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Review article

Efficient N management using winter oilseed rape. A review

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Abstract – During the last decades the acreage of winter oilseed rape has been increased considerably in Europe. Rapeseed can take up a large amount of nitrogen before winter (>100 kg N/ha) and thus prevent nitrate leaching and pollution. Winter wheat is often grown subsequently, using oilseed rape as a favorable preceding crop. However, under wheat large nitrogen losses via leaching are frequently observed in humid climates during winter, mainly due to high amounts of soil mineral N available in fall and the small N uptake in fall of wheat as a subsequent crop. The low N offtake by the seeds results in a lower N-use efficiency and increases the N surpluses (>90 kg N/ha) compared with winter wheat (c. 40 kg N/ha). In addition, a large soil N pool increases the risk of N_2O emission, with its impact on climate change. In our review we discuss several options to increase nitrogen-use efficiency in oilseed rape-based cropping systems ranging from optimizing N fertilization practices to options arising from adopted tillage practices and crop rotation. N application in fall normally increases dry matter accumulation and N uptake before winter. However, because of its limited yield effects in most situations, fall N supply also boosts N surpluses. N fertilization in spring exceeding the need of the crop for optimal seed yield increases the risk of N leaching and decreases the farmer's net revenue. Considering the amount of N taken up by the canopy before the first spring application improves the determination of the optimal spring N supply. Measuring canopy N in fall gave the best results. At the cropping system level, time and intensity of soil tillage after the harvest of oilseed rape has concurrent goals of controlling volunteer rape, and achieving a successful establishment of the following crop, but avoiding an increased N mineralization. Changing the crop rotation by growing catch crops which prevent N from leaching is very effective in reducing N losses from the system by >40%. However, the economic losses from growing a usually less profitable spring crop probably limit the acceptance by farmers. Despite the problems addressed above, looking at the whole cropping system, oilseed rape is indispensable because of its beneficial effects on yield levels and nitrogen-use efficiency of following cereals, especially wheat, because alternative crops are often not realistic alternatives.

oilseed rape / *Brassica napus* / N fertilization / N leaching / seed yield / N balance

Contents

1. INTRODUCTION

The 'Nitrate Directive' (Directive 91/676/EEC) released in 1991 by the European Union aims to reduce water pollution caused or induced by nitrates from agricultural sources and prevent such pollution (European Union, 1991). In addition, the 'Water Framework Directive' (Directive 2000/60/EC) expands the scope of water protection to all waters and sets clear objectives that a 'good ecological and chemical status' must be achieved for all European water bodies by 2015 (European Union, 2000). The Water Frame Directive demands the prevention of deterioration in status and a progressive reduction of pollution. Concerning agricultural production, the impact of nitrogen (N) fertilization on the nitrate concentration of the water bodies becomes a crucial point in this context. Agriculture is the major contributor to nitrate contamination of groundwater (Fraters et al., 1998). For example, the German implementation of the Nitrate Directive ('Düngeverordnung') became effective in 2007 in a revised form and defines for the

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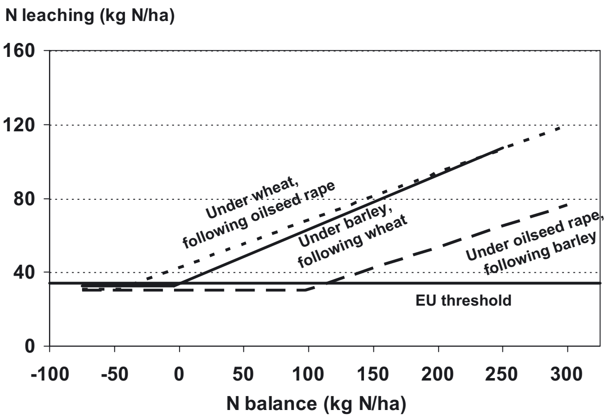

Figure 1. Relationship between N balance (kg N/ha) and annual N leaching (kg N/ha) during the subsequent leaching period in different preceding crop – crop combinations (1991/92–1999/2000). The EU drinking water threshold (50 ppm nitrate) is given for 300 mm percolation (Sieling and Kage, 2006).

first time, among other regulations, legal thresholds for the N balance, calculated from N fertilization minus N offtake by the harvest products (Düngeverordnung, 2006). The surplus must not exceed a threshold of 90 kg N/ha on a 3-year average in the years 2006–2008, declining to 60 kg N/ha in 2009–2011 in order to reduce the environmental impact of N fertilization. Purely arable cropping systems with low amounts of organic N inputs are often regarded as low risk in terms of N leaching. The calculations of Henke et al. (2007), however, revealed that ex post optimized N levels of an oilseed rape – winter wheat – winter barley rotation were near the threshold of 60 kg N/ha, and a current survey of N balances in regions with high percentages of oilseed rape in the crop rotation showed that the N surpluses were often clearly above the acceptable level (Kelm et al., 2007).

N balances on a field scale or in larger areas are often used to estimate the leaching risk (Doluschnitz et al., 1992; Lord et al., 2002; Jansons et al., 2003; Sacco et al., 2003). However, there is much evidence that, in the short term, the link between fertilizer use (except excessive amounts) and nitrate in water is not very direct (Fig. 1) (Sieling and Kage, 2006). The N surplus in itself may not be sufficient to quantitatively determine the amount of N loss via various pathways, because of the complex interactions with other environmental parameters. For example, the large reserve of organic N in soils and vegetation will inevitably contribute nitrate to leaching once the land is tilled (Macdonald et al., 1989; Sylvester-Bradley and Chambers, 1992). N leaching depends on the amount of water percolating through the soil, mainly affected by winter rainfall (Webb et al., 2000), and the N concentration in the leachate. The latter is closely related to the mineral N pool in the soil at the beginning of and/or during the leaching period (Goss et al., 1991). Most of the N leached from arable soils originates from inorganic N present in late summer, fall or early winter when soils start to drain and plant demand is low or non-existent. Generally, N leaching positively correlates with the N supply. Mineral N application has been shown to significantly increase N losses only for N rates exceeding the ex post determined economic optimum (e.g. Engels and Kuhlmann, 1993; Davies and Sylvester-Bradley, 1995; Goulding et al., 2000). Results from the Broadbalk Wheat Experiment in Rothamsted (United Kingdom) indicated that in most years only a little fertilizer-derived N remained in inorganic form at harvest from applications of up to 192 kg N/ha (Glendining et al., 1996). In the short term, therefore, reduction of N fertilization below the optimum had only small effects on fall soil mineral N and, in consequence, on N losses over winter (Macdonald et al., 1989; Lickfett, 1993; Zerulla et al., 1993; Shepherd and Sylvester-Bradley, 1996). More serious problems may arise from the use of organic manures and slurries, which are often applied to the stubbles after harvest on arable land, when no plant uptake occurs. Compared with mineral N fertilizers, crops utilize slurry N poorly, due to overwinter losses by leaching or denitrification (Smith and Chambers, 1992; Sieling, 2005).

