b	4.96 ^a	4.67 ^b	4.69 ^b	4.77
Stem + pod wall DM [g m ⁻²]	800 ^b	945 ^a	872 ^{ab}	621 ^b	956 ^a	1040 ^a	872
Total DM [g m ⁻²]	1157 ^b	1421 ^a	1335 ^a	915 ^b	1426 ^a	1571 ^a	1304
Seed N amount [kg N ha ⁻¹]	113.2 ^b	140.9 ^a	135.3 ^a	77.7 ^c	137.9 ^b	173.9 ^a	129.8
Stem + pod wall N amount [kg N ha ⁻¹]	64.1	66.3	62.0	26.2 ^c	61.5 ^b	104.6 ^a	64.1
Total N amount [kg N ha ⁻¹]	177.2 ^b	207.4 ^a	197.4 ^{ab}	101.0 ^c	195.2 ^b	274.4 ^a	194.0
Harvest index (HI)	0.31 ^b	0.34 ^a	0.35 ^a	0.33	0.33	0.34	0.33
N Harvest index (NHI)	0.66 ^b	0.70 ^a	0.71 ^a	0.74 ^a	0.70 ^b	0.63 ^c	0.69

Note: [#]DM – dry matter; TSW – thousand seed weight.

[†]Different letters indicate significant differences ($P < 0.05$) between the varieties and the N treatments, respectively.

pronounced in the fertilized plots. Although N translocation was smaller, the share of N translocated in total above-ground N accumulation in June was increased. In both years, seed N amount differed between the varieties more than the N amount in stems and pod walls.

Nitrogen immobilization potential of the residues

The concept of NUE can be extended by considering the crop residues since they may decrease the soil nitrate pool after harvest compared to bare soil via N immobilization, thus reducing the risk of N losses (leaching, volatilization) during the subsequent period without large N uptake of the subsequent crop.

On average, the OSR crop left around 8.7 t ha⁻¹ of residues (stems and pod walls) on the plots; V2 left less residues than V5, while N fertilization increased the amount of residues compared to the unfertilized control (Table 5). The C concentration of the residues remained unaffected by the treatments; however, since V2 achieved the highest N concentration, all varieties returned similar N amounts with their residues to the plots, while N fertilization clearly increased them. The C/N ratio of the residues was narrowest with V2 and decreased with increasing N fertilization.

From the amount and quality of the residues, the potential N immobilization (I_{pot}) can be estimated (equation 4). Due to its lower amount of residues in combination with a narrower C/N ratio, V2 exhibited a significant lower potential to immobilize soil N compared to V5 and V8. The highest N immobilization (146 kg N ha⁻¹) was assumed to occur in the 120 kg N ha⁻¹ treatment, providing a high amount of residues with a still wide C/N ratio of 74. In the unfertilized plots, mainly the low amount of residues caused a reduction of I_{pot} despite the wide C/N ratio. In contrast, the highly fertilized plots only slightly increased the amount of residues, but clearly decreased their C/N ratio resulting in a lower I_{pot} . The potential N immobilization increased with increasing seed yield; however, the slope decreased with increasing N fertilizer amount (Figure 2).

Discussion

Based on N response curves for eight varieties derived from field trials running in five environments, the objective of the field trial was to assess the N use efficiency (NUE). This paper focused on the effects of different varieties, N treatments and their interactions, but not on those of the environments (years and/or sites); therefore, the environments were regarded as random factor. Including

Table 4. Components of the N translocation into the seeds (Hohenschulen, 2019 and 2020). The interaction variety \times N treatment was not significant for all components tested ($P > 0.05$).

