

Aus dem Institut für Pflanzenbau und Pflanzenzüchtung
der Christian-Albrechts-Universität zu Kiel
-Acker- und Pflanzenbau-

Entwicklung und Bewertung von Strategien zur Verbesserung der Stickstoffeffizienz im Winterrapsanbau

Dissertation
zur Erlangung des Doktorgrades
der Agrar- und Ernährungswissenschaftlichen Fakultät
der Christian-Albrechts-Universität zu Kiel

vorgelegt von

M. Sc. Johannes Henke

aus Harsum

Kiel, 2007

Dekan: Prof. Dr. J. Krieter

1. Berichterstatter: Prof. Dr. H. Kage

2. Berichterstatter: Prof. Dr. F. Taube

Tag der mündlichen Prüfung: 14.02.2008

Gedruckt mit Genehmigung der
Agrar- und Ernährungswissenschaftlichen Fakultät der
Christian-Albrechts-Universität zu Kiel

Inhaltsverzeichnis

Inhaltsverzeichnis	I
Abbildungsverzeichnis	III
Tabellenverzeichnis	V
Kapitel 1 Einleitung	1
1.1 Problemstellung	2
1.2 Ziele	4
1.3 Literatur	7
Kapitel 2 <i>Evaluation of different agronomic strategies to reduce nitrate leaching after winter oilseed rape (Brassica napus L.) using a simulation model</i>	10
2.1 Abstract	11
2.2 Introduction	11
2.3 Material and Methods	13
2.4 Results	21
2.5 Discussion	33
2.6 Conclusions	37
2.7 References	37
Kapitel 3 <i>Impact of uncertainty on the optimum nitrogen fertilization rate and agronomic, ecological and economic factors in an oilseed rape based crop rotation</i>	42
3.1 Summary	43
3.2 Introduction	44
3.3 Material and Methods	45
3.4 Results	48
3.5 Discussion	68

3.6	Conclusions	70
3.7	References	72
<i>Kapitel 4 Analysing soil and canopy factors affecting optimum nitrogen fertilization rates of oilseed rape (Brassica napus)</i>		74
4.1	Summary	75
4.2	Introduction	76
4.3	Material and Methods	77
4.4	Results	80
4.5	Discussion	85
4.6	Conclusions	88
4.7	References	89
<i>Kapitel 5 Abschließende Diskussion</i>		92
5.1	Problemstellung und zusammenfassende Darstellung der Untersuchungsergebnisse	93
5.2	Bewertung von Strategien zur Verbesserung der N-Effizienz im Winterrapsanbau	95
5.3	Literatur	108
<i>Kapitel 6 Zusammenfassung/Summary</i>		114

Abbildungsverzeichnis

Kapitel 2

Figure 1	Soil water dynamics, precipitation, evapotranspiration and drainage in WWCT (N3) in the simulation periods 2005/2006 (a) and 2006/2007 (b)	26
Figure 2	SMN dynamics, N uptake, net mineralization and N leaching in WWMT in the simulation periods 2005/2006 (a) and 2006/2007 (b)	29
Figure 3	SMN dynamics, N uptake, net mineralization and N leaching in treatment WWCT (a) and CC (b) in the simulation period 2005/2006	30

Kapitel 3

Figure 1	Oilseed rape yield response to N fertilization in 2002 described using (a) the linear response and plateau model, (b) the quadratic response and plateau model and (c) the quadratic model	49
Figure 2	Residuals of the regression (observed yield minus estimated yield) when (a) the linear response and plateau model, (b) the quadratic response and plateau model and (c) the quadratic model were fitted to yield data of OSR vs. N fertilization in 2002	50
Figure 3	Distribution of the generated parameters of the linear response and plateau model in each year for oilseed rape (a) C (Nopt), (b) P (plateau yield), (c) b (linear coefficient)	59
Figure 4	Linear response and plateau model fitted to the five individual years (1996, 1997, 1998, 1999 and 2002) for the crops oilseed rape, winter wheat and winter barley, as well as the mean yield response curve for the three crops derived from the 50000 simulated LRP models and the standard deviation of the mean yield	64
Figure 5	Quadratic model fitted to the five individual years (1996, 1997, 1998, 1999 and 2002) for the crops oilseed rape, winter wheat and winter barley, as well as the mean yield response curve for the three crops derived from the 50000 simulated Q models and the standard deviation of the mean yield	65

Kapitel 4

Figure 1	Regressions of measured vs. estimated canopy N in autumn 2006 (a) and spring (b)	83
----------	--	----

Figure 2	Regressions of Nopt vs. SMN at the start of spring growth (a), Nopt vs. canopy N in spring (b) and canopy N in autumn (c) for seven experimental locations in Germany in two years	84
----------	--	----

Kapitel 5

Abbildung 1	Szenarienanalyse: Mittlere N-Auswaschung über 9 Jahre an drei norddeutschen Standorten (Düngung je 200 kg N/ha)	97
Abbildung 2	Szenarienanalyse: Mittlere NO ₃ -Konzentration im Sickerwasser über 9 Jahre an drei norddeutschen Standorten (Düngung je 200 kg N/ha)	98
Abbildung 3	Einfluss des Harvest-Index auf die N-Auswaschung nach Winterraps	103

Tabellenverzeichnis

Kapitel 1

Tabelle 1	Maßnahmen zur Verbesserung der N-Effizienz im Winterrapsanbau (verändert nach Behrens 2002)	5
-----------	---	---

Kapitel 2

Table 1	Precipitation and temperature at the Hohenschulen experimental station during the experimental periods and in the long term	13
Table 2	Treatments in the field trial (OSR N fertilization level 200 kg N/ha; in treatment WWCT: 0, 160, 200, 240 kg N/ha)	15
Table 3	Parameters of the Van Genuchten equations	17
Table 4	Parameters of the mineralization submodel	19
Table 5	C in crop residues, N in crop residues C/N ratio, DM in crop residues and SMN at harvest in the different treatments (N3)	23
Table 6	C in crop residues, N in crop residues C/N ratio, DM in crop residues and SMN at harvest in WWCT (N1, N2, N3, N4)	24
Table 7	Statistical measures of the regressions measured vs. simulated soil water content in the different soil layers on both simulation periods	25
Table 8	Soil water (0-90 cm) at harvest, cumulative precipitation, cumulative evapotranspiration, cumulative drainage and soil water (0-90 cm)	27
Table 9	Statistical measures of the regressions measured vs. simulated SMN in the different soil layers in 2005/2006 and 2006/2007	28
Table 10	Measured and calculated key data of the N dynamics after OSR	32

Kapitel 3

Table 1	Intercept (a), linear coefficient (b), adj. R^2 , C, P, RMSE (root mean square error) and n of the linear response and plateau model (S.E. \pm)	52
Table 2	Intercept (a), linear coefficient (b), quadratic coefficient (c), adj. R^2 , C, P, RMSE and n of the quadratic response and plateau model (S.E. \pm)	53

Tabellenverzeichnis

Table 3	Intercept (a), linear coefficient (b), quadratic coefficient (c), adj. R ² , RMSE and n of the quadratic model	54
Table 4	<i>Ex post</i> Nopt (kg N/ha), grain yield (t/ha), net revenue (€/ha) and N balance (kg N/ha) at <i>ex post</i> Nopt of OSR, winter wheat and winter barley	56
Table 5	Grain yield (t/ha), net revenue (€/ha) and N balance (kg N/ha) in the rotation estimated with <i>ex ante</i> Nopt	58
Table 6	Effect of the Monte Carlo simulation of the LRP model parameters on Nopt (kg N/ha), grain yield (t/ha), net revenue (€/ha) and N balance (kg N/ha) at <i>ex post</i> Nopt in comparison to the <i>ex ante</i> Nopt estimated by the LRP model	60
Table 7	Mean <i>ex post</i> Nopt, <i>ex ante</i> Nopt with and without Monte-Carlo simulation (MC) and corresponding net revenues and N balances	62
Table 8	Intercept (a), linear coefficients (b,c), r ² , RSME and n of the protein function (SE ±)	66
Table 9	Nopt (kg N/ha), grain yield (t/ha), protein concentration (mg/g), net revenue (€/ha) and N balance (kg N/ha) of winter wheat at Nopt estimated by the Q model with and without having regard to protein concentration for each year	67

Kapitel 4

Table 1	Geographical position, climate and soil characteristics of the locations	77
Table 2	Sowing dates and plot size of the field trials in both years	78
Table 3	Fertilization treatments (autumn/spring) in each sowing date	78
Table 4	Autumn and spring canopy N (kg N/ha) and SMN in spring (kg/ha) at all locations in the years 2005/2006 and 2006/2007	81
Table 5	Intercept (a) and linear coefficient (b) of the regression Nopt vs. canopy N in autumn (SE ±), Model: $Y = a_{(location)} + bX$	85

Kapitel 5

Tabelle 1	Einfluss der Berücksichtigung der Qualität des Winterweizens und des Anbaus eines zweiten Weizens auf Nopt und das N-Bilanzsaldo im Vergleich zur Fruchtfolge Winterraps-Winterweizen-Wintergerste ohne Qualitätsberücksichtigung (<i>ex ante</i> Nopt)	100
-----------	--	-----

Kapitel 1

Einleitung

1.1 Problemstellung

In Ackerbaufruchtfolgen hat Winterraps (*Brassica napus* L.) in den letzten Jahrzehnten eine bedeutende Stellung erlangt. Durch die Zunahme der Verwertungsmöglichkeiten der Rapssaat und die Möglichkeit des Anbaus als nachwachsender Rohstoff auf Stilllegungsflächen ist der Flächenanteil von Winterraps ständig gestiegen. Die Anbaufläche hat in Deutschland zur Ernte 2007 ca. 1,5 Millionen ha erreicht (Statistisches Bundesamt 2007). Diese Fläche entspricht 12,9 % der gesamten Ackerfläche in Deutschland. In Schleswig-Holstein und Mecklenburg-Vorpommern liegt der Anteil des Winterraps an der Ackerfläche mit 18,7 % bzw. 23,8 % wesentlich höher (Statistisches Bundesamt 2007). Damit ist Winterraps ein bedeutender Bestandteil der typischen Fruchtfolgen Norddeutschlands. Üblicherweise steht Winterraps in der dreifeldrigen Fruchtfolge Winterraps-Winterweizen-Wintergerste (Rathke et al. 2006), wobei die Wintergerste häufig durch Winterweizen ersetzt wird. Winterraps stellt eine wichtige Vorfrucht für den nachfolgenden Winterweizen dar. Zahlreiche Versuchsergebnisse zeigen positive Ertragseffekte der Vorfrucht Winterraps auf den nachfolgenden Winterweizen (Christen 1999, Rathke et al. 2006). Sieling et al. (2005) stellten einen Mehrertrag von 9 dt/ha bei Rapsvorfrucht im Vergleich zur Weizenvorfrucht fest. Dieser positive Vorfruchteffekt des Winterrapses basiert auf dem gut strukturierten Boden nach der Ernte sowie der Unterbrechung von Infektionsketten im Getreideanbau (Lickfett 1993, Shepherd & Sylvester-Bradley 1996, Chan & Heenan 1996, Rathke et al. 2006). Ein positiver Einfluss auf den Ertrag des nachfolgenden Winterweizens durch eine gute Nährstoffversorgung, vor allem mit Stickstoff (N), nach Winterraps wird in der Literatur oft erwähnt (Lickfett 1993, Shepherd & Sylvester-Bradley 1996, Rathke et al. 2006), konnte aber am Standort Hohenschulen in langjährigen Versuchen nicht festgestellt werden (Christen 1997, Sieling et al. 2005).

Winterraps hat zur Realisierung hoher Erträge einen erheblichen N-Bedarf, verwertet N aber wenig effizient. Rathke et al. (2006) nennen einen N-Bedarf von 6 kg N je dt Samenertrag. Die N-Nutzungseffizienz (NUE) des Winterrapses lässt sich auf verschiedenen Ebenen betrachten (Novoa & Loomis 1981). Novoa & Loomis (1981) definieren die NUE auf Kulturpflanzenebene als Ertrag je aufgenommener Einheit N. Winterraps weist einen im Vergleich zum Weizen signifikant geringeren N-Harvestindex im Bereich 0.7-0.75 auf (Dreccer et al. 2000). Auf der Ebene des Anbausystems wird die NUE auf Pflanzenebene um

die sogenannte 'recovery fraction' (RF), dem Verhältnis von aufgenommener zur gedüngten N-Menge, erweitert (Novoa & Loomis 1981). Die RF ist definiert als aufgenommene N-Menge je Gesamt-N-Angebot multipliziert mit dem Verhältnis aus Gesamt-N-Angebot zur gedüngten N-Menge, sodass bei dieser Betrachtung auf der Ebene des Anbausystems Prozesse wie z. B. N-Auswaschung berücksichtigt werden (Novoa & Loomis 1981). Auf der Ebene des Produktionssystems ist der Rapsanbau durch hohe N-Bilanzüberschüsse und erhöhte N-Auswaschung nach Rapsanbau gekennzeichnet. So zeigen Schlagkarteiauswertungen von Ziesemer & Lehmann (2006) aus Mecklenburg-Vorpommern, dem größten Anbaugbiet für Winterraps in Deutschland, dass unter Praxisbedingungen N-Bilanzüberschüsse von 100 kg N/ha häufig vorkommen können. Kaiser & Ruser (2000) fanden in Untersuchungen zur Lachgasemission (N_2O) auf ackerbaulich genutzten Flächen keinen signifikanten Zusammenhang zwischen der N-Düngerhöhe und den N_2O -Emissionen, aber es wurde in der Studie ein signifikanter positiver Zusammenhang zwischen erhöhten N-Bilanzen und vermehrter Emission von N_2O gefunden, was vor dem Hintergrund der aktuellen Diskussion über verstärkte Lachgasemissionen beim Anbau nachwachsender Rohstoffe von Bedeutung ist. Weiterhin berichten zahlreiche Autoren von einer deutlich erhöhten N-Auswaschung nach Raps im Vergleich zu Getreide (Lickfett 1993, Sieling & Kage 2006, Rathke et al. 2006). Als Ursache für die Anreicherung an mineralischem N im Boden nach der Rapsernte können erhöhte N_{min} -Werte im Boden zum Zeitpunkt der Ernte oder Mineralisierung von Ernterückständen und verlorenen Blättern vor Ernte in Frage kommen (Lickfett 1993). Des weiteren ist die Zeitspanne zwischen Ernte und der Aussaat der typischen Nachfrucht Winterweizen relativ lang, so dass verstärkt bodenbürtiger N mineralisiert werden kann (Jensen et al. 1997). Diese N-Mengen können von der typischen Folgefrucht Winterweizen vor Winter nur partiell aufgenommen werden und sind somit auswaschungsgefährdet.

Der praktischen Landwirtschaft stehen heute verstärkte Anforderungen an die Umweltverträglichkeit gegenüber. Nennenswert sind hierbei die nationale Umsetzung der Wasserrahmenrichtlinie der EU (Richtlinie 2000/60 EG) (Anonymus 1997) und die Neuformulierung des Begriffes der guten fachlichen Praxis im Bundesnaturschutzgesetz (BNatSchG). Im BNatSchG werden unter anderem eine standortangepasste Bewirtschaftung und die Gewährleistung einer nachhaltigen Bodenfruchtbarkeit gefordert. Durch die Bindung der Direktzahlungen an nationale Fachrechtsauflagen (Cross-Compliance im Rahmen der Gemeinsamen Agrarpolitik der EU (GAP)) werden erhöhte

Ansprüche an den Schutz natürlicher Ressourcen für landwirtschaftliche Betriebe auch von besonderer ökonomischer Bedeutung sein. Mit der novellierten Düngeverordnung (Anonymus 2006) wird die Nitratrichtlinie der EU von 1991 (Anonymus 1991) auf nationaler Ebene umgesetzt. In der Düngeverordnung wird beim Nährstoffvergleich eine Zielgröße von N-Bilanzüberschüssen von 60 kg N/ha ab 2009 festgesetzt. Vor diesem Hintergrund gilt es, die N-Effizienz im Winterrapsanbau zu verbessern, um einerseits den gesetzlichen Anforderungen an die Umweltbelastungen nachzukommen, andererseits aber durch eine optimierte Produktionstechnik das Anbausystem Rapsfruchtfolge wirtschaftlich zu gestalten.

1.2 Ziele

Ziele der vorliegenden Arbeit sind die Analyse der N-Effizienz im Winterrapsanbau auf der Ebene des Anbausystems, die Quantifizierung der N-Auswaschung sowie die Erarbeitung und Bewertung von Optimierungsstrategien. Behrens (2002) nennt eine Reihe möglicher Verbesserungsmaßnahmen, die die N-Effizienz im Winterrapsanbau verbessern könnten (Tabelle 1).

Tabelle 1: Maßnahmen zur Verbesserung der N-Effizienz im Winterrapsanbau (verändert nach Behrens 2002)

Maßnahme	Ziel
Gestaltung der Fruchtfolge	→ Vermeidung von Verlusten durch Kürzung der vegetationsfreien Zeit
Bodenbearbeitungsintensität	→ Verringerung der Mineralisation
Anbau von Zwischenfrüchten	→ Konservierung von Stickstoff in der vegetationsfreien Zeit
Bewässerung und Pflanzenschutz	→ Steigerung der N-Aufnahme bzw. Vermeiden von N-Verlusten durch gesunde Pflanzen
Ermittlung des N-Düngerbedarfs	→ Gezielter Einsatz von N-Düngemitteln unter Berücksichtigung des im Boden und im Pflanzenbestand vorhandenen und während der Vegetationszeit mineralisierbaren Stickstoffs
Wahl der Düngerform	→ Vermeidung von N-Form-spezifischen Verlusten → Steigerung der physiologischen Effizienz durch Berücksichtigung der Präferenz von Pflanzenarten für eine bestimmte N-Form
Zeitpunkt der Düngung	→ Vermeidung von N-Verlusten → Gezielte Förderung einzelner Ertragskomponenten
Düngungstechnik	→ Vermeiden von N-Verlusten → Verbesserung der räumlichen Verfügbarkeit → Verminderung der N-Immobilisierung
Wahl der Sorte	→ Nutzung genotypischer Unterschiede in der N-Aufnahme und N-Verwertungseffizienz

In den folgenden Kapiteln dieser Arbeit werden die Ansätze Gestaltung der Fruchtfolge, Anbau von Zwischenfrüchten, Bodenbearbeitungsintensität und Ermittlung des N-Düngebedarfs intensiv erörtert.

Anhand eines Simulationsmodells und mehrjähriger Daten aus zwei Feldversuchen wird in **Kapitel 2** die N-Dynamik nach der Winterrapserte bei verschiedenen N-Düngeniveaus zum Raps, verschieden intensiver Bodenbearbeitung und unterschiedlicher Folgefrucht analysiert. Submodelle für den Bodenwasserhaushalt, Mineralisations- und Immobilisationsprozesse und der Bodenbearbeitung, sowie der Pflanzen-N-Aufnahme wurden zu einem Simulationsmodell verknüpft, mit dem sich die N-Auswaschung quantifizieren lässt und die Effekte der untersuchten produktionstechnischen Maßnahmen auf die N-Dynamik untersuchen lassen. Der Einsatz eines Simulationsmodells führt zu einem umfangreicheren Systemverständnis, anhand dessen sich in Kombination mit Ergebnissen aus dem Feldversuch erste Optimierungsansätze

erarbeiten lassen und weiterer Untersuchungsbedarf für die Verbesserung der N-Effizienz im Winterrapsanbau aufgezeigt werden kann.

In **Kapitel 3** wurde der Einfluss von Unsicherheit auf die Bemessung der optimalen N-Düngermenge in der Fruchtfolge Winterraps-Winterweizen-Wintergerste empirisch bearbeitet. Drei verschiedene Formen von Unsicherheit wurden unterstellt und der Einfluss der entsprechend ermittelten ökonomisch optimalen N-Düngermengen auf die N-Bilanz und den Erlös der einzelnen Kulturen und der Fruchtfolge untersucht.

Unsicherheiten in der N-Düngebedarfsermittlung kann durch eine Optimierung durch Anpassung an Standort und Bestandesentwicklung begegnet werden. Eine Methode zur bestandesangepassten N-Düngebedarfsermittlung wird in **Kapitel 4** vorgestellt. Dabei wurden die N-Mengen in Rapsbeständen in Herbst und Frühjahr neben N_{min} im Frühjahr in einem bundesweiten Versuch auf sieben Standorten ermittelt und ihre Beziehung zur optimalen N-Düngermenge empirisch untersucht.

In der abschließenden Diskussion (Kapitel 5) werden die Ergebnisse aus den vorherigen Kapiteln in einen gemeinsamen Kontext gestellt und Optimierungsstrategien aufgezeigt und bewertet.

1.3 Literatur

- ALLIRAND, J.-M., JULLIEN, A., SAVIN, A. & NEY, B. (2007). Oilseed rape leaves falling off depends on both leaf nitrogen content and transmitted radiation. In: Proceedings of the 12th International Rapeseed Congress (Wuhan), III (Agronomy), 307-310.
- ANONYMUS (1991). Nitratrichtlinie: Richtlinie 91/676/EWG des Rates vom 12. Dezember 1991 zum Schutz der Gewässer vor Verunreinigung durch Nitrat aus landwirtschaftlichen Quellen. Amtsblatt der Europäischen Gemeinschaft Nr. L 375.
- ANONYMUS (1997). Elemente einer Richtlinie des Rates für den Schutz und die Bewirtschaftung der Gewässer der Gemeinschaft (Wasserrahmenrichtlinie). Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, Bonn.
- ANONYMUS (2006). Verordnung über die Anwendung von Düngemitteln, Bodenhilfsstoffen, Kultursubstraten und Pflanzenhilfsmitteln nach den Grundsätzen der guten fachlichen Praxis beim Düngen (Düngeverordnung). Bundesgesetzblatt Jahrgang 2006, Teil I Nr. 2, ausgegeben am 13.01.2006.
- BEHRENS, T. (2002). Stickstoffeffizienz von Winterraps (*Brassica napus* L.) in Abhängigkeit von der Sorte sowie einer in Menge, Zeit und Form variierten Stickstoffdüngung. Dissertation, Universität Hannover.
- CHAN, K. Y. & HEENAN, D. P. (1996). The influence of crop rotation on soil structure and soil physical properties under conventional tillage. *Soil & Tillage Research* 37, 113-125.
- CHRISTEN, O. (1997). Untersuchungen zur Anbautechnik von Winterweizen nach unterschiedlichen Vorfruchtkombinationen. Habilitationsschrift, Universität Kiel. Schriftenreihe des Instituts für Pflanzenbau und Pflanzenzüchtung der Agrarwissenschaftlichen Fakultät der CAU, Bd. 7.
- DRECCER, M. F., SCHAPENDONK, A. H. C. M., SLAFER, G. A. & RABBINGE, R. (2000). Comparative response of wheat and oilseed rape to nitrogen supply: absorption and utilisation efficiency of radiation and nitrogen during the reproductive stages determining yield. *Plant and Soil* 220, 189-205.

- JENSEN, L. S., CHRISTENSEN, L., MUELLER, T. & NIELSEN, N. E. (1997). Turnover of ¹⁵N-labelled fertilizer N in soil following of oilseed rape (*Brassica napus* L.). *Plant and Soil* 190, 193-202.
- KAISER, E.-A. & RUSER, R. (2000). Nitrous oxide emissions from arable soils in Germany – An evaluation of six long-term field experiments. *Journal of Plant Nutrition and Soil Science* 163, 249-260.
- LICKFETT, T. (1993). Auswirkungen verminderter Produktionsintensität in zwei Rapsfruchtfolgen auf Elemente des N-Haushalts im System Boden-Pflanze. Dissertation Göttingen.
- MALAGOLI, P., LAINE, P., ROSSATO, L. & OURRY, A. (2005a). Dynamics of Nitrogen Uptake and Mobilization in Field-Grown Winter Oilseed Rape (*Brassica napus*) from Stem Extension to Harvest. I. Global N Flows between Vegetative and Reproductive Tissues in Relation to Leaf Fall and their Residual N. *Annals of Botany* 95, 853-861.
- MALAGOLI, P., LAINE, P., ROSSATO, L. & OURRY, A. (2005b). Dynamics of Nitrogen Uptake and Mobilization in Field-Grown Winter Oilseed Rape (*Brassica napus*) from Stem Extension to Harvest. II. An ¹⁵N-labelling-based Simulation Model of N Partitioning Between Vegetative and Reproductive Tissues. *Annals of Botany* 95, 1187-1198.
- NOVOA, R. & LOOMIS, R. S. (1981). Nitrogen and Plant Production. *Plant and Soil* 58, 177-204.
- 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. *Agriculture, Ecosystems and Environment* 117, 80-108.
- SCHJOERRING, J. K., BOCK, J. G. H., GAMMELVIND, L., JENSEN, C. R. & MOGENSEN, V. O. (1995). Nitrogen incorporation and remobilization in different shoot components of field-grown winter oilseed rape (*Brassica napus* L.) as affected by rate of nitrogen application and irrigation. *Plant and Soil* 177, 255-264.
- 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. *Journal of Agricultural Science, Cambridge* 126, 63-74.

SELING, K., STAHL, C., WINKELMANN, C. & CHRISTEN, O. (2005). Growth and yield of winter wheat in the first 3 three years of a monoculture under varying N fertilization in NW Germany. *European Journal of Agronomy* 22, 71-84.

STATISTISCHES BUNDESAMT (2007). Land- und Forstwirtschaft, Fischerei, Landwirtschaftliche Bodennutzung, Anbau auf dem Ackerland, Agrarstrukturerhebung 2007, Fachserie 3, Reihe 3.1.2, Statistisches Bundesamt, Wiesbaden.

ZIESEMER, A. & LEHMANN, E. (2006). Zusammenfassung aktueller Ergebnisse der anbautechnischen Forschung und ökonomischen Auswertungen im Acker- und Pflanzenbau, Fo-Nr.: 1/05. Landesforschungsanstalt für Landwirtschaft und Fischerei Mecklenburg-Vorpommern, Gülzow.

Kapitel 2

Evaluation of different agronomic strategies to reduce nitrate leaching after winter oilseed rape (*Brassica napus* L.) using a simulation model

**J. Henke, U. Böttcher, D. Neukam, K. Sieling &
H. Kage**

Submitted to Nutrient Cycling in Agroecosystems

2.1 Abstract

Winter oilseed rape (OSR) demands high levels of N fertilizer, often exceeding 200 kg N/ha. Large amounts of residual soil mineral nitrogen (SMN) after harvest are regularly observed, and therefore N leaching during the percolation period over winter is increased. In this study agronomic strategies to control nitrate leaching after OSR were investigated combining field measurements of a two year trial with comparison of soil management and crop rotation measures and a five year field trial (SMN, soil water content, crop N uptake) with simulation modeling. The simulation model comprised submodels for soil water dynamics, mineralization processes and N uptake to reproduce the complex processes of the N dynamics and to calculate N concentration in the leachate and total volume of percolation water based on the agreement between measured data and model results. Although SMN in the layer 60-90 cm was overestimated, the model could reproduce the measured data with an acceptable degree of accuracy. Overfertilization of OSR increased N leaching and therefore the precise calculation of N fertilizer doses is a first step to prevent N leaching. Compared to ploughing, minimum tillage decreased N leaching when winter wheat was grown as the subsequent crop. Volunteer OSR and Phacelia were grown as catch crops after OSR harvest. N leaching could be decreased especially when Phacelia was grown but nitrate concentrations in the drainage water were higher and exceeded the EU threshold for drinking water when volunteer OSR was grown. The results of this study give strong evidence that reduced tillage or growing of non cruciferous catch crops decrease N leaching and may be used as agricultural measures to prevent N pollution.

2.2 Introduction

In Germany winter oilseed rape (OSR) has become a more and more important crop in the last decades because of its profitability, the beneficial value as preceding crop for cereals and the opportunity to grow OSR for biofuel production on set-aside. OSR demands high levels of nitrogen (N) fertilizer often exceeding 200 kg N/ha to achieve maximum yields. However, N offtake by the seed is comparatively low leading to high positive N surpluses on the crop scale (Shepherd and Sylvester-Bradley 1996, Sieling et al. 1999). In addition N-harvest-index of OSR, ranging between 0.6 to 0.7, is low compared to cereals (Malagoli et al. 2005). Although OSR 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 (SMN) content increases regularly during autumn

(Lickfett 1993). In consequence large amounts of nitrate are likely to be leached with drainage water (Sieling et al. 1999). Intensive tillage operations after harvest stimulate net mineralization of soil born N due to soil disturbance (Lickfett 1993). Additionally, the autumnal N uptake of winter wheat typically grown after OSR does generally not exceed 20-30 kg N/ha under the climatic conditions of NW Germany (Lickfett 1993, Sieling et al. 1999). However, 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. Secondly, changes in the crop rotation as the introduction of catch crops and spring crops can decrease SMN content during autumn and therefore reduce the risk of nitrate leaching after OSR. Justes et al. (1999) reported a significant reduction of SMN and nitrate leaching by a radish cover crop or volunteer OSR compared to a bare soil.

Simulation modeling as a methodological approach for calculating N leaching from agricultural soils has become a common tool in agro-ecological research. According to Köhler et al. (2006) the advantages using a simulation model for calculating N leaching compared to labor intensive and expensive lysimeter studies or leachate sampling by suction cups are to carry out the investigations under undisturbed soil conditions and to analyze different sites, many trial plots or larger scales. Additionally, the experimental data are accessible to a more intensive analysis of the processes influencing N leaching like the components of the soil water budget or the mineralization rates. Several model approaches deal with N dynamics after OSR harvest, especially in terms of crop residue decomposition (Mueller et al. 1997 (DAISY), Mary et al. 1999 (LIXIM), Trinsoutrot et al. 2000 (NCSOIL), Nicolardot et al. 2001 (STICS). The present modeling approach differs from these earlier studies because it combines processes of OSR residue decomposition, soil organic N mineralization as affected by tillage intensity and crop N uptake. In contrast to the other studies the combination of all these complex processes allows the investigation of different management practices on soil N dynamics and N leaching on the cropping system level. Data from a two year field trial were used for initialization and parameterization of the model. To test the general applicability and the functionality of the model and the parameterization, it was validated on field measurements of a five year independent dataset.

2.3 Material and Methods

Field trial

Site and weather conditions

A field trial was established in autumn 2003 on a pseudogleyic sandy loam (Luvisol: 170 g kg⁻¹ clay, pH 6.7, 9 mg kg⁻¹ P, 15 mg kg⁻¹ K, 13 g kg⁻¹ C_{org}) at the Hohenschulen Experimental Station of the University of Kiel, located in NW Germany 15 km west of Kiel.

The climate can be described as humid. Long term total rainfall averages 750 mm annually, with ca. 400 mm received during April-September, the main growing season, and ca. 350 mm during October-March. Rainfall and temperature of the experimental periods are given in Table 1.

Table 1: Precipitation and temperature at the Hohenschulen experimental station during the experimental periods and in the long term

Month	Experimental period					
	2005/2006		2006/2007		long term	
	Temp. (°C)	Rain (mm)	Temp. (°C)	Rain (mm)	Temp. (°C)	Rain (mm)
July	18.0	92	20.8	53	16.9	100
Aug.	16.9	49	18.6	143	17.9	59
Sept.	15.3	20	16.9	33	14.2	61
Oct.	11.8	67	12.5	80	9.8	75
Nov.	5.8	44	7.5	44	4.9	58
Dec.	2.8	46	6.3	39	1.6	62
Jan.	-0.6	14	5.1	118	1.2	48
Feb.	1.6	22	3.0	35	2.0	50
March	0.8	47	6.5	44	3.4	44
April	6.7	50	10.0	2	8.0	44
Sum		451		591		601

Treatments and Design

The field trial started in autumn 2003. In this paper results of the percolation periods 2005/2006 and 2006/2007 are presented. The treatments comprised different soil tillage operations and subsequent crops after OSR (Table 2), arranged in a split-plot design. In treatment VOSR volunteer OSR was grown as a catch crop after harvest whereas *Phacelia tanacetifolia* (Phacelia) was grown as a catch crop in treatment CC. In the treatments WWCT and WWMT winter wheat was grown after OSR with shallow tillage operations in WWMT compared to ploughing in WWCT. The treatments were randomized main plots, the randomized N treatments for OSR within the main plots were the four subplots. Only in WWCT all N treatments (N1=0 kg N/ha, N2=160 kg N/ha, N3=200 kg N/ha, N4=240 kg N/ha) were considered, in the other treatments detailed

investigations were only carried out at N3 level. Management treatments were compared at N3 whereas the effect of the fertilization level was investigated only in WWCT. Plot size was 12 x 12 m, subplot size 3 x 12 m. The four randomized N treatments were subplots within the main plots. N was applied as calcium ammonium nitrate with 27 % N and varied in amount and distribution. Fungicides and other crop management measures not involving the treatments (e. g. herbicides, sowing date) were handled in accordance with the farmers' normal practice. At crop maturity, an area of 10.5 m² was harvested by combine harvester and yield was standardized to t/ha at 91 % dry matter. Tillage depth in autumn was 10 cm with the compact disc cultivator, 20 cm with the cultivator and 30 cm with the plough.