On the other hand, however, the simple N balance is often the single parameter that can be estimated at the field, farm and regional level. It can give useful risk indications of specific farming practices, especially in the wider environment and if integrated over longer time periods (Öborn et al., 2003). Even if N fertilization meets plant N requirement in time and rate, long-term application of inorganic N fertilizer and, to a greater extent, of organic manures, may induce the building up of soil organic matter due to increased amounts and higher N concentration of crop residues being returned to the soil at harvest (Glendining et al., 1996). Up to certain levels this may be seen as a positive effect on soil fertility and the overall carbon balance, but it should also be clear that in consequence, N mineralization of soil organic N in the fallow periods, and consequently N leaching, may increase.

Farmers are asked to reduce the impact of nitrogen on the environment. Increased nitrogen supply to crops may increase yield but decreases N-use efficiency (Kuhlmann and Engels, 1989; Sieling and Hanus, 1997). If it has not been volatilized or denitrified, the N amount not utilized by the crop can accumulate in the soil and, in consequence, escalates the risk of leaching with corresponding environmental consequences.

Especially in rotations including winter oilseed rape N leaching is often a great problem (Fig. 1). Indeed, oilseed rape can be a suitable crop to conserve nitrogen throughout the winter, because of its large fall N uptake of 40–60 kg N/ha (Barraclough, 1989; Aufhammer et al., 1994). Due to its early development, oilseed rape often can utilize only a small proportion of the nitrogen mineralized in spring, especially under weather conditions with slow temperature increase in spring (Sieling et al., 1998a). Additional large amounts of easily mineralizable crop residue (petals and leaves) return to the soil after flowering. The harvest index (0.35) and the N-use efficiency of oilseed rape are low compared with cereals (Aufhammer et al., 1994; Shepherd and Sylvester-Bradley, 1996; Malagoli et al., 2005; Rathke et al., 2005; Sieling et al., 1998a, b, 1999; Sieling and Kage, 2006; Henke et al., 2007; Berry, 2009). Moreover, oilseed rape leaves the soil in a favorable structure, leading to an increased N release. All these facts result in large N amounts remaining in the soil (Shepherd and Sylvester-Bradley, 1996; Beaudoin, 2005). In most situations the subsequent crop following rape will be winter wheat (Sieling, 2005). Even sown early, N uptake of wheat before winter normally does not exceed 20 kg N/ha, which is only a small portion of the soil mineral N usually present after oilseed rape. In consequence, most of these N residues cannot be completely taken up by the subsequent wheat crop, and increase the risk of N leaching into the groundwater during the following percolation period (Goss et al., 1993; Sieling and Kage, 2006). Having a crop rotation where each crop is always following the same preceding crop, a differentiation between the preceding crop and the direct crop effects on N leaching is not possible.

Several approaches to reduce N leaching have been discussed, e.g. changes in crop rotation, growing of catch crops, reducing soil tillage in fall and reducing N fertilization (Allison et al., 1998; Kuhlmann and Engels, 1989; Lindén and Walgren, 1993; Rinnofner et al., 2008; Shepherd and Lord, 1996; Smith et al., 1990). However, acceptance by farmers often remains low, mainly due to economic losses.

The aim of this review was to investigate the necessity and the extent of some management measures carried out during (N fertilization in fall, N fertilization in spring) or following (soil tillage after harvest, growing catch crops) the rapeseed crop in order to improve the N-use efficiency and to reduce the environmental impact of oilseed rape production.

2. N FERTILIZATION IN FALL

Applying fall nitrogen to oilseed rape is common practice in NW Europe. In the last few years farmers have changed the crop rotation, replacing barley by wheat. In consequence, the sowing date is often delayed. In addition, they increasingly pass on plowing during seedbed preparation to reduce energy costs. To compensate for this worsening of establishment conditions, they additionally apply about 30–50 kg N/ha in fall, often directly upon the stubble of the preceding crop, to ensure crop N supply and adequate crop growth before winter.

In general it has to be distinguished if the rapeseed crop is actually able to take up fall-applied N before winter. If low temperature limits crop growth due to delayed sowing dates, applied N increases the soil mineral N (NO_3-N plus NH_4-N) pool and, in consequence, the potential of N leaching during the subsequent percolation period (Tab. I, sown in the 1st decade of September) (Sieling and Kage, 2007). In contrast, Engström et al. (2009) reported that application of 30 or 60 kg N/ha, at sowing, to winter oilseed rape did not affect the N leaching or seed yield. If fall N, especially in early-sown oilseed rape (Dejoux et al., 2003), leads to a better growth and enhances N accumulation before winter, it is a moot question whether the seed yield increases as well. Ogilvy and Bastiman (1992) reported that, although plots receiving nitrogen in the seedbed or at the two leaf stage appeared more vigorous before winter compared with unfertilized plants, neither the number of plants established, the survival over winter nor the seed yield appeared to be affected by this treatment (see also Tab. I, sown in the 1st decade of September). Sieling and Kage (2007) observed after a fall N supply of 40 kg N/ha a yield increase

Table I. Effect of fall-applied N and sowing date on N uptake before winter, soil mineral N before winter and seed yield of oilseed rape in 2005/06 (Henke, 2008).

Sowing date	Middle of August		Beginning of September	
Fall N (kg N/ha)	0	40	0	40
N uptake before winter (kg N/ha)	95	131	65	74
Soil mineral N content before winter (kg N/ha)	19	23	34	63
Seed yield (t/ha)	4.69	4.75	4.80	4.86

of about 0.2 t/ha which was related to an additional N offtake by the seeds of about 4 kg N/ha. In maximum only 10% of the applied N amount was removed from the system, whereas 36 kg N/ha remained in the soil and charged the N balance (Tab. II). Colnenne et al. (2002) and Flénet et al. (2009) observed in their experiments severe N deficiencies in fall, described in terms of the nitrogen nutrition index, together with a reduction in shoot biomass, tap root biomass, leaf area index and radiation-use efficiency compared with well supplied treatments. However, despite severe fall N deficiencies, no difference in seed yield was apparent. The authors assumed that all the time allowed enough growth in fall to ensure sufficient regrowth in spring. However, in other experiments fall nitrogen gave a small yield response where the preceding cereal straw was baled or incorporated instead of burning (Chalmers, 1989; Chalmers and Darby, 1992).

Due to its ability to take up substantial quantities of nitrogen before winter (Barraclough, 1989), oilseed rape is regarded as a suitable crop to utilize fall slurry and to prevent slurry nitrogen from leaching during the percolation period. Detailed analysis revealed the higher leaching potential of fall slurry (up to 4.3 times) and, to a smaller extent, of spring slurry (up to 1.7 times) compared with mineral N fertilizers. The larger losses from slurry could be caused by its slower rate of N mineralization and the release of N when the crop cannot use it (Sieling et al., 1998a; Sieling and Kage, 2006). Applying slurry (80 kg N_{total}/ha) in spring during crop growth instead of fall allows one to reduce the additional mineral N fertilization by 40 kg N/ha (Fig. 2). However, further details about the effect of slurry applied in fall and/or in spring on seed yield are scarce.

