Brassica Cover Crops for Nitrogen Retention in the Mid-Atlantic Coastal Plain

Jill E. Dean and Ray R. Weil* University of Maryland

Brassica cover crops are new to the mid-Atlantic region, and limited information is available on their N uptake capabilities for effective N conservation. Forage radish (*Raphanus sativus* L. cv. Daikon), oilseed radish (*Raphanus sativus* L. cv. Adagio), and rape (*Brassica napus* L. cv. Dwarf Essex) were compared with rye (*Secale cereale* L. cv. Wheeler), a popular cover crop in the region, with regard to N uptake ability and potential to decrease N leaching at two sites in Maryland. Plants were harvested in fall and spring for dry matter and N analysis. Soil samples from 0 cm to 105 to 180 cm depth were obtained in fall and spring for NH_4–N and NO_3–N analyses. Ceramic cup tension lysimeters were installed at depths of 75 to 120 cm to monitor NO_3–N in soil pore water. Averaged across 3 site-years, forage radish and rape shoots had greater dry matter production and captured more N in fall than rye shoots. Compared with a weedy fallow control, rape and rye caused similar decreases in soil NO_3–N in fall and spring throughout the sampled profile. Cover crops had no effect on soil NH_4–N. During the spring on coarse textured soil, pore water NO_3–N concentrations in freeze-killed Brassica (radish) plots were greater than in control and overwintering Brassica (rape) and rye plots. On fine textured soil, all cover crops provided a similar decrease in pore water NO_3–N concentration compared with control. On coarse textured soils, freeze-killed Brassica cover crops should be followed by an early-planted spring main crop.

Nutrient losses from agricultural sources were estimated to comprise 41% of the N loading to the Chesapeake Bay in 2003 (Chesapeake Bay Program, 2004). Nitrogen inputs may aggravate eutrophication of surface waters and contaminate drinking water, and the large land to water ratio within the watershed makes the Chesapeake Bay especially sensitive to nutrient pollution (Pionke et al., 2000). Cover crops provide many environmental and agronomic benefits (Weil and Kremen, 2007), including reduced soil erosion, increased soil organic matter (Fageria, 2007), alleviation of subsoil compaction (Williams and Weil, 2004), and suppression of weeds and other pests (Fisk et al., 2001). Cover crops have also been shown to be an effective means of reducing nutrient losses from agricultural lands (Jackson et al., 1993; Meisinger et al., 1991; Vos and Van Der Putten, 2004; Weinert et al., 2002). To reduce N loading to the Chesapeake Bay, the Maryland Agricultural Cover Crop Program provides financial incentives for farmers to grow small grain cover crops, such as rye (*Secale cereale* L.), wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), or oats (*Avena sativa* L.). The Maryland Agricultural Cover Crop Program was broadened in 2005 to include Brassica cover crop species.

Rye is the most widely grown cover crop in the Atlantic Coastal Plain, and its N scavenging capacity and adaptability to the soils and climates in the region has been well documented (Coale et al., 2001; Shipley et al., 1992; Staver and Brinsfield, 1998). Rye is therefore a logical benchmark to which Brassica performance can be compared. Brassica cover crops, such as forage radish (*Raphanus sativus* L.), oilseed radish (*Raphanus sativus* L.), and rape (*Brassica napus* L.), are relative newcomers to the Maryland Coastal Plain, but studies in Europe, Canada, and the western regions of the USA suggest that these cover crops are effective in capturing N, in some cases outperforming rye in taking up N and decreasing soil NO_3–N (Isse et al., 1999; Jackson et al., 1993; Kristensen and Thorup-Kristensen, 2004; Lainé et al., 1993; Thorup-Kristensen, 1994; Thorup-Kristensen, 2001; Vos and Van Der Putten, 2004; Weinert et al., 2002). Kristensen and Thorup-Kristensen (2004) observed total plant N uptake of forage radish to be significantly greater than rye, with values of 158 and 90.5 kg N ha^{-1}, respectively. Biomass production and N uptake by rye declines with delay in date of planting in the fall (Feyereisen et al.,