Table 2: Treatments in the field trial (OSR N fertilization level 200 kg N/ha; in treatment WWCT: 0, 160, 200, 240 kg N/ha)

Date		Treatment		
2005/2006	2006/2007	VOSR	CC	WWCT
			Oilseed rape (cv. Trabant) harvest	WWMT
26.7.2005	28.7.2006		Compact disc cultivator	Compact disc cultivator
26.8.2005	6.8.2006		Cultivator	
26.8.2005	7.8.2006		Rotary harrow/ Seed drill	
		Volunteer oilseed rape	Catch crop (Phacelia) (cv. Angelina)	Glyphosate
5.9.2005	12.9.2006			Compact disc cultivator
14.9.2005	14.9.2006			Compact disc cultivator
16.9.2005	15.9.2006			Compact disc cultivator
				Rotary harrow/Seed drill
				Winter wheat (cv. Tommi)
18.4.2006	15.3.2007	Glyphosate		
19.4.2006			Cultivator	
			Rotary harrow/Seed drill	
		Oats (cv.	Maize (cv. Ronaldinio)	

Plant and soil sampling

Plant samples were taken from OSR (0.5 m²) in VOSR (N3), WWCT (N1, N2, N3, N4) and WWMT (N3) at harvest. Because of identical crop husbandry the crop residues in VOSR were assumed to be equal to CC. Total number of plants, dry matter of stems and pod walls and corresponding C and N concentrations were determined at harvest (C/N-Analyser Vario MAX, CN Elementar Analysesysteme). For model calculations C and N amounts in the rooting system as well as the shoot to root ratios were assumed to be similar as given in Gosse et al. (1999). In the subsequent winter wheat (WWCT, WWMT) plant samples (0.25 m²) were taken at the end of autumn growth and beginning of spring growth. Total number of plants and shoots, total above ground dry matter and N concentration were measured. In volunteer OSR (VOSR) and the catch crop (CC) total above ground dry matter (0.25 m²) and its N concentration was quantified fortnightly from emergence to end of autumn growth. N concentration was determined using near infrared spectrometry (NIRS 5000, Foss).

Soil mineral nitrogen (NO₃-N plus NH₄-N: SMN) was investigated monthly in period 2005/2006 apart of periods with snow cover or freezing. Four cores per plot, mixed to one sample, were taken to a depth of 90 cm in 30 cm layers. Additionally soil samples (0-30 cm) were taken fortnightly in CC in autumn. In 2006/2007 soil mineral nitrogen was determined weekly (0-30 cm) and monthly (0-90 cm) in all treatments. Soil samples for SMN were stored frozen until analysis. After thawing overnight at room temperature, NO₃-N and NH₄-N were extracted using 0.0333 N CaCl₂ and analyzed colorimetrically. A sub-sample was oven-dried to determine the gravimetric soil moisture content.

Basic data of the field trial as amounts of crop residues, their C and N content, SMN and crop N uptake were used for initialization and parameterization of the simulation model.

Statistical analysis

Analyses of variance were performed at p=0.05 using the GLM procedure of the SAS statistical software package (SAS Institute Inc. 1989).

Model

The model was used to simulate the N dynamics in the soil system in the different management treatments after OSR harvest. The main objective was the

quantification of N losses via leaching in the different treatments by model calculation.

Water transport and evapotranspiration

The submodels which describe the water movement through the soil and evapotranspiration were presented in detail by Kage et al. (2003). Roughly, the water transport model calculates soil water movement by using the water content based formulation of the Richard's equation. Relationships between soil water diffusivity and the volumetric water content are described by the functions of van Genuchten (1980) in the revised form of Wösten and Van Genuchten (1988). Parameters for this relationship were estimated with the program RETC (van Genuchten et al. 1991) after characterizing soil texture. The derived parameter values are given in Table 3. Potential evapotranspiration is calculated using the Penman-Monteith equation (Monteith 1973).

Table 3: Parameters of the Van Genuchten equations

Soil	Depth (cm)	θ_r (cm ³ cm ⁻³)	θ_s (cm ³ cm ⁻³)	α cm ⁻¹	n	Ks cm d ⁻¹
Sandy loam	0-30	0	0.38647	0.04571	1.18979	60
	30-60	0	0.38365	0.06415	1.17722	60
	60-90	0	0.40166	0.08271	1.18283	50

In order to consider delayed water influx into the soil after snow fall a submodel of snow accumulation was adopted from the DAISY model (Hansen 1991) which is based on the model of Jansson and Haldin (1980). Basic parts of this submodel are the separate calculation of liquid water and total water expressed in equivalent water within the snow pack:

$$W_l = W_l + [R + M - E_s - J]\Delta t \tag{1}$$

$$W_t = W_t + [S + R - E_t - J]\Delta t \tag{2}$$

where W_l is the liquid water, W_t total water, R precipitation as rain, S precipitation as snow, M melted snow, E_s the evaporation from snow, E_t the evaporation and sublimation from snow and J the liquid water efflux from the snow pack.

Mineralization

The submodel for mineralization of crop residues and soil organic matter is a simplified modification of the model of Verberne et al. (1990) with four organic carbon pools C_i : soil organic matter C_{som} , microbial biomass C_{biom} , easily decomposable crop residues C_{dpm} and more resistant crop residues C_{rpm} . All

these pools have fixed C/N ratios and decompose by first order kinetic processes:

$$\frac{dC_i}{dt} = -k_i C_i f_j \quad (3)$$

where k_i are the rate coefficients of the four C pools and f_j ($0 < f_j < 1$) is a factor describing abiotic limitations of temperature (f_T) and soil water content (f_W). Net mineralization of each pool is then determined by multiplying with the N/C ratio:

$$\frac{dN_i}{dt} = \frac{dC_i}{dt} \frac{N_i}{C_i} \quad (4)$$

The fraction of easily decomposable C in plant residues f_{DPM} is calculated according to the following equation (Kage 2000):

$$f_{dpm} = \left(\frac{-N_{CR} CN_{dpm} CN_{rpm}}{C_{CR}} + CN_{dpm} \right) \frac{1}{-CN_{rpm} + CN_{dpm}} \quad (5)$$

where CN_{dpm} and CN_{rpm} are the C/N ratios of the easily decomposable crop residues C_{dpm} and more resistant crop residues C_{rpm} , respectively. N_{CR} and C_{CR} are the amounts of C and N in the crop residues.

Also shortage of mineral nitrogen affecting the decomposition processes is considered by the reducing factor f_{SMN} in the model. At the critical value SMN_{crit} of 2 kg SMN/ha in a soil layer of 10 cm mineralization processes decrease because of nitrogen shortage. The reducing process follows Michaelis-Menten kinetic where K_{SMN} is set at a value of 1 kg N/ha/10 cm:

$$f_{SMN} = \min \left(1, \max \left(0, \frac{(SMN - SMN_{crit})}{(SMN - SMN_{crit}) + K_{SMN}} \right) \right) \quad (6)$$

For further details of the mineralization submodel see Kage (2000). When crop residues are added to the soil they are assumed to decompose at the surface layer with a 50 % lower decomposition rate compared to incorporation into the first soil layer. In a first step the mineralization submodel was parameterized using a parameter set for decomposition of OSR residues taken from Mueller et al. 1997. The rate constant k_{rpm_biom} was slightly adjusted to the SMN values, k_{dpm_biom} was retained at 0.05, whereas k_{som_biom} and k_{biom_som} were optimized using

the SMN values of all treatments and years. The optimized rate constants of the mineralization submodel after optimization are presented in Table 4.

Table 4: Parameters of the mineralization submodel

Parameter	Pool	Description	C/N ratio	k (d ⁻¹)	Efficiency
k _{biom_som}	C _{biom}	Microbial biomass	6	0.00454351	1
k _{dpm_biom}	C _{dpm}	Fraction of easily decomposable residues	6	0.05	0.69
k _{rpm_biom}	C _{rpm}	Fraction of resistant residues	120	0.003	0.3
k _{som_biom}	C _{som}	Soil organic matter	10	0.000329036	0.5

The impact of tillage operations on soil nitrogen dynamics is included into the mineralization submodel in a simple descriptive way by introducing a factor f_{Till} ($f_{Till0}=1$). It is assumed that a tillage operation increases mineralization rates by adding a certain value, Min_{eff} ($Min_{eff}=5$), to f_{Till} which then boosts the decomposition rate in the tilled soil layer:

$$f_{Till} = f_{Till0} + Min_{eff} \quad (7)$$

$$\frac{dC_i}{dt} = -k_i C_i f_j f_{Till}. \quad (8)$$

The tillage effect, however, is assumed to affect mineralization rates only for a certain time span. Therefore, a factor d_{Till} , describing the 'decay rate' of f_{Till} with time is introduced:

$$\frac{df_{Till}}{dt} = -d_{Till} (f_{Till} - 1) \quad (9)$$

When tillage operations are carried out, crop residues are buried into the soil, and the amounts of the four carbon pools are equally distributed within the tilled soil layer.

Vertical nitrate transport

In well-aerated soils the concentration of ammonium is usually very low compared to nitrate. Therefore only nitrate nitrogen is considered in the model. Nitrate transport in the soil profile is calculated by a numerical solution of the convection-dispersion equation (Addiscott and Wagenet 1985). The initial condition for this equation was the measured SMN from 0 to 90 cm which was determined in a spatial resolution of 30 cm soil layers.

Plant N uptake

Plant N uptake of wheat, volunteer oilseed rape and Phacelia is calculated using an empirical function fitted to the experimental data. For winter wheat, volunteer OSR and Phacelia a logistic growth curve is fitted to the measured data

$$\frac{dN}{dt} = k_3 N T_{\text{eff}} \left(1 - \frac{N}{N_{\text{max}}} \right) \quad (10)$$

where k_3 is a growth rate parameter, T_{eff} the effective temperature and N_{max} the maximum N uptake. The start value N_0 was set at 0.001 kg N/ha. T_{eff} was calculated from

$$T_{\text{eff}} = \max(0, (T_a - T_b)) \quad (11)$$

where T_a is the daily average air temperature and T_b is the base temperature, assumed to be 3 °C.

Similar procedures are used to fit measured data of leaf area index (LAI), crop height and crop dry matter. The latter one is needed to estimate growth rates of a simple root system submodel, which describes temporal and spatial root length density distribution (Kage et al. 2004).

Parameter estimation and statistical evaluation

The above described algorithms were implemented as sub-models within the HUME modeling environment (Kage and Stützel 1999), which supports parameter estimation based on the Marquardt algorithm (Marquardt 1963).

Analyses of the residual errors for statistical evaluation (observed value minus estimates value) were done using the statistical measures modeling efficiency (EF) and root mean square (RMSE). EF (Smith et al. 1997) is described as

$$EF = 1 - \frac{\sum (y_i - \hat{y}_i)^2}{\sum (y_i - \bar{y})^2} \quad (12)$$

where y_i is the value of the i^{th} observation, \hat{y}_i is the i^{th} model prediction and \bar{y} is the average of the observations. The maximum value of the EF is one for complete agreement between simulated and measured values, but also negative

values are possible if the model describes the data less well than the observation mean.

The other statistical parameter used in this study is the RMSE

$$\text{RMSE} = \sqrt{\frac{\sum (y_i - \hat{y}_i)^2}{n}} \quad (13)$$

giving the average absolute model prediction error.

Model validation

The model validation was carried out using independent data from another field trial which is presented more detailed by Sieling et al. 1999. This field trial comprised similar N fertilization levels and tillage systems after OSR harvest (conventional and minimum). A five year dataset containing SMN, soil water and plant N uptake values was used. Due to the model validation, the general applicability of the model was tested. Furthermore scenario calculations for analyzing the effects of different N fertilizer levels were carried out.

Scenario calculations

Underlying a relationship between N fertilization level and SMN at harvest as described by Shepherd & Sylvester-Bradley (1996), Makowski et al. (2005) and Beaudoin et al. (2005) corresponding SMN values at harvest at the N fertilization levels 0, 80, 160, 200, 240 and 300 kg N/ha were used as initial SMN values in the model. A nine year weather data set from the experimental site was used for this purpose. All other boundary conditions were kept constant.

2.4 Results

Field experiment

Data from the field experiment are presented in Table 5 and 6. Dry matter (DM) of the crop residues, C in crop residues and the C/N ratio did not differ at $p=0.05$ between the four treatments fertilized at N3 (200 kg N/ha) (Table 5). The years significantly affected N in crop residues at harvest. The different N fertilization levels in WWCT significantly influenced the measured and calculated parameters. In both years DM at N2 and N3 but not at N4 were significantly higher than N1 (Table 6). The lower DM values of N4 were associated with lower seed yields compared to N2 and N3 in 2006 (data not shown). In 2007 seed yield of N4 was lower than in N3 (data not shown). Comparing both years, DM was

significantly higher in 2007 at all fertilization levels, as well as C and N in crop residues except at N1. C and N in crop residues were similar at N2, N3 and N4, but were significantly higher than at N1 in both years. SMN at harvest rose with increasing fertilization and was significantly higher in N4 (Table 6).

Table 5: C in crop residues, N in crop residues, C/N ratio, DM in crop residues and SMN at harvest in the different treatments (N3)

Year	Treatment	C in crop residues (kg C/ha)	N in crop residues (kg N/ha)	C/N ratio	DM in crop residue (kg DM/ha)	SMN at harvest (kg N/ha)
2006	VOSR	4241.1	67.7	62	9788.1	79.0
	CC	4241.1	67.7	62	9788.1	79.0
	WWCT	4436.9	75.1	61	10123.5	53.3
	WWMT	4082.2	73.2	55	9383.8	74.0
2007	VOSR	5414.0	111.6	48	12385.2	54.7
	CC	5414.0	111.6	48	12385.2	54.7
	WWCT	5275.0	87.1	61	11871.0	52.3
	WWMT	4396.1	81.2	54	9923.6	50.3
LSD _{0.05}	Treatment	ns	ns	ns	ns	ns
LSD _{0.05}	Year	ns	17.20	ns	ns	16.18
LSD _{0.05}	Treatment*Year	ns	ns	ns	ns	ns

Table 6: C in crop residues, N in crop residues, C/N ratio, DM in crop residues and SMN at harvest in WWCT (N1, N2, N3, N4)

Year	Treatment	N fertilization level	C in crop residues (kg/ha)	N in crop residues (kg N/ha)	C/N ratio	DM in crop residue (kg DM/ha)	SMN at harvest (kg N/ha)
2006	WWCT	1	2434.2	34.8	70	5606.4	45.0
	WWCT	2	4048.3	61.3	66	9220.5	56.3
	WWCT	3	4436.9	75.1	61	10123.5	53.3
	WWCT	4	3888.6	68.5	57	8890.8	98.0
2007	WWCT	1	3418.3	28.0	122	7643.3	30.7
	WWCT	2	5094.7	83.3	61	11441.7	33.3
	WWCT	3	5275.0	87.1	61	11871.0	52.3
	WWCT	4	4683.4	97.8	48	10519.5	74.7
LSD _{0.05}	Fertilizer level	1408.80	21.35	8.8	3168.40	35.25	
LSD _{0.05}	Year	699.99	10.64	4.4	1578.70	ns	
LSD _{0.05}	Fertilizer level*Year	ns	ns	13.2	ns	ns	

Model results*Soil water*

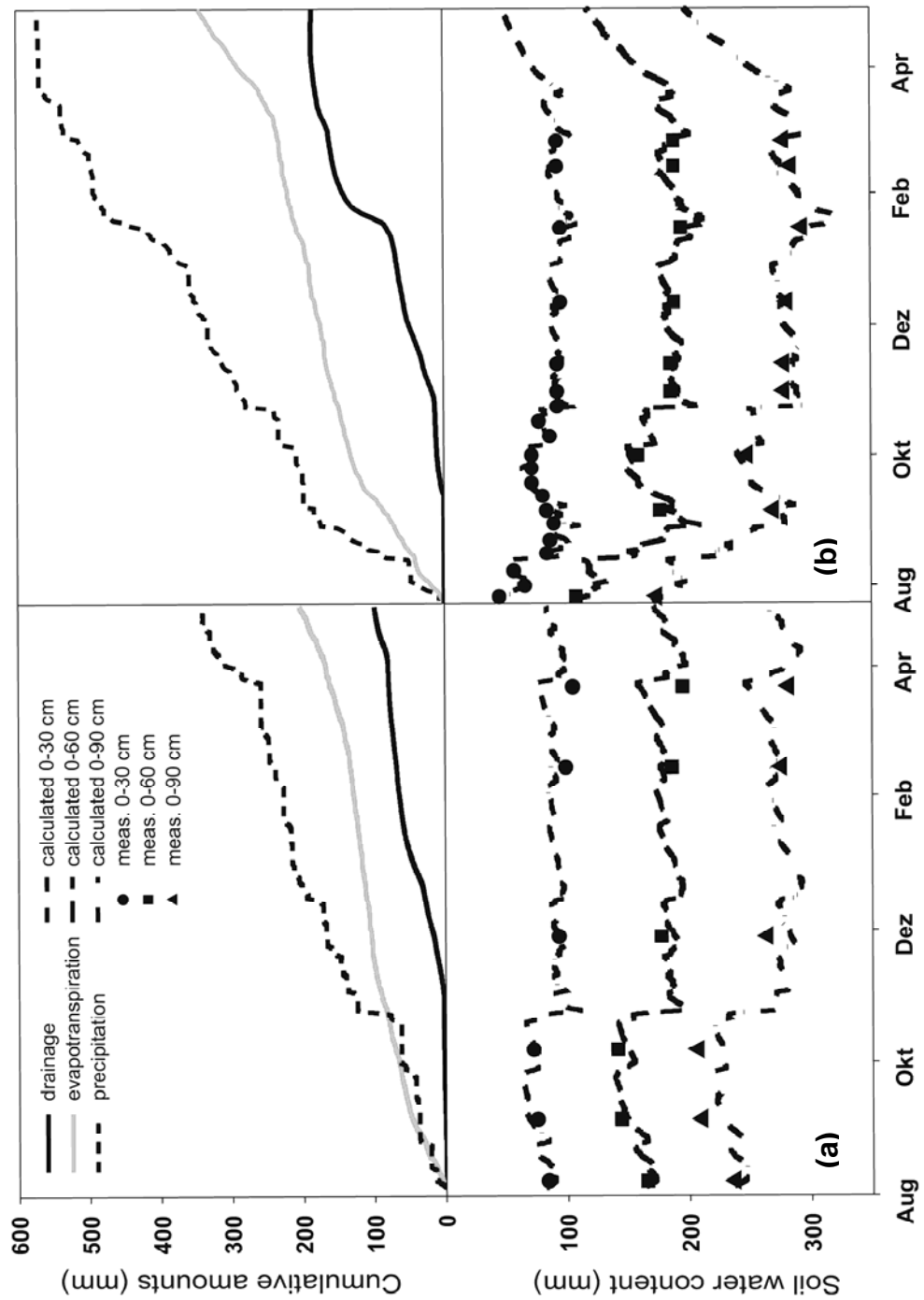
The parameters of the statistical evaluation of the submodel for soil water are given in Table 7.

Table 7: Statistical measures of the regressions measured vs. simulated soil water content in the different soil layers of both simulation periods

Depth (cm)	n	slope	intercept	r^2	RMSE (Vol. %)	EF
0-30	186	0.755	5.95	0.66	3.25	0.57
30-60	105	0.900	1.98	0.76	2.39	0.71
60-90	105	0.684	9.58	0.52	3.77	0.37
0-90	105	0.961	1.20	0.80	2.05	0.80

The model reproduced soil water dynamics in the layer 0-90 cm with an RMSE of 2.05 Vol. %. In the layer 0-30 cm RMSE was 3.25 Vol. %, in 30-60 cm 2.39 Vol. % and in 60-90 cm 3.77 Vol. %. EF was highest in the whole profile (0.80) and lowest in the horizon 60-90 cm (0.37). The dynamics of soil water, cumulative precipitation, cumulative evapotranspiration and cumulative drainage water in both years in WWCT at N3 are shown in Figure 1. Due to heavy rainfalls after harvest 2006 the soil profile was refilled with water earlier than in autumn 2005 although the initial soil water content was much lower at harvest 2006. Therefore the percolation period started about one month earlier in autumn 2006 in this treatment (Figure 1).

Fig. 1: Soil water dynamics, precipitation, evapotranspiration and drainage in WWCT (N3) in the simulation periods 2005/2006 (a) and 2006/2007 (b)



Key data of the water balance are presented in Table 8. Drainage was higher in 2006/2007 because of 140 mm more rainfall during the observation period. The model calculated c. 30-50 % less drainage water in the two treatments with a catch crop (VOSR, CC), because the catch crops used more water for transpiration. The amount of drainage water was also influenced by the amount of soil water in the profile (0-90 cm) at harvest. The different amounts of soil water at harvest in WWCT can be explained by the varying OSR canopies due to different N fertilization levels.

Table 8: Soil water (0-90cm) at harvest, cumulative precipitation, cumulative evapotranspiration, cumulative drainage and soil water (0-90 cm) at the end of simulation in all treatments

Year	Treatment	N level	Soil water (0-90cm) at harvest (mm)	Cum. Precipitation (mm)	Cum. Evapotrans. (mm)	Cum. Drainage (mm)	Soil water (0-90 cm) at the end of simulation (mm)
2005/2006	VOSR	3	243		296	36	261
	CC	3	243		281	45	261
	WWCT	1	279		252	108	261
	WWCT	2	252	343	246	84	261
	WWCT	3	243		219	100	261
	WWCT	4	261		248	91	261
	WWMT	3	243		231	91	261
2006/2007	VOSR	3	117		378	100	216
	CC	3	117		356	106	225
	WWCT	1	171		365	183	198
	WWCT	2	135	570	362	148	198
	WWCT	3	171		364	184	198
	WWCT	4	144		362	153	198
	WWMT	3	108		322	148	207

Soil mineral N, net mineralization and N leaching

According to our calculations, the decomposition of the incorporated OSR residues started rapidly. Until October 20-40 % of the C added to the soil as crop residues were decomposed. Until the end of simulated time span 30-50 % of the crop residues were decomposed depending on the year (data not shown).

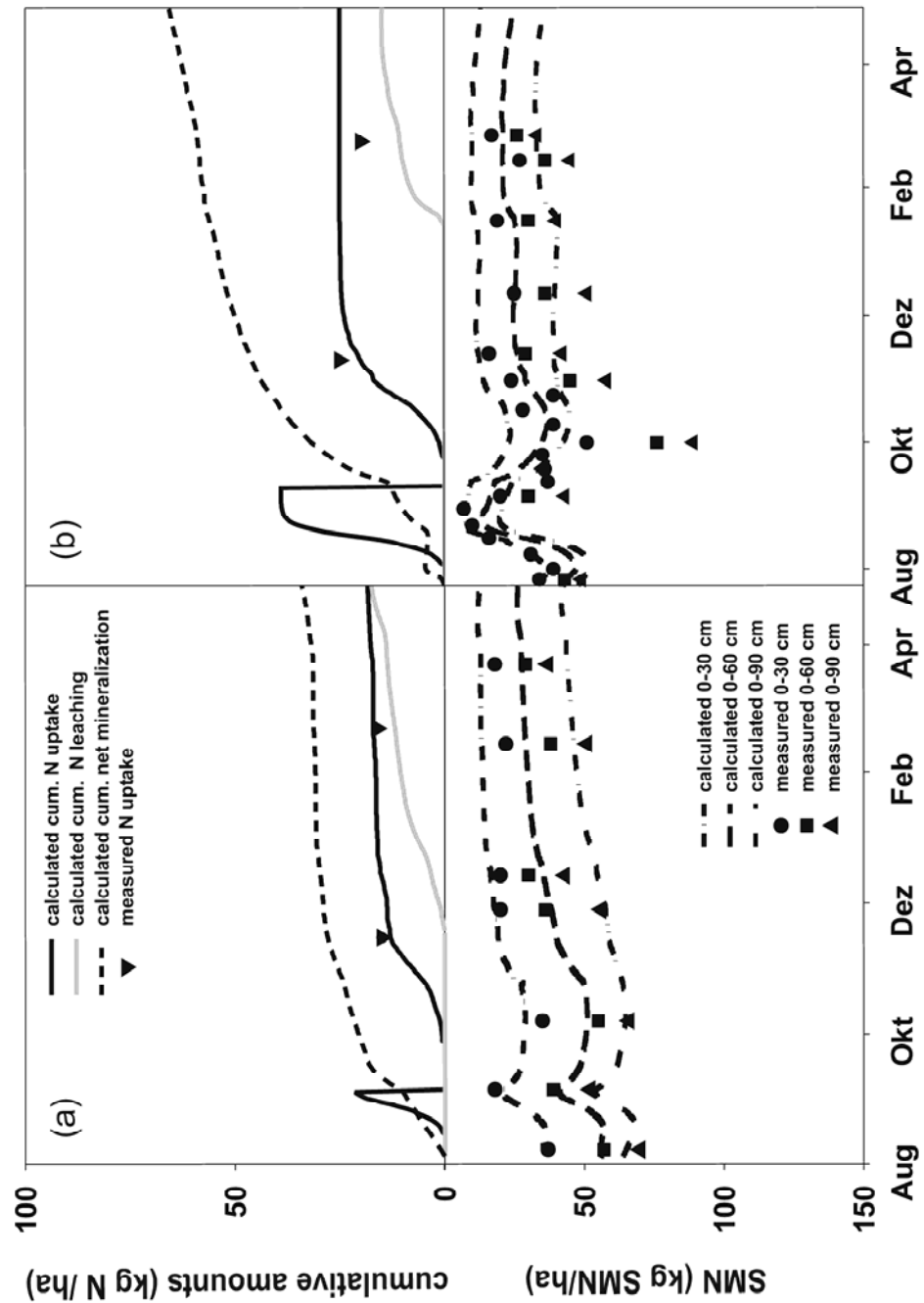
The results of the statistical evaluation after model calibration of the SMN dynamics are given in Table 9. In the whole profile the model reproduced SMN dynamics with a RMSE of 14.44 kg SMN/ha and an EF of 0.52. However, the coefficients of determination and EF in the single soil layer also decreased. In the horizon 60-90 cm EF was even negative. SMN was overestimated by the model compared to the data measured in the field.

Table 9: Statistical measures of the regressions measured vs. simulated SMN in the different soil layers in 2005/2006 and 2006/2007

Calibration data						
Depth (cm)	n	slope	intercept	r ²	RMSE (kg SMN/ha)	EF
0-30	186	0.72	9.21	0.41	10.43	0.26
30-60	105	0.74	1.48	0.47	6.06	0.27
60-90	105	0.47	3.33	0.26	6.04	-0.82
0-90	105	0.85	6.12	0.53	14.44	0.52
Validation data						
Depth (cm)	n	slope	intercept	r ²	RMSE (kg SMN/ha)	EF
0-30	72	0.83	4.19	0.64	5.57	0.60
30-60	72	0.70	1.91	0.58	5.22	0.29
60-90	66	0.64	-0.23	0.47	7.76	-0.72
0-90	66	0.68	8.63	0.63	13.77	0.26

Soil N dynamics of WWMT in both simulation periods and WWCT N3 and CC in 2005/2006 are presented in Figure 2 and 3. The model simulation resulted in strongly different N leaching values between the years and the treatments. Due to the lower drainage rates in 2005/2006 (Table 8) mean N leaching was lower in 2005/2006.

Fig. 2: SMN dynamics, N uptake, net mineralization and N leaching in WWMT in the simulation periods 2005/2006 (a) and 2006/2007 (b)



In both simulation periods N leaching was highest in WWCT N4 (38 and 37 kg N/ha) and lowest in CC (7 and 7 kg N/ha) (Table 10). Comparing the treatments at N3, smaller differences in N leaching between the treatments were observed (Table 10). The low amount of leached N in WWCT in 2005/2006 can be explained against the background of 20 kg less SMN at harvest in this treatment compared to the other treatments at the same fertilization level. Growing volunteer OSR or Phacelia as a catch crop after harvest led to smaller rates of N leaching than in the other treatments at the same fertilization level. Figure 3

shows that the delay of N leaching in CC reduced the amount of leached N compared to WWCT.

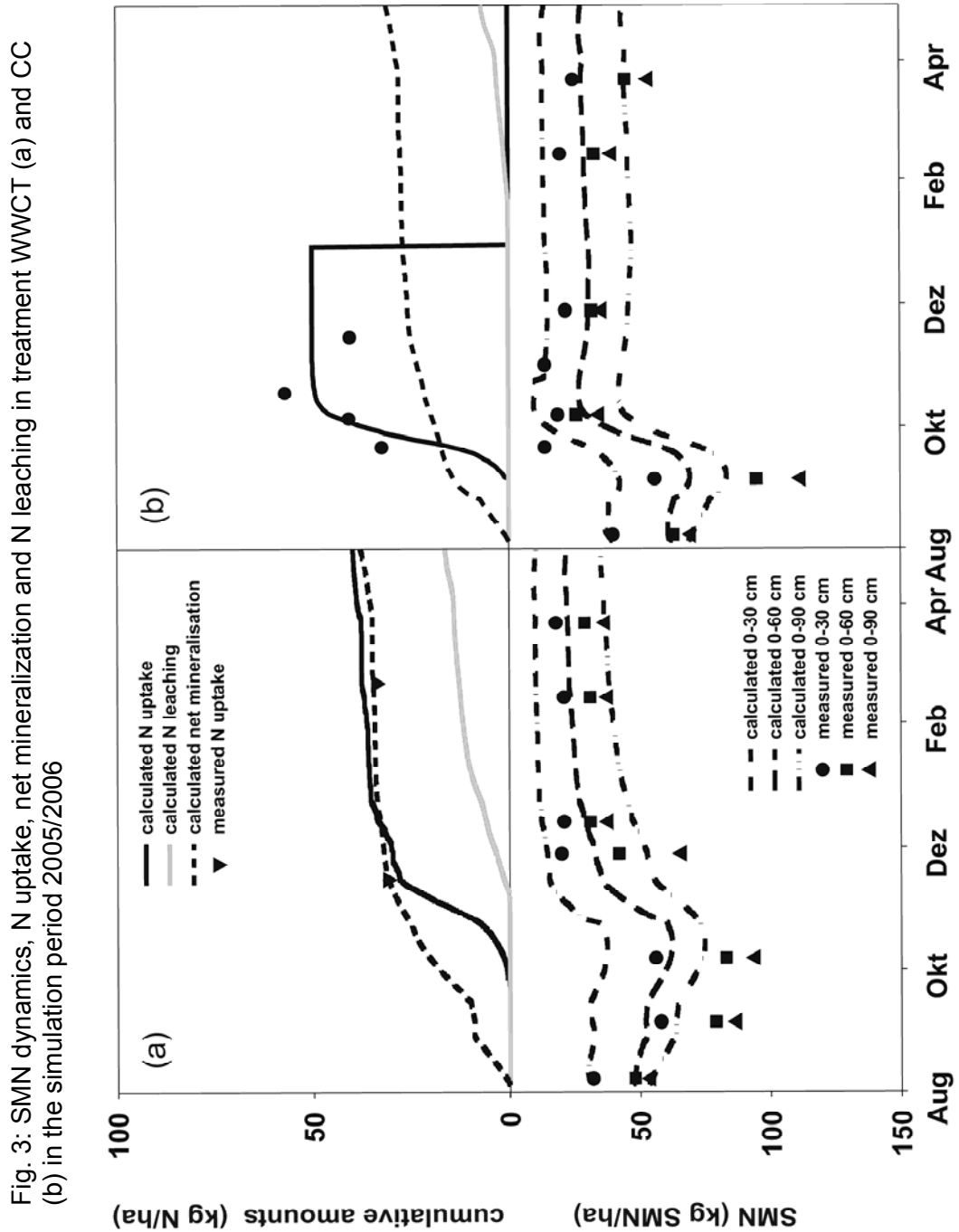


Fig. 3: SMN dynamics, N uptake, net mineralization and N leaching in treatment WWCT (a) and CC (b) in the simulation period 2005/2006

The minimum tillage strategy in WWMT reduced N leaching in 2006/2007 by 19 kg N/ha. Although SMN at harvest was 21 kg N/ha higher than in WWCT, N leaching in WWMT was not increased (difference 1 kg N/ha) (Table 10). Simulated net mineralization was strongly affected by the years. The higher precipitation and temperatures in 2006/2007 (Table 1) increased net mineralization in all treatments compared to 2005/2006. Due to the one-time

shallow tillage operation after harvest in VOSR the net mineralization during the simulation periods was diminished compared to the other treatments with more intensive tillage operations. In CC an intensive tillage operation with a cultivator was carried out after harvest, and therefore net mineralization was as high as the ploughed treatments. However, these tillage operations were shortly after OSR harvest and were compensated by the high N uptake of the catch crop Phacelia leading to a low N leaching loss. Nevertheless, despite the low N leaching values in the catch crop treatments, especially in VOSR the EU drinking water threshold of 50 ppm nitrate was exceeded remarkably due to the lowest amounts of drainage water (Table 7). The results also clearly show the influence of overfertilization in treatment WWCT at N4. The high input of fertilizer N increased SMN at harvest and consequently N leaching and N concentrations in drainage water. The EU threshold was only met in CC, WWMT and the reduced N fertilization levels of WWCT in 2006/2007.