N fertilization of oilseed rape in fall seems to be necessary only if N really limits crop growth, for example on poor soils or in the case of minimum tillage if the seeds germinate within a straw layer. If farmers assume that the rapeseed crop needs N in fall, N fertilizer should be applied to the crop itself and not before sowing (Sieling and Kage, 2007). On the other hand, the effect of a late N shortage in fall, e.g. on light soils, on yield potential of an early-sown and well-established rapeseed crop remains unclear.

3. N FERTILIZATION IN SPRING

An exact estimation of fertilizer N demand has become increasingly important to minimize the environmental impact,

Table II. Effect of 40 kg N/ha applied in fall on above-ground dry matter before winter, N uptake before winter, seed yield and simple N balance of the fall-applied fertilizer N of oilseed rape (2003/04–2005/06, cv. Talent, minimum tillage following wheat).

	Above-ground dry matter (g/m^2)	N uptake (kg N/ha)	Seed yield (t/ha)	N balance (kg N/ha)
Unfertilized control	48.2^{b‡}	18.2^{b}	4.59^{b}	–
40 kg N/ha on the wheat stubble	68.1^{ab}	24.7^{b}	4.71^{ab}	+36
40 kg N/ha directly after drilling	86.6^{a}	36.3^{a}	4.69^{ab}	+37
40 kg N/ha in the 2-4 leaf stage of oilseed rape	87.0^{a}	36.7^{a}	4.81^{a}	+33

‡ Within a column, means followed by the same letter are not significantly different at $P < 0.05$.

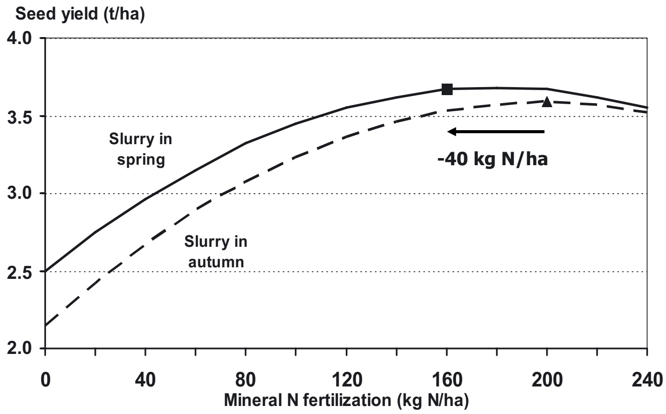

Figure 2. Effects of slurry application in fall and spring on seed yield of oilseed rape.

but also to achieve high seed yields and maximum economic returns. For this purpose, a better understanding of the course of N uptake and the yield formation is essential. Seed yield of oilseed rape consists of the number of plants/m^2, the number of pods per plant, the number of seeds per pod and the single seed weight (Grosse et al., 1992; Diepenbrock, 2000; Rathke et al., 2006). The onset of branches and buds starts even in late fall, whereas the final number of pods per plant and seeds per pod are determined within 1–2 weeks after flowering. Fall-sown oilseed rape normally receives nitrogen in spring as a split application at the beginning of growth and at stem elongation. This means that N fertilizers are normally applied before yield formation occurs. In contrast to wheat, it is not possible to directly support yield formation. In addition, some results showed that nitrate uptake increases from stem elongation to the beginning of flowering, whereas nitrate uptake during pod filling was low (Merrien et al., 1988; Jensen et al., 1997; Rossato et al., 2001). Other authors reported that N uptake remained high even after the start of pod filling (Schjoerring et al., 1995; Hocking et al., 1997; Malagoli et al., 2005). Spink (2009) pointed out that late N is required to maintain pod filling. However, most of the N supply in the pods was achieved mainly by N mobilization from vegetative parts (stem, leaves, taproot) (Malagoli et al., 2005).

The spring nitrogen requirement mainly depends on expected yield level and soil type (Chalmers and Darby, 1992). Zhao et al. (1993) suggested a maximum yield response to a N rate around 200 kg N/ha, which was in good agreement with the results of Bilsborrow et al. (1993), who obtained >85% of the maximum recorded yield with an application of 150 kg N/ha. Over the years 1989/90 to 1991/92, Aniol (1993) tested N amounts from 0 to 320 kg N/ha, varying the timing and distribution pattern. Using a multiple regression model he estimated a yield maximum of 5.04 t/ha in plots receiving 308 kg N/ha. Comparing similar amounts of N, distributions with a larger amount at the earlier stages (beginning of growth) increased the seed yield more than high rates at later stages. Split application ensured that high yield performance and optimum yield stability were achieved simultaneously (Boelcke et al., 1991). In contrast, Darby and Hewitt (1990) observed only small effects of timing and distribution of fertilizer N on seed yield. Super-optimal N can cause yield losses and increases the potential for leaching loss during the following winter (Islam and Evans, 1994; Shepherd and Sylvester-Bradley, 1996; Sieling et al., 1997; Engström et al., 2009).

N uptake by the seeds ranged from 69 kg/N ha in an unfertilized control to 175 kg/N ha in plots which had received 320 kg N/ha (Aniol, 1993), thus leaving large amounts of fertilizer N in the system. Crop recovery of labeled fertilizer applied to oilseed rape in spring varied considerably with the soil and year, ranging from 31 to 70% (Chalmers and Darby, 1992; Jensen et al., 1997; Macdonald et al., 1997; Sieling et al., 1998a; Beims, 2005). Approximately half of the fertilizer-derived nitrogen was contained in the seed, and, where recovery of labeled nitrogen by the crop was poor, up to 39% of labeled fertilizer remained in the soil.

In Germany N fertilizers are commonly applied according to growth stage (Rathke et al., 2006), taking soil mineral N content at the start of spring growth into account by the 'Nmin method' developed by Wehrmann and Scharpf (1979). In general, high canopy N is considered in the calculation of N fertilization rates by subtracting a fixed value of 20 kg N/ha, which hardly accounts for the actual canopy development, and corresponding N amounts taken up by the canopy before fertilization. In contrast, balance-sheet methods regarding the amounts of mineralization of soil-borne N and the amount of N in rapeseed canopies at the end of fall and the end of winter have been developed in France (Reau et al., 1994; Makowski et al., 2005), resulting in an optimized N fertilization of oilseed rape with on average lower doses of N fertilizer (Hébinger, 2009).