Published in J. Environ. Qual. 38:520–528 (2009).
doi:10.2134/jeq2008.0066
Received 5 Feb. 2008.
*Corresponding author (rweil@umd.edu).
© ASA, CSSA, SSSA
677 S. Segoe Rd., Madison, WI 53711 USA

1109 HJ Patterson Hall, Dep. of Environmental Science and Technology, Univ. of Maryland, College Park, MD 20742.

Abbreviations: CMREC, University of Maryland Central Maryland Research & Education Center-Beltsville facility; WREC, University of Maryland Wye Research & Education Center; CMREC1, University of Maryland Central Maryland Research & Education Center-Beltsville facility study year 1 site; WREC1, University of Maryland Wye Research & Education Center study year 1 site; CMREC2, University of Maryland Central Maryland Research & Education Center-Beltsville facility study year 2 site; WREC2, University of Maryland Wye Research & Education Center study year 2 site.

2006). Such declines with delayed planting dates are even more pronounced for the Brassicas than for rye (Kristensen and Thorup-Kristensen, 2004). Vos and Van Der Putten (1997) and Thorup-Kristensen (2001) suggest that Brassicas are likely to outperform rye only when planted early in the fall.

Dissolved NO_3 moves through the soil by mass flow unimpeded by cation exchange reactions and may quickly be transported beyond the rooting zone of plants. For the most effective N conservation, cover crops need extensive rooting systems that grow deep quickly (Meisinger et al., 1991; Sainju and Singh, 1997). Nitrogen uptake from deep soil layers has a greater effect on decreasing leaching losses than N uptake from surface layers (Thorup-Kristensen, 2001; Thorup-Kristensen and Nielsen, 1998). Vos and Van Der Putten (1998) concluded that the cereal rye rooting systems did not behave differently from those of the rape and oilseed radish root systems to a depth of 40 cm based on root length per unit area and aboveground dry matter. However, Kristensen and Thorup-Kristensen (2004) measured ^{15}N uptake of 6.2 and 0.1 mg N subplot^{-1} (0.9 × 0.8 m subplot) by forage radish and rye, respectively, at 1.1 m soil depth. Nitrate-N remaining in the top 1.0 m of the soil profile was 11.9 and 32.2 kg ha^{-1} for forage radish and rye, respectively, and NO_3–N remaining at the 1.0- to 2.5-m depth was 6.2 and 27.2 kg ha^{-1} for forage radish and rye, respectively, clearly indicating the effectiveness of forage radish to capture N from deep soil layers (Kristensen and Thorup-Kristensen, 2004).

This study compares forage radish, oilseed radish, and rape to rye in relation to plant N uptake, depletion of soil profile NO_3–N, and maintenance of low soil pore water NO_3–N. The cover crops were also compared with unweeded, fallow control plots, which represent the typical farmer practice where no cover crop is grown. This comparison allowed us to estimate soil profile NO_3–N depletion from November to May and changes in soil pore water NO_3–N concentration in spring attributable to the various cover crops. The objective of this research was to evaluate the potential of the Brassica cover crops to capture excess soil N when planted in late summer in the mid-Atlantic region.

Materials and Methods

As part of a broad set of field experiments designed to investigate environmental and agronomic effects of Brassica cover crops, N capture by several cover crops was studied at two field sites in Maryland (Univ. of Maryland Central Maryland Research and Education Center at Beltsville facility [CMREC] and Wye Research and Education Center [WREC]) from August 2003 through May 2005 (Fig. 1). Randomized complete block was used for the experimental design.