Table 10: Measured and calculated key data of the N dynamics after OSR

Year	Treatment	N level	SMN at harvest (kg SMN/ha)	N uptake at the end of autumn growth (kg N/ha) measured	SMN (0-90 cm) at the end of autumn growth (kg SMN/ha) measured	Cum. net mineralization (kg N/ha) calculated	Cum. N leaching (kg N/ha) calculated	NO ₃ concentration in drainage water (ppm) calculated
2005/2006	VOSR	3	79	37	31	17	11	138
	CC	3	79	40	36	31	7	67
	WWCT	1	45	27	48	35	13	52
	WWCT	2	56	43	65	27	10	52
	WWCT	3	53	30	66	38	16	71
	WWCT	4	98	36	74	39	38	182
	WWMT	3	74	14	56	34	17	84
	VOSR	3	55	44	25	34	14	62
2006/2007	CC	3	55	58	21	47	7	28
	WWCT	1	31	32	17	55	14	33
	WWCT	2	33	29	32	47	16	49
	WWCT	3	52	33	24	61	34	81
	WWCT	4	75	35	37	62	37	106
	WWMT	3	50	25	42	66	15	44

Model validation

The parameters of the statistical evaluation of the validation data (SMN) are shown in Table 9. The model reproduced the dynamics in the whole profile (0-90 cm) with a RMSE of 13.77 kg SMN/ha. EF of 0.26 was lower compared to the calibration data. In the layer 60-90 cm the EF of -0.72 was lowest like in the calibration dataset.

Scenario calculations

The nine year scenario calculation resulted in strongly increasing N leaching values when the amount of N fertilization and consequently SMN at harvest rose. Without N fertilization mean N leaching amounted 27 kg N/ha whereas mean N leaching rose to 27, 32, 36, 58 and 90 kg N/ha when N fertilization was increased to 80, 160, 200, 240 and 300 kg N/ha.

2.5 Discussion

N leaching occurs when the presence of nitrate in the soil coincides with periods of water percolation. Consequently, N leaching is an unavoidable phenomenon under humid climate conditions in particular in arable cropping and between two successive crops. According to Di and Cameron (2002) the prevention of SMN accumulation in the soil after harvest is the key to reduce N leaching which is higher after OSR compared to cereals (Sieling and Kage 2006). The aim of this study was therefore to quantify N leaching losses after growing OSR combining a field trial and a model approach underlying different treatments after OSR harvest. For this purpose we used a simulation model comprising of model modules for soil water dynamics, the mineralization processes of soil organic N and crop residue N, effects of tillage and the N uptake by the subsequent crop to oilseed rape. This methodological approach of simulation modeling has the advantage that regularly field-measured SMN data combined with soil moisture data can be used for calculating N leaching (Mary et al. 1999, Köhler et al. 2006). Additionally, the experimental data are accessible for a detailed analysis of the different processes influencing nitrate leaching in the cropping system studied, like the components of the soil water budget, the mineralization rate, the crop residues decomposition and the SMN dynamics after OSR harvest. The model modules differed in their level of detail and their degree of mechanistic character. Whereas the nitrogen uptake of the crops following winter wheat is simulated using a simple logistic growth equation fitted to experimental data, the soil water balance calculation is based on well accepted mechanistic approaches, i.e. the

Penman-Monteith and the continuity equation approach. The soil mineralization submodel is somewhat in between these extremes. It is based on carbon fluxes and therefore able to predict immobilization of nitrogen during the decomposition process of crop residues but it consists of a comparable small number of carbon pools and is therefore probably not appropriate for the prediction of mineralization processes over a wider range of soil conditions. But due to the small number of pools only a few parameter values have to be identified. This was done in the present study by taking some values from comparable mineralization models and by direct parameter estimation from measured SMN data. After slight adaptations the parameter set of the mineralization submodel taken from Mueller et al. (1997) were applicable to our data.

In the present study the complex interactions of residue decomposition, different tillage intensities and also subsequent crop growth were investigated. Water dynamics could be reproduced very well by the model. In the whole profile (0-90 cm) the RMSE was 2.05 Vol. % or 18.45 mm in both years. Also the SMN dynamics were reproduced well in the whole profile (0-90 cm) with a RMSE of 14.44 kg SMN/ha but in the layer 60-90 cm the model performance were not entirely satisfactory. Additionally, the strong increase of SMN after tillage operations could often not reproduced by the model. In the layer 60-90 cm the model overestimated SMN and therefore also N leaching to some extend. Several processes of N loss like denitrification or preferential flow which are very hard to measure with satisfactory precision could be possible reasons for this overestimation of the low SMN in deeper soil layers. Another explanation for this effect could be the high variability in soil properties due to heterogeneous soil at the experimental site which originates from glaciofluvial parent material. Additionally, the precision of the sampling and analyzing method is questionable when SMN values were rather low like in the layer 60-90 cm (Aufhammer et al. 1989). The same authors reported also tremendous differences in SMN when sampling points and sample handling were varied.

Mary et al. (1999) and Justes et al. (1999) analyzed N dynamics after OSR harvest applying the LIXIM model to field measurements of three different treatments after OSR. The outcomes of the modeling study of Mary et al. (1999) resulted in low RMSE values for SMN content ranging from 2.4 kg SMN/ha to 5.7 kg SMN/ha. However, the conditions required for the application of this model were the absence of plant cover or slowly growing crop transpiring little water, shallow rooting and little N uptake (Mary et al. 1999). Additional management

practices like tillage were not carried out. Kersebaum (2007) modeled the N dynamics in a six year crop rotation using the HERMES model. The model outcomes for SMN (0-90 cm) resulted in a RMSE of 24.8 kg SMN/ha. It is obvious that beside the validity of the model the number of processes considered by a model and their complexity and interactions might have strong influence on the model performance. Nevertheless, keeping the restrictions and shortcomings of our approach in mind, the model applied is an efficient scientific tool for analyzing the N dynamics after OSR harvest. It satisfactorily reproduced consistent results for the various treatments in the field trial regarding tillage operation, subsequent crop and N fertilization level resulting in different amounts of N leaching.

In the present study, increasing amounts of N fertilization to OSR strongly raised SMN at OSR harvest and in autumn. Several studies resulted in remarkably higher SMN values sometimes exceeding 100 kg SMN/ha at OSR 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 (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. Amounts of N fertilizer above 200 kg N/ha led to a strong increase of 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 OSR canopy properties.

The differences between the tillage treatments (WWCT vs. WWMT) and winter wheat as the subsequent crop indicate that minimum tillage combined with a short period of growing volunteer OSR as a catch crop before sowing of winter wheat can decrease N leaching. These results agree with the findings of Lickfett (1993) and Goss et al. (1993) who reported about diminished SMN when tillage operations intensities in autumn were reduced or totally omitted after OSR harvest.

Due to the tillage operations, however, not only the soil is mixed but also OSR residues are incorporated into the soil. The C/N ratio in OSR residues under a

regular fertilization regime of about 200 kg N/ha were about 50 to 60 (Table 5). Justes et al. (1999) and Mary et al (1999) report about N immobilization of about 20 kg N/ha after OSR residue incorporation (C/N=54, N fertilization 270 kg N/ha). Jensen et al. (1997) observed a decrease of SMN of 18 and 25 kg SMN/ha after incorporation of 4 or 8 t OSR residues/ha, respectively. In addition, Trinsoutrot et al. (2000) stated that the N amounts mineralized from OSR residues and then returned to the subsequent crop are relatively small. According to these results, it is obvious that the incorporation of OSR residues by tillage operations after harvest lead to N immobilization depending of the amount and quality (C/N) of the residues. Because of missing treatments without residues the effect of straw incorporation could not be separated from tillage effects in the present study. Nevertheless, immobilization processes are taken into account in the carbon based mineralization submodel. However, several studies showed that straw incorporation is an indispensable part of a proper N management after harvest to prevent N leaching (Justes et al. 1999, Trinsoutrot et al. 2000, Beaudoin et al. 2005).

Growing catch crops to reduce the level of SMN and prevent N leaching is a common agronomic practice especially in water protection areas. In the present study the establishment of the two catch crops after OSR harvest reduced N leaching especially when Phacelia was grown. Lickfett (1993) recommended volunteer OSR to grow over winter without any tillage operation, thus reducing mineralization of soil born N and consequently N leaching. Using this strategy, the cumulative mineralization could be reduced in the present study compared to the treatments with winter wheat as the subsequent crop, but N leaching was still lower in the Phacelia treatments. Additionally, growing volunteer OSR is characterized by two disadvantages. Firstly, due to the low drainage rate, the nitrate concentration in the percolation water was raised remarkably and exceeded the EU drinking water threshold to a higher extent than the other treatments. Secondly, growing volunteer OSR could be critical because a high density of OSR in the rotation can promote pathogens and pests (Christen 2006). Phacelia took up most N in autumn and N leaching and nitrate concentration were lowest in both years at N fertilization level 3. However, growing catch crops combined with a spring crop is less profitable than cropping winter wheat which is commonly grown after OSR and therefore compensatory payments would be necessary especially in water protection areas. In 2005/2006 the EU drinking water threshold of 50 ppm nitrate was exceeded in all treatments. In 2006/2007 this threshold could be met in CC, WWMT and the reduced N fertilization levels

N1 and N2 of WWCT. It is obvious, that the amounts of percolation water and consequently N leaching strongly depend on weather conditions. In the present study it was shown clearly that the proper calculation of N fertilization combined with reduced tillage after harvest or growing a non cruciferious catch crop are appropriate strategies to reduce N leaching and nitrate concentrations in percolation water.

2.6 Conclusion

Amounts of N leaching after growing OSR are higher than after cereals. In the present study possible strategies to reduce N leaching were investigated combining a field trial and simulation modeling approach. The simulation model reproduced the N dynamics after OSR well and was an efficient scientific tool for calculating N leaching. The results gave strong evidence that excessive amounts of fertilizer N increased SMN at harvest and therefore the leaching potential. A proper calculation of N fertilizer rates is a first step to prevent N losses. Growing the most profitable crop winter wheat after OSR with minimum tillage combined with a short term volunteer OSR growth seems an appropriate practice to diminish N mineralization in autumn and N leaching. Although SMN was immobilized in the course of OSR residue decomposition, ploughing or other intensive tillage operations should be avoided after OSR. Catch crops over winter and the introduction of spring crops have the highest potential for the reduction of N leaching but these strategies are combined with return losses compared to cropping winter wheat. Therefore minimum or zero tillage and growing winter wheat should become the standard practice after OSR.

Acknowledgement

We grateful thank Mr. Ruediger Stroeh, Mrs. Gunda Schnack, Mrs. Cordula Weise and Mrs. Kirsten Schulz for their expert technical assistance.

2.7 References

- ADDISCOTT, T. M. & WAGENET, J. (1985). Concepts of solute leaching in soils: a review of modeling approaches. *Journal of Soil Science* 36, 411-424.
- AUFHAMMER, W., FEDEROLF, K.-G., KEMPF, H., KÜBLER, E. & STÜTZEL, H. (1989). Variabilitätsursachen und Aussagemöglichkeiten der N_{\min} -Methode (Variability and significance of the " N_{\min} -procedure"). *Landwirtschaftliche Forschung* 42, 281-292.

- BEAUDOIN, N., SAAD, J. K., VAN LAETHEM, C., MACHET, M., MAUCORPS, J. & MARY, B. (2005). Nitrate leaching in intensive agriculture in Northern France: Effect of farming practices, soils and crop rotations. *Agriculture, Ecosystems and Environment* 111, 292-310.
- CHRISTEN O (2006). Raps in der Fruchtfolge – ist die Grenze der Ausdehnung erreicht ? (with English summary). *UFOP-Schriften* 29, Öl- und Proteinpflanzen, OIL 2005,119-128.
- DI, H. J., CAMERON, K. C. (2002). Nitrate leaching in temperate agroecosystems: sources, factors and mitigation strategies. *Nutrient Cycling in Agroecosystems* 46, 237-256.
- 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. *Journal of Soil Science* 44, 35-48.
- GOSSE, G., CELLIER, P., DENOROY, P., GABRIELLE, B., LAVILLE, P., LEVIEL, B., JUSTES, E., NICOLARDOT, B., MARY, B., RECOUS, S., GERMON, J.-C., HENAULT, C. & LEECH, P. K. (1999). Water, carbon and nitrogen cycling in a rendzina soil cropped with winter oilseed rape: the Châlons Oilseed Rape Database. *Agronomie* 19, 119-124.
- HANSEN, S., JENSEN, H. E., NIELSEN, N.E. & SVEDSEN, H. (1991) Simulation of nitrogen dynamics and biomass production in winter wheat using the Danish simulation model DAISY. *Fertilizer Research* 27, 245-259.
- JANSSON, P. E. & HALDIN, S. (1980). Soil water and heat model. Technical description. Technical Report 26, 1980. Swedish Coniferous Forest Project. Dept. of Ecology and Environment Research. Swedish University of Agricultural Science, Uppsala, Sweden.
- JENSEN, L. S., MUELLER, T., MAGID, J. & NIELSEN, N. E. (1997) Temporal variation of C and N mineralization, microbial biomass and extractable organic pools in soil after oilseed rape straw incorporation in the field. *Soil Biology and Biochemistry* 29, 1043-1055.
- 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. *Nutrient Cycling in Agroecosystems* 55, 207-220.

- KAGE, H. & STÜTZEL, H. (1999). HUME: an object oriented component library for generic modular modelling of dynamic systems. In: Donatelli CSM, Villalobos F, Villar JM (eds) Modelling Cropping Systems, ESA conference, Lleida, June 1999. Lleida, European Society of Agronomy, p 299.
- KAGE, H. (2000). Simulation modelling for improving nitrogen use efficiency in intensive cropping systems. Habilitationsschrift, University of Hannover.
- KAGE, H., ALT, C. & STÜTZEL, H. (2003). Aspects of nitrogen use efficiency of cauliflower I. A simulation modeling based analysis of nitrogen availability under field conditions. *Journal of Agricultural Science, Cambridge* 141, 1-16.
- KAGE, H., KOCHLER, M. & STÜTZEL, H. (2004). Root growth and dry matter partitioning of cauliflower under drought stress conditions: measurement and simulation. *European Journal of Agronomy* 20, 379-394.
- KERSEBAUM, K. C. (2007). Modelling nitrogen dynamics in soil-crop systems with HERMES. *Nutrient Cycling in Agroecosystems* 77, 36-52.
- KÖHLER, K., DUYNISVELD, W. H. M. & BÖTTCHER, J. (2006). Nitrogen fertilization and nitrate leaching into groundwater on arable sandy soil. *Journal of Plant Nutrition and Soil Science* 169, 185-195.
- LICKFETT, T. (1993). Auswirkungen verminderter Produktionsintensität in zwei Rapsfruchtfolgen auf Elemente des N-Haushalts im System Boden-Pflanze. Dissertation, University of Göttingen.
- MAKOWSKI, D., MALTAS, A., MORISON, M. & REAU, R. (2005). Calculating N fertilizer doses for oil-seed rape using plant and soil data. *Agronomy for Sustainable Development* 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 I. Global N Flows between Vegetative and Reproductive Tissues in Relation to Leaf Fall and their Residual N. *Annals of Botany* 95, 853-861.
- MARQUARDT, D.W. (1963). An algorithm for least-squares estimation of nonlinear parameters. *J. Soc. Ind. Appl. Math.* 11, 431-441.

- MARY, B., BEAUDOIN, N., JUSTES, E. & MACHET, J. M. (1999). Calculation of nitrogen mineralization and leaching in fallow soil using a simple dynamic model. *European Journal of Soil Science* 50, 549-566.
- MONTEITH, J. L. (1973). *Principles of environmental physics*. Edward Arnold, London.
- MUELLER, T., JENSEN, L. S., MAGID, J. & NIELSEN, N. E. (1997). Temporal variation of C and N turnover in soil after oilseed rape straw incorporation in the field: simulations with the soil-plant-atmosphere model DAISY. *Ecological modeling* 99, 247-262.
- NICOLARDOT, B., RECOUS, S. & MARY, B. (2001). Simulation of C and N mineralization during crop residue decomposition: A simple dynamic model based on the C:N ratio of the residues. *Plant and Soil* 228:83-103.
- SAS INSTITUTE INC. (1989). *SAS/STAT® User's Guide, Version 6, 4th edn, Vol. 2*. Cary, NC, SAS Institute.
- 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. *Journal of Agricultural Science, Cambridge* 126, 63-74.
- SELING, K., 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. *Journal of Agricultural Science, Cambridge* 132, 127-137.
- SELING, K. & KAGE, H. (2006). N balance as an indicator of N leaching in an oilseed rape – winter wheat – winter barley rotation. *Agriculture, Ecosystems and Environment* 115, 261-269.
- SMITH, P., SMITH, J. U., POWLSON, D. S., MCGILL, W. B., ARAH, J. R. M., CHERTOV, O. G., COLEMAN, K., FRANKO, U., FROLKING, S., JENKINSON, D. S., JENSEN, L. S., KELLY, R. H., KLEIN-GUNNEWIEK, H., KOMAROV, A. S., LI, C., MOLINA, J. A. E., MUELLER, T., PARTON, W. J., THORNLEY, J. H. M. & WHITMORE, A. P. (1997). A comparison of the performance of nine soil organic matter models using datasets from seven long-term experiments. *Geoderma* 81, 153-225.

- 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. *Nutrient Cycling in Agroecosystems* 56, 125-137.
- VAN GENUCHTEN, M. T. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal* 44, 892-898.
- VAN GENUCHTEN, M. T., LEIJ, F. J. & YATES, S. R. (1991). "The RETC Code for Quantifying the Hydraulic Functions of Unsaturated Soils, Version 1.0.," Rep. No. EPA Report 600/2-91/065. U.S. Salinity Laboratory, USDA, ARS, Riverside.
- WÖSTEN, J. H. M., VAN GENUCHTEN, M. T. (1988). Using texture and other soil properties to predict the unsaturated soil hydraulic functions. *Soil Science Society of America Journal* 52,1762-1770.

Kapitel 3

**Impact of uncertainty on the optimum
nitrogen fertilization rate and agronomic,
ecological and economic factors in an oilseed
rape based crop rotation**

J. Henke, G. Breustedt, K. Sieling & H. Kage (2007)

Journal of Agricultural Science, Cambridge 145, 455-468

3.1 Summary

Crop yield and optimum nitrogen fertilization rates (Nopt) are often calculated *ex post* by specific functions of the nitrogen fertilization rate, but doing this uncertainties in terms of model choice, annual nitrogen response variations and parameter estimation are neglected. In the present study, Nopt, grain yields, net revenues and N balances were estimated for the three crops of an oilseed rape (OSR) – winter wheat – winter barley rotation. The effects of uncertainties were considered using three different statistical models, estimating an identical Nopt over the years and carrying out of Monte-Carlo simulations where model parameters were varied according to their estimated standard errors. The statistical models used were the quadratic polynomial function (Q), the linear response and plateau function (LRP) and the quadratic response and plateau function (QRP).

The Q model tended to estimate the highest Nopt values for the three crops followed by the QRP and the LRP model in an initial *ex post* analysis. The highest corresponding mean net revenues in the rotation were estimated by the LRP model followed by the Q and QRP model; mean N balances increased in the order LRP, QRP and Q. In the comparison of the crops OSR showed the highest N balances followed by wheat and barley. Considering the protein concentration in wheat Nopt values estimated by the Q model were considerably higher than without the economic effects of grain quality.

In order to consider uncertainties in annual nitrogen response, an *ex ante* Nopt over the years was determined by maximizing the cumulated net revenues over all years in the rotation. *Ex ante* Nopt was higher as the mean of the *ex post* Nopt values for the QRP and LRP model. Average grain yields and net revenues were lower, N balances were higher. Running the Monte-Carlo simulations, *ex post* Nopt was obtained by 10000 generated functions in each year and *ex ante* Nopt by 50000 generated functions of years 1996, 1997, 1998, 1999 and 2002. This led to an increase in Nopt especially for the LRP model, while effects on the estimation of Nopt by the Q model were rather small. For the LRP model corresponding mean net revenue decreased and mean N balance rose. In contrast, due to marginal changes in Nopt, the consideration of uncertainties in the estimations had only a small effect on net revenue and N balance in the Q model.

In general, all kinds of uncertainty tended to increase N_{opt} but this effect was much higher for the LRP model as compared to the Q model. This increase in N_{opt} was associated with decreasing net revenues and increasing N balances. Exceptionally in OSR using the Q model, however, the *ex ante* approaches considering uncertainty led to slightly lower N_{opt} values compared to the *ex post* value.

3.2 Introduction

Fertilizer recommendations have to take rising economic and, particularly, ecological concerns into account. Therefore the exact estimation of optimum nitrogen fertilization rates (N_{opt}) for arable crops becomes increasingly important. Most commonly, N_{opt} is estimated from results of field experiments where crop yield is calculated *ex post* as a function of the nitrogen fertilization rate. In many cases the estimated parameters are used for calculating *ex ante* nitrogen fertilization recommendations. It is, however, well known that the selection of the statistical model describing the yield response to nitrogen fertilization can considerably affect estimated N_{opt} (Bock & Sikora 1990; Cerrato & Blackmer 1990; Bullock & Bullock 1994; Colwell 1994; Bélanger *et al.* 2000). Furthermore, the *ex post* determination of optimum fertilization rates does not consider the inevitable uncertainty resulting from year to year and site to site variations in weather and soil conditions. Since farmers do not know weather conditions in advance when making their fertilizing decision, it can be assumed that, in practice, they would use an identical N amount each year to adapt to annual nitrogen response variations.

The aim of the present study was to quantify the impact of yield models' functional form, *ex post* vs. *ex ante* recommendations and uncertainty in model parameter estimation on fertilization recommendations. Therefore three kinds of uncertainty in the estimation of N_{opt} and corresponding grain yields, net revenues as well as N balances were analysed in an OSR - wheat - barley rotation. Firstly, the uncertainty of model choice was analysed by estimating N_{opt} using three different statistical models. Secondly, year-to-year variation in nitrogen response was investigated by calculating an N_{opt} where the total net revenue over the years were maximum in each crop. This is called the *ex ante* approach; however, our dataset was too small to validate the *ex ante* N_{opt} on independent data. Finally, a Monte-Carlo simulation was performed to quantify the effect of uncertainty on the estimation of model parameters.

3.3 Materials und Methods

Field experiment

The experimental data presented here originate from a field trial established in autumn 1990 on a pseudogleyic Luvisol of sandy loam texture at the Hohenschulen Experimental Farm of the University of Kiel, located c. 15 km west of Kiel, Schleswig-Holstein, NW Germany. Total rainfall averages 750 mm annually at the experimental site, with c. 400 mm received during April-September, the main growing season, and c. 350 mm during October-March. Further details of the experiment were previously reported by Sieling *et al.* (1997).

In the present study, a dataset from 1996 to 2002 was used. In 2000 and 2001 nitrogen concentration data of OSR were missing. The experiment comprised the rotation OSR (cv. Falcon), winter wheat (cv. Orestis) and winter barley (cv. Alpaca). All plots were ploughed. Fungicides and other crop management factors (e.g. herbicides, seed date) were handled in accordance with the farmers' normal practice. Mineral N fertilization (0-280 kg N/ha) was applied at three times (at the beginning of spring growth, at stem elongation and ear emergence for wheat and barley and at the beginning of spring growth, at stem elongation and at bud formation for OSR) as calcium ammonium nitrate (0.27 kg N/kg fertilizer). The first and the second application rate varied from 0-120 kg N/ha, the third from 0-80 kg N/ha each in increments of 40 kg N/ha. In total there were 32 different N treatments. Pig slurry was applied to half of the OSR plots in spring (80 kg total N/ha), while the other half received only mineral N fertilizer. It was assumed that 0.75 of the total N was $\text{NH}_4\text{-N}$ and so 60 kg N/ha was available for the crop. Only total N amounts were included in the calculations; application times and rates of distribution were disregarded. The plot size was 7 x 3 m. At crop maturity, an area of 6.75 m² was harvested by combine and yield was standardized to a dry matter content of 0.86 for wheat and barley and 0.91 for OSR. The N uptake by the grain was obtained by multiplying the grain dry matter with the grain N concentration determined with near infrared spectroscopy (NIRS 5000, Foss). N-balances (kg N/ha) were calculated as applied fertilizer N (kg N/ha) minus N-offtake by the grain (kg N/ha).

Statistical Analyses

Nopt was estimated following three different approaches (*ex post*, *ex ante*, Monte-Carlo simulation). The different underlying yield response functions to

nitrogen fertilization (linear response and plateau (LRP), quadratic response and plateau (QRP), quadratic (Q)) are described by three statistical models, which were fitted to the dataset of each crop (OSR, wheat, barley) using the REG and NLIN procedure of the SAS Software package (SAS Institute Inc. 1989). Additionally the influence of quality payments for wheat protein concentration was analysed.

The LRP model is specified by three parameters:

$$Y = a + bX + \varepsilon \quad \text{if } X < C \tag{1}$$

$$Y = P + \varepsilon \quad \text{if } X \geq C$$

where Y is the grain yield (t/ha), X the application rate of N (kg N/ha), a the intercept b the linear coefficient and ε the error term. C is the nitrogen application rate at the intersection of the linear model and the plateau, P describes the plateau yield.

The QRP model is specified by four parameters:

$$Y = a + bX + cX^2 + \varepsilon \quad \text{if } X < C \tag{2}$$

$$Y = P + \varepsilon \quad \text{if } X \geq C$$

where Y is the grain yield (t/ha), X the application rate of N (kg N/ha), a the intercept, b the linear, c the quadratic coefficient and ε the error term. C is the nitrogen application rate at the intersection of the quadratic model and the plateau, P describes the plateau yield. In order to ensure a smooth derivative function, the additional side condition $dY/dX=0$ at $X=C$ is introduced.

The Q model is specified by three parameters:

$$Y = a + bX + cX^2 + \varepsilon \tag{3}$$

where Y is the grain yield (t/ha), X the nitrogen application rate (kg N/ha), a the intercept, b the linear, c the quadratic coefficient and ε the error term.

Adjusted coefficients of determination (adj. R^2) considering the different number of function parameters were determined using regression analyses for the Q model. For the LRP and the QRP model adj. R^2 was calculated by the analysis of variance routine on the SAS output:

$$\text{adj. } R^2 = 1 - (1 - r^2) \frac{n - 1}{n - k - 1} \quad (4)$$

where n is the number of observations and k the number of variables.

The years 2000 and 2001 were omitted from calculations for the whole rotation because of the missing nitrogen concentration data for OSR.

Nopt was defined as the rate at which maximum economic returns were produced (Colwell 1994), calculated by marginal value product = marginal factor cost = nitrogen price for the QRP and the Q model.

The obtained parameter estimates were used for different approaches to estimate Nopt, grain yield at Nopt and the corresponding economic net revenues and N balances. At first an *ex post* analysis was made, i.e. Nopt was estimated for the three crops within the rotation and the different models in each year. Secondly, an *ex ante* Nopt for all analyzed years and each crop was estimated by maximizing the objective function:

$$\text{Max } \sum_{i=1}^I (pwY_i(N) - pnN) \quad (5)$$

where $Y_i(N)$ is the response function in year i , I is the total number of years, pw is the price of the crop and pn the price of nitrogen fertilizer (Bullock and Bullock 1994). A numerical solution of this function was calculated using the Newton method provided by the solver procedure of Microsoft Excel®.

In order to consider the uncertainties in the model parameter estimations Monte-Carlo simulations were carried out. After testing the residuals of the regression models for normality we assumed a normal distribution of the model parameters characterized by the mean and the standard deviation of the parameters. For each year 10000 random combinations of the model parameters were generated assuming a multivariate normal distribution with correlated variables by using the Cholesky decomposition of the correlation matrix (Greene 2003). First to consider uncertainties in an *ex post* analysis Nopt was obtained separately for each random draw. Second the *ex ante* Nopt was calculated by maximizing the mean economic net revenue of all 50000 response functions generated for the years 1996, 1997, 1998, 1999 and 2002.

Market prices were assumed to be 0,6 €/kg N, 200 €/t OSR, 100 €/t wheat and 90 €/t barley.

In order to consider the effect of the N application rate on quality parameters, N_{opt} for wheat was also estimated regarding protein concentration and grain yield. For this purpose the Q model and an empirical function relating the grain protein content to the nitrogen application rate and the yield level was used:

$$Prot = (a + bX + cY + \varepsilon) 5.75 \quad (6)$$

where Prot is the protein concentration (mg/g), X the nitrogen application rate (kg N/ha), Y the grain yield (t/ha) a the intercept, b and c the linear coefficients, ε is the error term and 5.75 the conversion factor. The impact of protein concentration on net revenues were defined according to Baker *et al.* (2004) by Eqn (7),

$$NR = (Y pw) - (N pn) + ((P - 115) 5 Y) \quad (7)$$

where NR is the net revenue (€/ha), Y the grain yield (t/ha), N the nitrogen application rate (kg N/ha), P the protein concentration (mg/g), pw the market price for wheat at 115 mg/g protein concentration, pn the N fertilizer price (0.6 €/kg N) and 5 the premium or discount for protein concentration (€/t).

3.4 Results

Statistical features

As an example for the common *ex post* analysis, the application of the statistical models for yields of OSR in 2002 is shown in Figure 1 and 2 gives the corresponding regression residuals. The model outcomes resulted in different values for N_{opt} (160 kg N/ha (LRP), 192 kg N/ha (QRP) and 217 kg N/ha (Q)).