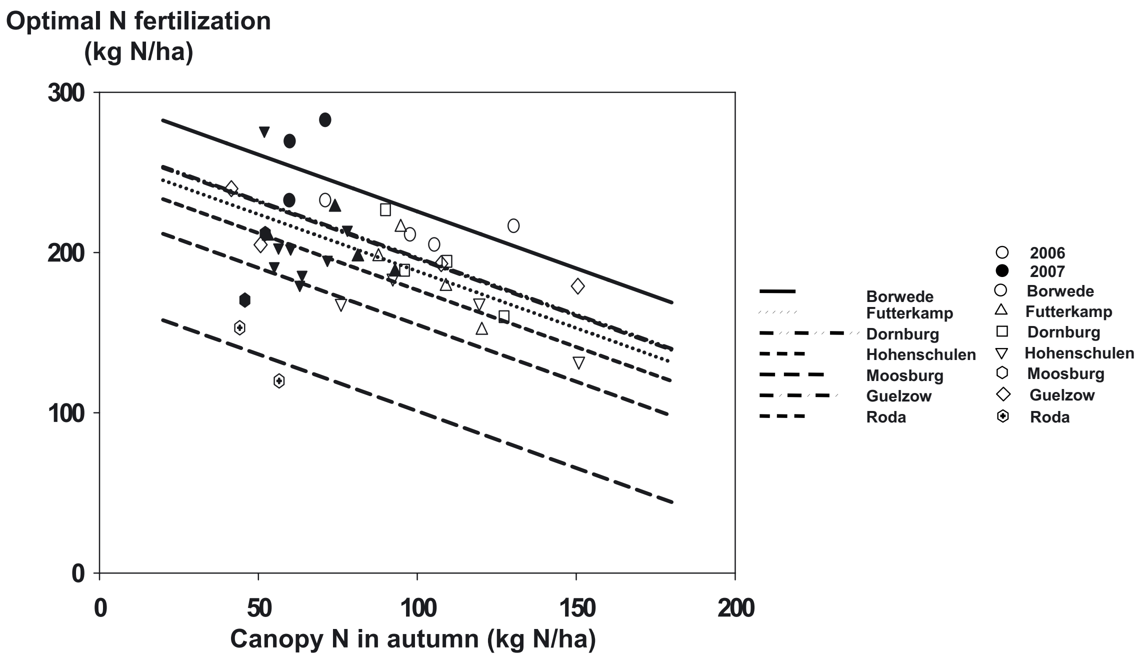

Figure 3. Regression of the optimal N fertilization on canopy N in fall for seven experimental sites in Germany in two years (Henke et al., 2009).

In a series of field trials consisting of seven sites and two years, Henke et al. (2009) tried to verify this approach under different climatic conditions in order to derive site-specific N fertilization rates. First, several methods which can easily be used by the farmers for estimating canopy N were tested. The use of digital photos giving information on the leaf area index, and in consequence on the above-ground biomass and N uptake, was limited to canopies with a leaf area index <1. Also counting the number of leaves was not suitable for estimating the amount of N in the aerial biomass, whereas weighing above-ground fresh matter, as done in France, gave good results. Estimating canopy N by weighing fresh matter of a defined area with several replications is based on the assumption that aerial dry matter content and N concentrations vary only a little at early growth stages. Reau et al. (1994) found a nearly constant N concentration of 4.5% N (in dry matter) at early growth stages of oilseed rape. Colnenne et al. (1998) described a critical N dilution curve for winter oilseed rape with a constant N concentration of 4.48% at early growing stages. N concentration decreased when dry matter (t/ha) exceeded 1 t dry matter/ha following the equation $N_{conc} = 4.48\ W^{-0.25}$, where N_{conc} is the N concentration in the aerial dry matter (% N) and W the shoot dry matter (t/ha). The N concentration of 4.5% found by Henke (2008) in aerial dry matter confirmed the results of Reau et al. (1994) and Colnenne et al. (1998). The measured dry matter contents in fall averaged 10%, leading to conversion factors of 45 in fall (kg N/ha in the canopy = 45 * kg fresh matter/m^2) (Henke, 2008).

In a second step, economically optimal N fertilizer amounts were estimated from quadratic N response curves and related to the soil mineral N content in spring, and N in the rapeseed canopy in fall and/or in spring. The site caused a large variation; however, no interactions with the parameters were significant, meaning that the effects were similar at all sites. Soil mineral N in spring showed no correlation with the optimal N fertilizer amounts, since oilseed rape can take up large amounts of N before winter and therefore often depletes the mineral N pool in the soil. Even canopy N in spring only slightly correlated with the optimal N fertilizer amounts, since leaf losses, and consequently N losses, over winter highly influence canopy N at the beginning of spring growth (Dejoux et al., 2003). Based on 2 years, measuring canopy N in fall gave the best results. The regression (Fig. 3) showed a significant negative relationship between canopy N in fall and the optimal N fertilizer amounts. The slope of this regression was –0.7, indicating that these N amounts should be partly considered when calculating N fertilization rates (Henke et al., 2009).

Experimental results on the impact of canopy N in fall or at the beginning of spring growth on the optimal N fertilizer amounts are scarce. Gabrielle et al. (1998) and Dejoux et al. (1999a, b) reported N losses caused by leaf losses due to frost over winter. Dejoux et al. (1999a) found a recovery of the N losses over winter by the rapeseed crop in spring of about 40% under the climatic conditions of their experimental site located in the Paris Basin (France). This recovery could be explained by the synchronization of lost leaves' decomposition and N uptake by the rapeseed crop in spring (Dejoux et al., 2003). If leaf losses occur over winter, N from dropped leaves is quickly mineralized in spring. Dejoux et al. (1999a) measured a decomposition fraction of added ^{15}N-labeled leaves of 0.94 before harvest. However, Dejoux et al. (2003) also found a fraction of gaseous N losses of 0.4 of N applied with frozen leaves estimated by unrecovered ^{15}N. These results indicate that N losses over winter are likely to be recovered in spring to some extent, and consequently N fertilization rates can be reduced. This recovery potential is totally neglected when canopy N in spring is used as an indicator for N fertilization rates in spring. Additionally, Dejoux et al. (2003) reported that the differences between canopies which varied largely in fall decreased during winter. Consequently, N fertilization rates would be overestimated if canopy N in spring was taken into account when deriving N fertilization rates. For these reasons canopy N in fall seems to be a more favorable indicator compared with canopy N in spring for the derivation of N fertilization rates. Besides the recovery of N derived from fallen leaves in spring, N uptake of unfertilized oilseed rape canopies in fall could be an indicator for the N mineralization potential of the location. In the case of insignificant leaf losses over winter, a well-developed rapeseed canopy showed a higher leaf area index at the beginning of spring growth than a poor canopy, which, in consequence, allows for reduced N fertilization rates (Mendham et al., 1981).

The results of Henke et al. (2009) clearly demonstrate that canopy N in fall is a suitable indicator for optimizing N fertilization rates. The implementation of this approach into practical use by farmers is based on an average rapeseed canopy with 50 kg N/ha accumulated in fall (1.1 kg FM/m^2) which will be fertilized in spring according to the official recommendation (e.g. 200 kg N/ha). Each kg N/ha exceeding the threshold of 50 kg N/ha reduces the N fertilization in spring by 0.7 kg N/ha. However, it is not possible to give absolute recommendations. In addition, the causes of the large site-to-site variations remain to be clarified. On the other hand, besides a reduction of N fertilization if canopy N is high, the study does not indicate that N fertilizer rates need to be increased if canopy N in fall is very poor because the crop is often not able to utilize the additionally applied N for its yield formation.