Component	Variety			N treatment [kg N ha ⁻¹]			Average
	V2	V5	V8	0	120	240	
2019							
Above-ground N amount at GS 80 [kg N ha ⁻¹]	220.9	250.9	239.0	106.1 ^{ct}	256.5 ^b	348.1 ^a	236.9
N uptake between GS 80 and harvest [kg N ha ⁻¹]	18.4	14.4	17.1	29.2	11.0	9.7	16.6
Above-ground N amount at harvest [kg N ha ⁻¹]	225.1	243.8	243.1	131.7 ^c	245.9 ^b	334.3 ^a	237.3
N amount in seeds [kg N ha ⁻¹]	137.1	155.2	157.5	95.3 ^b	161.6 ^a	192.9 ^a	149.9
N amount in stem and pod walls [kg N ha ⁻¹]	88.0	88.2	86.1	36.7 ^c	84.0 ^b	141.5 ^a	87.4
N translocation [#] [kg N ha ⁻¹]	118.7	142.2	140.7	70.0 ^b	151.5 ^a	183.1 ^a	134.9
Ratio [†]	0.54	0.58	0.61	0.62 ^a	0.59 ^{ab}	0.51 ^b	0.57
2020							
Above-ground N amount at GS 69 [kg N ha ⁻¹]	107.5	134.5	115.7	62.0 ^b	111.1 ^{ab}	184.5 ^a	119.2
N uptake between GS 69 and harvest [kg N ha ⁻¹]	25.5	36.3	42.0	13.9	43.6	46.3	34.6
Above-ground N amount at harvest [kg N ha ⁻¹]	125.7 ^b	165.4 ^a	151.2 ^{ab}	71.1 ^c	151.3 ^b	219.8 ^a	147.4
N amount in seeds [kg N ha ⁻¹]	84.2 ^b	122.4 ^a	111.2 ^a	51.7 ^c	112.2 ^b	153.8 ^a	105.9
N amount in stem and pod walls [kg N ha ⁻¹]	41.6	43.0	40.0	19.5 ^c	39.1 ^b	66.1 ^a	41.5
N translocation [#] [kg N ha ⁻¹]	61.1	86.1	70.9	41.5 ^b	67.8 ^{ab}	108.8 ^a	71.0
Ratio [‡]	0.56	0.64	0.56	0.62	0.57	0.56	0.59

[#]N translocation into the seeds = N amount at GS 80 (2019) and GS65 (2020), respectively, minus 50% of leaf N minus N amount in stem and pod walls at harvest.

[†]N translocated into the seeds related to the total N amount at GS 80 (2019) and 65 (2020), respectively

[‡].Different letters indicate significant differences ($P < 0.05$) between the varieties and the N treatments, respectively

Table 5. DM, C and N amount, and immobilization potential of the oilseed rape residues (stems + pod walls) (Hohenschulen, 2019 and 2020). The interaction variety \times N treatment was not significant for all parameters tested.

Parameter	Variety			N treatment [kg N ha ⁻¹]			Average
	V2	V5	V8	0	120	240	
Dry matter [kg ha ⁻¹]	7999 ^b	9450 ^{a†}	8718 ^{ab}	6207 ^b	9556 ^a	10403 ^a	8722
C concentration [g kg ⁻¹]	431.8	436.9	441.8	437.6	438.2	434.6	436.8
N concentration [g kg ⁻¹]	7.49 ^a	6.59 ^b	6.52 ^b	4.47 ^c	6.26 ^b	9.87 ^a	6.87
C amount [kg C ha ⁻¹]	3430 ^b	4092 ^a	3832 ^{ab}	2703 ^b	4158 ^a	4493 ^a	3785
N amount [kg N ha ⁻¹]	64.1	66.3	62.0	26.2 ^c	61.5 ^b	104.6 ^a	64.1
C/N ratio	64.9 ^b	75.7 ^a	78.4 ^a	97.8 ^a	74.3 ^b	47.0 ^c	73.0
Immobilization potential [‡] [kg N ha ⁻¹]	107.5 ^b	138.0 ^a	129.9 ^a	109.2 ^b	146.2 ^a	120.0 ^b	125.1

Note: [†]Different letters indicate significant differences ($P < 0.05$) between the varieties and the N treatments, respectively.

[‡]According to Verberne et al. (1990).