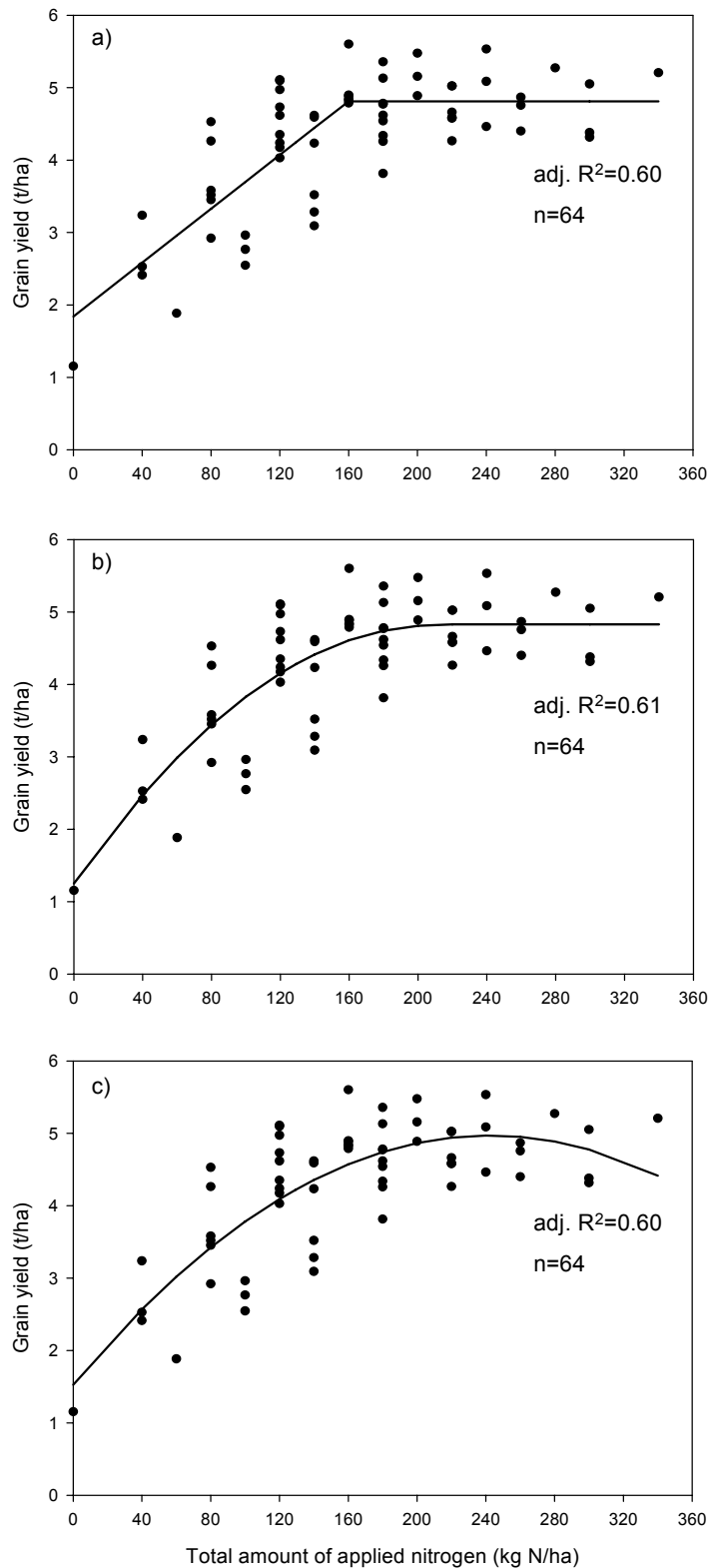


Fig. 1: Oilseed rape yield response to N fertilization in 2002 described using a) the linear response and plateau model, b) the quadratic response and plateau model and c) the quadratic model

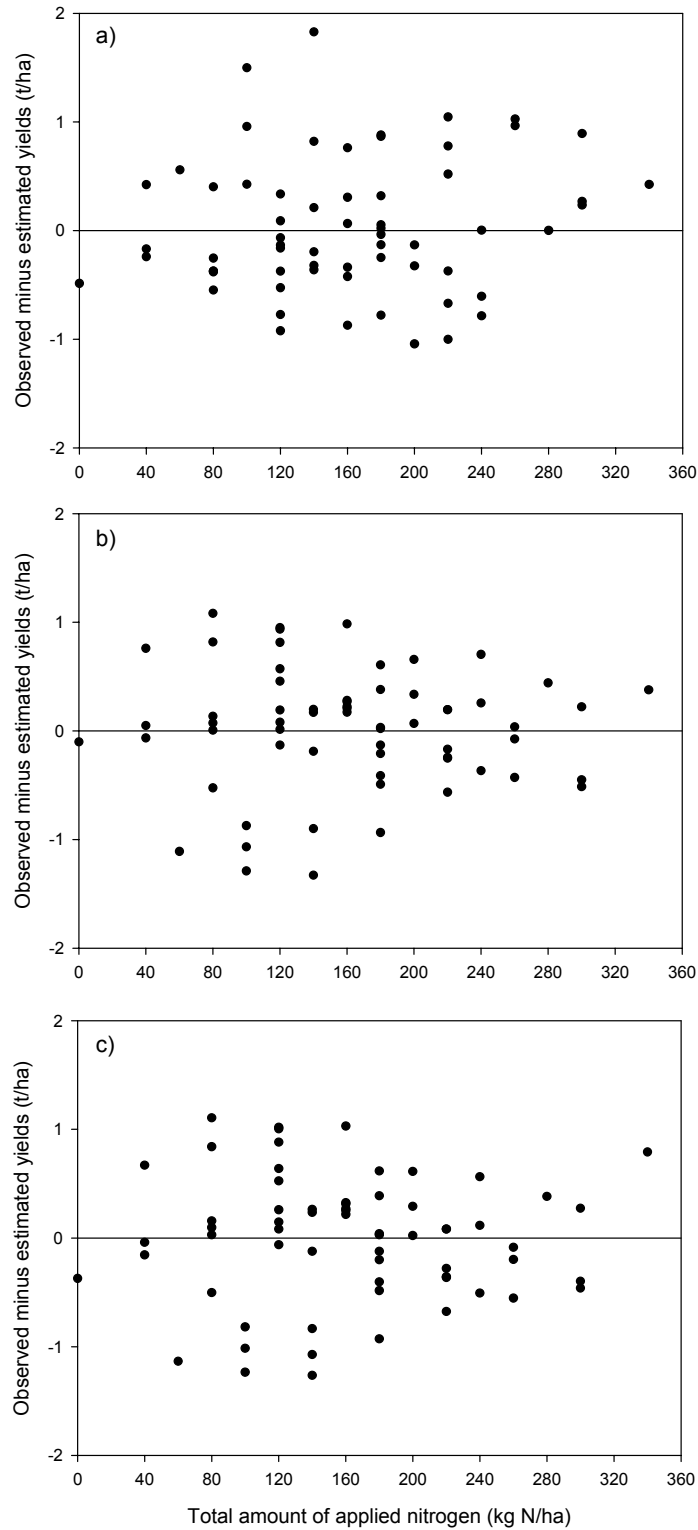


Fig. 2: Residuals of the regression (observed yield minus estimated yield) when a) the linear response and plateau model, b) the quadratic response and plateau model and c) the quadratic model were fitted to yield data of oilseed rape vs. N fertilization in 2002

Parameters of all model fits are given in Tables 1-3. The differences in the adj. R^2 values for grain yield between the models for a given crop and year were rather small. Also, differences between the intercepts of the QRP and the Q model were marginal, but the LRP model estimated higher yields without fertilization. Differences in the intercept between the years, i. e. different weather and soil conditions, were considerable. The intercept estimated by the Q model varied from 2.74 to 7.08 in wheat, indicating a variable N availability from natural sources between the years. Analysis of variance showed that all model fits were significant ($P < 0.05$), except the QRP model in barley in 1998 ($P = 0.0567$) (data not shown). According to a Shapiro-Wilk-Test ($P = 0.05$) (Thode 2002) the residuals of the Q model were normally distributed in 16 of 19, 15 of 19 and 14 of 19 crop and year combinations for the Q, LRP and QRP model respectively (data not shown).

Table 1: Intercept (a), linear coefficient (b), adj. R², C, P, RMSE and n of the linear response and plateau model (SE ±)

Crop	Year	a	b*10 ⁻²	C	P	adj. R ²	RMSE	n
Oilseed rape	1996	1.58	1.50 (0.003)	165 (14.3)	4.06 (0.116)	0.48	0.62	64
	1997	2.82	0.95 (0.005)	137 (36.6)	4.12 (0.131)	0.11	0.84	63
	1998	2.67	1.38 (0.002)	220 (20.1)	5.71 (0.214)	0.56	0.71	64
	1999	1.36	1.37 (0.002)	188 (11.6)	3.94 (0.102)	0.64	0.45	63
	2002	1.84	1.86 (0.003)	160 (12.5)	4.81 (0.099)	0.60	0.58	64
Winter wheat	1996	6.92	2.14 (0.007)	106 (19.5)	9.19 (0.134)	0.43	0.63	32
	1997	5.19	2.80 (0.010)	135 (23.7)	8.98 (0.320)	0.31	1.36	32
	1998	4.53	3.83 (0.011)	88 (11.9)	7.92 (0.191)	0.41	0.90	32
	1999	4.26	3.99 (0.009)	151 (16.5)	10.28 (0.323)	0.59	1.16	31
	2000	4.58	3.84 (0.006)	131 (10.2)	9.61 (0.240)	0.70	0.86	32
	2001	3.58	6.42 (0.016)	93 (12.4)	9.56 (0.396)	0.57	1.37	22
	2002	2.83	4.03 (0.005)	134 (9.4)	8.24 (0.220)	0.78	0.79	31
Winter barley	1996	3.94	2.14 (0.009)	108 (24.6)	6.25 (0.165)	0.34	0.77	32
	1997	3.27	2.50 (0.010)	122 (23.5)	6.32 (0.322)	0.20	1.36	32
	1998	4.66	3.89 (0.03)	62.9 (30.2)	7.10 (0.210)	0.13	1.08	31
	1999	3.65	4.06 (0.015)	92 (16.9)	7.38 (0.273)	0.28	1.28	32
	2000	3.77	2.97 (0.005)	136 (13.2)	7.80 (0.230)	0.63	0.83	32
	2001	5.82	4.11 (0.011)	102 (14.4)	10.00 (0.204)	0.52	0.96	32
	2002	2.46	3.91 (0.006)	138 (12.0)	7.87 (0.269)	0.69	0.97	32

Table 2: Intercept (a), linear coefficient (b), quadratic coefficient (c), adj. R², C, P, RMSE and n of quadratic response and plateau model (SE ±)

Crop	Year	a	b*10 ⁻²	c*10 ⁻⁵	C	P	adj. R ²	RMSE	n
Oilseed rape	1996	1.60 (0.342)	1.80 (0.004)	-3.00 (<0.001)	300	4.30	0.49	0.61	64
	1997	2.60 (0.641)	1.76 (0.012)	-5.00 (<0.001)	176	4.16	0.10	0.84	63
	1998	2.39 (0.381)	1.99 (0.005)	-3.00 (<0.001)	331	5.69	0.56	0.70	64
	1999	1.11 (0.309)	2.02 (0.004)	-3.00 (<0.001)	336	4.51	0.64	0.46	63
	2002	1.25 (0.390)	3.38 (0.006)	-8.00 (<0.001)	211	4.83	0.61	0.58	64
Winter wheat	1996	6.71 (0.549)	3.50 (0.014)	-12.40 (<0.001)	140	9.17	0.38	0.64	32
	1997	4.94 (1.032)	3.99 (0.017)	-9.50 (<0.001)	210	9.13	0.30	1.34	32
	1998	4.29 (0.815)	5.99 (0.023)	-24.70 (<0.001)	121	7.92	0.38	0.90	32
	1999	2.65 (1.336)	7.98 (0.023)	-21.00 (<0.001)	189	10.23	0.58	1.17	31
	2000	3.86 (0.646)	6.55 (0.013)	-18.50 (<0.001)	176	9.66	0.71	0.83	32
	2001	3.23 (1.240)	9.63 (0.034)	-36.50 (<0.001)	131	9.58	0.52	1.40	22
	2002	2.30 (0.607)	6.34 (0.011)	-16.70 (<0.001)	189	8.31	0.76	0.80	31
Winter barley	1996	3.67 (0.675)	3.68 (0.017)	-13.20 (<0.001)	139	6.24	0.29	0.79	32
	1997	2.94 (1.155)	4.15 (0.024)	-12.60 (<0.001)	164	6.35	0.17	1.36	32
	1998	4.57 (1.055)	5.66 (0.044)	-31.60 (<0.001)	89	7.10	0.10	1.08	31
	1999	3.24 (1.155)	6.81 (0.033)	-28.10 (<0.001)	121	7.37	0.26	1.28	32
	2000	3.59 (0.601)	4.09 (0.010)	-9.50 (<0.001)	215	8.00	0.60	0.84	32
	2001	5.35 (0.852)	6.96 (0.023)	-26.30 (<0.001)	132	9.96	0.49	0.97	32
	2002	2.34 (0.632)	4.98 (0.010)	-10.20 (<0.001)	243	8.41	0.71	0.93	32

Table 3: Intercept (a), linear coefficient (b), quadratic coefficient (c), adj. R², RMSE and n of the quadratic model (SE ±)

Crop	Year	a	b*10 ⁻²	c*10 ⁻⁵	adj. R ²	RMSE	n
Oilseed rape	1996	1.60 (0.334)	1.79 (0.004)	-2.88 (<0.001)	0.50	0.61	64
	1997	2.36 (0.425)	2.20 (0.005)	-6.29 (<0.001)	0.21	0.78	63
	1998	2.39 (0.381)	1.99 (0.005)	-2.67 (<0.001)	0.56	0.70	64
	1999	1.10 (0.296)	2.03 (0.004)	-3.38 (<0.001)	0.64	0.46	63
	2002	1.52 (0.321)	2.84 (0.004)	-5.85 (<0.001)	0.60	0.59	64
Winter wheat	1996	7.08 (0.446)	2.54 (0.007)	-7.20 (<0.001)	0.34	0.68	32
	1997	5.40 (0.933)	2.95 (0.013)	-5.33 (<0.001)	0.33	1.34	32
	1998	5.41 (0.663)	2.86 (0.010)	-7.45 (<0.001)	0.25	1.01	32
	1999	3.41 (1.055)	6.44 (0.015)	-14.60 (<0.001)	0.58	1.19	31
	2000	4.50 (0.571)	4.92 (0.009)	-10.90 (<0.001)	0.70	0.87	32
	2001	3.81 (1.040)	7.67 (0.018)	-23.90 (<0.001)	0.51	1.45	22
	2002	2.74 (0.546)	5.23 (0.008)	-11.60 (<0.001)	0.75	0.83	31
Winter barley	1996	3.87 (0.510)	3.08 (0.008)	-9.32 (<0.001)	0.33	0.77	32
	1997	2.84 (0.920)	4.15 (0.013)	-11.50 (<0.001)	0.24	1.32	32
	1998	5.06 (0.661)	3.33 (0.010)	-11.70 (<0.001)	0.25	1.00	31
	1999	3.67 (0.755)	5.62 (0.011)	-19.00 (<0.001)	0.43	1.15	32
	2000	3.74 (0.554)	3.73 (0.008)	-7.87 (<0.001)	0.61	0.84	32
	2001	6.00 (0.660)	5.08 (0.010)	-15.00 (<0.001)	0.47	1.00	32
	2002	2.41 (0.611)	4.82 (0.009)	-9.56 (<0.001)	0.72	0.93	32

Ex post Nopt

The Q model estimated the highest *ex post* Nopt values for all years and crops except for OSR in 1999, the LRP model the lowest Nopt (Table 4). Mean Nopt values increased by c. 30 kg N/ha from the LRP to the QRP model in wheat and barley and c. 60 kg N/ha in OSR. The QRP model differed from the Q model by c. 30 kg N/ha in wheat, c. 20 kg N/ha in barley and c. 10 kg N/ha in OSR (Table 4). The Q model estimated slightly higher grain yields at Nopt, compared to the QRP and LRP model which gave quite similar results for all crops. Between the years, estimated Nopt and corresponding grain yields differed considerably. In wheat, the estimated Nopt was in the range 135-220 kg N/ha for the Q model, 117-178 kg N/ha for the QRP model and 88-151 kg N/ha for the LRP model (Table 4). The highest net revenues were calculated by the LRP model, followed by the Q and QRP model. Mean N balance values in OSR were up to 105 kg N/ha when Nopt was estimated by the Q model, followed by the QRP model (101 kg N/ha) and the LRP model (52 kg N/ha). The lowest N balances which were even negative in winter wheat and winter barley were calculated by the LRP model in all three crops. Regarding the rotation these negative N balances were levelled out by the positive N balance of OSR. Within the crops N balances decreased in the order OSR, wheat, barley. In particular N balances of OSR indicate large nitrogen residuals after harvest.

Table 4: Ex post Nopt (kg N/ha), grain yield (t/ha), net revenue (€/ha) and N balance (kg N/ha) at ex post Nopt of OSR, winter wheat and winter barley

	Nopt (kg N/ha)			Grain yield (t/ha)			N balance (kg N/ha)					
	LRP	QRP	Q	LRP	QRP	Q	LRP	QRP	Q			
Oilseed rape												
1996	165	250	259	4.1	4.2	4.3	713	695	708	59	127	133
1997	137	146	151	4.1	4.1	4.3	742	735	760	34	42	43
1998	220	282	317	5.7	5.6	6.0	1009	954	1016	60	118	136
1999	188	287	256	3.9	4.4	4.1	675	715	663	94	173	153
2002	160	192	217	4.8	4.8	4.9	866	844	856	15	43	60
mean	174	231	240	4.5	4.6	4.7	801	788	800	52	101	105
CV (%)	18.1	26.2	25.5	16.4	13.1	16.9	17.1	13.8	17.5	57.2	56.8	47.5
Winter wheat												
1996	106	117	135	9.2	9.1	9.2	855	840	839	-43	-36	-27
1997	136	178	220	9.0	9.0	9.3	817	796	799	-15	19	51
1998	88	109	152	7.9	7.9	8.0	737	724	712	-33	-17	15
1999	151	176	200	10.3	10.2	10.5	937	913	926	-15	-1	8
2000	131	161	198	9.6	9.6	10.0	882	865	878	-17	1	17
2001	93	124	148	9.6	9.6	9.9	899	886	903	-82	-59	-47
2002	134	172	200	8.2	8.3	8.6	743	722	736	-18	9	23
mean	120	148	179	9.1	9.1	9.3	839	821	828	-32	-12	6
CV (%)	19.9	20.4	18.5	9.0	8.8	9.1	9.2	9.2	9.9	77.5	228.4	584.4
Winter barley												
1996	108	114	130	6.3	6.2	6.3	498	485	490	-1	6	16
1997	122	138	152	6.3	6.3	6.5	495	481	494	17	32	42
1998	63	79	114	7.1	7.1	7.3	602	589	592	-35	-21	4
1999	92	109	130	7.4	7.3	7.8	609	594	621	-12	1	11
2000	136	180	194	7.8	7.9	8.0	621	601	605	9	34	40
2001	102	120	147	10.0	9.9	10.2	839	821	833	-79	-65	-54
2002	138	211	217	7.9	8.3	8.4	625	620	623	6	52	55
mean	109	136	155	7.5	7.6	7.8	613	599	608	-14	6	16
CV (%)	24.5	33.3	24.2	16.7	17.2	17.0	18.7	18.9	18.8	246.3	707.8	219.2
mean				728	714	722				8	36	48

Ex ante Nopt

In order to give *ex ante* recommendations which take variability of growing conditions among years into account, we calculated an identical fertilization rate over the years for each crop at which the sum of the net revenues over the years was maximal. *Ex ante* Nopt values were 189 kg N/ha (LRP), 239 kg N/ha (QRP) and 222 kg N/ha (Q) in OSR, 151 kg N/ha (LRP), 162 kg N/ha (QRP) and 184 kg N/ha (Q) in wheat and 138 kg N/ha (LRP), 132 kg N/ha (QRP) and 145 kg N/ha (Q) in barley. On an average, *ex ante* Nopt was higher about 25 kg N/ha for the LRP model and 7 kg N/ha for the QRP model but 8 kg N/ha lower for the Q model compared to the mean of the Nopt values obtained *ex post*. At least on average over the three different models, the corresponding grain yields and also net revenue values, however, were lower and N balance values were higher compared with the scenario of a variable, *ex post* calculated Nopt for each year (Table 4 and 5). Table 5 shows the influence of *ex ante* Nopt on N balances and net revenues in the rotation. Compared to the LRP and Q model mean net revenues in the rotation were 10 €/ha lower calculating with the QRP model (Table 7). In general, the differences between *ex post* and *ex ante* Nopt were higher for the LRP model compared to the Q model. Comparing the mean *ex post* and the *ex ante* Nopt estimated by the LRP model it was clearly observable that the *ex ante* Nopt is the more favourable choice for fertilization recommendation because mean net revenue in the rotation increased for 14 €/ha (Table 7).

Table 5: Grain yield (t/ha), net revenue (€/ha) and N balance (kg N/ha) in the rotation estimated with *ex ante* Nopt

	Grain yield (t/ha)			Net revenue (€/ha)			N balance (kg N/ha)		
	LRP	QRP	Q	LRP	QRP	Q	LRP	QRP	Q
Oilseed rape									
1996	4.1	4.2	4.2	699	694	700	80	119	105
1997	4.1	4.2	4.2	710	687	697	77	118	104
1998	5.3	5.4	5.5	942	943	967	45	86	68
1999	3.9	4.2	3.9	674	701	655	95	135	125
2002	4.8	4.8	4.9	849	821	856	40	83	64
mean	4.4	4.6	4.5	775	770	775	67	108	93
CV (%)	13.0	12.2	14.5	14.9	14.5	17.0	35.3	21.0	28.1
Winter wheat									
1996	9.2	9.2	9.3	828	820	821	-18	-11	-1
1997	9.0	8.9	9.0	808	794	792	-3	8	25
1998	7.9	7.9	8.2	701	695	704	15	24	38
1999	10.3	10.1	10.3	937	909	922	-15	-7	1
2002	8.2	8.2	8.4	734	721	734	-6	3	14
mean	8.9	8.9	9.1	802	788	795	-5	3	16
CV (%)	10.3	9.6	9.4	11.5	10.8	10.7	262.9	419.9	104.8
Winter barley									
1996	6.2	6.2	6.4	479	482	488	24	19	27
1997	6.3	6.2	6.4	486	480	493	32	27	36
1998	7.1	7.1	7.4	556	560	582	28	22	28
1999	7.4	7.4	7.8	581	585	617	23	18	21
2002	7.9	7.1	7.4	626	562	578	6	11	17
mean	7.0	6.8	7.1	546	534	552	23	19	26
CV (%)	10.0	8.0	9.1	11.5	9.2	10.5	43.5	30.1	27.5
mean				707	697	707	28	44	45

Monte-Carlo analysis

As an example result, the distribution of the model parameters for the LRP model in OSR are shown in Figure 3. The C (Nopt) and b (linear coefficient) distribution curves of the year 1997 show the difficulties in determining Nopt *ex post* in this year. Ten thousand generated parameters were too few to obtain a smooth curve because the number of generated parameters in each class was much lower compared to other years with more narrow distributions.

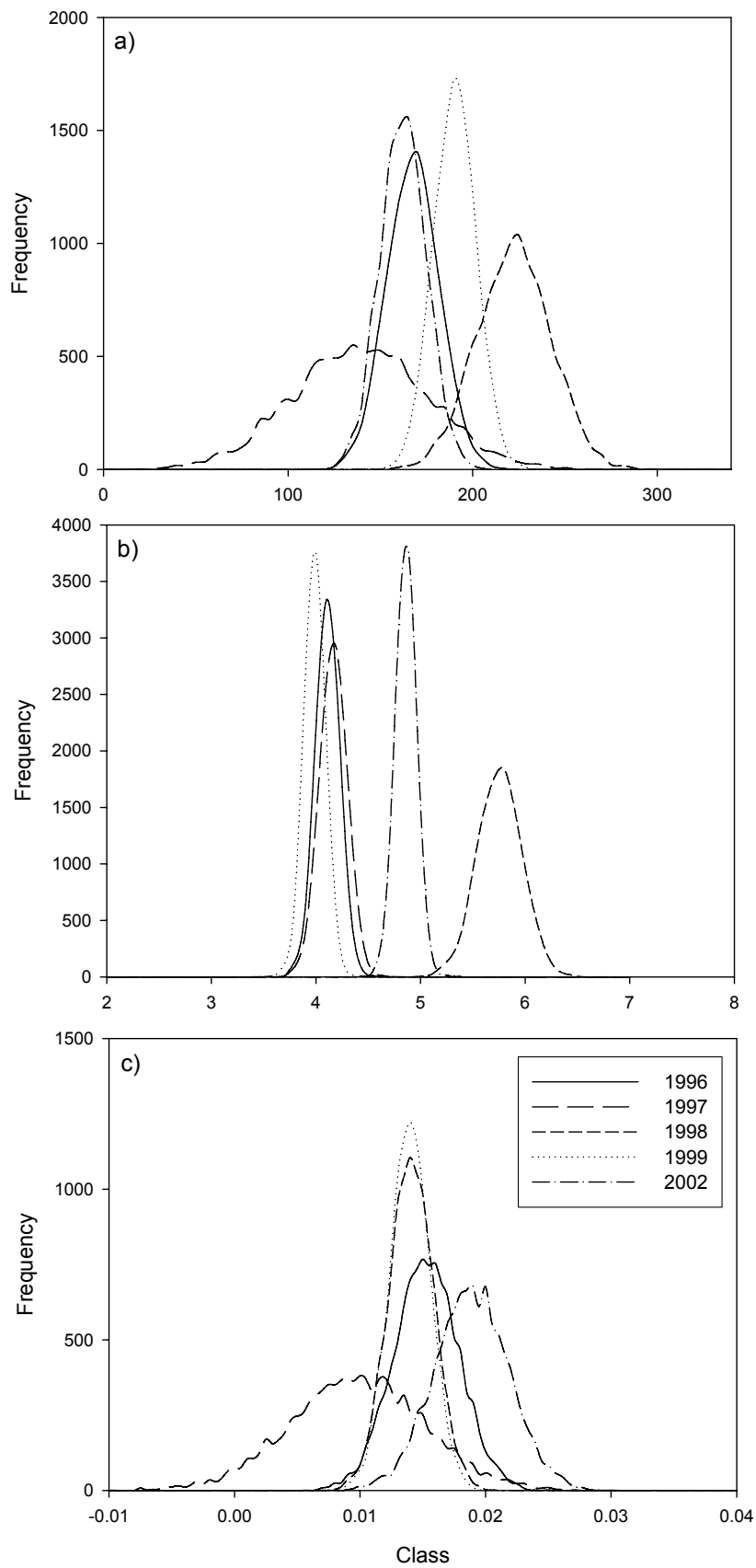


Fig. 3: Distribution of the generated parameters of the linear response and plateau model in each year for oilseed rape a) C (Nopt), b) P (plateau yield), c) b (linear coefficient)

Table 6: Effect of the Monte Carlo simulation of the LRP model parameters on Nopt (kg N/ha), grain yield (t/ha), net revenue (€/ha) and N balance (kg N/ha) at *ex post* Nopt in comparison to the *ex ante* Nopt estimated by the LRP model

	Nopt (kg N/ha)		Grain yield (t/ha)		N balance (kg N/ha)	
	<i>ex post</i>	<i>ex ante</i>	<i>ex post</i>	<i>ex ante</i>	<i>ex post</i>	<i>ex ante</i>
Oilseed						
rape						
1996	175	202	4.1	4.1	691	91
1997	154	202	4.1	4.1	702	88
1998	234	202	5.7	5.5	971	52
1999	196	202	3.9	3.9	667	107
2002	170	202	4.8	4.8	841	51
mean	186		4.5	4.5	774	78
CV (%)	16.6		16.4	14.4	16.7	32.3
Winter						
wheat						
1996	111	156	9.2	9.2	825	-15
1997	148	156	9.0	9.0	805	2
1998	98	156	7.9	7.9	698	19
1999	165	156	10.3	10.3	934	-13
2002	143	156	8.2	8.2	731	-2
mean	133		8.9	8.9	799	-2
CV (%)	20.8		10.3	10.6	11.5	81.7
Winter						
barley						
1996	110	136	6.3	6.3	481	1
1997	131	136	6.3	6.3	487	25
1998	65	136	7.1	7.1	558	-33
1999	103	136	7.4	7.4	583	-4
2002	148	136	7.9	7.9	619	13
mean	111		7.0	7.0	546	0
CV (%)	28.2		10.0	10.0	11.3	5447.5
						43.8

The effect of the Monte-Carlo simulation on the *ex post* LRP model parameters was an increase in Nopt (Tables 4 and 6). This effect was clearly observable, especially in OSR. Mean Nopt over the single years increased by 12 kg N/ha. In wheat, mean Nopt increased by 10 kg N/ha and in barley it only increased by 6 kg N/ha, calculated by the mean of only the years 1996, 1997, 1998, 1999 and 2002. Because of missing data on N concentration of OSR in the years 2000 and 2001, these years were omitted in the calculations for the comparison of the mean model outcomes for the crops in the rotation for the *ex ante* approach.

Also, *ex ante* analyses for the LRP model were conducted by running Monte-Carlo simulations. This led again to a considerable increase in N_{opt} of 13 kg N/ha in OSR, a small increase of 5 kg N/ha in wheat but a decrease of 2 kg N/ha in barley (Table 7). The effects of mean net revenue in the rotation were small but mean N balance rose (Table 7).

Table 7: Mean *ex post* Nopt, *ex ante* Nopt with and without Monte-Carlo simulation (MC) and corresponding net revenues and N balances

	<i>ex post</i> Nopt (kg N/ha)			<i>ex ante</i> Nopt (kg N/ha)			<i>ex ante</i> Nopt (t/ha) MC		
	LRP	QRP	Q	LRP	QRP	Q	LRP	QRP	Q
Oilseed rape	174	231	240	189	239	222	202	225	225
Winter wheat	123	150	181	151	162	184	156	188	188
Winter barley	105	130	149	138	132	145	136	148	148
Net revenue at <i>ex post</i> Nopt (€/ha)			Net revenue at <i>ex ante</i> Nopt (€/ha)			Net revenue at <i>ex ante</i> Nopt (€/ha) MC			
LRP	QRP	Q	LRP	QRP	Q	LRP	QRP	Q	
Oilseed rape	768	769	772	775	770	775	774	775	
Winter wheat	780	789	795	802	788	795	799	795	
Winter barley	533	534	551	546	534	552	546	552	
N balance at <i>ex post</i> Nopt (kg N/ha)			N balance at <i>ex ante</i> Nopt (kg N/ha)			N balance at <i>ex ante</i> Nopt (kg N/ha) MC			
LRP	QRP	Q	LRP	QRP	Q	LRP	QRP	Q	
Oilseed rape	56	101	108	67	108	93	78	96	
Winter wheat	-20	-4	13	-5	3	16	-2	18	
Winter barley	0	18	29	23	19	26	21	28	

When the Monte-Carlo simulation for the Q model was carried out for the *ex post* approach only marginal changes in Nopt were observed for each crop, therefore annual data are not presented. The Monte-Carlo simulation for the *ex ante* Nopt estimated by the Q model over the years led to a slight increase of the Nopt values to 225 kg N/ha in OSR, 188 kg N/ha in wheat and 148 kg N/ha in barley compared to the *ex ante* Nopt without Monte-Carlo simulation (Table 7). It was therefore concluded that the Q model is quite stable with regard to parameter estimation uncertainty. The Monte-Carlo simulation for the *ex ante* Nopt entailed only marginal effects in wheat and barley when the LRP model was used, but in OSR Nopt increased for about 10 % from 189 kg N/ha to 202 kg N/ha (Table 7). Regarding N balances and net revenues the Monte-Carlo simulation led to negligible changes. Although Nopt in OSR increased due to Monte-Carlo simulation there were still stronger differences between the production functions, i. e. between the LRP and the Q model in Nopt and N balance (Table 7). Mean yields, standard deviations of the 50000 generated LRP and Q models and the functions of the years 1996, 1997, 1998, 1999 and 2002 are given in Figure 4 and 5 for the three crops.