In the future the algorithm developed by Henke et al. (2009) allows optimizing N fertilization of oilseed rape site-specifically. Results of Müller et al. (2008) and Behrens and Diepenbrock (2006) showed that N uptake of oilseed rape in fall can be estimated on a field scale using vegetation indices derived from hyperspectral reflection measurements. Based on these data, an application map for the N fertilization in spring can be generated which takes the within-field variation into account according to the approach presented by Henke et al. (2009). In France, a system based on satellite observations called 'Farmstar-colza' is currently being tested to draw a map of the fields with nitrogen supply advice, to practice modular application on the crops and to increase the precision of the crop N absorption assessment (Lagarde and Champolivier, 2006; Hébinger 2009).

4. N DYNAMIC AFTER OILSEED RAPE

In contrast to the topics discussed above, soil tillage following oilseed rape does not affect the N balance of the crop, but strongly influences the N dynamics in the soil. As shown above, rapeseed demands high levels of nitrogen fertilizer, often exceeding 200 kg N/ha to achieve maximum yields. However, N offtake by the seed and N harvest index, ranging between 0.6 and 0.7, are low compared with cereals (Shepherd and Sylvester-Bradley, 1996; Sieling et al., 1999; Malagoli et al., 2005). Although rapeseed residues lead to N immobilization after incorporation into the soil (Jensen et al., 1997; Justes et al., 1999; Trinsoutrot et al., 2000), soil mineral N content increases regularly during fall (Lickfett, 1993). In consequence, large amounts of nitrate are likely to be leached with drainage water during the subsequent percolation period (Sieling et al., 1999; Sieling and Kage, 2006).

Increasing amounts of N fertilization to oilseed rape strongly raised soil mineral N content at the harvest of oilseed rape and during the subsequent fall. Several studies resulted in a remarkably higher soil mineral N content, sometimes exceeding 100 kg soil mineral N/ha at oilseed rape harvest following a two-straight-line function if high amounts of N fertilizer were used (Shepherd and Sylvester-Bradley, 1996; Sieling et al., 1999; Beaudoin et al., 2005; Makowski et al., 2005). Di and Cameron (2002) reported a threshold level of N fertilization above 200 kg N/ha which increased N leaching in arable cropping. Sieling and Kage (2006) stated a positive correlation between a simple N balance, calculated from N fertilization minus N offtake by the seed, and N leaching, and between mineral N fertilization and N leaching. This positive correlation between excessive N fertilization and N leaching is also confirmed by the scenario calculations made by Henke et al. (2008). Amounts of N fertilizer above 200 kg N/ha led to a strong increase in N leaching, whereas amounts below 200 kg N/ha differed slightly. These results show the importance of more precise calculations of N fertilizer doses considering soil and oilseed rape canopy properties (see Chap. 3).

According to Di and Cameron (2002), the prevention of soil mineral N accumulation in the soil after harvest is the key to reducing N leaching. There are several well-known agronomic measures to reduce mineralization of soil organic N, and in consequence, nitrate leaching after harvest. First of all, reducing tillage depth and delaying tillage after harvest diminish soil disturbance (Goss et al. 1993), and consequently soil N release, since intensive tillage operations after harvest stimulate net mineralization of soil-borne N due to soil disturbance (Lickfett, 1993). Using a combined approach of field trials and modeling, Henke et al. (2008) observed that minimum tillage combined with a short period of growing volunteer rapeseed as a catch crop before sowing of winter wheat can decrease N leaching.

Due to the tillage operations, however, not only the soil is mixed but also oilseed rape residues are incorporated into the soil. The C/N ratio in oilseed rape residues under a regular fertilization regime of about 200 kg N/ha was about 50 to 60. Justes et al. (1999) and Mary et al. (1999) report N immobilization of about 20 kg N/ha after rapeseed residue incorporation (C/N = 54, N fertilization 270 kg N/ha). Jensen et al. (1997) observed a decrease in soil mineral N of 18 and 25 kg N/ha after incorporation of 4 or 8 t oilseed rape residues/ha, respectively. In addition, Trinsoutrot et al. (2000) stated that the N amounts mineralized from rapeseed residues and then returned to the subsequent crop are relatively small.

The studies showed that straw incorporation is an indispensable part of proper N management after harvest to prevent N leaching (Justes et al., 1999; Trinsoutrot et al., 2000; Beaudoin et al., 2005).

Secondly, changes in the crop rotation such as the introduction of catch crops and spring crops can decrease soil mineral N content during fall and therefore reduce the risk of nitrate leaching after oilseed rape. However, growing catch crops combined with a spring crop is less profitable than cropping winter wheat, which is commonly grown after oilseed rape, and therefore compensatory payments would be necessary, especially in water protection areas. Justes et al. (1999) reported a significant reduction of the soil mineral N content and nitrate leaching by a radish cover crop or volunteer rapeseed compared with a bare soil. Henke et al. (2008) suggested Phacelia as a catch crop, whereas Lickfett (1993) recommended volunteer oilseed rape to grow over winter without any tillage operation, thus reducing mineralization of soil-borne N, and consequently N leaching. However, additionally growing volunteer rapeseed is characterized by two disadvantages. Firstly, due to a lower drainage rate, the nitrate concentration in the percolation water can rise remarkably and exceed the threshold for drinking water of the European Union to a higher extent than the other treatments (Henke et al., 2008). Secondly, growing volunteer rapeseed could be critical because a high density of oilseed rape in the rotation can promote pathogens and pests (Christen, 2006).

5. CONCLUSION

Concerning N leaching, oilseed rape is an ambivalent crop. In fall, oilseed rape can take up large amounts of N and prevent it from leaching, whereas after harvest, due to a low N-use efficiency, N surplus and, in consequence, N losses via leaching are often high, especially if wheat follows. In order to minimize the environmental impact, farmers have to reconsider critically N fertilization of oilseed rape and to skip practices that have only small effects on yield, e.g. N fertilization in fall. In addition, N already taken up by the crop before winter should be taken into account when estimating spring N fertilization. Each kg fall canopy N exceeding 50 kg N/ha reduces spring N fertilization by 0.7 kg N/ha under German conditions. However, under the currently high prices for oilseed rape, some management measures might make sense from the economic point of view, being an important aspect for the farmers, although they do not decrease the N surpluses. Apart from the discussion of the N balance, appropriate management after oilseed rape harvest can reduce N leaching, if minimum tillage (or even no-till) is used and/or catch crops are grown.

Despite the problems addressed above, it should be pointed out that oilseed rape is indispensable as a favorable preceding crop for cereals, especially wheat. Growing legumes will raise similar problems as in oilseed rape, whereas the area of sugar beets is limited. Increasing the percentage of wheat within the rotation, up to monoculture, is also not sustainable, because wheat yield decreases while the amount of fertilizer N will increase to achieve optimal yields.