Experiments CMREC1 and CMREC2

The soil at CMREC was a complex of two highly permeable sandy soils, Cedartown and Evesboro loamy sands, with Ap horizons averaging 65 mg clay g^{-1}, 800 mg sand g^{-1}, 17 mg organic matter g^{-1} soil, and pH 6.5. In two blocks of the experimental design, the dominant soil was Evesboro loamy sand (mesic, coated Lamellic Quartzipsamment) with a clay content <60 mg g^{-1} to 120 cm depth. In the remaining two blocks, the dominant soil was Cedartown loamy sand (siliceous, mesic Psammentic Hapludult), which includes an argillic horizon at 80 to 120 cm containing 150 to 200 mg clay g^{-1}. The CMREC site is situated at 39.02°N, 76.53°W, with a moist continental climate (30-yr average mean annual precipitation, 1112 mm; mean annual temperature, 12.8°C). Figure 2 shows the normal and actual cumulative precipitation and monthly mean temperatures for CMREC over the course of the experiment.

The soil at CMREC was last plowed on 31 Mar. 1999 and was then put in a no-till corn (*Zea mays* L.)/winter wheat (*Triticum aestivum* L.)/double crop soybean (*Glycine max* (L.) Merr.) rotation until wheat harvest in July 2003. Neither animal manure nor cover crops were used on the site before this study. During this experiment, a corn/full-season soybean rotation was used. Although both years of the study were conducted in the same field, the plots used for the study during fall 2003 to spring 2004 (CMREC1) were different from the ones used in fall 2004 to spring 2005 (CMREC2) to avoid the possibility of residual effects of the previous year's cover crops and artifacts from the previous year's deep coring. For CMREC2, rye and rape were added to the cover crop treatments, thus providing the same treatments as at WREC.

On 13 Aug. 2003, forage radish (*Raphanus sativus* L. cv. Daikon) and oilseed radish (*Raphanus sativus* L. cv. Adagio) were no-till drilled (13 kg seed ha^{-1}) into wheat stubble for CMREC1. Previous experience had shown that soluble N levels following moderately fertilized wheat or corn are so low in the surface horizons of very sandy soil that fall-planted nonleguminous cover crops typically have highly chlorotic, stunted shoots and fail to grow vigorous root systems. Therefore, 56 kg ha^{-1} of N as $(NH_4)_2SO_4$ was applied to all plots at time of cover crop planting to ensure adequate nutrition for normal plant growth and to make certain that ample N would be present to allow measurement of the cover crops' potential for N uptake. Cover crop plots were 3.7 by 9.1 m with 15-cm row spacing. Both cover crops freeze-killed during December 2003 through January 2004. The plots used for CMREC1 and CMREC2 were planted to glyphosate-resistant soybeans (cultivar NK S39-Q4; 155,000 seeds ha^{-1}; 38-cm row spacing) on 12 May 2004. Soybeans were mowed at reproductive stage R8 in the CMREC2 plots on 18 Aug. 2004 to provide a source of mineralizing organic N (208 kg total N ha^{-1}, as determined by dry matter and N analysis) for evaluating the N uptake performance of cover crops planted later in the month. On 25 Aug. 2004, forage radish, oilseed radish, rape (*Brassica napus* L. cv. Dwarf Essex), and rye (*Secale cereale* L. cv. Wheeler) were planted in CMREC2 (using 13, 13, 10, and 126 kg seed ha^{-1}, respectively). Cover crop plots were 3.7 by 9.1 m with 15-cm row spacing. Forage and oilseed radishes freeze-killed in December 2004 to January 2005, and rape and rye were killed when all plots were sprayed with glyphosate (2.3 L ha^{-1} AI; N-(phosphonomethyl)-glycine) on 27 Apr. 2005. On 5 May 2005, lime was surface applied according to soil test recommendations at a rate of 1120 kg ha^{-1}. The CMREC2 plots were planted to corn (Pioneer 34B62; 65,000 seeds ha^{-1}; 76-cm row spacing) on 10 May 2005.