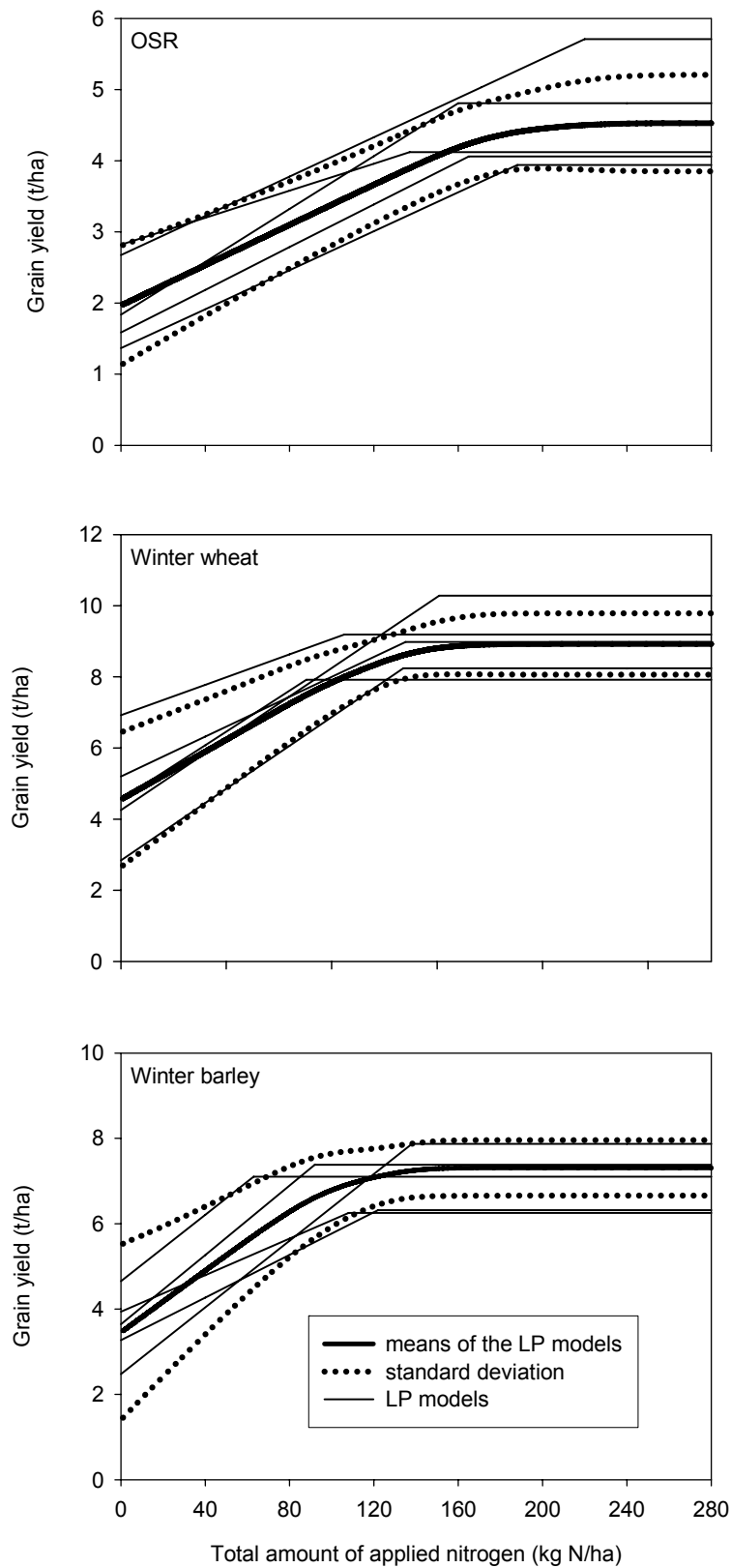


Fig. 4: Linear response and plateau model fitted to five individual years (1996, 1997, 1998, 1999, 2002) for the crops oilseed rape, winter wheat and winter barley, as well as the mean yield response curve for the three crops derived from 50000 simulated LRP models and the standard deviation of the mean yield

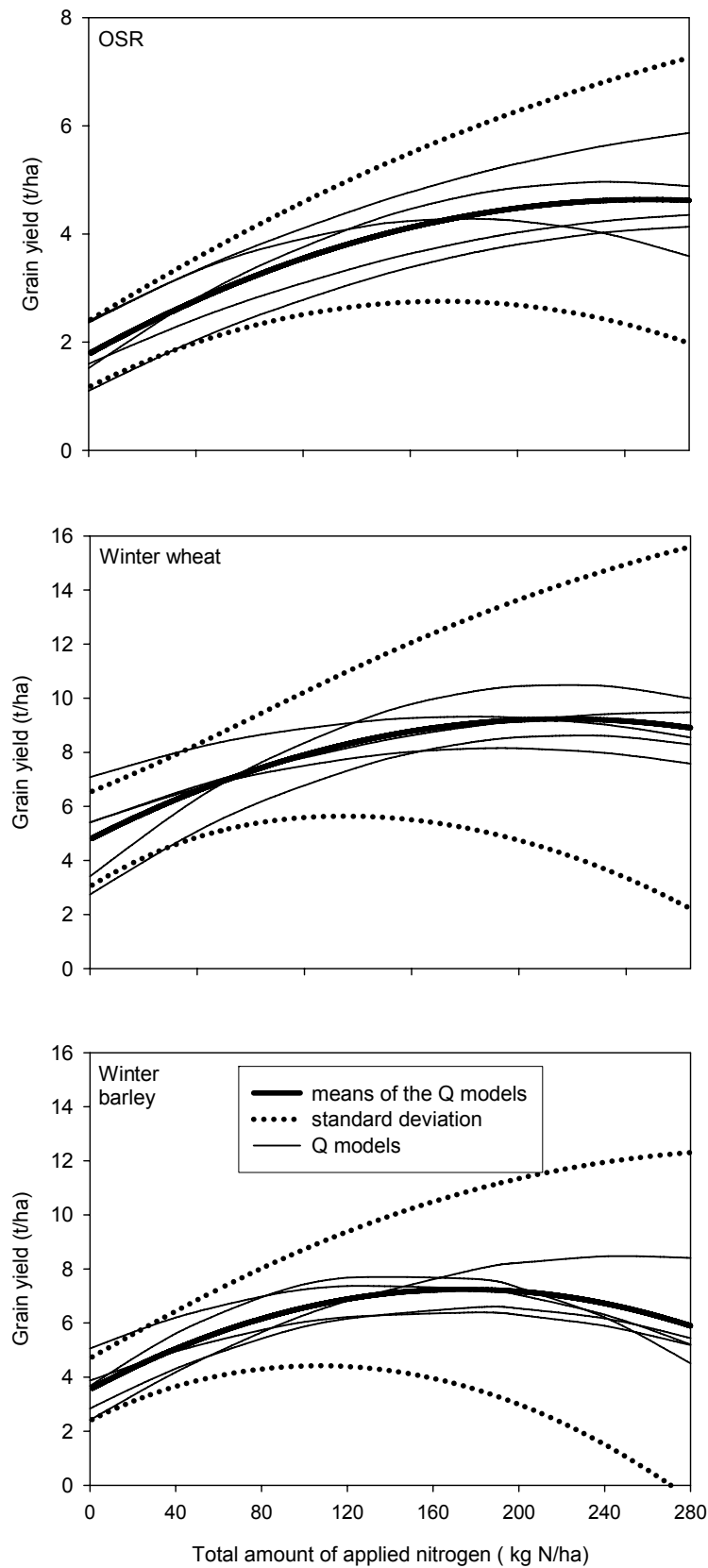


Fig. 5: Quadratic model fitted to five individual years (1996, 1997, 1998, 1999, 2002) for the crops oilseed rape, winter wheat and winter barley, as well as the mean yield response curve for the three crops derived from 50000 simulated Q models and the standard deviation of the mean yield

Nopt regarding protein concentration

Protein contents of wheat could be described using Eqn 6 with a quite different accuracy for the different years (Table 8). Using this simple statistical model, however, the determination of Nopt considering quality payment in wheat was only possible applying the Q model. This is because the plateau yield of the other two models and the quality surplus to nitrogen price ratio led to infinitely high optimum N rates.

Table 8: Intercept (a), linear coefficients (b,c), r^2 , RSME and n of the protein function (SE \pm)

Crop	Year	a	b*10 ⁻³	c*10 ⁻²	r ²	RSME	n
Winter wheat	1996	2.18 (0.340)	5.63 (0.001)	-9.77 (0.04)	0.81	0.17	32
	1997	2.26 (0.363)	2.14 (0.001)	-6.60 (0.05)	0.10	0.38	32
	1998	1.95 (0.242)	3.26 (0.001)	-5.74 (0.03)	0.50	0.20	32
	1999	1.55 (0.213)	5.47 (0.001)	-4.85 (0.03)	0.64	0.22	31
	2000	1.49 (0.870)	5.07 (0.003)	-3.78 (0.13)	0.14	0.75	32
	2001	2.13 (0.176)	3.02 (0.001)	-2.89 (0.02)	0.40	0.19	22
	2002	2.05 (0.169)	4.20 (0.001)	-5.68 (0.03)	0.59	0.19	31

The calculated effects of the quality payment on the estimates for Nopt were considerable (Table 9). Mean Nopt for the wheat crop increased from 179 to 235 kg N/ha, mean net revenue from 828 to 910 €/ha and mean N balance from 6 to 42 kg N/ha. Estimating an identical Nopt considering protein concentration the N amount rose from 184 to 243 kg N/ha (Table 7). In the rotation mean N balance in the single years increased from 48 to 62 kg N/ha and mean net revenue from 722 to 749 €/ha (Table 9). These results indicate that taking grain protein concentrations into account has a tremendous influence on Nopt in wheat as well as corresponding N balance and net revenue of the whole rotation increasing the economic productivity of the wheat crop by 82 €/ha.

3.5 Discussion

The aim of the present paper was to quantify uncertainties in estimating N_{opt} and agronomic, ecological and economic variables in an OSR – wheat – barley rotation.

Simple statistical nitrogen response models, as used in the present study, are quite commonly used for making *ex ante* N fertilizer recommendations. The validity of these simple response models, however, is generally limited because the complex relationship between the crop yield and the N rate in interaction with variable soil and weather conditions can not be mimicked by those simple equations. Therefore, very often only empirical reasons are considered for the acceptance or rejection of any of these models. Colwell (1994) listed statistical values like r^2 and analysis of variance for the accuracy of fertilization rates estimated by different models as criteria for model choice. The obtained differences in adj. R^2 values in our study were small between models for all crops in a year (Table 1, 2 and 3) and agree with the results of Cerrato & Blackmer (1990), Bullock & Bullock (1994) and Bélanger *et al.* (2000). In addition regression residuals have to be normally distributed for the proper application of the above mentioned empirical criteria. In the present study, this criterion was fulfilled in most of the cases. Also the quality of the dataset used for model comparison is important. The present data include many different N rates but these are scattered remarkably because of missing replications and a different splitting of total N amounts. This may have hampered to some extent a clear distinction between the descriptive quality of the models in this study. Statistical and empirical features, however, can only be one criteria for justifying one model over the others.

The differences in the *ex post* N_{opt} values and the intercepts (available soil mineral N) between the years and the corresponding yields, net revenues and N balances show clearly the annual variations in nitrogen response of all investigated crops. In consequence, N balances varied greatly between the years because many factors like climate and plant stress, which cannot be influenced by the farmer, affect N use efficiency and therefore N balances. This illustrates the principle difficulties in controlling N balances.

Ex post N_{opt} values differed noticeably between the models. This agrees well with results of Cerrato & Blackmer (1990) and Bélanger *et al.* (2000). The LRP model tends to overestimate yields at N_{opt} (Cerrato & Blackmer 1990,

Bélanger *et al.* 2000). This may be one reason that the LRP model estimated highest net revenues and lowest N balance values (Table 4).

Uncertainty in annual nitrogen response was considered by determining an *ex ante* Nopt. It was found that this kind of uncertainty led to higher N rates compared to the mean of *ex post* Nopt values. The same effect for the used price cost ratios can be expected if a multi site identical Nopt would be calculated because of different production functions due to variable soil mineral nitrogen and yield potential (Babcock 1992). The *ex ante* Nopt values of the Q model were quite similar with the official fertilization recommendations.

Uncertainties in model parameter estimates were taken into account by using Monte-Carlo simulations. This leads to both higher *ex post* and higher *ex ante* Nopt values, especially when estimated by the LRP model. The differences between the two models in Nopt therefore became smaller whereas the overall Nopt increases. The stronger effect of the Monte-Carlo simulation on the LRP model compared to the Q model is caused by the curves' progression (Figures 4 and 5). The Q model punishes very high N fertilization rates because of reducing yields when exceeding maximum yield, whereas the maximum yield estimated by the LRP model remains constant. In general, the influence of the uncertainties due to year-to-year variation and parameter estimates uncertainty on the LRP model was much higher than on the Q model thereby decreasing the differences between both models. Several studies conclude that the LRP model is more suitable to describe crop response to fertilization (Paris and Knapp 1989; Kuhlmann 1992; Baeumer 1994). Baeumer (1994) argued in an agronomic way that high Nopt, as estimated by the Q model probably leads to high yields but does not exclude over-fertilization. In contrast, using a lower Nopt, as obtained from the LRP model, prevents over-fertilization but highest yields are not assured. He favoured the application of the LRP model as a regulative strategy in order to avoid increasing negative effects of over-fertilization (e.g. N leaching, weeds). The results of the presented study, however, indicate that the use of the LRP model may lead to sub-optimal yields and net revenues if fertilization recommendations are derived by simply averaging *ex post* Nopt values estimated by this model for a range of environmental conditions. As an example mean net revenue calculated with the mean *ex post* Nopt were 780 € for the LRP model in winter wheat compared to 802 € calculated with the *ex ante* Nopt. Despite the fact, that the LRP model may be the best model for describing yield response under homogenous boundary conditions, the heterogeneity of annual climate and

different soil conditions leads to a situation where the Q model seems to be safer in terms of preventing financial losses under conditions of uncertainty. Similar conclusions were drawn by Wagner (1995a, 1995b) by analyzing yield response in different environments and over different spatial scales within agricultural fields. On the other hand, the risk of high positive N balances rises and the introduction of penalty functions may therefore reverse this ranking of models.

Due to the national implementation of the EU Nitrate Directive German farmers face restricted N balances of 60 kg N/ha averaged over three years beginning 2009. In our study this limitations could be met by *ex post* and *ex ante* analysis on a plot level but it is likely that the EC drinking water directive leads to more restrictive limits. Sieling & Kage (2006) reported that more than 34 kg N/ha leaching already exceeds the EC threshold of 50 mg/l nitrate in drinking water for a drainage rate of 300 mm typically for the experimental site. However, a stronger restriction of N balances in arable cropping systems would probably not only be associated with a reduction of N fertilization but also with other changes in production systems. Because OSR is the crop with the highest N balance surplus, the competitiveness of OSR against other crops may decrease in the situation of strongly restricted N balances. A reduction to a sub-optimal N fertilization rate, however, can also have negative effects on the efficiency of other inputs and consequently on the overall resource use efficiency in arable cropping (de Wit 1992). According to Sylvester-Bradley & Chambers (1992) and Sieling & Kage (2006) there is no direct short-term correlation between N balance and nitrogen leaching. Nitrogen losses due to leaching are mainly affected by weather conditions, the preceding crop and the N supply. It is also important to mention that increasing N fertilization does not automatically increase N losses via leaching if N is transformed to yield. These results underline the importance of the considerations of uncertainties for fertilization recommendations because the empirical *ex post* knowledge about N_{opt} is hardly to adopt when a decision about the actual N rate is made. Sylvester-Bradley & Chambers (1992) reported that fertilizer N recommendations only accommodate a small proportion of the variation in optimum N fertilizer amounts.

3.6 Conclusions

Nitrogen response to yield and thereby net revenues and N balances varied between the single years and the estimated models in the three crops. Taking uncertain year-to-year variations and model parameter estimates into account *ex ante* N_{opt} tended to increase for OSR and wheat. Additionally the mean net

revenue of the whole rotation rose using the *ex ante* approach compared to the calculations with the averaged *ex post* Nopt. This effect was especially observable calculating with the LRP model but there was a smaller or even reverse effect in case of OSR when calculating with the Q model. However, simulation of parameter estimation uncertainty had a smaller effect especially on net revenues and N balances. It is therefore concluded that the effects of uncertainty depend on the yield models' functional form (LRP vs. Q). The Q model seems to be quite unsusceptible against uncertainties in year-to-year nitrogen response variation and parameter estimation uncertainty but the LRP model show an explicit increase in net revenues when uncertainties were considered. According to our calculations restricted N balances of 60 kg N/ha surplus could be met without serious impact on profits. In practice, however, for arable farms with similar rotation and climatic conditions as underlying this study such a restriction might be critical because of other uncertainties in N use efficiency not considered in this study.

3.7 References

- BABCOCK, B. A. (1992). The effects of uncertainty on optimal nitrogen applications. *Review of Agricultural Economics* 14, 271-280.
- BAEUMER, K., (1994). Düngung. In: Diercks, R., Heitefuss, R. (Eds.), *Integrierter Landbau*. BLV, München, pp. 88-110.
- BAKER, D. A., YOUNG, D. L., HUGGINS, D. R. & PAN, W. L., (2004). Economically Optimal Nitrogen Fertilization for Yield and Protein in Hard Red Spring Wheat. *Agronomy Journal* 96, 116-123.
- BÉLANGER, G., WALSH, J. R., RICHARDS, J. E., MILBURN, P. H. & ZIADI, N., (2000). Comparison of Three Statistical Models Describing Potato Yield Response to Nitrogen Fertilizer. *Agronomy Journal* 92, 902-908.
- BOCK, B. R. & SIKORA, F. J., (1990). Modified-Quadratic/Plateau Model for Describing Plant Responses to Fertilizer. *Soil Science Society of America Journal* 54, 1784-1789.
- BULLOCK, D. G. & BULLOCK, D. S., (1994). Quadratic and Quadratic-Plus-Plateau Models for Estimating Optimal Nitrogen Rate of Corn: A Comparison. *Agronomy Journal* 86, 1991-1995.
- CERRATO, M. E. & BLACKMER, A. M., (1990). Comparison of Models Describing Corn Yield to Nitrogen Fertilizer. *Agronomy Journal* 82, 138-143.
- COLWELL, J. D., (1994). *Estimating Fertilizer Requirements. A Quantitative Approach*. CAB International, Wallingford.
- GREENE, W. H., (2003). *Econometric Analyses*, fifth edition. Prentice Hall International Edition, New Jersey.
- KUHLMANN, F., (1992). Zum 50. Todestag von Friedrich Aereboe: Einige Gedanken zur Intensitätslehre. *Agrarwirtschaft* 41, 222-230.
- PARIS, Q. & KNAPP, K., (1989). Estimation of von Liebig Response Functions. *American Journal of Agricultural Economics* 71, 178-186.
- SAS INSTITUTE INC., (1989). *SAS/STAT® User's Guide*, Version 6, fourth Edition, Volume 2. Cary, NC.
- SELING, K., GÜNTHER-BORSTEL, O. & HANUS, H., (1997). Effect of slurry application on N leaching in different crop combinations. *Journal of Agricultural Science, Cambridge* 128, 79-86.

- SELING, K. & KAGE, H., (2006). N balance as an indicator of N leaching in an oilseed rape - winter wheat - winter barley rotation. *Agriculture, Ecosystems and Environment* 115, 261-269.
- 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. *Aspects of Applied Biology* 30, Nitrate and Farming Systems, 85-94.
- THODE, H. C., (2002). *Testing for Normality*. Dekker, New York.
- WAGNER, P., (1995a). Konsequenzen für die Projektion von Politikmaßnahmen bei Annahme unterschiedlicher Produktionsfunktionen. In: Grosskopf, W., Hanf, C.-H., Heidhues, F., Zeddies, J. (Eds.), *Schriften der Gesellschaft für Wirtschafts- und Sozialwissenschaften des Landbaus e.V.* 31, 389-404.
- WAGNER, P., (1995b). Überlegungen zur Modellierung von Produktionsfunktionen. In: Noell, C. & Pohlmann, J. M. (Eds.), *Berichte der GIL*, 7, 306-313. Halle: Gesellschaft für Informatik in der Landwirtschaft.
- WIT, C. T. DE, (1992). Resource use efficiency in agriculture. *Agricultural Systems* 4, 125-151.

Kapitel 4

Analysing soil and canopy factors affecting optimum nitrogen fertilization rates of oilseed rape (*Brassica napus*)

J. Henke, K. Sieling, W. Sauermann & H. Kage

4.1 Summary

Due to the national implementation of the EU Nitrate Directive, N balance surpluses will be restricted to 60 kg N/ha averaged over three years starting in 2009. With N surpluses up to more than 100 kg N/ha winter oilseed rape (OSR) is a main contributor to N balance surpluses in OSR based crop rotations in northern Germany. The exact calculation of N fertilization rates becomes therefore more and more important to meet the target of 60 kg N/ha N balance surplus on a farm level base. Currently, soil mineral nitrogen (SMN) at the beginning of spring growth is commonly used as an indicator for the calculation of N fertilization rates in spring. However, amounts of SMN at the beginning of spring growth under OSR are usually low and canopy N is only taken into account to a very limited extent. This might lead to N fertilization rates in exceeding the optimum fertilization rate (Nopt). In the present study the effects of SMN in spring and of canopy properties like canopy N in autumn and spring on Nopt were investigated. Multi-site field trials with four different canopies in autumn, as a result of two sowing dates and two N fertilization levels in autumn in each sowing date, and five N fertilization levels in spring in each autumn treatment were carried out in 2005/2006 and 2006/2007. As a simple method for estimating canopy N (kg N/ha) as a prerequisite for accounting canopy N in practice, the product of weighed above ground fresh matter (kg/m²) and a factor accounting for DM content and N concentration was tested resulting in a conversion factor of 45 for estimation canopy N in autumn and of 54 for that in spring.

Nopt in spring was estimated *ex post* by quadratic response functions using the seed yield data of the spring N fertilization treatments. Regression analyses yielded no relationship between SMN at the beginning of spring growth or canopy N in spring and Nopt. In contrast, a significant negative correlation between canopy N in autumn and Nopt was found. Therefore canopy N in autumn may be used as an indicator for calculating N fertilization rates in spring, and, consequently, N fertilization rates should be reduced when canopy N in autumn is high.

4.2 Introduction

Winter oilseed rape (OSR) acreage has risen up to 13 % of the total arable land in Germany, and in northern Germany even up to 20 % of the total acreage used for arable cropping (Statistisches Bundesamt 2007). This is because of its profitability, the beneficial value as a preceding crop for cereals and the opportunity to grow winter oilseed rape (OSR) for biofuel production on set-aside. OSR demands high amounts of N fertilizer often exceeding 200 kg N/ha to get maximum yields but N offtake by the seeds is comparatively low leading to high N balance surpluses (fertilizer N minus N offtake by the seed) (Shepherd & Sylvester-Bradley 1996, Sieling et al. 1999, Sieling & Kage 2006, Rathke et al. 2006, Henke et al. 2007). Excessive N fertilization rates can boost soil mineral nitrogen ($\text{NO}_3\text{-N}$ plus $\text{NH}_4\text{-N}$: SMN) after harvest which can lead to high N leaching rates during winter (Shepherd & Sylvester-Bradley 1996, Beaudoin et al. 2005). For the protection of water bodies the national implementation of the EU Nitrate Directive ('Düngeverordnung') restricts N balance surpluses to 60 kg N/ha averaged over three years starting in 2009 on the farm level. Compared to cereals, N balance surplus of OSR can rise up to more than 100 kg N/ha (Henke et al. 2007) and in consequence the threshold of 60 kg N/ha in a three year rotation may be exceeded. An exact estimation of fertilizer N demand becomes therefore increasingly important to meet the 60 kg N/ha threshold, but also to achieve high seed yields and maximum economic returns. In Germany N fertilizers are commonly applied according to growth stage (Rathke et al. 2006) taking SMN at the start of spring growth into account by the Nmin method (Wehrmann et al. 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. However, this hardly accounts for the actual canopy development and corresponding N amounts taken up by the canopy before fertilization. In contrast, an approach using balance sheets has been developed in France, which takes the mineralization of soil borne N and the N amount in the OSR canopy at the end of autumn and the end of winter into account (Reau et al. 1994, Makowski et al. 2005). The results indicate a reduced N fertilization of OSR. However, a detailed investigation of fertilization strategies under different climatic conditions is necessary and extremely important because different boundary conditions strongly influence N dynamics in the plant-soil system and consequently the N fertilization needs.

Hence, the aim of this study was to analyze possible functional relationships between the optimum N fertilization rate (Nopt), SMN at the beginning of spring growth and the amounts of canopy N at the end of autumn and beginning of spring growth. Additionally, weighing of above ground fresh matter was evaluated as a simple and rapid procedure for estimating N amounts in OSR canopies.

4.3 Material and Methods

Field trials

The experimental data originate from field trials established 2005/2006 and 2006/2007 at seven locations in Germany (Hohenschulen, Futterkamp, Borwede, Dornburg, Guelzow, Roda and Moosburg). Positions and main characteristics of the locations are given in Table 1. The cultivar Trabant (hybrid) was grown at Futterkamp, Borwede, and Dornburg, the cultivar NK Fair (open pollinating) at Guelzow, Moosburg and Roda, at Hohenschulen both cultivars were tested. In both years the trials were well developed in autumn and at the beginning of spring growth. However, due to plant losses or drought stress in several plots in spring, canopies at some locations were seriously damaged. Therefore the trials in Hohenschulen (early sowing) and Roda in 2005/2006 and Guelzow, Dornburg, Roda (early sowing) and Moosburg (early sowing) in 2006/2007 had to be omitted in the data analysis.

Table 1: Geographical position, climate and soil characteristics of the locations

Location	Position	Long term rainfall (mm)	Long term average temperature (°C)	Texture
Hohenschulen	54° 19' N, 9° 58' E	716	8.4	sandy loam
Futterkamp	54° 16' N, 10° 39' E	677	8.3	sandy loam
Gülzow	53° 47' N, 12° 3' E	542	8.3	loamy Sand
Borwede	52° 48' N, 8° 39' E	725	8.7	loamy silt
Dornburg	51° 0' N, 11° 40' E	596	8.8	loam- sandy loam
Moosburg	48° 28' N, 11° 56' E	814	7.7	sandy loam
Roda [†]	51° 3' N, 12° 33' E	711	8.7	Loam

[†]only 2006/07

Two different sowing dates (normal, late) and two levels of N fertilization in autumn (0, 40 kg N/ha) were used to establish differently developed OSR canopies in autumn. The normal sowing was done in the third decade of August and the late one in the first decade of September. Sowing dates are given in Table 2. Fertilizer in autumn was applied at emergence of the late sown OSR in both sowing dates. In order to estimate Nopt based on a N response curve, five different levels of N fertilization (0, 80, 160, 240, 280 kg N/ha) in each of the four

autumn treatments were split applied in spring at the start of spring growth and at the start of stem elongation as calcium ammonium nitrate (0.27 N). Fertilization treatments and treatment numbers are given in Table 3.

Table 2: Sowing dates and plot size of the field trials in both years

Year	Location	Sowing Date		Plot Size (m ²)
2005/06	Hohenschulen	normal	19/08/2005	9.0
		late	01/09/2005	
2005/06	Futterkamp	normal	23/08/2005	15.0
		late	06/09/2005	
2005/06	Borwede	normal	22/08/2005	13.44
		late	05/09/2005	
2005/06	Moosburg	normal	27/08/2005	10.5
		late	14/09/2005	
2005/06	Gülzow	normal	25/08/2005	12.0
		late	06/09/2005	
2005/06	Dornburg	normal	17/08/2005	13.5
		late	05/09/2005	
2006/07	Hohenschulen	normal	25/08/2006	9.0
		late	05/09/2006	
2006/07	Futterkamp	normal	25/08/2006	15.0
		late	06/09/2006	
2006/07	Borwede	normal	21/08/2006	13.44
		late	04/09/2006	
2006/07	Moosburg	normal	24/08/2006	10.0
		late	13/09/2006	
2006/07	Gülzow	normal	24/08/2006	10.5
		late	07/09/2006	
2006/07	Dornburg	normal	17/08/2006	13.5
		late	06/09/2006	
2006/07	Roda	normal	23/08/2006	15.0
		late	12/09/2006	

All plots were ploughed, fungicides and other crop management factors (e. g. herbicides) were handled in accordance with farmers' normal practice. The design was a split-plot design with four replicates where the factor sowing date was not repeated at the locations. The fertilization treatments were fully randomized within the sowing dates.

Table 3: Fertilization treatments (autumn/spring) in each sowing date

Treatment	N fertilization in autumn (kg N/ha)	N fertilization in spring (kg N/ha)
1	0	0
2	0	80
3	0	160
4	0	240
5	0	280
6	40	0
7	40	80
8	40	160
9	40	240
10	40	280

Plant and soil samples were taken at the end of autumn growth (end of November) and the beginning of spring growth before the first N fertilization (end of February) in all replicates of treatment 3 and 8 in each sowing date. Plant samples (1 m x 1.5 m) were taken, and the number of plants and the above ground dry matter (DM) were determined and standardized to 1 m². N concentration in DM was determined using near infrared spectrometry (NIRS 5000, Foss).

In autumn 2006 and spring 2007 above ground fresh matter (FM) was weighed to derive a simple factor for estimating canopy N. Soil samples for SMN were taken at plant sampling and stored frozen until analysis. After thawing overnight at room temperature, NO₃-N and NH₄-N were extracted using 0.0333 N CaCl₂ and analyzed colorimetrically. The plots were harvested by combine harvester and yield was standardized to t/ha based on 0.91 DM. The harvested areas are given in Table 2. Oil and N concentration in the seed were determined by NIRS.

Statistical Analysis

Because of the failures of some field trials the data basis differed with the years. Therefore, analysis of variance for autumn canopy N, spring canopy N and SMN in spring was done separately for each year using the GLM procedure of the SAS statistical package (SAS Institute 1989). Standard errors for sowing date based on the location x sowing date interactions, those for N fertilization in autumn based on the location x sowing date x N fertilization in autumn interaction effects. Nopt was calculated *ex post* underlying a quadratic yield response function (Colwell 1994, Henke et al. 2007). This function is specified by three parameters:

$$Y = a + bX + cX^2 + \varepsilon \quad (1)$$

where Y is the seed yield (t/ha), X the N application rate (kg N/ha), a the intercept, b the linear coefficient, c the quadratic coefficient and the ε error term. The parameter values were estimated using the REG procedure of the SAS statistical package (SAS Institute 1989). Although quadratic response functions estimate higher Nopt values compared to linear response plateau functions or other statistical models, this function was chosen because linear response plateau functions systematically underestimate Nopt and overestimate yields at Nopt (Cerrato & Blackmer 1990, Henke et al. 2007). Additionally, Henke et al. (2007) found that quadratic response functions are more stable with regard to parameter estimation uncertainty. Nopt was defined as the rate at which also

maximum economic returns were produced, calculated by marginal value product = marginal factor cost = nitrogen price (Henke et al. 2007). The assumed market price for OSR was 280 €/t and for N 0.6 €/kg N.

Regression analyses of Nopt on the measured parameters SMN at the start of spring growth, canopy N in autumn and canopy N in spring were done using the GLM procedure of the SAS statistical package (SAS Institute 1989). All locations and years were pooled for each regression analysis. The regression model was:

$$Y = a_{(\text{location})} + bX \quad (2)$$

where Y is Nopt, X canopy N in autumn, canopy N in spring or SMN in spring, a the intercept and b the linear coefficient. Since the interactions year x location, all three measured parameters (SMN at the beginning of spring growth, canopy N in autumn, canopy N in spring) x location, all three measured parameters x year and all three parameters x location x year were not significant in an initial covariance analysis ($p > 0.05$), these interactions were omitted in the regression model. The effect of the year was also not significant ($p > 0.05$) and was therefore not considered in the regression model. The location effect was significant ($p < 0.05$) and therefore the intercept a was estimated separately for each location.