REFERENCES

Allison M.F., Armstrong M.J., Jaggard K.W., Todd A.D. (1998) Integration of nitrate cover crops into sugar beet (*Beta vulgaris*) rotations. I. Management and effectiveness of nitrate cover crops, J. Agr. Sci. 130, 53–60.

Aniol H. (1993) Ertrag, Ertragsstruktur und Stickstoffaufnahme von Winterraps (*Brassica napus* L.) in Abhängigkeit von N-Menge, N-Verteilung und Genotyp, Ph.D. thesis, University Kiel.

Aufhammer W., Kübler E., Bury M. (1994) Stickstoffaufnahme und Stickstoffrückstände von Hauptfrucht- und Ausfallrapsbeständen, J. Agron. Crop Sci. 172, 255–264.

Barraclough P.B. (1989) Root growth, macro-nutrient uptake dynamics and soil fertility requirements of a high-yielding winter oilseed rape crop, Plant Soil 119, 59–70.

Beaudoin N., Saad J.K., van Laethem C., Machet J.M., Maucorps J., Mary B. (2005) Nitrate leaching in intensive agriculture in Northern France: Effect of farming practices, soils and crop rotations, Agr. Ecosys. Environ. 111, 292–310.

Behrens T., Diepenbrock W. (2006) Using hemispherical radiation measurements to predict weight-related growth traits in oilseed rape (*Brassica napus* L.) and barley (*Hordeum vulgare* L.) canopies, J. Agron. Crop Sci. 192, 465–474.

Beims S. (2005) Untersuchungen zur N-Effizienz und zum N-Mineralisationspotenzial in langjährig unterschiedlichen Düngungssystemen mit Hilfe von ^{15}N-markiertem Mineraldünger, Schriftenreihe des Instituts für Pflanzenbau und Pflanzenzüchtung der Agrarwissenschaftlichen Fakultät der CAU, Bd. 38.

Berry P. (2009) Breeding for improved nitrogen use efficiency in oilseed rape, European Workshop 'N fertilization of winter oilseed rape', 23–24 March 2009, Berlin, Germany, http://www.pflanzenbau.uni-kiel.de/veranstaltungen/n-duengung_wraps/Berry.pdf (08/09/2009).

Bilsborrow P.E., Evans E.J., Zhao F.J. (1993) The influence of spring nitrogen on yield, yield components and glucosinolate content of autumn-sown oilseed rape (*Brassica napus*), J. Agr. Sci. 120, 219–224.

Boelcke B., Léon J., Schulz R.R., Schröder G., Diepenbrock W. (1991) Yield stability of winter oilseed rape (*Brassica napus* L.) as affected by stand establishment and nitrogen fertilization, J. Agron. Crop Sci. 167, 241–248.

Chalmers A.G. (1989) Autumn and spring fertiliser nitrogen requirements for winter oilseed rape, Asp. Appl. Biol. 23, 125–133.

Chalmers A.G., Darby R.J. (1992) Nitrogen application to oilseed rape and implications for potential leaching loss, Asp. Appl. Biol. 30, 425–430.

Christen O. (2006) Raps in der Fruchtfolge – ist die Grenze der Ausdehnung erreicht? (with English summary), UFOP-Schriften 29, Öl- und Proteinpflanzen, OIL 2005, pp. 119–128.

Colnenne C., Meynard J.-M., Reau R., Justes E., Merrien A. (1998) Determination of a critical nitrogen dilution curve for winter oilseed rape, Ann. Bot. 81, 311–317.

Colnenne C., Meynard J.-M., Roche R., Reau R. (2002) Effects of nitrogen deficiencies on autumnal growth of oilseed rape, Eur. J. Agron. 17, 11–28.

Davies D.B., Sylvester-Bradley R. (1995) The contribution of fertiliser nitrogen to leachable nitrogen in the UK: A review, J. Sci. Food Agr. 68, 399–406.

Darby R.J., Hewitt M.V. (1990) A comparison of the effects of single or multiple spring applications of prilled urea or 'Nitro-chalk' to winter oilseed rape (*Brassica napus*), J. Agr. Sci. 115, 363–368.

Dejoux J.-F., Recous S., Meynard J.-M, Trinsoutrot I., Leterme P. (1999a) The fate of nitrogen from winter-frozen rapeseed leaves: mineralization, fluxes to the environment and uptake by rapeseed crop in spring, Plant Soil 218, 257–272.

Dejoux J.-F., Meynard J.-M., Reau R. (1999b) Rapeseed new crop management with early sowing in order to reduce N-leaching and N-fertilization, in: New Horizons for an Old Crop, Proceedings of the 10th International Rapeseed Congress, GCIRC: CD-ROM, Canberra, Australia.

Dejoux J.-F., Meynard J.-M., Reau R., Roche R., Saulas P. (2003) Evaluation of environmentally-friendly crop management systems based on very early sowing dates for winter oilseed rape in France, Agronomie 23, 725–736.

Di H.J., Cameron K.C. (2002) Nitrate leaching in temperate agroecosystems: sources, factors and mitigation strategies, Nutr. Cycl. Agroecosys. 46, 237–256.

Diepenbrock W. (2000) Yield analysis of winter oilseed rape (*Brassica napus* L.): a review, Field Crop. Res. 67, 35–49.

Doluschitz R., Welck H., Zeddies J. (1992) Stickstoffbilanzen landwirtschaftlicher Betriebe - Einstieg in die ökologische Buchführung? Ber. Landwirtsch. 70, 551–565.

Düngeverordnung (2006) Bekanntmachung der Neufassung der Düngeverordnung, Bundesgesetzblatt I 2, 33–43.

Engels T., Kuhlmann H. (1993) Effect of the rate of fertilizer on apparent net mineralization of N during and after cultivation of cereal and sugar beet crops, Z. Pflanzenernachr. Bodenk. 154, 149–154.

Engström L., Stenberg M., Lindén B. (2009) Methods to reduce nitrate leaching after winter oilseed rape and peas, European Workshop 'N fertilization of winter oilseed rape', 23–24 March 2009, Berlin, Germany, http://www.pflanzenbau.uni-kiel.de/veranstaltungen/n-duengung_wraps/Engstroem.pdf (08/09/2009).

European Union (1991) Implementation of nitrate Directive (Directive 91/676/EEC), URL: http://ec.europa.eu/environment/water/water-nitrates/directiv.html (31/10/2006).

European Union (2000) The EU Water Framework Directive - integrated river basin management for Europe, URL: http://ec.europa.eu/environment/water/water-framework/index_en.html (07/03/2008).

Flénet F., Sieling K., Wagner D., Colnenne C. (2009) Is there a need for N fertilizer in autumn in winter oilseed rape (WOSR)? European Workshop 'N fertilization of winter oilseed rape', 23–24 March 2009, Berlin, Germany, http://www.pflanzenbau.uni-kiel.de/veranstaltungen/n-duengung_wraps/Flenet.pdf (08/09/2009).

Fraters D., Boumans L.J.M., Van Drecht G., De Haan T., De Hoop W.D. (1998) Nitrogen monitoring in groundwater in the sandy regions of the Netherlands, Environ. Pollut. 102, 479–485.