Experiments WREC1 and WREC2

The soil at WREC is a Mattapex silt loam (fine-silty, mixed, active, mesic Aquic Hapludult). The Ap soil horizon is characterized

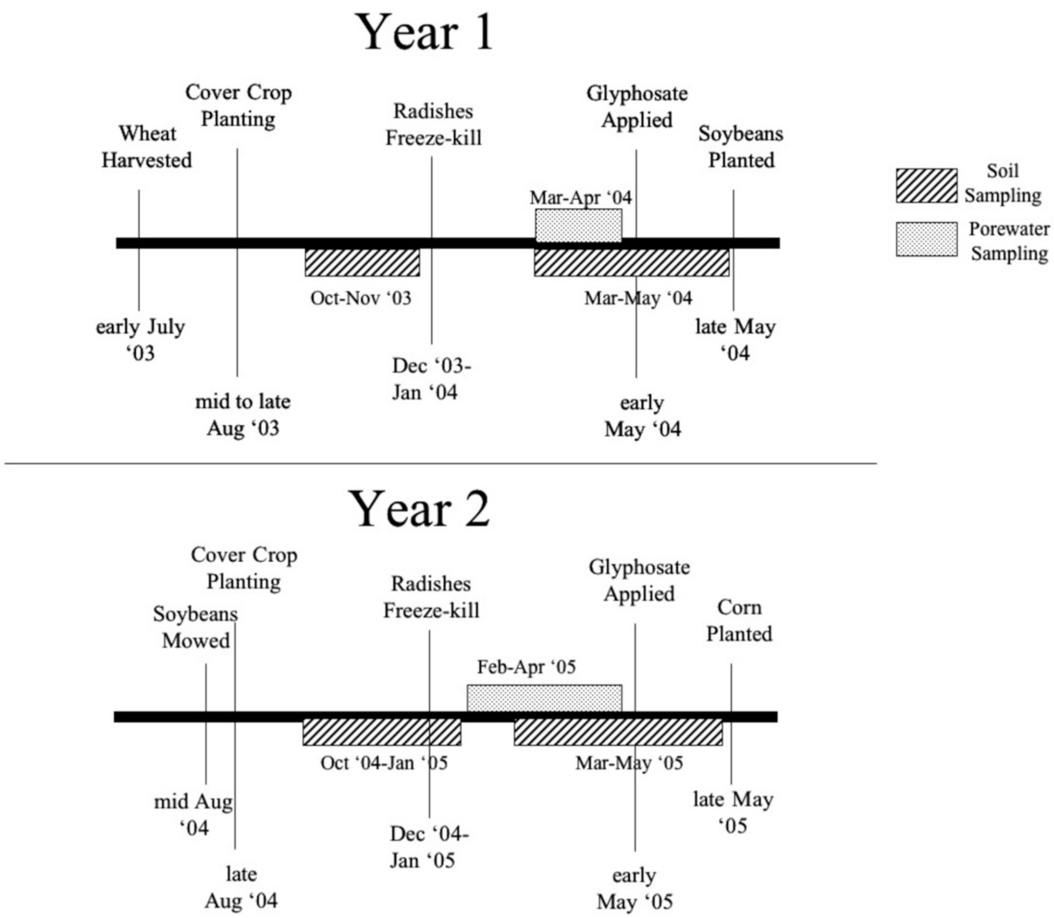

Fig. 1. Timeline for field experiment activities at Univ. of Maryland Central Maryland Research and Education Center-Beltsville facility (CMREC) and Wye Research and Education Center (WREC) from 1 Aug. 2003 through 31 May 2005. Field operations were performed at similar times for CMREC and WREC; therefore, the timeline approximates the activities at both sites.

by 270 mg sand g^{-1}, 180 mg clay g^{-1}, 20 mg organic matter g^{-1}, and pH 6.3. Mattapex silt loam was formed from loess deposits overlaying coastal plain sediments. An argillic horizon (260 mg clay g^{-1}) was observed from 30 to 50 cm depth, and loam-loamy