4.4 Results

Canopy N in autumn, canopy N in spring and SMN in spring

Table 4 shows the effects of sowing date and N fertilization in autumn on canopy N in autumn and spring and SMN in spring. In 2005 mean canopy N in autumn was 114 kg N/ha in the early sowing date and 82 kg N/ha in the late one. The effect of sowing date on N uptake in autumn was not significant. Due to N fertilization in autumn canopy N rose significantly ($p < 0.05$) from 88 kg N/ha to 111 kg N/ha in 2005. Leaf losses over winter 2005/2006 lowered significantly ($p < 0.05$) canopy N in spring compared to autumn. It decreased from 114 kg N/ha to 71 kg N/ha in the early sowing date and from 82 kg N/ha to 57 kg N/ha in the late sowing date. Differences between the sowing dates were not significant. The mean decrease over winter was 28 kg N/ha in the treatments without N fertilization in autumn and 42 kg N/ha in the treatments with N fertilization in autumn. Canopy N in spring 2006 differed significantly between the autumn N fertilizer treatments. SMN in spring 2006 was similar in the early and late sowing dates and the N fertilization treatments in autumn.

Table 4: Autumn and spring canopy N (kg N/ha) and SMN in spring (kg/ha) at all locations in the years 2005/2006 and 2006/2007

	Autumn canopy N (kg N/ha)	Spring canopy N (kg N/ha)	SMN (kg /ha)
Year 2005/06			
Location*			
Borwede	99	69	51
Dornburg	106	45	43
Futterkamp	103	91	33
Gülzow	88	51	56
Hohenschulen (NK Fair) †	106	83	32
Hohenschulen (Trabant) †	114	82	32
Sowing date			
early	114	71	35
late	82	57	56
S.E. (Error D.F.) ‡	52.1 (3)	21.9 (3)	33.1 (3)
N fertilization in autumn (kg N/ha)			
0	88	60	44
40	111	69	47
S.E. (Error D.F.) ‡	15.2 (3)	7.0 (3)	5.5 (3)
Year 2006/07			
Location*			
Borwede	68	89	14
Dornburg	97	155	20
Futterkamp	75	90	20
Gülzow	42	64	20
Hohenschulen (NK Fair)	61	87	25
Hohenschulen (Trabant)	64	91	22
Moosburg	97	144	14
Roda	62	93	13
Sowing date			
early	80	108	19
late	61	95	18
S.E. (Error D.F.) ‡	47.6 (7)	34.3 (7)	7.8 (7)
N fertilization in autumn (kg N/ha)			
0	64	93	18
40	78	110	19
S.E. (Error D.F.) ‡	10.6 (7)	12.3 (7)	2.4 (7)

* no error estimate possible

† only Data of the early sowing date, trials were omitted for statistical analyses

‡ Standard errors for sowing dates are based on location x sowing date interactions, those for N fertilization in autumn based on location x sowing date x N fertilization in autumn interactions

In autumn 2006 canopy N was not affected by the sowing dates. In the unfertilized treatments mean autumn canopy N was 64 kg N/ha. N fertilization in autumn significantly increased canopy N in autumn by 14 kg N/ha. During winter 2006/2007 no leaf losses occurred because severe frosts did not occur. In consequence the OSR crop accumulated N until spring, and canopy N rose significantly ($p < 0.05$) from 80 kg N/ha to 108 kg N/ha in the early sowing date and from 61 kg N/ha to 95 kg N/ha in the late sowing date. Mean canopy N in spring 2007 differed significantly between 93 kg N/ha in the unfertilized treatment

and 110 kg N/ha in the fertilized treatment. Differences in SMN in spring were small and not significant at $p=0.05$.

Estimation of canopy N from fresh mass samples

Mean DM content in above ground biomass was 0.101 (SE 0.0112) in autumn 2006 and 0.120 (SE 0.0096) in spring 2007. In autumn 2005 mean N concentration in above ground DM of OSR was 0.042 (SE 0.0093) and in autumn 2006 0.047 (SE 0.0074). In spring 2006 mean N concentration was 0.039 (SE 0.0040) and in spring 2007 0.042 (SE 0.0043). N concentration averaged for all four sampling dates in 2005/06 and 2006/07 was 0.043. In these early growing stages no relationship between DM and N concentration could be observed. To extend the data base of N concentration measurements the results of two more field trials were considered. In the field trials of Sieling (2000) and Sieling & Kage (2007) at Hohenschulen similar mean N concentrations in above ground OSR DM in autumn and spring averaged with the present data to 0.45 were found. Due to different DM contents in autumn and spring separate factors for deriving kg N/ha from FM (kg/m^2) were calculated for both sampling dates, respectively. After converting in units of kg N/ha a conversion factor for estimating canopy N in autumn of approximately 45 was obtained ($\text{FM kg/m}^2 \times \text{N concentration} \times \text{DM content} \times 10000 = \text{kg N/ha}$). Due to the higher DM content in spring the conversion factor for estimating canopy N in spring rose to 54. The regressions of measured canopy N vs. estimated canopy N are given in Figure 1. RMSE in autumn 2006 was 9 kg N/ha and 11 kg N/ha in spring 2007.

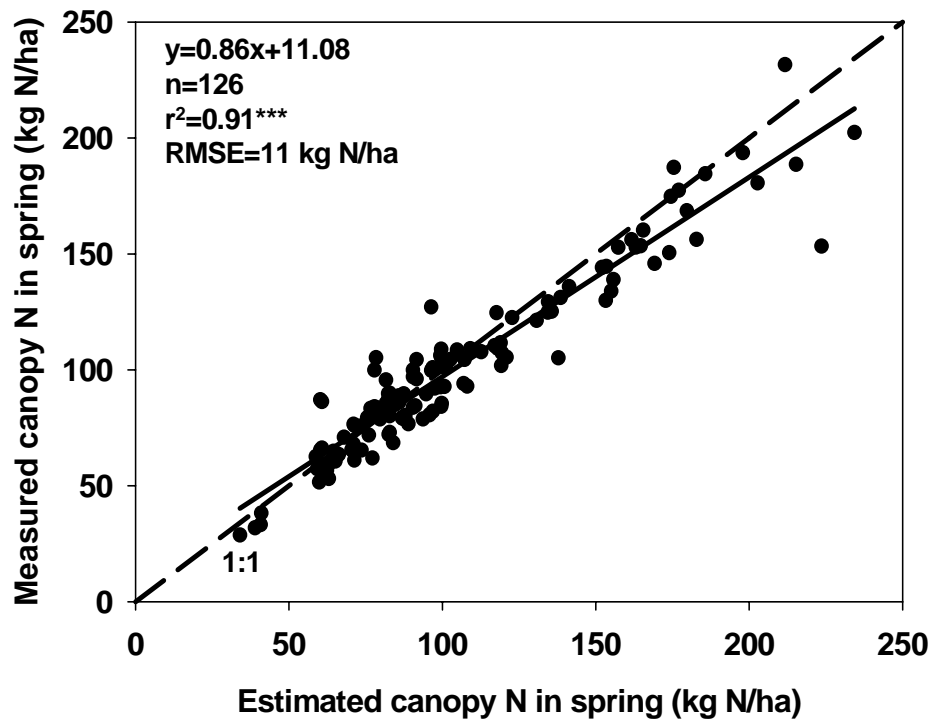
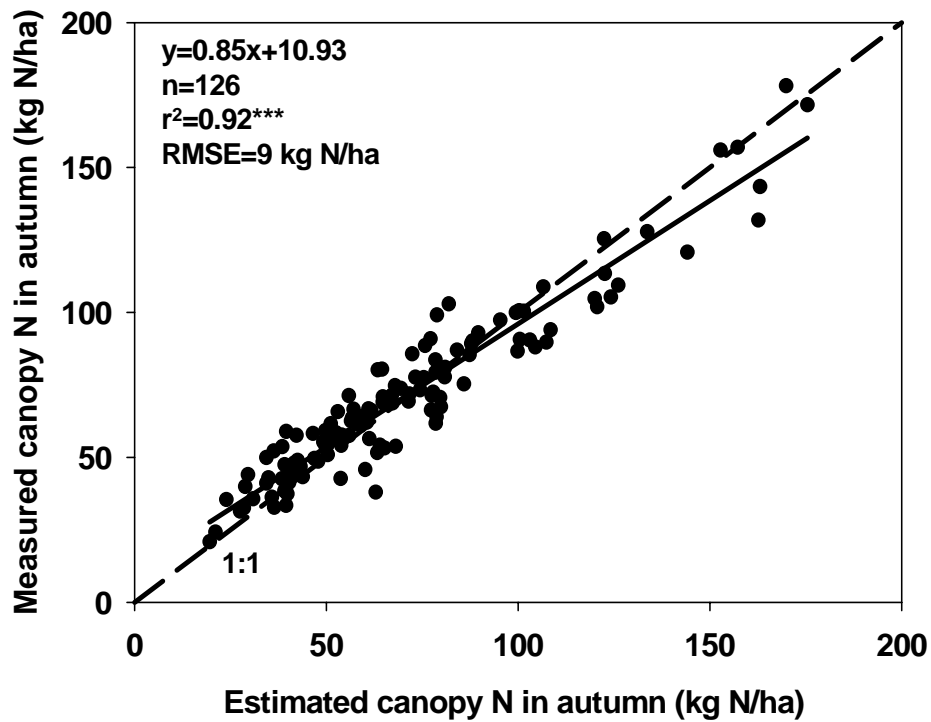


Fig. 1: Regressions of measured vs. estimated canopy N in autumn 2006 (a) and spring 2007 (b)

Regression of Nopt on canopy N in autumn and spring and SMN in spring

The level of estimated Nopt between the locations differed remarkably (Figure 2, Table 5). Nopt ranged from 120 kg N/ha in Roda in 2007 to 283 kg N/ha in Borwede in 2007. The regression line of Borwede lies clearly above of those of Roda. The difference between the regression lines of Borwede and Roda are 124

kg N/ha in the regression Nopt vs. canopy N in autumn. The regression lines of all other locations are in between these locations and differed much less.

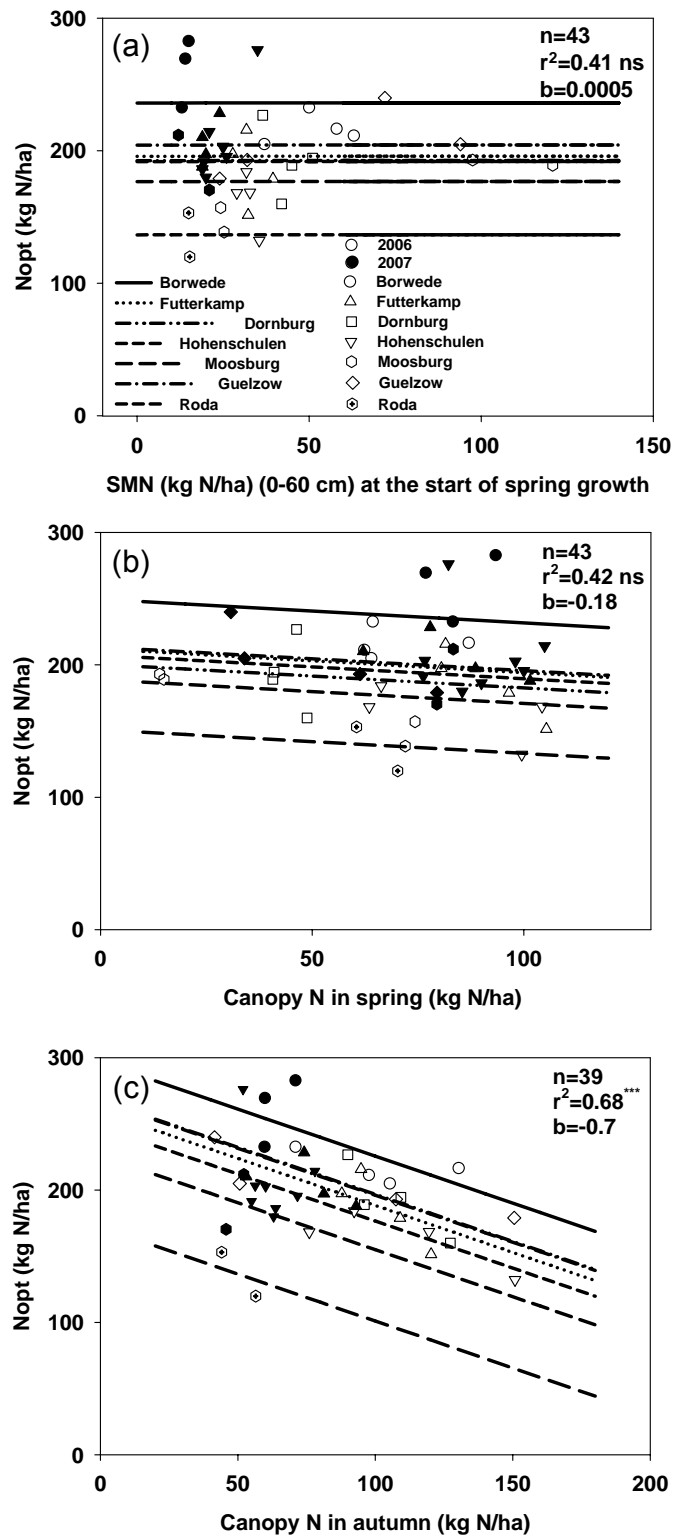


Fig. 2: Regression of Nopt vs. SMN at the start of spring growth (a), Nopt vs. canopy N in spring (b) and canopy N in autumn (c) for seven experimental locations in Germany in two years

Regression analyses showed no significant relationship between Nopt and SMN at the start of spring growth or Nopt and canopy N in spring (Figure 2a and b). However, Nopt and canopy N in autumn correlated significantly (Figure 2c). Coefficient of determination was 0.68 and the slope of the regression line -0.7 showed a negative correlation between canopy N in autumn and Nopt in spring (Figure 2c). In this study canopy N in autumn was the only measured parameter which revealed a significant relationship to Nopt in spring in the regression analysis. The parameters of the regression Nopt vs. canopy N in autumn are given in Table 5.

Table 5: Intercept (a) and linear coefficient (b) of the regression Nopt vs. canopy N in autumn (SE \pm), Model: $Y=a_{(location)}+bX$

Parameter	Location	a	b
Canopy N in autumn	Roda	172.51 (16.856)	
	Borwede	296.61 (34.934)	
	Futterkamp	259.30 (34.854)	
	Dornburg	267.72 (37.140)	-0.71 (0.136)
	Hohenschulen	247.54 (33.911)	
	Moosburg	225.94 (38.636)	
	Guelzow	267.00 (36.392)	

4.5 Discussion

The aim of the present study was to investigate the relationship between SMN at the start of spring growth, canopy N in autumn or canopy N in spring and Nopt in spring under different environmental conditions of Germany in order to derive site specific N fertilization rates. These can help to meet the N balance target and avoid excessive N fertilizer use. Additionally, a simple method for estimating canopy N from above ground FM was introduced.

Compared to cereals OSR has the potential to take up large amounts of N. More than 100 kg N/ha in autumn have been reported by several authors (Reau et al. 1994, Sieling 2000). The two years of the field trial were favourable for OSR autumn growth because the long term average temperature sum from September to the end of November was exceeded in 2005/06 by 160 °C and in 2006/07 by 280 °C. In consequence large amounts of N could be taken up in autumn.

Mineralization of soil organic N over winter is under the climatic conditions of Germany usually quite low but leaching losses occur regularly. In consequence the amounts of SMN are likely to decrease over winter and differences in SMN at beginning of spring growth between different fields are smaller compared to the end of autumn (Sieling et al. 1999). In the present study SMN at the beginning of spring growth averaged over all treatments and locations was 41 kg SMN/ha in 2005/2006 and even 19 kg SMN/ha in 2006/2007. Therefore it is doubtful that the very low amounts of SMN at the beginning of spring growth could be a suitable indicator for calculating N fertilization rates in OSR. In the present study the regression analysis showed no relationship between SMN at the start of spring growth and Nopt in spring (Fig. 2).

Estimating canopy N by weighing FM of a defined area with several replications is based on the assumption that aerial DM content and N concentrations vary only little at early growth stages. Reau et al. (1994) found a nearly constant N concentration of 0.045 N at early growth stages of OSR. Colnenne et al. (1998) described a critical N dilution curve for winter oilseed rape with a constant N concentration of 0.0448 N at early growing stages. N concentration decreased when DM (t/ha) exceeded 1 t DM/ha following the equation $N_{conc} = 4.48 W^{-0.25}$ where N_{conc} is the N concentration in the aerial DM (% N) and W the shoot DM (t/ha). In the present study the N concentration of 0.045 N in aerial DM confirmed the results of Reau et al. (1994) and Colnenne et al. (1998). However, the measured DM contents in autumn and spring of 0.101 and 0.120, respectively, and the derived conversion factors of 45 in autumn and 54 in spring need to be validated in further investigations.

Leaf losses and consequently N losses over winter highly influence canopy N at the beginning of spring growth (Dejoux et al. 2003). In the present study canopy N at the beginning of spring growth varied largely. In 2005/2006 N losses due to leaf losses occurred whereas in 2006/2007 N amounts in the canopy increased during winter because of continuous plant growth. This high variability could be a simple explanation for the missing relationship between canopy N in spring and Nopt. In contrast, the regression results showed that there was a significant negative relationship between canopy N in autumn and Nopt. The slope of this regression was -0.7, indicating that these N amounts should be partly considered when calculating N fertilization rates. Experimental results about the impact of canopy N in autumn or at the beginning of spring growth on Nopt are scarce. Gabrielle et al. (1998) and Dejoux et al. (1999a, 1999b) 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 OSR 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 with the synchronization of lost leaves decomposition and N uptake by the OSR crop in spring (Dejoux et al. 2000). 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 labelled leaves of 0.94 before harvest. However, Dejoux et al. (2000) 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 autumn decreased during the course the winter. Consequently N fertilization rates would be overestimated if canopy N in spring would be considered deriving N fertilization rates. For these reasons canopy N in autumn seems to be a more favourable indicator compared to 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 OSR canopies in autumn could be an indicator for the N mineralization potential of the location. In case of insignificant leaf losses over winter, a well developed OSR canopy showed a higher leaf area index (LAI) at the beginning of spring growth than a poor canopy, which, in consequence, allows for reduced N fertilization rates (Mendham et al. 1981).

In the present study it was shown that canopy N in autumn is a suitable indicator for optimizing N fertilization rates. For instance, in Futterkamp calculated Nopt was 150 kg N/ha when canopy N in autumn was 120 kg N/ha and 210 kg N/ha when canopy N in autumn was 53 kg N/ha. However, differences in Nopt at the different locations varied largely. Different yield levels could not account for the tremendous Nopt differences. For instance, in Borwede OSR yielded about 5 t/ha in 2006 and about 3.3 t/ha in 2007 averaged over all treatments, however the relationship between Nopt and N amounts in autumn seems to be identical (Fig. 2c). In both years yields in Futterkamp were higher but the Nopt level lower than in Borwede. Detailed investigation of the N mineralization potential in spring at the experimental sites and further yield analysis could contribute to characterize this site specific characteristics in N response of OSR. In general, indicators considering soil mineralization dynamics are unsatisfactorily introduced in

practical N fertilization recommendations and must be an important research topic in future. Nevertheless, although it is not possible to give absolute recommendations, the derived relationship between N_{opt} and canopy N in autumn seems to be a reliable new factor for a relative correction considering high amounts of canopy N in autumn of site specific usual fertilizer rates which correspond to long term average canopy development and corresponding canopy N in OSR. However, besides a reduction of N fertilization if canopy N is high the present study does not indicate that N fertilizer rates need to be increased if canopy N in autumn is very poor.

4.6 Conclusion

Amounts of SMN at the beginning of spring growth are usually low with only small variation and therefore the use of SMN as an indicator for N fertilization rates is not suitable in OSR. In the present study, no relationship between SMN at the beginning of spring growth and N_{opt} could be observed. Additionally, no significant correlation between canopy N in spring and N_{opt} were determined. However, in the present investigations canopy N in autumn significantly correlated with N_{opt} . Canopy N was satisfactorily estimated by simple field method which consisted of weighing FM (kg/m^2) and multiplying by conversion factors derived in our study, 45 or 54 for autumn and spring canopy N (kg N/ha), respectively. Together with the canopy N estimation method, canopy N in autumn should be considered as a new indicator for calculating optimized N fertilization rates in spring. In practice, canopy N in autumn can be used as a relative correction factor taking N amounts above a long term average into account. If canopy N in autumn is above the long term average, which we estimate to be about 50 kg N/ha , N fertilization rates should be reduced. Because the slope of the regression N_{opt} vs. canopy N in autumn was 0.7 this study results in the relative N fertilization recommendation that N fertilization amounts in spring should be reduced for 0.7 of the excess of 50 kg N/ha in autumn under German conditions.

Acknowledgement

The authors thank Dr. Gerhard Rave for providing the statistical analysis. Furthermore we thank Mrs. Jutta Gronow and Dr. Wolfgang Sauermann for collecting the yield data and supervising the field trials and Dr. Ralf-Rainer Schulz, Dr. Gerhard Baumgärtel, Dr. Erhard Albert, Mr. Torsten Graf and Mr. Andreas Baer for their collaboration conducting the field trials. This project was

kindly funded by the Union zur Förderung von Öl- und Proteinpflanzen e. V. (UFOP).

4.7 References

- 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. *Agriculture, Ecosystems and Environment* 111, 292-310.
- 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*). *Journal of Agricultural Science, Cambridge* 120, 219-224.
- CERRATO, M. E. & BLACKMER, A. M. (1990). Comparison of models for describing corn yield response to nitrogen fertilizer. *Agronomy Journal* 82, 138-143.
- COLLWELL, J. D. (1994). *Estimating Fertilizer Requirements. A Quantitative Approach*. Wallingford, UK: BAB International.
- COLNENNE, C., MEYNARD, J. M., REAU, R., JUSTES, E. & MERRIEN, A. (1998). Determination of a Critical Nitrogen Dilution Curve for Winter Oilseed Rape. *Annals of Botany* 81, 311-317.
- 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 and 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.
- GABRIELLE, B., DENOROY, P., GOSSE, G., JUSTES, E. & ANDERSON, M. N. (1998). A model of leaf area development and senescence for oilseed rape. *Field Crops Research* 57, 209-222.

- HENKE, J., BREUSTEDT, G., SIELING, K. & KAGE, H. (2007). Impact of uncertainty on the optimum nitrogen fertilization rate and agronomic, ecological and economic factors in an oilseed rape based crop rotation. *Journal of Agricultural Science, Cambridge* 145, 455-468.
- MAKOWSKI, D., MALTAS, A., MORISON, M. & REAU, R. (2005). Calculating N fertilizer doses for oil-seed rape using plant and soil data. *Agronomy for Sustainable Development* 25, 159-161.
- 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.). *Journal of Agricultural Science, Cambridge*, 96, 389-416.
- 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. *Agriculture, Ecosystems and Environment* 117, 80-108.
- REAU, R., WAGNER, D. & PALLEAU, J. P. (1994). End of winter diagnosis: Winter rapeseed and nitrogen fertilization. In: *Proceedings of the third congress of the European Society for Agronomy* (Eds M. Borin & M. Sattin), pp. 220-221. Padova: European Society for Agronomy.
- SAS INSTITUTE INC. (1989). *SAS/STAT® User's Guide, Version 6, 4th edn, Vol. 2*. Cary, NC: SAS Institute.
- 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. *Journal of Agricultural Science, Cambridge* 126, 63-74.
- 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. *Journal of Agricultural Science, Cambridge* 132, 127-137.
- SIELING, K., SCHRÖDER, H. & HANUS, H. (1998). Mineral and slurry nitrogen effects on yield, N uptake and apparent N-use efficiency of oilseed rape (*Brassica napus* L.). *Journal of Agricultural Science, Cambridge* 130, 165-172.

- SELING, K. (2000). Untersuchungen zu den Auswirkungen unterschiedlicher Produktionssysteme auf einige Parameter des N-Haushalts von Boden und Pflanze. Habilitationsschrift. Schriftenreihe des Instituts für Pflanzenbau und Pflanzenzüchtung der Agrarwissenschaftlichen Fakultät des CAU Kiel, Bd. 16.
- SELING, K. & KAGE, H. (2006). N balance as an indicator of N leaching in an oilseed rape - winter wheat - winter barley rotation. *Agriculture, Ecosystems and Environment* 115, 261-269.
- SELING, K. & KAGE, H. (2007). The potential of semi-dwarf oilseed rape genotypes to reduce the risk of N leaching. *Journal of Agricultural Science, Cambridge*, in press.
- STATISTISCHES BUNDESAMT (2006). Land- und Forstwirtschaft, Fischerei, Fachserie 3, Reihe 3.1.2, Statistisches Bundesamt, Wiesbaden.
- WEHRMANN, J. & SCHARPF, H.C. (1979). Der Mineralstickstoffgehalt des Bodens als Maßstab für den Stickstoffdüngerbedarf (Nmin-Methode). *Plant and Soil* 52, 109-126.

Kapitel 5

Abschließende Diskussion

5.1 Problemstellung und zusammenfassende Darstellung der Untersuchungsergebnisse

Der Anbauumfang von Winterraps (*Brassica napus* L.) hat in norddeutschen Ackerbaufruchtfolgen in den letzten Jahren auf bis zu ca. 20 % der ackerbaulich genutzten Fläche zugenommen (Statistisches Bundesamt 2007). Hinsichtlich der N-Effizienz ist Winterraps allerdings kritisch zu bewerten. N-Auswaschung nach Winterrapsanbau stellt neben quantitativ deutlich geringeren gasförmigen Verlusten in Form von Ammoniak (NH_3) oder Lachgas (N_2O) den wichtigsten N-Verlustpfad dar. Sieling (2000) fand Auswaschungsverluste nach Winterraps in Schleswig-Holstein (Hohenschulen) von 58 kg N/ha im Mittel über sechs Jahre. Jährliche gasförmige N-Verluste sind nach Untersuchungen in Niedersachsen und Dänemark dagegen mengenmäßig eher als gering zu veranschlagen (2-5 kg $\text{NH}_3\text{-N}$, 1,3 kg N/ha N_2O), werden aber wegen ihrer Bedeutung als Klimagase aktuell stark diskutiert (Kaiser et al. 1998, Kaiser & Ruser 2000, Schjoerring & Mattson 2001). In einem langjährigen Feldversuch am Standort Hohenschulen überschritt die N-Auswaschung nach Winterraps die mittlere N-Auswaschung nach Winterweizen um 10 kg N/ha und nach Wintergerste um 23 kg N/ha (Sieling 2000).

Der praktischen Landwirtschaft stehen heute allerdings verstärkte Anforderungen an die Umweltverträglichkeit in Form der novellierten Düngeverordnung (Anonymus 2006) als nationalen Umsetzung der EG-Nitratrichtlinie (Anonymus 1991) oder aber auch der EU-Wasserrahmenrichtlinie (Anonymus 1997) gegenüber. Die novellierte Düngeverordnung sieht dabei im Rahmen eines Nährstoffvergleichs eine Begrenzung des N-Bilanzsaldos von 60 kg N/ha im dreijährigen Mittel beginnend mit dem Düngjahr 2009 vor. In den für Norddeutschland typischen Fruchtfolgen Winterraps-Winterweizen-Wintergerste bzw. Winterraps-Winterweizen-Winterweizen leistet aber gerade der Winterraps einen erheblichen Beitrag zum mittleren N-Bilanzsaldo, sodass der Grenzwert von 60 kg N/ha auch in Ackerbaufruchtfolgen nicht immer eingehalten werden kann (Sieling & Kage 2006, Henke et al. 2007).

Übergeordnetes Ziel dieser Arbeit war es, die N-Dynamik im System Boden-Pflanze nach Winterrapsanbau auf der Ebene des Produktionssystems Rapsfruchtfolge zu analysieren, um daraus Strategien zur Verbesserung der N-Effizienz zu erarbeiten. Als mögliche Verbesserungsstrategien zur Steigerung der N-Effizienz wurden die Ansätze Gestaltung der Fruchtfolge, Anbau von

Zwischenfrüchten, Bodenbearbeitungsintensität und optimierte Ermittlung des N-Düngebedarfs in den Untersuchungen berücksichtigt.

In **Kapitel 2** wurde die N-Dynamik nach Winterrapsanbau durch die Kombination der methodischen Ansätze Feldversuch und Simulationsmodellierung untersucht. Die N-Dynamik nach Winterraps ließ sich mit dem Modell sehr gut abbilden. Damit liegt nun ein für den Standort Hohenschulen valides Bewertungstool vor, mit dem der Einfluss produktionstechnischer Maßnahmen auf die N-Dynamik nach Winterraps analysiert werden kann. Der Anbau einer Zwischenfrucht, wie zum Beispiel Phacelia oder Ausfallraps, an Stelle der typischen Folgefrucht Winterweizen reduzierte die N-Auswaschung deutlich. Phacelia konnte nach der Rapsernte im Herbst noch bis ca. 60 kg N/ha aufnehmen und somit N über Winter konservieren. Ausfallraps nahm zwar geringere N-Mengen auf, durch Verzicht auf die Bodenbearbeitung im Herbst wurde in dieser Variante aber die Mineralisation aus bodenbürtigem N, der maßgeblich zur N-Auswaschung beiträgt, deutlich vermindert. Eine starke Verringerung der Bodenbearbeitungsintensität mit Verzicht auf Pflugeinsatz und reduzierter, flacher Bodenbearbeitung in Kombination mit einem kurzzeitigen Aufwuchs von Ausfallraps trug ebenfalls zu deutlich niedrigeren N-Frachten bei. Schließlich konnte anhand der Messdaten aus dem Feldversuch, aber auch durch eine Szenarienrechnung mit dem Simulationsmodell gezeigt werden, dass mit steigender und vor allem deutlich überhöhter N-Düngung die N-Auswaschung nach Winterraps erheblich anstieg. Deshalb wurde in den weiteren Kapiteln dieser Arbeit ein besonderes Augenmerk auf die N-Düngung gelegt.

Die Entscheidung über die Düngungshöhe ist immer eine Entscheidung unter Unsicherheit, da viele Faktoren, welche die Düngungshöhe beeinflussen können, nicht vorhersehbar sind. Vor allem im Winterraps findet die N-Düngung im zeitigen Frühjahr statt, während wichtige Prozesse der Ertragsbildung erst zu späteren Zeitpunkten einsetzen. Der Einfluss der Unsicherheit auf die optimale Düngungshöhe (Nopt), die N-Bilanz und die N-Kosten freien Leistungen in einer Winterraps-Winterweizen-Wintergerste Fruchtfolge wurde daher in **Kapitel 3** empirisch untersucht. Dabei wurden die Unsicherheiten Wahl des statistischen Modells zur Berechnung der optimalen N-Düngermenge, Jahresvariation in der Ertragsreaktion auf N und Unsicherheit in der Schätzung der Funktionsparameter des verwendeten statistischen Modells betrachtet. Die Wahl des statistischen Modells hatte einen erheblichen Einfluss auf Nopt und damit auch auf die N-Bilanz. Unter Berücksichtigung der weiteren Unsicherheiten erhöhte sich Nopt

tendenziell, wobei dieser Effekt in Abhängigkeit des Modells unterschiedlich stark ausgeprägt war. Eine quadratische Funktion war unanfälliger gegenüber den untersuchten Unsicherheiten als eine Linear-Plateau-Funktion. Winterraps hatte in der untersuchten Fruchtfolge die höchsten Nopt und steuerte den größten Anteil zum mittleren N-Bilanzsaldo der Fruchtfolge bei. Eine Begrenzung des N-Bilanzsaldos auf 60 kg N/ha war anhand der Ergebnisse unter Versuchsbedingungen und der daraus abgeleiteten Berechnungen einzuhalten, kann aber in der Praxis aufgrund weiterer, hier nicht berücksichtigten Unsicherheiten, übertroffen werden.