Gabrielle B., Denoroy P., Gosse G., Justes E., Anderson M.N. (1998) A model of leaf area development and senescence for oilseed rape, Field Crop. Res. 57, 209–222.

Glendining M.J., Powlson D.S., Poulton P.R., Bradbury N.J., Palazzo D., Li X. (1996) The effects of long-term applications of inorganic nitrogen fertilizer on soil nitrogen in the Broadbalk Wheat Experiment, J. Agr. Sci. 127, 347–363.

Goss M.J., Howse K.R., Lane P.W., Christian D.G., Harris G.L. (1993) Losses of nitrate-nitrogen in water draining from under autumn-sown crops established by direct drilling or mouldboard ploughing, J. Soil Sci. 44, 35–48.

Goss M.J., Williams B.L., Howse K.R. (1991) Organic matter turnover and nitrate leaching, in: Wilson W.S. (Ed.), The advances in soil organic matter research: The impact on agriculture and the environment, The Royal Society of Chemistry, pp. 107–114.

Goulding K.W.T., Poulton P.R., Webster C.P., Howe M.T. (2000) Nitrate leaching from the Broadbalk Wheat Experiment, Rothamsted, UK, as influenced by fertilizer and manure inputs and the weather, Soil Use Manage. 16, 244–250.

Grosse F., Léon J., Diepenbrock W. (1992) Untersuchungen zur Ertragsbildung und Ertragsstruktur bei Winterrps (*Brassica napus* L.). I. Genotypische Variabilität, J. Agron. Crop Sci. 169, 70–93.

Hébinger H. (2009) N fertilization decision support systems for WOSR based on a predictive balance sheet method, European Workshop 'N fertilization of winter oilseed rape', 23–24 March 2009, Berlin, Germany, http://www.pflanzenbau.uni-kiel.de/veranstaltungen/n-duengung_wraps/Hebinger.pdf (08/09/2009).

Henke J. (2008) Entwicklung und Bewertung von Strategien zur Verbesserung der Stickstoffeffizienz im Winterrapsanbau, Schriftenreihe des Instituts für Pflanzenbau und Pflanzenzüchtung der Agrarwissenschaftlichen Fakultät der CAU, Band 54.

Henke J., Böttcher U., Neukam D., Sieling K., Kage K. (2008) Evaluation of different agronomic strategies to reduce nitrate leaching after winter oilseed rape (*Brassica napus* L.) using a simulation model, Nutr. Cycl. Agoecosys. 82, 299–314.

Henke J., Sieling K., Kage H., Breustedt G. (2007) Impact of uncertainty on the optimum nitrogen fertilization rate and agronomic, ecological and economic factors in an oilseed rape based crop rotation, J. Agr. Sci. 145, 455–468.

Henke J., Sieling K., Sauermann W., Kage H. (2009) Analysing soil and canopy factors affecting optimum nitrogen fertilization rates of oilseed rape (*Brassica napus*), J. Agr. Sci. 147, 1–8.

Hocking P.J., Randall P.J., DeMarco D. (1997) The response of dryland canola to nitrogen fertilizer: partitioning and mobilization of dry matter and nitrogen, and nitrogen effects on yield components, Field Crop. Res. 54, 201–220.

Islam N., Evans E.J. (1994) Influence of lodging and nitrogen rate on yield and yield attributes of oilseed rape (*Brassica napus* L.), Theor. Appl. Genet. 88, 530–534.

Jansons V., Buismanis P., Dzalbe I., Kirsteina D. (2003) Catchment and drainage field nitrogen balances and nitrogen loss in three agriculturally influenced Latvian watersheds, Eur. J. Agron. 20, 173–179.

Jensen L.S., Christensen L., Mueller T., Nielsen N.E. (1997) Turnover of residual ^{15}N-labelled fertilizer N in soil following harvest of oilseed rape (*Brassica napus* L.), Plant Soil 190, 193–202.

Justes E., Mary B., Nicolardot B. (1999) Comparing the effectiveness of radish cover crop, oilseed rape volunteers and oilseed rape residues incorporation for reducing nitrate leaching, Nutr. Cycl. Agroecosys. 55, 207–220.

Kelm M., Neumann H., Hüwing H., Kemper N. (2007) Wissen wo man steht. Landwirtschaftliche Produktionssysteme in Schleswig-Holstein: Leistungen und ökologische Effekte. Ergebnisse des Projektes COMPASS, Institut für Pflanzenbau und Pflanzenzüchtung -Grünland und Futterbau/Ökologischer Landbau- und Institut für Phytopathologie der CAU Kiel, ISBN 3-9811625-0-9.

Kuhlmann H., Engels T. (1989) Nitrogen utilisation in relation to N-fertilisation, The Fertiliser Society of London 287, 28–43.

Lagarde F., Champolivier L. (2006) Le raisonnement et les avancées techniques permettent de réduire la fertilization azotée : le cas de Farmstar-colza®, Olégineux Crops, Gras Lipides 13, 384–387.

Lickfett T. (1993) Auswirkungen verminderter Produktionsintensität in zwei Rapsfruchtfolgen auf Elemente des N-Haushaltes im System Boden-Pflanze, PhD thesis, University of Göttingen.

Lindén B., Walgren B. (1993) Nitrogen mineralization after leys ploughed in early or late autumn, Swed. J. Agr. Res. 23, 77–89.

Lord E.I., Anthony S.G., Goodlass G. (2002) Agricultural nitrogen balance and water quality in the UK, Soil Use Manage. 18, 363–369.

Macdonald A.J., Powlson D.S., Poulton P.R., Jenkinson D.S. (1989) Unused fertiliser nitrogen in arable soils - its contribution to nitrate leaching, J. Sci. Food Agr. 46, 407–419.

Macdonald A.J., Poulton P.R., Powlson D.S., Jenkinson D.S. (1997) Effects of season, soil type and cropping on recoveries, residues and losses of ^{15}N-labelled fertilizer applied to arable crops in spring, J. Agr. Sci. 129, 125–154.

Makowski D., Maltas A., Morison M., Reau R. (2005) Calculating N fertilizer doses for oil-seed rape using plant and soil data, Agron. Sustain. Dev. 25, 159–161.

Malagoli P., Laine P., Rossato L., Ourry A. (2005) Dynamics of nitrogen uptake and mobilization in field grown winter oilseed rape (*Brassica napus*) from stem extension to harvest. 1. Global N flows between vegetative and reproductive tissues in relation to leaf fall and their residual N, Ann. Bot. 95, 853–861.

Mary B., Beaudoin N., Justes E., Machet J.M. (1999) Calculation of nitrogen mineralization and leaching in fallow soil using a simple dynamic model, Eur. J. Soil Sci. 50, 549–566.

Mendham N.J., Shipway P.A., Scott R.K. (1981) The effects of delayed sowing and weather on growth, development and yield of winter oil-seed rape (*Brassica napus* L.), J. Agr. Sci. 96, 389–416.