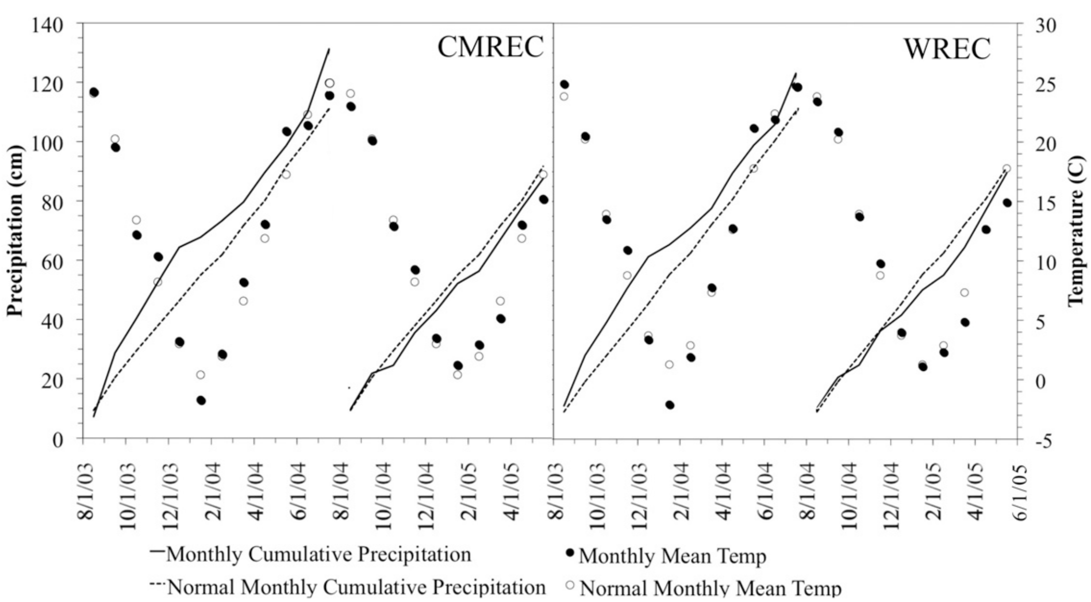

Fig. 2. Mean monthly temperature and cumulative monthly precipitation at University of Maryland Central Maryland Research and Education Center-Beltsville facility (CMREC) and Wye Research and Education Center (WREC) from 1 Aug. 2003 through 31 May 2005. The normal data are based on 30-yr averages at each site. Precipitation data are cumulative from 1 Aug. 2003 to 31 July 2004 and from 1 Aug. 2004 to 31 May 2005.

sand textured coastal plain sediments were observed below 100 to 120 cm depth. The WREC site is situated at 39.03°N, 76.04°W, with a moist continental climate (30-yr average mean annual precipitation, 1103 mm; mean annual temperature, 13.3°C). Figure 2 shows the daily precipitation and average daily temperature for WREC over the course of the experiment.

No-till management was practiced at WREC for this experiment and during the previous 5 yr with a corn (dent or sweet) and soybean rotation. Plots used from fall 2003 to spring 2004 (WREC1) had been subject to forage radish, oilseed radish, rape, rye, or no cover crop treatments since August 2001. In the second year, the study (WREC2) was conducted on adjacent land that had not had cover crops during the previous 25 yr. No differences in soil profile characteristics were observed between WREC1 and WREC2. Treatment plot dimensions and row spacing were the same as at CMREC.

On the WREC1 plots, sweet corn (cv. 'Incredible') was planted on 5 May 2003 with 38 kg N ha^{-1} as 16-8-8 and sidedressed on 17 June 2003 with an additional 92 kg N ha^{-1} as urea ammonium nitrate solution. After sweet corn harvest, glyphosate (0.93 L ha^{-1} AI) was applied on 1 Aug. 2003. Forage radish, oilseed radish, rye, and rape were planted in WREC1 on 19 Aug. 2003 (seeding rates, 14, 14, 126, and 10 kg ha^{-1}, respectively). Forage and oilseed radishes freeze-killed during December 2003 to January 2004. The rape and rye cover crops were rolled down on 5 May 2004, and all plots were sprayed with glyphosate (1.4 L ha^{-1} AI) on the following day.