In Kapitel 3 wurde der erhebliche Beitrag des Winterrapses zum N-Bilanzsaldo einer Fruchtfolge deutlich herausgestellt. Es konnte weiterhin eindeutig gezeigt werden, dass die N-Düngung starken Unsicherheiten unterliegt. Deshalb kommt einer exakten, standort- und bestandesangepassten Bemessung der N-Düngermenge und der Realisierung der Ertragspotenziale gerade im Winterrapsanbau eine enorme Bedeutung zu. Da Winterraps bereits im Herbst große N-Mengen aufnehmen kann und die Nmin-Mengen im Frühjahr regelmäßig sehr gering sind, sollten auch die N-Mengen im Bestand bei der Düngebedarfsermittlung berücksichtigt werden. In **Kapitel 4** wurden daher Einflussfaktoren auf die optimale Düngermenge von Winterraps wie Nmin im Frühjahr, N-Menge im Bestand im Herbst und N-Menge im Bestand im Frühjahr in einem mehrortigen Feldversuch untersucht. Es konnte gezeigt werden, dass es keinen Zusammenhang zwischen der optimalen N-Düngermenge und Nmin im Frühjahr gab, obwohl auch im Winterraps die Düngermenge standardmäßig mit der Nmin-Methode ermittelt wird. N-Mengen im Bestand im Frühjahr hatten keinen Einfluss auf die optimale N-Düngermenge. Einen signifikanten negativen Einfluss auf die optimale N-Düngermenge hatten allerdings die N-Mengen im Bestand im Herbst. Die N-Menge im Bestand im Herbst ist also ein Indikator, der bei der N-Düngebedarfsermittlung in Zukunft stärker berücksichtigt werden sollte, um die N-Düngung der Bestandesentwicklung anzupassen.

5.2 Bewertung von Strategien zur Verbesserung der N-Effizienz im Winterrapsanbau

Fruchtfolge

In den letzten Jahrzehnten haben sich Fruchtfolgen unter norddeutschen Anbaubedingungen zunehmend verengt. Winterraps steht häufig in der dreifeldrigen Fruchtfolge Winterraps-Winterweizen-Wintergerste. Die einzelnen Kulturen können die N-Effizienz der Fruchtfolge maßgeblich beeinflussen. Bei der

Stellung in der Fruchtfolge bietet der Winterraps im Hinblick auf N-Auswaschungsverluste Vor- und Nachteile. Winterraps ist in der Lage im Herbst im Vergleich zu Getreide deutlich höhere N-Mengen aufzunehmen (Sieling et al. 1998, Dejoux et al. 2003). Als Nachfrucht nach einer Getreidevorfrucht leistet der Winterraps daher einen deutlichen Beitrag zur Verringerung der N-Auswaschung in der Fruchtfolge (Sieling 2000, Rathke et al. 2006). Sieling et al. (1999) stellten unter Winterraps eine um 15-20 kg N/ha geringere N-Auswaschung als unter Getreide fest. Auf der anderen Seite sind verstärkte N-Auswaschungsverluste nach Raps häufig festgestellt worden (Sieling 2000, Rathke et al. 2006). Die typische Folgefrucht nach Winterraps Winterweizen nimmt im Herbst im Vergleich zum Winterraps wesentlich geringere N-Mengen auf. In den vorliegenden Ergebnissen aus Kapitel 2 wurden N-Aufnahmen im Herbst bis maximal 30 kg N/ha gemessen. Durch den frühen Erntezeitpunkt des Raps und die damit verbundene lange Zeitspanne für Mineralisation von bodenbürtigen N kommt es in Kombination mit einer geringen N-Aufnahme des Winterweizens im Herbst regelmäßig zu einer erhöhten N-Auswaschung nach Winterrapsanbau. Durch eine Änderung der Fruchtfolge mit Einführung einer Zwischenfrucht und einer darauf folgenden Sommerung kann pflanzenbaulich auf dieses Problem reagiert werden. Zwischenfrüchte haben, wenn sie direkt nach der Rapsernte etabliert werden, ein deutlich höheres N-Aufnahmepotenzial, so dass N im Bestand über Winter konserviert werden kann und Auswaschungsverluste verringert werden können (Lickfett 1993, Justes et al. 1999, Beaudoin et al. 2005). Gleichzeitig zeigte sich in den Ergebnissen aus Kapitel 2, dass der höhere Wasserverbrauch eines Zwischenfruchtbestandes den Wassergehalt des Bodens im Herbst im Vergleich zum Winterweizen reduzierte und damit die N-Auswaschung verzögert einsetzte. Eine solche Änderung in der Fruchtfolge kann sich aber aus ökonomischer Sicht negativ auswirken, da zum einen die Aussaat der Zwischenfrucht Kosten verursacht, gleichzeitig Sommerungen wie Hafer oder Mais gegenüber dem Winterweizen in Ackerbaufruchtfolgen nicht immer konkurrenzfähig sind. Zwischenfruchtanbau bietet sich aber in Gebieten mit speziellem Interesse am Grundwasserschutz an und wird hier häufig durch entsprechende finanzielle Entschädigungen ausgeglichen. Als günstige Alternative zum Zwischenfruchtanbau bietet es sich an, den Aufwuchs des Ausfallrapses über Winter als Zwischenfrucht zu benutzen und somit größeren N-Mengen ins Frühjahr zu transferieren (Lickfett 1993). Der Anbau von Ausfallraps ist aber in den engen Rapsfruchtfolgen Norddeutschlands aus phytosanitären Gründen bedenklich.

Die Bewertung von verschiedenen Fruchtfolgevarianten anhand von Feldversuchsdaten von einem Standort ist eingeschränkt. Die Modellierung bietet die Möglichkeit durch Szenarienrechnungen, welche verschiedene Standorte und Witterungsverläufe beinhalten, die Wirksamkeit der untersuchten Maßnahmen umfassender zu beurteilen. Um die Standorteinflüsse auf die N-Dynamik und letztendlich die N-Auswaschung nach Winterraps weitreichender zu untersuchen, wurden solche Szenarienrechnungen mit dem Simulationsmodell aus Kapitel 2 durchgeführt. Dazu wurden neunjährige Witterungsdaten der drei norddeutschen Standorte Gülzow (Ls, 542 mm langjähriger mittlerer Jahresniederschlag), Hohenschulen (Ls, 750 mm langjähriger mittlerer Jahresniederschlag) und Hannover (S, 661 mm langjähriger mittlerer Jahresniederschlag) herangezogen und die Standorteffekte für die Nachfrüchte Weizen gepflügt, Weizen pfluglos und Zwischenfrucht Phacelia berechnet. Für die Szenarienrechnungen wurde eine N-Düngung von 200 kg N/ha zum Winterraps zu Grunde gelegt.

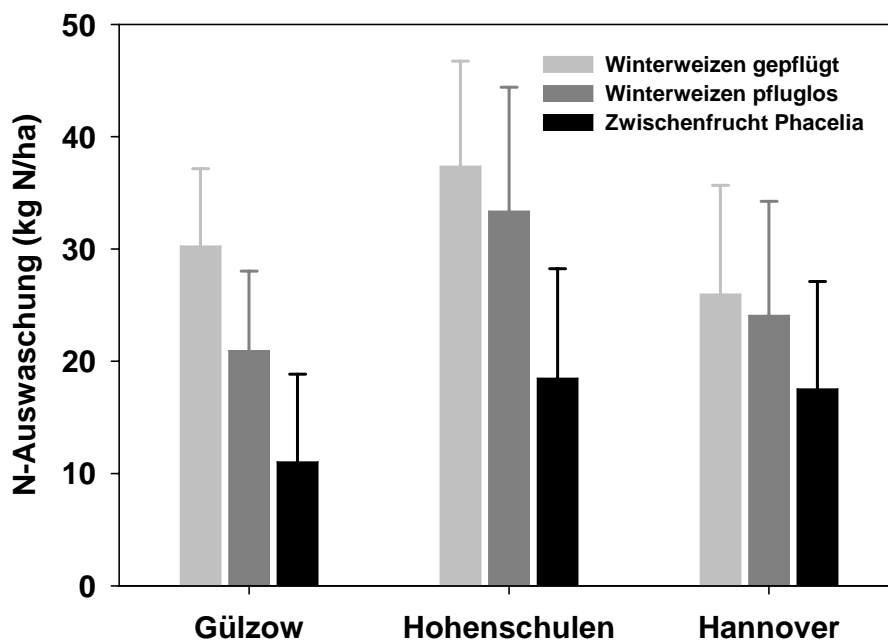


Abbildung 1: Szenarienanalyse: Mittlere N-Auswaschung über 9 Jahre an drei norddeutschen Standorten (Düngung je 200 kg N/ha)

Die in Abbildung 1 dargestellten N-Frachten zeigen deutliche Unterschiede zwischen den einzelnen Standorten, allerdings ist die Abstufung der drei Bewirtschaftungsstrategien innerhalb eines Standortes gleich. An den Standorten Gülzow und Hannover waren die N-Frachten in allen drei untersuchten Varianten deutlich geringer als am Standort Hohenschulen.

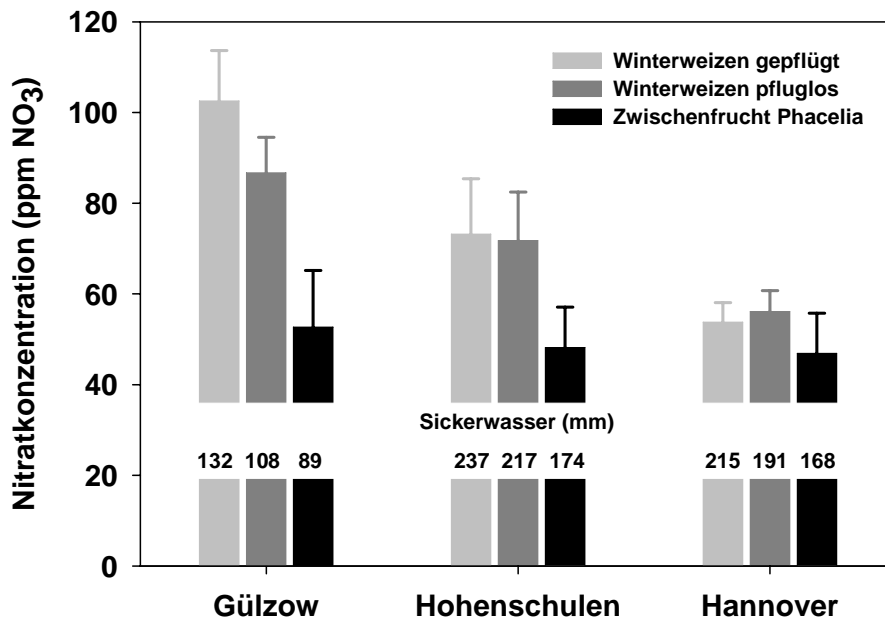


Abbildung 2: Szenarienanalyse: Mittlere NO₃-Konzentration im Sickerwasser über 9 Jahre an drei norddeutschen Standorten (Düngung je 200 kg N/ha)

Abbildung 2 zeigt die mittleren NO₃-Konzentrationen und die mittleren Sickerwassermengen. Es fällt auf, dass am Standort Gülzow die Sickerwassermengen deutlich geringer waren als in Hohenschulen oder Hannover. Zu erklären ist dies mit den deutlich geringen mittleren Jahresniederschlägen, die ca. 200 mm geringer als in Hohenschulen und ca. 100 mm geringer als in Hannover waren. Durch diese geringe Sickerwassermenge erhöhten sich die NO₃-Konzentrationen im Sickerwasser erheblich und überschritten bei allen drei Varianten den EU-Grenzwert von 50 ppm NO₃. In Hohenschulen waren die Sickerwassermengen entsprechend den höheren Jahresniederschlägen größer und die NO₃-Konzentrationen folglich kleiner. Allerdings wurde aber auch in Hohenschulen der EU-Grenzwert in allen drei Varianten überschritten. Am Standort Hannover waren die NO₃-Konzentrationen auch bei höheren Sickerwassermengen gering. Durch niedrigere Herbst- und Wintertemperaturen und eine damit verminderte N-Mineralisation am Standort lassen sich die geringeren N-Frachten im Vergleich zu Hohenschulen erklären. Alle geprüften Varianten hatten auf den drei Standorten ähnliche Effekte, es zeigten sich aber deutliche Unterschiede in der Abstufung der Varianten. So würde der Zwischenfruchtanbau am Standort Hannover zwar die N-Auswaschung reduzieren, aber bei weitem nicht so effektiv wie auf den anderen Standorten. Standorteigenschaften sollten also bei der Wahl des

Produktionsverfahrens stets berücksichtigt werden, um ein hohes Maß an Effektivität zu gewährleisten.

Positiv nach Winterraps ist allerdings die Vorfruchtwirkung auf den Winterweizen zu erwähnen. Mehrerträge des Weizens nach Rapsvorfrucht im Vergleich zur Weizenvorfrucht sind in zahlreichen Publikationen dokumentiert (Christen 2001, Sieling et al. 2005, Rathke et al. 2006). Weiterhin zeigten Sieling et al. (2005), dass der maximale Ertrag eines Weizens nach Raps bei einer Düngermenge von 210 kg N/ha erzielt werden konnte, ein Weizen nach zweimaliger Weizenvorfrucht aber 270 kg N/ha für seinen maximalen Ertrag, der 17 dt/ha niedriger war als nach Rapsvorfrucht, benötigte. Da im Weizen nach Raps bei einer geringeren N-Düngungshöhe höhere Erträge als nach Weizenvorfrucht zu erwarten sind, kann die Vorfruchtwirkung des Winterraps einen positiven Beitrag zur N-Effizienz des folgenden Winterweizens beitragen. Jedoch wird in den meisten Fällen Qualitätsweizen nach Winterraps angebaut. Berücksichtigt man den Proteingehalt bei der Berechnung der optimalen N-Düngermenge, so konnte in Kapitel 3 gezeigt werden, dass sich diese deutlich erhöht. Weiterhin steht anstelle der Wintergerste häufig ein zweiter Winterweizen in der Fruchtfolge. Diese Änderung in der Fruchtfolge hat deutliche Auswirkungen auf das N-Bilanzsaldo der gesamten Fruchtfolge. In Tabelle 1 sind die Effekte einer Berücksichtigung der Qualität bei der N-Düngung im Weizen nach Raps und des Anbaus eines zweiten Weizens dargestellt (Sieling et al. 2005, Henke et al. 2007).

Tabelle 1: Einfluss der Berücksichtigung der Qualität des Winterweizens und des Anbaus eines zweiten Weizens auf Nopt und das N-Bilanzsaldo im Vergleich zur Fruchtfolge Winterraps-Winterweizen-Wintergerste ohne Qualitätsberücksichtigung (*ex ante* Nopt)

	Nopt (kg N/ha)	N-Bilanzsaldo (kg N/ha)
Winterraps	222	93
Winterweizen	243	54
(Qualität)		
Winterweizen	200	43
Mittelwert		63
Winterraps	222	93
Winterweizen	184	15
Wintergerste	145	26
Mittelwert		45

Nach den Ergebnissen in Tabelle 1 führt die Berücksichtigung der Qualität des Weizens zu einer Erhöhung der N-Düngermenge um ca. 40 kg N/ha, wobei sich die N-Bilanz für den Winterweizen auch um ca. 40 kg N/ha erhöht. Einen ebenso deutlichen Effekt hat die Einführung eines zweiten Winterweizens anstelle der Wintergerste. Die Düngermenge erhöht sich um 55 kg N/ha und das N-Bilanzsaldo um 17 kg N/ha. Im Mittel über die Fruchtfolge würde sich das N-Bilanzsaldo um 18 kg N/ha erhöhen und damit den Grenzwert von 60 kg N/ha überschreiten. Obwohl der Beitrag des Winterrapses an der mittleren N-Bilanz der Fruchtfolge mit Abstand am höchsten ist, zeigt sich bei dieser Berechnung, dass auch der Weizen deutlich erhöhte N-Bilanzsalden aufweisen kann. Hier gilt es besonders die N-Düngung exakt an Standort und Bestand anzupassen und hohe Erträge durch weitere produktionstechnische Maßnahmen abzusichern, um N-Bilanzüberschüsse zu verringern.

Andere Blattfrüchte wie Körnerleguminosen oder Zuckerrüben stellen unter heutigen Bedingungen keine Alternative zum Winterraps dar. Der Anbau von Zuckerrüben ist durch die Agrarmarktpolitik begrenzt und deshalb auf vielen Standorten nicht möglich. Zwar wurde bei Körnerleguminosen ein ähnlich guter Vorfruchteffekt wie beim Winterraps auf den folgenden Winterweizen vielfach beobachtet (Widdowsen et al. 1985, McEwen et al. 1989, Christen 1997, Sieling 2007), eine Nitratproblematik nach Körnerleguminosenanbau ist aber ebenso wie beim Winterraps vorhanden (Kage 1992, Beaudoin et al. 2005).

Die Gestaltung einer Fruchtfolge kann maßgeblich die N-Effizienz beeinflussen. Winterraps fällt durch seinen besonders hohen Beitrag zum mittleren N-Bilanzsaldo der Fruchtfolge auf. Da es in norddeutschen Fruchtfolgen keine Alternativen zum Winterrapsanbau gibt, gilt es die Vorfruchtwirkung des Winterraps optimal auszunutzen, gleichzeitig aber die Produktionstechnik zum Winterraps und vor allem nach der Rapsernte dahingehend zu verbessern, dass N-Bilanzüberschüsse reduziert und N-Auswaschungsverluste minimiert werden.

Bodenbearbeitung und Ernterückstände

Um Verbesserungsstrategien für die N-Effizienz im Winterrapsanbau zu erarbeiten, ist eine genaue Analyse der N-Dynamik nach der Rapsernte, wo regelmäßig die größten N-Verluste in Form von Auswaschung auftreten, sehr wichtig. Dies wurde in Kapitel 2 unter Zuhilfenahme des Simulationsmodells durchgeführt. Mineralisationsprozesse führen nach der Rapsernte zu einem deutlichen Anstieg der N_{min}-Werte. Die Mineralisation im Herbst lässt sich durch verschiedene produktionstechnische Maßnahmen beeinflussen. Die Untersuchung verschiedener Verfahren nach der Rapsernte (Kapitel 2) führte zu dem Ergebnis, dass sich durch reduzierte Bodenbearbeitungsintensität die N-Auswaschung im Vergleich zum Pflugeinsatz deutlich vermindert. Verstärkt wurde dieser Effekt der Bodenbearbeitung durch den kurzzeitigen Aufwuchs von Ausfallraps im Herbst. Der Einfluss von Minimalbodenbearbeitung auf die N-Auswaschung wurde auch in einem Feldversuch in England anhand von Dränwasseruntersuchungen geprüft (Brimstone Farm Experiment, Goss et al. 1993). Durch sehr flache Bodenbearbeitung bzw. Direktsaat konnte die N-Auswaschung nach Winterrapsanbau im Vergleich zum Pflug hier um ca. 10 % vermindert werden. Ursächlich hierfür ist einerseits eine begrenzte Durchlüftung des Bodens und dadurch eine reduzierte Mineralisation von bodenbürtigem, organischem N (Lickfett 1993, Catt et al. 2000), auf der anderen Seite wird durch eine intensivere Bodenbearbeitung verstärkt bodenbürtiger N aus einem sogenannten geschützten Pool freigesetzt (Hütsch & Mengel 1992, Kristensen et al. 2000). Neben der Intensität der Bodenbearbeitung wäre der Zeitpunkt einer Bearbeitung eine weitere Möglichkeit die N_{min}-Dynamik nach Raps im Herbst zu beeinflussen. Lickfett (1993) stellte fest, dass durch einen späten Aussattermin für den nachfolgenden Winterweizen (November/Dezember) die Mineralisation von bodenbürtigem N im Herbst auf einem Standort in Niedersachsen deutlich vermindert werden konnte. Allerdings verschlechtern sich die Startbedingungen des Winterweizens mit einem sehr späten Saatzeitpunkt.

Gekoppelt an die Bodenbearbeitung ist natürlich auch die Einarbeitung der Ernterückstände des Winterrapses, die einen erheblichen Einfluss auf die N-Dynamik haben. In den vorliegenden Untersuchungen in Kapitel 2 variierten die N-Mengen in den Ernterückständen zwischen 68 und 112 kg N/ha bei gleicher, ortsüblicher N-Düngung zum Raps (200 kg N/ha) wobei die C/N-Verhältnisse der Ernterückstände zwischen 50 und 60 lagen. Damit liegen auch die C/N-Verhältnisse von Winterraps-Ernterückständen über einem kritischen C/N-Verhältnis, welches in der Literatur mit 21-30 angegeben wird und oberhalb dessen zunächst kein N mehr mineralisiert wird (Sieling 2000). Zahlreiche Literaturquellen berichten über N-Immobilisierung im Boden im Herbst nach Einarbeitung von Raps-Ernterückständen (Lickfett 1993, Justes et al. 1999, Mary et al. 1999, Trinsoutrot et al. 2000a, Trinsoutrot et al. 2000b, Nicolardot et al. 2001). Trotz einer N-Immobilisierung durch die Einarbeitung der Ernterückstände nach Winterrapsanbau, kommt es im Herbst zu einem Anstieg der N_{min}-Werte. Da Winterrapsenernterückstände ein wesentlich geringeres C/N-Verhältnis als Getreidestroh haben, ist das kurzfristige N-Immobilisierungspotenzial auch dementsprechend geringer und höhere N_{min}-Werte als nach Getreide sind die Folge.

Durch eine gezielte Bodenbearbeitung lässt sich die N-Dynamik nach Winterraps beeinflussen und N-Auswaschungsverluste vermindern. Dabei ist es wichtig die Tiefe der Bodenbearbeitung auf ein praktikables Minimum zu reduzieren, um die Mineralisation aus bodenbürtigen N so gering wie möglich zu halten, gleichzeitig aber die Ernterückstände einzuarbeiten. Eine pfluglose Bearbeitung, die in der gleichen Bearbeitungstiefe wie das Pflügen durchgeführt wird liefert keinen positiven Effekt zur Reduzierung von N_{min} im Herbst (Kristensen et al. 2003).

Genotypen

Neben den untersuchten Strategien zur Verbesserung der N-Effizienz im Winterrapsanbau könnte auf der Ebene der Kulturpflanze Winterraps eine verbesserte N-Effizienz der Genotypen einen Beitrag zu Verminderung der Nitratproblematik leisten. Aus züchterischer Sicht wäre ein erster Schritt eine Erhöhung des Harvest-Index (Möllers et al. 2000, Friedt et al. 2003). Im Feldversuch aus Kapitel 2 hatte der Winterraps einen Harvest-Index im Bereich 0,3-0,4. Möllers et al. (2000) und Friedt et al. (2003) stellten eine gewisse Variation im Harvest-Index in Sortimenten üblicher Sorten fest. Weitere Literaturquellen über die Züchtung auf N-effizientere Winterraps-Genotypen sind aber rar. Neuere Züchtungsbestrebungen gehen dahin, den Harvest-Index und

N-Harvest-Index durch Einkreuzung von Verzweigungsgenen zu erhöhen. Diese Züchtungsbestrebungen resultierten in sogenannten Halbzwerghybriden, die im Vergleich zu konventionellen Sorten eine verminderte Wuchshöhe aufweisen. Sieling & Kage (2007a) untersuchten ein Sortiment von aktuellen Hybrid-, Liniensorten und zwei Halbzwerghybriden im Hinblick auf Unterschiede im Harvest-Index und N-Harvest-Index. Die Hypothese, dass diese neuen Genotypen durch eine verminderte Wuchshöhe bei gleichem Ertragsniveau weniger oberirdische Biomasse bilden und sich damit der Harvest-Index und N-Harvest-Index erhöhen konnte nicht bestätigt werden (Sieling & Kage 2007a). In diesem Zusammenhang erlaubt eine Szenarienanalyse anhand des Simulationsmodells aus Kapitel 2, den Einfluss eines veränderten Harvest-Index auf die N-Auswaschung prozessorientiert zu untersuchen und zu diskutieren. Dabei wurden die stark vereinfachenden Annahmen getroffen, dass der Ertrag über alle Harvest-Indizes gleich ist. Die N-Düngung zum Raps betrug 200 kg N/ha, die Nachfrucht war Winterweizen und als Grundbodenbearbeitung wurde gepflügt. Das C/N-Verhältnis der Ernterückstände wurde mit 63 konstant gesetzt.

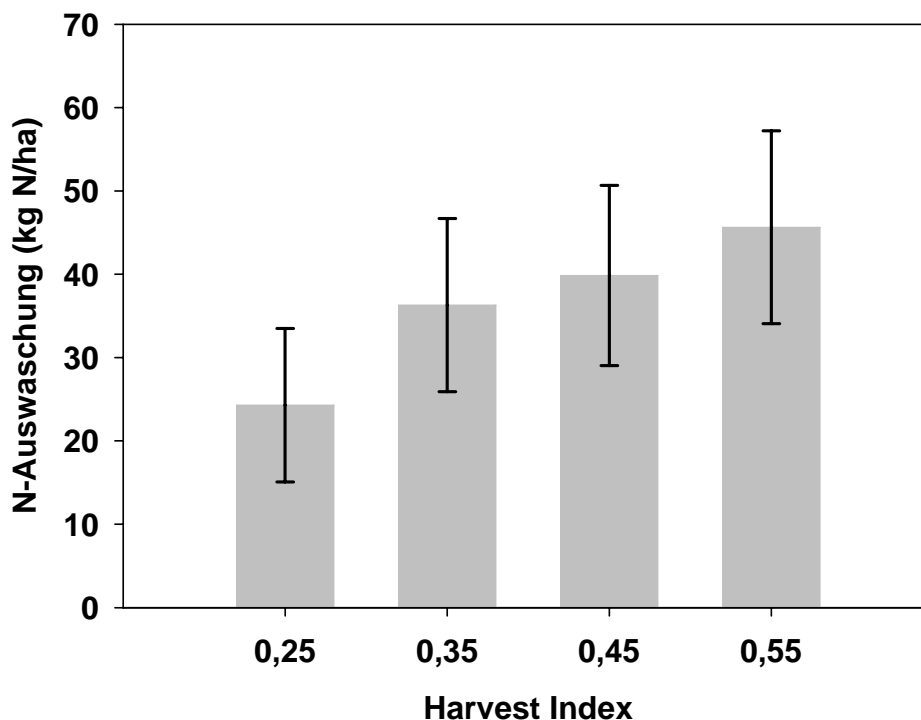


Abbildung 3: Einfluss des Harvest-Index auf die N-Auswaschung nach Winterraps

In diesen Szenarienrechnungen erhöhte sich die N-Auswaschung mit steigendem Harvest-Index. Ursächlich hierfür sind die geringeren Mengen an Ernterückständen, die mit steigendem Harvest-Index nach der Ernte in den Boden eingearbeitet werden und hier aufgrund des hohen C/N-Verhältnisses zu

einer N-Immobilisierung im Herbst führen. Bei einem erhöhten Harvest-Index und einer gleichen N-Menge in den Samen würde allerdings relativ zur Biomasse mehr N aus den vegetativen Pflanzenteilen umverlagert werden müssen, was dann zu einem höheren C/N-Verhältnis in den Ernterückständen und damit zu einem erhöhten N-Immobilisierungspotenzial nach Einarbeitung in den Boden führen würde. Dieser Aspekt wurde bei den stark vereinfachenden Annahmen für diese Szenarienanalyse nicht berücksichtigt. Der Verbesserung der N-Retranslokation innerhalb der Rapspflanze durch eine Synchronisation von Blattseneszenz und N-Einlagerung in die Samen und damit einer Erhöhung des N-Harvest-Index und der N-Verwertungseffizienz in Verbindung mit höheren C/N-Verhältnisse in den Ernterückständen und eventuell einem verringertem Düngbedarf wird eine daher Schlüsselrolle in der Verbesserung der N-Effizienz von Rapsorten zugeschrieben (Schjoerring et al. 1995, Malagoli et al. 2005, Rathke et al. 2006, Allirand et al. 2007).

Bisher sind Züchtungsbestrebungen auf eine konsequente Verbesserung der N-Effizienz von Winterraps-Genotypen eher gering. Erste neuere Ansätze wie die Züchtung von Halbzwerghybriden können bis jetzt aber noch keinen Beitrag zu einer verbesserten N-Effizienz leisten. In den Untersuchungen von Möllers et al. (2000) und Friedt et al. (2003) stellten sich Hybridsorten als N-effizienter heraus, da sie bei gleicher N-Düngung ein höheres Ertragspotential ausschöpfen konnten. Obwohl der Züchtungsfortschritt auf N-Effizienz heute noch eher gering ist, kann die Sortenwahl aus bestehenden Sortimenten ein Baustein in der Verbesserung der N-Effizienz, wenn ein hohes Ertragspotential ausgeschöpft werden kann. Für weitere Züchtungsanstrengungen schlägt Habekotté (1997) zur Realisierung von sehr hohen Erträgen und einem damit verbundenen erhöhten Harvest-Index und N-Harvest-Index einen Ideotyp vor, der einen frühen Blühbeginn und eine späte Abreife aufweist, um die Sink-Source-Kapazität in der Samenfüllungsphase zu optimieren, gleichzeitig aber auch eine für die Strahlungsaufnahme des Bestandes optimierte Stellung der Schoten und einen geringeren Blattflächenindex haben würde. Bei der Charakterisierung von Raps-Ideotypen leistet die Simulationsmodellierung durch Abbildung des Pflanzenwachstums und der Stoffflüsse innerhalb der Pflanze heute einen wichtigen Beitrag (Gabrielle et al. 1998, Malagoli et al. 2005, Allirand et al. 2007, Jullien et al. 2007).

N-Düngung

Bei der Optimierung der N-Effizienz im Winterrapsanbau kommt der N-Düngung natürlich eine bedeutende Rolle zu, besonders vor dem Hintergrund eines in Zukunft begrenzten N-Bilanzsaldos von 60 kg N/ha. Eine überhöhte N-Düngung führt jedoch nicht nur zu einem hohen N-Bilanzsaldo, sondern erhöht auch maßgeblich N_{min}-Werte zur Ernte und damit das N-Auswaschungspotenzial. In Kapitel 2 wurde gezeigt, dass ein positiver Zusammenhang zwischen einer erhöhten N-Düngung und einer verstärkter N-Auswaschung besteht. Bei der N-Düngung im Winterrapsanbau besteht daher ein enormer Optimierungsbedarf in der landwirtschaftlichen Praxis.

Häufig wird der Winterraps schon im Herbst mit N gedüngt. Sieling und Kage (2007b) konnten aber keine signifikanten Ertragseffekte bei einer Herbstdüngung im pfluglosen Winterrapsanbau feststellen. Des Weiteren wird im Herbst gedüngter N nur unzureichend von Rapsbeständen aufgenommen. In den in Kapitel 4 vorgestellten Versuchsergebnissen, wurde in den im Herbst mit 40 kg N/ha gedüngten Rapsbeständen im Mittel über alle Standorte und Saatzeiten in beiden Versuchsjahren nur ca. 20 kg N/ha mehr im Vergleich zu den ungedüngten Beständen gefunden. Eine N-Düngung im Herbst sollte folglich keine Standardmaßnahme sein, sondern nur in wenigen Ausnahmefällen, wenn die Überwinterungsfähigkeit eines Bestandes, zum Beispiel bei einer extremen Spätsaat, gefährdet ist, durchgeführt werden.

Für die Bemessung der N-Düngermenge werden standardmäßig Sollwerte nach dem N_{min}-Konzept benutzt (Wehrmann & Scharpf 1986). Dabei werden N-Mengen, die sich bereits vor der Düngung im Rapsbestand befinden nur pauschal mit 20 kg N/ha oder gar nicht auf die N-Düngermenge angerechnet. In Kapitel 4 konnte anhand der zweijährigen Versuchsdaten deutlich gezeigt werden, dass es keinen Zusammenhang zwischen N_{min} im Frühjahr und der optimalen N-Düngermenge gibt. Allerdings konnte ein signifikanter Zusammenhang zwischen der N-Menge im Bestand im Herbst und der optimalen N-Düngermenge gefunden werden. Da N_{min}-Werte im Frühjahr unter Raps regelmäßig sehr gering sind, ist die Berücksichtigung der schon bereits aufgenommenen N-Mengen sehr wichtig, zumal N-Verluste durch Blattabfall von Rapsbeständen über Winter im Frühjahr zu einem gewissen Teil wieder zur Verfügung stehen können (Dejoux et al. 2000) oder aber zu Vegetationsbeginn weit entwickelte Bestände einen Entwicklungsvorsprung haben, auf den mit einer reduzierten N-Düngermenge reagiert werden kann (Mendham et al. 1981). Die

N-Aufnahme eines ungedüngten Rapsbestandes im Herbst kann aber auch aufgrund der langen Vegetationszeit im Herbst ein Indikator für das N-Mineralisationspotenzial im Frühjahr am Standort sein. Die Berücksichtigung der bodenbürtigen N-Mineralisation ist bei der Bemessung von Düngermengen wichtig, kann aber in der Praxis nur schwierig abgeschätzt werden und unterliegt starken jährlichen Schwankungen wie in Kapitel 3 gezeigt werden konnte. Um die Bemessung der N-Düngermengen zu optimieren wird in der Literatur eine bessere Prognose der N-Mineralisation anhand von Simulationsmodellen gefordert (Mary et al. 1999). Die Mineralisation wird heute anhand von empirischen Daten bei der N-Düngung berücksichtigt. Für eine durch Modellierung optimierte N-Düngung müsste die standortspezifische Mineralisation und die Pflanzen-N-Aufnahme im Modell abgebildet werden und letztendlich die N-Düngung an diese Parameter angepasst werden. Dabei müsste dann die N-Düngung teilweise später im Vegetationsverlauf terminiert werden. Problematisch hierbei ist aber, dass der frühe N-Bedarf des Rapses durch die, unter norddeutschen Bedingungen später einsetzende, Mineralisation nicht gedeckt werden kann. Die N-Aufnahme eines Rapsbestandes im Herbst könnte einen ersten, sehr einfachen Beitrag zu einer Abschätzung des unsicheren Faktor N-Mineralisation leisten.