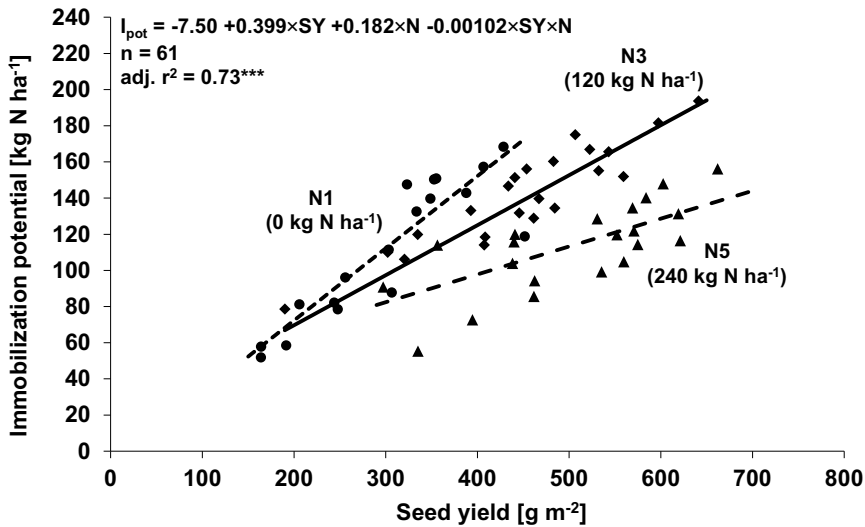


Figure 2. Effect of the seed yield (SY) [g m⁻²] and fertilizer N amount (N) [kg N ha⁻¹] on the immobilization potential (I_{pot}) [kg N ha⁻¹] of the OSR residues (Hohenschulen, 2019 + 2020).

them as a fixed factor in the analysis did not increase the explanatory power as the interaction environment \times variety \times N treatment was not significant.

The choice of the function type influences the N response curves and the parameters derived, e.g. the economic optimum N rate or the N rate to achieve maximum seed yield (Cerrato and Blackmer 1990; Bullock and Bullock 1994; Bäckman et al. 1997; Bélanger et al. 2000; Lyons et al. 2019). In this paper, N responses were estimated by fitting one quadratic (Q) function for all eight varieties including the interaction variety \times N treatment with the environments and replications as random factors. Contrary to the expectation, no significant interactions could be identified, indicating that all varieties responded similarly to the N fertilization. The Q function represents the law of diminishing marginal returns before reaching its maximum, but postulates decreasing yields afterwards, an assumption, which is only justified in some exceptional cases (e.g. lodging) (Meyer-Aurich and Karatay 2019). In addition to the quadratic approach, we also tested a quadratic-Plateau (QP) approach which assumes constant yields after reaching its maximum. Therefore, several authors considered this function type to describe best the N response of crops from the physiological point of view (Cerrato and Blackmer 1990, Henke et al. 2007; Lyons et al. 2019; Nigon et al. 2019). However, the QP estimates had to be done separately for each variety in each environment. Since in several cases no estimates were possible, the QP function type was discarded. In addition, the derived economic optimum N fertilizer rates differed only slightly between both approaches.

In order to take the variation in seed N concentration into account, the NUE approach used here related the N yield (N offtake by the seeds) to the fertilizer N amount, thus diverging from that proposed by Moll et al. (1982) and used by several authors (Stahl et al. 2016; Storer et al. 2018) which considers only the seed yield. However, from an environmental point of view, it seemed to be more meaningful to consider the N yield because it is directly related to the N surplus. Since varieties with lower seed yield often achieve higher seed N concentrations, the differences between the varieties turned out to be less pronounced if the N yield instead of the seed yield was considered (Figure 1a, b). Nevertheless, at a given N fertilization, NUE clearly correlated positively with the seed yield, thus being more relevant than the seed N concentration as reported by several authors (Kessel et al. 2012; Stahl et al. 2016, 2017; He et al. 2017).

The apparent fertilizer N recovery (AFR) additionally takes the N yield of the unfertilized control into account; the latter reflects the N supply from the soil and deposition. Neglecting the 'Added

Nitrogen Interaction' (Jenkinson et al. 1985), AFR relates the fertilizer induced N yield increase to the applied N amount. In the present study, the varieties only slightly differed in the AFR (34.8–37.2%) at the economic optimum N fertilizer rate, indicating a quite similar use of the fertilizer N; however, the N surplus of the high yielding variety V5 was 17 kg N ha⁻¹ lower than that of V2 yielding the least.

Due to the law of diminishing marginal returns, it could be expected that AFR decreased with increasing N fertilization. Interestingly, AFR in the 120 kg N ha⁻¹ treatment was higher than that in the 60 kg N ha⁻¹ treatment (41.6 vs. 35.0%), a fact, which was already observed in previous experiments where a moderate mineral N fertilization improved the use of N from pig slurry compared to the unfertilized treatment (Sieling et al. 1998). Presumably, 30 kg N ha⁻¹ applied as the first splitting at the beginning of spring growth was too little to enable the OSR crop to utilize the fertilizer N adequately. It should be noted that NUE and AFR values for the single N treatments were derived from the measurements while those for N_{opt} were estimated from the N response curves for the seed N yield; thus, the outcome of both approaches may slightly differ.