Merrien A., Palleau J.P., Maisonneuve C. (1988) Besoins en éléments minéraux du colza cultivé en France, in: Physiologie et élaboration du rendement du Colza, Paris: Cétiom Editions, pp. 34–46.

Müller K., Böttcher U., Meyer-Schatz F., Kage H. (2008) Analysis of vegetation indices derived from hyperspectral reflection measurements for estimating crop canopy parameters of oilseed rape (*Brassica napus* L.), Biosyst. Eng. 101, 172–182.

Öborn I., Edwards A.C., Witter E., Oenema O., Ivarsson K., Withers P.J.A., Nilsson S.I., Richert Stinzing A. (2003) Element balances as a tool for sustainable nutrient management: a critical appraisal of their merits and limitations within an agronomic and environmental context, Eur. J. Agron. 20, 211–225.

Ogilvy S.E., Bastiman B. (1992) The effect of rate and timing of autumn nitrogen on the pre-flowering dry matter production and seed yield of winter oilseed rape, Asp. Appl. Biol. 30, 413–416.

Rathke G.W., Behrens T., Diepenbrock W. (2006) Integrated nitrogen management strategies to improve seed yield, oil content and nitrogen efficiency of winter oilseed rape (*Brassica napus* L.): A review, Agr. Ecosyst. Environ. 117, 80–108.

Rathke G.-W., Christen O., Diepenbrock W. (2005) Effects of nitrogen source and rate on productivity and quality of winter oilseed rape (*Brassica napus* L.) grown in different crop rotations, Field Crop. Res. 94, 103–113.

Reau R., Wagner D., Palleau J.P. (1994) End of winter diagnosis: Winter rapeseed and nitrogen fertilization, in: Borin M., Sattin M. (Eds.), Proceedings of the third congress of the European Society for Agronomy, Podova: European Society for Agronomy, pp. 220–221.

Rinnofner T., Friedel J.K., de Kruijff R., Pietsch G., Freyer B. (2008) Effect of catch crops on N dynamics and following crops in organic farming, Agron. Sustain. Dev. 28, 551–558.

Rossato L., Lainé P., Ourry A. (2001) Nitrogen storage and remobilisation in *Brassica napus* L. during the growth cycle: nitrogen fluxes within the plant and changes in soluble protein patterns, J. Exp. Bot. 52, 1655–1663.

Sacco D., Bassanimo M., Grignani C. (2003) Developing a regional agronomic information system for estimating nutrient balances at a larger scale, Eur. J. Agron. 20, 199–210.

Schjoerring J.K., Bock J.G.H., Gammelvind L., Jensen C.R., Mogensen, V.O. (1995) Nitrogen incorporation and remobilisation in different shoot components in field-grown winter oilseed rape (*Brassica napus* L.) as affected by rate of nitrogen application and irrigation, Plant Soil 177, 255–264.

Shepherd M.A., Lord E.I. (1996) Nitrate leaching from a sandy soil: the effect of previous crop and post-harvest soil management in an arable rotation, J. Agr. Sci. 127, 215–229.

Shepherd M.A., Sylvester-Bradley R. (1996) Effect of nitrogen fertilizer applied to winter oilseed rape (*Brassica napus*) on soil mineral nitrogen after harvest and on the response of a succeeding crop of winter wheat to nitrogen fertilizer, J. Agr. Sci. 126, 63–74.

Sieling K. (2005) Growth stage specific application of slurry and mineral N to oilseed rape, wheat and barley, J. Agr. Sci. 142, 495–502.

Sieling K., Hanus H. (1997) N-Aufnahme und N-Verwertungseffizienz zweier Weizensorten bei variierter mineralischer N-Düngung, Pflanzenbauwissenschaften 1, 57–62.

Sieling K., Kage H. (2006) N balance as an indicator of N leaching in an oilseed rape - winter wheat - winter barley rotation, Agr. Ecosyst. Environ. 115, 261–269.

Sieling K., Kage H. (2007) Autumnal N fertilization of late sown oilseed rape after minimum tillage, Proceedings of the 12th International Rapeseed Congress (Wuhan, China), III (Agronomy), pp. 375–378.

Sieling K., Günther-Borstel O., Hanus H. (1997) Effects of slurry application and mineral nitrogen fertilization on N leaching in different crop combinations, J. Agr. Sci. 128, 79–86.

Sieling Günther-Borstel O., Teebken T., Hanus H. (1999) Soil mineral N and N net mineralization during autumn and winter under an oilseed rape – winter wheat – winter barley rotation in different crop management systems, J. Agr. Sci. 132, 127–137.

Sieling K., Schröder H., Hanus H. (1998a) Mineral and slurry nitrogen effects on yield, N uptake, and apparent Nuse efficiency of oilseed rape (*Brassica napus*), J. Agr. Sci. 130, 165–172.

Sieling K., Schröder H., Hanus H. (1998b) Yield, N uptake, and apparent N-use efficiency of winter wheat and winter barley grown in different cropping systems, J. Agr. Sci. 131, 375–387.

Smith K.A., Chambers B.J. (1992) Improved utilisation of slurry nitrogen for arable cropping, Asp. Appl. Biol. 30, 127–134.

Smith S.J., Schepers S.J., Porter L.K. (1990) Assessing and managing agricultural nitrogen losses to environment, Adv. Soil Sci. 14, 1–13.

Spink J. (2009) Nitrogen rate and timing to achieve an optimum canopy size, European Workshop 'N fertilization of winter oilseed rape', 23–24 March 2009, Berlin, Germany, http://www.pflanzenbau.uni-kiel.de/veranstaltungen/n-duengung_wraps/Spink.pdf (08/09/2009).

Sylvester-Bradley R., Chambers B.J. (1992) The implications of restricting use of fertilizer nitrogen for the productivity of arable crops, their profitability and potential pollution by nitrate, Asp. Appl. Biol. 30, 85–94.

Trinsoutrot I., Nicolardot B., Justes E., Recous S. (2000) Decomposition in the field of residues of oilseed rape grown at two levels of nitrogen fertilisation. Effects on the dynamics of soil mineral nitrogen between successive crops, Nutr. Cycl. Agroecosys. 56, 125–137.

Webb J., Harrison R., Ellis S. (2000) Nitrogen fluxes in three arable soils in the UK, Eur. J. Agron. 13, 2007–223.

Wehrmann J., Scharpf H.C. (1979) Der Mineralstickstoffgehalt des Bodens als Maßstab für den Stickstoffdüngerbedarf (Nmin-Methode), Plant Soil 52, 109–126.

Zerulla W., Isermann K., Henjes G. (1993) Einfluss langjähriger unterschiedlicher N-Düngung auf Ertrag und N-Verlagerung im Bodenprofil verschiedener Ackerböden, Agribiol. Res. 46, 277–285.

Zhao F.J., Evans E.J., Bilsborrow P.E., Syers J.K. (1993) Influence of sulphur and nitrogen on seed yield and quality of low glucosinolate oilseed rape (*Brassica napus* L.), J. Sci. Food Agr. 63, 29–37.