Durch die praxisüblichen, frühen Düngetermine ergibt sich auch bei der Erhebung von Pflanzenparametern das Problem, dass sich optimale Düngermengen anhand der erhobenen Parameter zu diesem Zeitpunkt noch nicht ermitteln lassen. So kann ein Düngekonzept, wie zum Beispiel der Nitrogen-Nutrition-Index (Colnenne et al 1998), bei dem die N-Konzentration in der Pflanze im Vegetationsverlauf berücksichtigt wird, ebenso im Winterraps nicht zur Anwendung kommen. Folgt man den Untersuchungsergebnissen aus Kapitel 4, so lässt sich bei weit entwickelten Rapsbeständen im Herbst die N-Düngermenge im Frühjahr deutlich reduzieren. In weiteren Versuchen muss nun dieser neue Aspekt in der Düngebedarfermittlung untersucht werden. Eine einfache, praxistaugliche Methode zur Bestimmung der N-Mengen im Bestand ist die Wägung der Frischmasse und Umrechnung auf oberirdische N-Menge im Bestand mit dem Faktor 45 im Herbst. Ein nächster Optimierungsschritt wäre die teilflächenspezifische N-Düngung von Winterraps. Die N-Menge im Bestand im Herbst lässt sich mittels spektraler Reflexion teilflächenspezifisch abschätzen (Müller et al. 2007). Eine den N-Mengen im Bestand angepasste N-Düngungskarte würde dann im Frühjahr die Applikation einer teilflächenspezifisch angepassten N-Düngermenge erlauben. Weiterhin können

Daten von Ertragskarten, die weitere Informationen über einzelne Teilflächen enthalten können, in die Düngungskarte mit einbezogen werden. Bei der Untersuchung der Ursachen für mögliche Ertragsunterschiede auf Teilflächen kann die Modellierung in Zukunft ein wichtiges Werkzeug sein.

Weitere Optimierungsmöglichkeiten im Hinblick auf die N-Effizienz bestehen bei der Anwendung organischer Düngemittel im Winterrapsanbau. Häufig wird im Winterraps im Herbst eine organische Düngung mit Gülle durchgeführt. Allerdings ist die Ausnutzung des Güllestickstoffs mit nur 5 % im Herbst äußerst gering (Sieling et al. 1998). Sieling et al. (1998) empfehlen eine Gülledüngung im Frühjahr, da hier mit 24 % eine deutlich günstigere scheinbare N-Ausnutzung festgestellt wurde. Verschiedene Untersuchungen über die Ertragswirksamkeit einer Gülledüngung stellten eher leicht negative Ertragstendenzen im Vergleich zur rein mineralischen Düngung fest (Rathke et al. 2005). Rathke et al. (2005) und Rathke et al. (2006) machen hierfür eine verzögerte Wirkung des Güllestickstoffs verantwortlich, da N aus der organischen Masse der Gülle erst mineralisiert werden muss. Um die N-Effizienz der organischen Düngung im Winterrapsanbau zu optimieren sind weitere Forschungsarbeiten über die kombinierte Anwendung mineralischer und organischer Düngemittel nötig (Sieling et al. 1998, Rathke et al. 2006).

Zusammenfassend betrachtet, lässt sich feststellen, dass die N-Effizienz im Winterrapsanbau nicht durch einen Faktor, sondern durch mehrere Bausteine positiv beeinflusst werden kann. So können die Ergebnisse der vorliegenden Arbeit einen Beitrag leisten, dass Produktionssysteme im Winterrapsanbau, vor allem im Hinblick auf die N-Düngung, zukünftig N-effizienter gestaltet werden können. Produktionstechnische Optimierungen, wie die teilflächenspezifische N-Düngung, der verbesserte Einsatz organischer Dünger zu Winterraps oder Produktionsverfahren, die zu einer geringeren Mineralisation von bodenbürtigen N nach der Winterrapsenernte führen, werden zukünftig verstärkt von Interesse sein, vor allem vor dem Hintergrund, dass züchterische Ansätze bis heute keine wesentliche Verbesserung der N-Effizienz, außer einer Erhöhung des Ertragsniveaus des Winterrapses, hervorgebracht haben.

5.3 Literatur

- ALLIRAND, J.-M., JULLIEN, A., SAVIN, A. & NEY, B. (2007). Oilseed rape leaves falling off depends on both leaf nitrogen content and transmitted radiation. In: Proceedings of the 12th International Rapeseed Congress (Wuhan, China), III (Agronomy), pp. 307-310. New Jersey, USA: Science Press USA Inc.
- ANONYMUS (1991). Nitratrichtlinie: Richtlinie 91/676/EWG des Rates vom 12. Dezember 1991 zum Schutz der Gewässer vor Verunreinigung durch Nitrat aus landwirtschaftlichen Quellen. Amtsblatt der Europäischen Gemeinschaft Nr. L 375.
- ANONYMUS (1997). Elemente einer Richtlinie des Rates für den Schutz und die Bewirtschaftung der Gewässer der Gemeinschaft (Wasserrahmenrichtlinie). Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, Bonn.
- ANONYMUS (2006). Verordnung über die Anwendung von Düngemitteln, Bodenhilfsstoffen, Kultursubstraten und Pflanzenhilfsmitteln nach den Grundsätzen der guten fachlichen Praxis beim Düngen (Düngeverordnung). Bundesgesetzblatt Jahrgang 2006, Teil I Nr. 2, ausgegeben am 13.01.2006.
- 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. *Agriculture, Ecosystems and Environment* 111, 292-310.
- CHRISTEN, O. (1997). Untersuchungen zur Anbautechnik von Winterweizen nach unterschiedlichen Vorfruchtkombinationen. Habilitationsschrift, Christian-Albrechts-Universität zu Kiel. Schriftenreihe des Instituts für Pflanzenbau und Pflanzenzüchtung, 7.
- CATT, J. A., HOWSE, K. R., CHRISTIAN, D. G., LANE, P. W. & GOSS, M. J. (2000). Assessment of tillage strategies to decrease nitrate leaching in the Brimstone Farm Experiment, Oxfordshire, UK. *Soil & Tillage Research* 53, 185-200.
- CHRISTEN, O. (2001). Yield, yield formation and yield stability of wheat, barley and rapeseed in different crop rotations. *Pflanzenbauwissenschaften* 5, 33-39.

- COLNENNE, C., MEYNARD, J. M., REAU, R., JUSTES, E. & MERRIEN, E. (1998). Determination of a critical nitrogen dilution curve for winter oilseed rape. *Annals of Botany* 81, 311-317.
- DEJOUX, J.-F., RECOUS, S., MEYNARD, J.-M., TRINSOUTROT, I. & LETERME, P. (2000). The fate of nitrogen from winter-frozen rapeseed leaves: mineralization, fluxes to the environment and uptake by rapeseed crop in spring. *Plant and Soil* 218, 257-272.
- 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.
- FRIEDT, W., LÜHRS, W., MÜLLER, M. & ORDON, F. (2003). Utility of Winter Oilseed Rape (*Brassica napus* L.) Cultivars and New Breeding Lines for Low-input Cropping Systems. *Pflanzenbauwissenschaften* 7, 49-55.
- GABRIELLE, B., DENOROY, P., GOSSE, G., JUSTES, E. & ANDERSEN, M. N. (1998). Development and evaluation of a CERES-type model for winter oilseed rape. *Field Crops Research* 57, 95-111.
- 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. *Journal of Soil Science* 44, 35-48.
- HABEKOTTÉ, B. (1997). Options for increasing seed yield of winter oilseed rape (*Brassica napus* L.): a simulation study. *Field Crops Research* 54, 109-126.
- HENKE, J., BREUSTEDT, G., SIELING, K. & KAGE, H. (2007). Impact of uncertainty on the optimum nitrogen fertilization rate and agronomic, ecological and economic factors in an oilseed rape based crop rotation. *Journal of Agricultural Science, Cambridge* 145, 455-468.
- HÜTSCH, B. & MENGEL, K. (1992). Effect of long-term ploughing and direct drilling on the distribution and leaching of mineral nitrogen in a loamy and a sandy soil. *European Journal of Agronomy* 1, 213-219.

- JULLIEN, A., ALLIRAND, J.-M., COURNEDE, P.-H., MATTHIEU, A. & NEY, B. (2007). Is it possible to simulate rapeseed organ mass in relation to N nutrition ? Calibration of the functional-structural model GREENLAB for the oilseed rape *Brassica napus* L. during the vegetative phase for two nitrogen levels. In: Proceedings of the 12th International Rapeseed Congress (Wuhan, China), III (Agronomy), pp. 414-417. New Jersey, USA: Science Press USA Inc.
- 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. *Nutrient Cycling in Agroecosystems* 55, 207-220.
- KAGE, H. (1997). Zu den Ursachen hoher Restnitratmengen beim Anbau von Ackerbohnen. Dissertation. Universität Göttingen.
- KAISER, E.-A., KOHRS, K., KÜCKE, M., SCHNUG, E., HEINEMEYER, O. & MUNCH, J. C. (1998). Nitrous oxide release from arable soil: Importance of N-fertilization, crops and temporal variation, *Soil Biology and Biochemistry* 30, 1553-1563.
- KAISER, E. A. & RUSER, R. (2000). Nitrous oxide emissions from arable soils in Germany – An evaluation of six long-term field experiments. *Journal of Plant Nutrition and Soil Science* 163, 249-260.
- KRISTENSEN, H. L., MCCARTY, G. W. & MEISINGER, J. J. (2000). Effects of Soil Structure Disturbance on Mineralization of Organic Soil Nitrogen, *Soil Science Society of America Journal* 64, 371-378.
- KRISTENSEN, H. L., DEBOSZ, K. & MCCARTY, G. W. (2003) Short-term effects of tillage on mineralization of nitrogen and carbon in soil. *Soil Biology & Biochemistry* 35, 979-986.
- LICKFETT, T. (1993). Auswirkungen verminderter Produktionsintensität in zwei Rapsfruchtfolgen auf Elemente des N-Haushalts im System Boden-Pflanze. Dissertation. Universität Göttingen.
- 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. II. An ¹⁵N-labelling-based Simulation Model of N Partitioning Between Vegetative and Reproductive Tissues. *Annals of Botany* 95, 1187-1198.

- MARY, B., BEAUDOIN, N., JUSTES, E. & MACHET, M. (1999). Calculation of nitrogen mineralization and leaching in fallow soil using a simple dynamic model. *European Journal of Soil Science* 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*). *Journal of Agricultural Science, Cambridge* 96, 389-416.
- MCEWEN, J., DARBY, R. J., HEWITT, M. V. & YEOMAN, D. P. (1989). Effects of field beans, fallow, lupins, oats, oilseed rape, peas, ryegrass, sunflowers and wheat on nitrogen residues in the soil and on the growth of a subsequent wheat crop, *Journal of Agricultural Science* 96, 209-219.
- MÖLLERS, C., KESSEL, B., KAHLMEYER, M., OSSENKOP, A. & BECKER, H. C. (2000). Untersuchungen zur genotypischen Variabilität der Stickstoff-Effizienz bei Winterraps. In: *Stickstoffeffizienz landwirtschaftlicher Kulturpflanzen* (Edt C. Möllers), pp. 30-47. Berlin: Erich Schmidt Verlag.
- MÜLLER, K., BÖTTCHER, U., MEYER-SCHATZ, F. & KAGE, H. (2007). Analyse von Reflexionsspektren im Winterraps. In: *Mitteilungen der Gesellschaft für Pflanzenbauwissenschaften*, 50. Jahrestagung vom 18. bis 20. September 2007 in Bonn (Eds. A. Hermann & F. Taube), pp. 270-271. Kiel: Schmidt & Klaunig.
- NICOLARDOT, B., RECOUS, S. & MARY, B. (2001). Simulation of C and N mineralization during crop residue decomposition: A simple dynamic model based on the C:N ratio of the residues. *Plant and Soil* 228, 83-103.
- 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 Crops Research* 95, 103-113.
- 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. *Agriculture, Ecosystems and Environment* 117, 80-108.

- SCHJOERRING, J. K., BOCK, J. G. H., GAMMELVIND, L., JENSEN, C. R. & MOGENSEN, V. O. (1995). Nitrogen incorporation and remobilization in different shoot components of field-grown winter oilseed rape (*Brassica napus* L.) as affected by rate of nitrogen application and irrigation. *Plant and Soil* 177, 255-264.
- SCHJOERRING, J. K. & MATTSON, M. (2001). Quantification of ammonia exchange between agricultural cropland and the atmosphere: Measurements over two complete growth cycles of oilseed rape, wheat, barley and pea. *Plant and Soil* 228, 105-115.
- SELING, K., GÜNTHER-BORSTEL, O. & HANUS H. (1997). Effect of slurry application and mineral nitrogen fertilization on N leaching in different crop combinations. *Journal of Agricultural Science, Cambridge* 128, 79-86.
- SELING, K., SCHRÖDER, H. & HANUS, H. (1998). Mineral and slurry nitrogen effects on yield, N uptake, and apparent N-use efficiency of oilseed rape (*Brassica napus*). *Journal of Agricultural Science, Cambridge* 130, 165-172.
- SELING, K., 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. *Journal of Agricultural Science, Cambridge* 132, 127-137.
- SELING (2000). Untersuchungen zu den Auswirkungen unterschiedlicher Produktionssysteme auf einige Parameter des N-Haushaltes von Boden und Pflanze. Habilitationsschrift, Christian-Albrechts-Universität zu Kiel. Schriftenreihe des Instituts für Pflanzenbau und Pflanzenzüchtung, 16.
- SELING, K., STAHL, C., WINKELMANN, C. & CHRISTEN, O. (2005). Growth and yield of winter wheat in the first 3 years of a monoculture under varying N fertilization in NW Germany. *European Journal of Agronomy* 22, 71-84.
- SELING, K. & KAGE, H. (2006). N balance as an indicator of N leaching in an oilseed rape - winter wheat – winter barley rotation. *Agriculture, Ecosystems and Environment* 115, 261-269.
- SELING, K. & KAGE, H. (2007a). The potential of semi-dwarf oilseed rape genotypes to reduce the risk of N leaching. *Journal of Agricultural Science, Cambridge*. doi:10.1017/S0021859607007472

- SIELING, K. & KAGE, H. (2007b). Autumnal N fertilization of late sown oilseed rape after minimum tillage. In: Proceedings of the 12th International Rapeseed Congress (Wuhan, China), III (Agronomy), pp. 375-378. New Jersey, USA: Science Press USA Inc.
- SIELING, K. (2007). persönliche Mitteilung
- STATISTISCHES BUNDESAMT (2007). Land- und Forstwirtschaft, Fischerei, Landwirtschaftliche Bodennutzung, Anbau auf dem Ackerland, Agrarstrukturerhebung 2007, Fachserie 3, Reihe 3.1.2, Statistisches Bundesamt, Wiesbaden.
- TRINSOUTROT, I., NICOLARDOT, B., JUSTES, E & RECOUS, S. (2000a). Decomposition in the field of residues of oilseed rape grown at two levels of nitrogen fertilization. Effects on the dynamics of soil mineral nitrogen between successive crops. *Nutrient Cycling in Agroecosystems* 56, 125-137.
- TRINSOUTROT, I., RECOUS, S., MARY, B. & NICOLARDOT, B. (2000b). C and N fluxes of decomposing ¹³C and ¹⁵N Brassica napus L.: effects of residue composition and N content. *Soil Biology & Biochemistry* 32, 1717-1730.
- WEHRMANN, J. & SCHARPF, H. C. (1986). The Nmin-method – an aid to integrating various objectives of nitrogen fertilization. *Journal of Plant Nutrition and Soil Science* 149, 428-440.
- WIDDOWSON, F. V., PENNY, A., GUTTERIDGE, R. J., DARBY, R. J. & HEWITT, M. V. (1985). Tests of amounts and times of application of nitrogen and sequential sprays of aphicide and fungicides on winter wheat, following either beans or wheat, and the effects of take-all (*Gaeumannomyces graminis* var. *tritici*), on two varieties at Saxmundham, Suffolk 1980-3. *Journal of Agricultural Science, Cambridge* 105, 97-122.
- ZIESEMER, A. & LEHMANN, E. (2006). Zusammenfassung aktueller Ergebnisse der anbautechnischen Forschung und ökonomischen Auswertungen im Acker- und Pflanzenbau, Fo-Nr.: 1/05. Landesforschungsanstalt für Landwirtschaft und Fischerei Mecklenburg-Vorpommern, Gülzow.

Kapitel 6

Zusammenfassung Summary

Zusammenfassung

Der Anbauumfang von Winterraps (*Brassica napus* L.) hat in norddeutschen Ackerbaufruchtfolgen in den letzten Jahren auf bis zu ca. 20 % der ackerbaulich genutzten Fläche zugenommen. Hinsichtlich der N-Effizienz ist Winterraps allerdings kritisch zu bewerten. N-Auswaschung nach Winterrapsanbau stellt den wichtigsten N-Verlustpfad dar. Der praktischen Landwirtschaft stehen heute allerdings verstärkte Anforderungen an die Umweltverträglichkeit gegenüber.

Übergeordnetes Ziel dieser Arbeit war es daher, die N-Dynamik im System Boden-Pflanze nach Winterrapsanbau auf der Ebene des Produktionssystems Rapsfruchtfolge zu analysieren, um daraus Strategien zur Verbesserung der N-Effizienz zu erarbeiten. Als mögliche Verbesserungsstrategien zur Steigerung der N-Effizienz wurden die Ansätze Gestaltung der Fruchtfolge, Anbau von Zwischenfrüchten, Bodenbearbeitungsintensität und optimierte Ermittlung des N-Düngebedarfs in den Untersuchungen berücksichtigt.

Die N-Dynamik nach Winterrapsanbau wurde durch die Kombination der methodischen Ansätze Feldversuch und Simulationsmodellierung untersucht. Der Einfluss verschiedener produktionstechnischer Maßnahmen auf die N-Dynamik nach Winterraps kann mit dem Modell untersucht und bewertet werden. Der Anbau einer Zwischenfrucht, wie zum Beispiel Phacelia oder Ausfallraps, an Stelle der typischen Folgefrucht Winterweizen reduzierte die N-Auswaschung deutlich. Phacelia konnte nach der Rapsernte im Herbst noch bis ca. 60 kg N/ha aufnehmen und somit N über Winter konservieren. Ausfallraps nahm zwar geringere N-Mengen auf, durch Verzicht auf die Bodenbearbeitung im Herbst wurde in dieser Variante aber die Mineralisation aus bodenbürtigem N, der maßgeblich zur N-Auswaschung beiträgt, deutlich vermindert. Eine starke Verringerung der Bodenbearbeitungsintensität mit Verzicht auf Pflugeinsatz und reduzierter, flacher Bodenbearbeitung in Kombination mit einem kurzzeitigen Aufwuchs von Ausfallraps trug ebenfalls zu deutlich niedrigeren N-Frachten bei. Schließlich konnte anhand der Messdaten aus dem Feldversuch, aber auch durch eine Szenarienrechnung mit dem Simulationsmodell gezeigt werden, dass mit steigender und vor allem deutlich überhöhter N-Düngung die N-Auswaschung nach Winterraps erheblich anstieg.

Die Entscheidung über die Düngungshöhe ist immer eine Entscheidung unter Unsicherheit, da viele Faktoren, welche die Düngungshöhe beeinflussen können, nicht vorhersehbar sind. Daher stellte die Untersuchung und Quantifizierung des

Einfluss von Unsicherheit auf die optimale Düngungshöhe (Nopt), die N-Bilanz und die N-Kosten freien Leistungen in einer Winterraps-Winterweizen-Wintergerste Fruchtfolge einen weiteren Schwerpunkt dieser Arbeit da. Die Unsicherheiten Wahl des statistischen Modells zur Berechnung der optimalen N-Düngermenge, Jahresvariation in der Ertragsreaktion auf N und Unsicherheit in der Schätzung der Funktionsparameter des verwendeten statistischen Modells betrachtet. Die Wahl des statistischen Modells hatte einen erheblichen Einfluss auf Nopt und damit auch auf die N-Bilanz. Unter Berücksichtigung der weiteren Unsicherheiten erhöhte sich Nopt tendenziell, wobei dieser Effekt in Abhängigkeit des Modells unterschiedlich stark ausgeprägt war. Eine quadratische Funktion war unanfälliger gegenüber den untersuchten Unsicherheiten als eine Linear-Plateau-Funktion. Winterraps hatte in der untersuchten Fruchtfolge die höchsten Nopt und steuerte den größten Anteil zum mittleren N-Bilanzsaldo der Fruchtfolge bei. Eine Begrenzung des N-Bilanzsaldos auf 60 kg N/ha, wie in der novellierten Form der Düngeverordnung vorgesehen, war anhand der Ergebnisse unter Versuchsbedingungen und der daraus abgeleiteten Berechnungen einzuhalten, kann aber in der Praxis aufgrund weiterer, hier nicht berücksichtigten Unsicherheiten, übertroffen werden.

Einer exakten, standort- und bestandesangepassten Bemessung der N-Düngermenge und der Realisierung der Ertragspotenziale kommt gerade im Winterrapsanbau eine enorme Bedeutung zu. Da Winterraps bereits im Herbst große N-Mengen aufnehmen kann und die Nmin-Mengen im Frühjahr regelmäßig sehr gering sind, sollten auch die N-Mengen im Bestand bei der Düngebedarfsermittlung berücksichtigt werden. Daher wurden Einflussfaktoren auf die optimale Düngermenge von Winterraps wie Nmin im Frühjahr, N-Menge im Bestand im Herbst und N-Menge im Bestand im Frühjahr in einem mehrortigen Feldversuch untersucht. Es konnte gezeigt werden, dass es keinen Zusammenhang zwischen der optimalen N-Düngermenge und Nmin im Frühjahr gab, obwohl auch im Winterraps die Düngermenge standardmäßig mit der Nmin-Methode ermittelt wird. N-Mengen im Bestand im Frühjahr hatten keinen Einfluss auf die optimale N-Düngermenge. Einen signifikanten negativen Einfluss auf die optimale N-Düngermenge hatten allerdings die N-Mengen im Bestand im Herbst. Die N-Menge im Bestand im Herbst ist also ein Indikator, der bei der N-Düngebedarfsermittlung in Zukunft stärker berücksichtigt werden sollte, um die N-Düngung der Bestandesentwicklung anzupassen.

Die N-Effizienz im Winterrapsanbau lässt sich nicht nur durch einen Faktor, sondern durch mehrerer Bausteine positiv beeinflussen. So können die Ergebnisse der vorliegenden Arbeit einen Beitrag leisten, dass Produktionssysteme im Winterrapsanbau, vor allem im Hinblick auf die N-Düngung, zukünftig N-effizienter gestaltet werden können. Weitere produktionstechnische Optimierungen, wie die teilflächenspezifische N-Düngung, ein verbesserter Einsatz organischer Düngemittel zu Winterraps oder Produktionsverfahren, die zu einer geringen Mineralisation von bodenbürtigen N nach der Winterrapsenernte führen, werden zukünftig von Interesse sein, um Produktionssysteme mit Winterraps unter den gegebenen umweltrelevanten Gesichtspunkten N-effizient gestalten zu können.

Summary

Winter oilseed rape (OSR) acreage in crop rotations has risen up to 20 % of the total arable land in northern Germany. However, concerning nitrogen efficiency OSR is relatively poor. Nitrate leaching after growing OSR is the main contributor of N pollution in arable cropping. Therefore farmers face with more and more requirements in terms of environmental sustainability.

Therefore the superior aim of this thesis was to analyse the N dynamic in the plant soil system after growing OSR on the cropping system level and the development of strategies for N efficiency improvement. Possible strategies like adapted crop rotations, growing of catch crops, tillage intensity and an optimized calculation of N fertilization rates were considered in the present investigations.

N dynamics after OSR harvest were investigated combining the methodological approaches field trial and simulation modeling. The influence of different agronomic strategies on N dynamics after growing OSR can be investigated and evaluated by using a simulation model. Growing catch crops like volunteer OSR or Phacelia after OSR harvest decreased N leaching remarkably. Phacelia took up up to 60 kg N/ha in autumn and consequently these amounts could be transferred into spring. Volunteer OSR took up smaller amounts of N but due to no tillage operations in this treatment N mineralization of soil borne organic N in autumn and consequently N leaching over winter could be reduced. A strong reduction of tillage operations intensity in autumn with avoiding of ploughing in combination with short growing period of volunteer OSR yielded also in lower amounts of leached N. Finally, it could be shown by the field trial measurements but also doing scenario calculations with the simulation model that increasing N fertilization rates and particularly overfertilization led to remarkably higher N leaching losses.

The decision about N fertilization rates is always an uncertain decision because many factors which can potentially influence N fertilizer amounts are unpredictable. Therefore another main focus of this thesis was the quantification of uncertainty on N fertilization rates, N balances and net revenues in an OSR-winter wheat-winter barley rotation. Three levels of uncertainty, model choice for calculation optimum N fertilization rates (Nopt), year to year variation and uncertainty in model parameter estimation were observed. The choice of the statistical model had a tremendous impact on Nopt and consequently on N balances. Regarding the other observed uncertainties Nopt rose but the increase

depended on the underlying statistical model. The quadratic response function was more stable against the observed uncertainties compared to a linear response function. However, within the crop rotation OSR had the highest Nopt and was the main contributor to the mean N balance of the crop rotation. A restricted N balance of 60 kg N/ha, as proposed by the amended fertilization legislation could be met, but in practice, however, for arable farms with similar rotation and climatic conditions as underlying this study such a restriction might be critical because of other uncertainties in N use efficiency not considered in this study.

Especially in OSR the exact calculation of N fertilizer rates becomes more and more important to prevent N pollution. Because OSR can take up large amounts of N in autumn and consequently amounts of soil mineral nitrogen (SMN) at the beginning of spring growth are usually low, canopy N should be considered calculating N fertilization rates. Therefore the influence of SMN at the beginning of spring growth but also of canopy N in autumn and spring on Nopt in spring was investigated in a multi-site field trial. It could be clearly shown that there is no relationship between SMN in spring and Nopt although SMN in spring is a common parameter for calculating Nopt in spring. Canopy N in spring had also no influence on Nopt in spring. However, a significant correlation between canopy N in autumn and Nopt in spring could be found. Therefore canopy N should be considered calculating N fertilizer rates to adapt these to canopy development.

Nitrogen efficiency can be improved by several approaches in the cropping system. The results of this thesis can contribute to an increased N efficient cropping of OSR especially in terms of N fertilization. Further developments in crop husbandry like site specific N fertilization in OSR, an optimized use of organic fertilizers or tillage strategies with low N mineralization of soil born N after harvest in autumn will be required in future time to develop OSR cropping systems which meet ecological and economic concerns.

Danke...

Herrn Prof. Dr. H. Kage danke ich für die Überlassung des Themas, die stets gewährte große Unterstützung, die vielen Freiheiten und die immer offene Bürotür.

Herrn Prof. Dr. F. Taube danke ich für die Übernahme des Koreferats.

Herrn Priv.-Doz. Dr. K. Sieling danke ich die Unterstützung und Motivation bei der Verfassung der Artikel, die stete Diskussionsbereitschaft und die gute Zusammenarbeit.

Dr. U. Böttcher danke ich für die große Unterstützung beim Modellieren und das geduldige Beantworten zahlloser Fragen.

Dr. A. Pacholski möchte ich für das emsige Korrekturlesen und die vielen Verbesserungsvorschläge herzlich danken.

Dr. G. Breustedt danke ich für die Einblicke in die Monte-Carlo-Simulation und die freundschaftliche Zusammenarbeit.

Bei Dr. G. Rave bedanke ich mich für die Unterstützung bei statistischen Fragen und Problemen.

Meinen Mitdoktoranden Babette Wienforth, Karla Müller, Franziska Meyer-Schatz, Dorothee Neukam, Dirk Gericke, Michael Kohl und Tobias Johnen danke ich für die Diskussionsbereitschaft und das angenehme Arbeitsklima in der Zeit am Institut.

Ich danke Herrn L. Rizos für die große Geduld mit mir und meinem Computer.

Frau G. Schnack, Frau C. Weise, Frau K. Schulz und Frau D. Ziermann danke ich für die große Unterstützung bei den Probennahmen und -aufbereitungen.

Ich danke Herrn R. Ströh und allen Mitarbeitern auf dem Versuchsgut Hohenschulen für die Unterstützung bei der Versuchsdurchführung.

Thorsten Harms und Asiak Fischer danke ich für ihre tolle Einsatzbereitschaft und die teilweise langen Abende im Gewächshaus.

Für die gute Zusammenarbeit im Rahmen des UFOP-Projekts danke ich Frau J. Gronow, Herrn Dr. W. Saueremann, Herrn Dr. R.-R. Schulz, Herrn Dr. G. Baumgärtel, Herrn Graf, Herrn Baer und Herrn Dr. habil Albert.

Bei der Union zur Förderung von Öl- und Proteinpflanzen e.V. (UFOP) möchte ich mich für die großzügige Finanzierung und die Ermöglichung der Teilnahme am International Rapeseed Congress in Wuhan bedanken.

Meiner lieben Freundin Marlyn Kaper danke ich von ganzem Herzen für die zeitlichen Entbehrungen, das große aufgebrachte Verständnis und die Hilfe im Kleingarten (=Fruchtfolgeversuch).

Bei meinen Eltern möchte ich mich für die große Unterstützung und Förderung in meinem bisherigen Werdegang bedanken.

Lebenslauf

Persönliche Daten

Familienname	Henke
Vorname	Johannes
Geburtsdatum	11.04.1978
Geburtsort	Hildesheim
Familienstand	ledig
Staatsangehörigkeit	deutsch

Schulbildung

Grundschule Harsum
Orientierungsstufe St. Augustinusschule, Hildesheim
Gymnasium Josephinum, Hildesheim: Abitur

Wehrdienst

09/1997 – 07/1998	Grundwehrdienst
-------------------	-----------------

Universitätsausbildung

10/1999 – 07/2002	Studium der Agrarwissenschaften, Fachrichtung Pflanzenproduktion an der Christian-Albrechts Universität zu Kiel: Bachelor of Science (B.Sc.)
10/2002 – 01/2003	Auslandsstudium an der Wageningen University
01/2003 – 06/2004	Studium der Agrarwissenschaften, Fachrichtung Pflanzenproduktion an der Christian-Albrechts Universität zu Kiel: Master of Science (M.Sc.)

Praktika

08/1998 – 07/1999	Landwirtschaftliches Praktikum: Praktikantenprüfung
-------------------	---

Tätigkeiten

10/2004 – 10/2007	Wissenschaftlicher Mitarbeiter am Institut für Pflanzenbau und Pflanzenzüchtung, Acker- und Pflanzenbau, CAU Kiel
seit 11/2007	Produktmanager Winterraps, Syngenta Seeds GmbH, Bad Salzuflen

Bielefeld, den 16.12.2007