Translocation of N from the vegetative parts present after flowering into the seeds could be analyzed at the Hohenschulen site and had to be calculated separately for each year since the crop development differed considerably being more advanced in 2019. In general, the OSR canopy was more vigorous in 2019 with a higher biomass accumulation, N uptake and translocation. Nevertheless, the behavior was similar despite differing in the absolute levels. In both years, no significant variety effects could be identified due to the large variation in the data; however, V2 achieved the lowest values in the majority of cases. Based on the comparison of the N concentration of the green and the yellowed leaves, it was assumed that only 50% of the N in the green leaves were available to be translocated which is lower than observed by Malagoli et al. (2005). About 57% (2019) and 68% (2020) of the N taken up until GS80 and GS69 in 2019 and 2020, respectively, have been translocated into the seeds being higher than observed by Girondé et al. (2015).

Berry et al. (2010), He et al. (2017) as well as Stahl et al. (2019) highlighted the relevance of the number of seeds (per pod or per area) as sinks for the amount of N translocated. Our results similarly revealed a positive relationship between the number of seeds m⁻² (calculated from the seed yield and the thousand grain weight, Table 3) and the amount of N translocation with r² values of 0.46 and 0.38 in 2019 and 2020, respectively, both significant with $P < 0.05$.

Normally, N utilization is considered for a single crop only; however, as mentioned by Dresbøll and Thorup-Kristensen (2014), expanding the perspective by the subsequent crop or the whole crop rotation may be more meaningful, since a subsequent crop could use N not taken up by the preceding crop, thus increasing NUE. Such a successful N transfer requires that no or only small N amounts are lost from the soil nitrate pool during autumn and winter (via leaching or N₂O emissions). Short-term immobilization due to the incorporation of residues with a wide C/N ratio can reduce the nitrate pool and delay mineralization of organic N. Beside cereal straw, also the residues of OSR (stems and pod walls) seem to be suitable (e.g. Justes et al. 1999; Trinsoutrot et al. 2000; Coppens et al. 2006; Engström and Lindén 2012). The potential of the residues to immobilize N, estimated according to Verberne et al. (1990), varied between the varieties and the N treatments. The residues of V2 exhibited the lowest immobilization potential since they had the lowest C ratio, but the narrowest C/N ratio. Within a given N treatment, I_{pot} positively correlated with the seed yield, since high yielding canopies left more residues on the field. With higher N fertilization, the N concentration of the residues increased, thus reducing its C/N ratio and consequently I_{pot}.

Altogether, in our experiments, V5 performed best with respect to seed yield and NUE and its components as well as the immobilization potential of its residues. Consequently, breeding for increased seed yields via enhanced seed numbers seems to be the best way to also improve NUE (Berry et al. 2010; Stahl et al. 2019).

However, there is one problem left. The variety V2 showed the lowest yields and N immobilization potential out of all varieties evaluated; thus, a high soil mineral N (SMN) content after harvest in 0–90 cm depth could be expected. However, the measurements revealed a significant lower SMN content after V2 than after V5 and V8 (Table 6; no effects

Table 6. Soil mineral N content after harvest in 0–90 cm depth [kg N ha⁻¹] (Hohenschulen, 2019 and 2020).

N treatment [kg N ha ⁻¹]	Variety			Average
	V2	V5	V8	
0	23	26	28	26 ^{b#}
120	24	29	33	29 ^b
240	39	54	70	54 ^a
Average	29 ^b	37 ^a	44 ^a	

Note: [†]Different letters indicate significant differences ($P < 0.05$) between the varieties and the N treatments, respectively.

Interaction variety \times N treatment: significant ($P = 0.017$).

at the end of autumn growth and the beginning of spring growth); a result which could not be explained by the canopy parameters presented previously and which has to remain inexplicable.

Conclusions

The results of the field trials revealed that all varieties tested achieved their optimum yields with N amounts ranging between 187 and 204 kg N ha⁻¹; however, at significantly different yield levels. Consequently, they also differed in the amount and quality of their residues left affecting the soil N dynamic after harvest. High amounts of residues with a wide C/N ratio increase the potential to reduce the soil nitrate pool in autumn and to decrease the risk of N losses during winter. Although the residues of the varieties differed in their C/N ratio, breeding for higher yields also seems to be a promising approach to improve the N transfer into subsequent crops due to an increased N immobilization potential of the residues. The highest N immobilization potential was observed with moderate N supply while the amount of residues was least in the unfertilized treatment, whereas high N fertilization narrowed the C/N ratio of the residues. Therefore, growing high-yielding varieties and applying N fertilization for optimum yield seem to have the potential to increase the N use efficiency at the crop rotation level and to reduce the environmental impact of rapeseed production.

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Disclosure statement

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