The WREC2 plots were no-till planted to glyphosate-resistant soybeans (cultivar NK S39-Q4; 155,000 seeds ha^{-1}) with 76-cm row spacing on 21 May 2004. Glyphosate (1.9 L ha^{-1} AI) was sprayed for weed control within soybeans on 23 June 2004. On 18 Sept. 2004, the soybeans on the WREC2 plots were mowed to provide a readily mineralizable organic source of N on these plots for evaluating the N capture capacity of the cover crops during fall 2004 to spring 2005. At the time of mowing, the soybeans were at reproductive stage R8 and contained 250 kg N ha^{-1} in their aboveground tissues (based on measured dry matter and N content).

Forage radish, rye, and rape (seeding rates: 14, 126, and 10 kg ha^{-1}) were planted at WREC2 on 24 Sept. 2004. Forage radish freeze-killed in late December 2004. All plots were sprayed with glyphosate (1.9 L ha^{-1} AI) on 3 May 2005, and corn (Pioneer 34B62; 40,000 seeds ha^{-1}) was planted on 19 May 2005 without N fertilizer. The crop was side-dressed with N fertilizer in mid-June.

Field Sampling

Plant and soil samples were taken from random locations at least 1 m from the edge of the plot. Plants were sampled by block over several days in early October and November and in April through May of each year. Three 0.25-m^2 quadrats of plant material were harvested in each plot, and the dry weight of these samples was determined after drying. During the second study year, two 0.25-m^2 quadrats of plant tissues were sampled from each plot, and the fresh weight of the harvested quadrat was measured. Subsamples were removed for analysis of water and nitrogen contents. Plant shoots were harvested for all treatments. For the Brassicas, which have large fleshy taproots, root material was sampled to approximately 15 cm depth by pulling up the whole plant and washing the roots free of soil. Plant dry matter measurements were used in conjunction with N analysis to determine plant N uptake (Eq. [1]):

$$\text{N uptake (kg ha}^{-1}\text{)} = \text{DM} \times \text{N} \qquad [1]$$

where DM is plant dry matter (kg ha^{-1}), and N is N content (kg kg^{-1}). After collection, plants were dried at 65°C and ground to pass a 1-mm sieve.

Soil was sampled to depths of 105 to 180 cm depending on site conditions using a fully enclosed, drop hammer–driven Veihmeyer corer (Devera et al., 1980; Veihmeyer, 1929). Seasonal perched water tables, precipitation, and equipment capabilities limited the depth of coring and the number of cores possible to collect per day. Cores were placed in 4-cm-diameter PVC troughs for examination and divided into 15-cm sections. Three soil cores were taken in each plot and homogenized to represent the plot. Soil samples were taken on the same dates as plant samples for each plot. Soil bulk density was calculated for each 15 cm of core (Eq. [2]).

$$\text{Bulk density (g cm}^{-3}\text{)} = M/(\pi \times r^2 l) \qquad [2]$$

where M is the dry mass of sample in grams, r is the radius of the cutting tip, and l is the length of the sample (15 cm). Bulk density values for soil samples deeper than 30 cm were averaged over the sampling period for each location in 30-cm increments (30–60, 60–90, 90–120, 120–150, and 150–180 cm). Bulk density for CMREC was averaged over 2 yr. For WREC1 and WREC2, bulk density was averaged separately due to variation in bulk density between the two locations. Due to the mutability of surface horizons by freeze-thaw cycles and traffic, surface soil samples (0–15, 15–30 cm) were not averaged over years, and the bulk density for the individual sampling date was used for calculations.

Tension lysimeters (1.9 cm diameter) with 100-kPa ceramic tips were installed in plots at both sites in February-March 2004 (one per plot) and February-March 2005 (two per plot) to monitor pore water NO_3^-–N concentration. Lysimeters were sampled weekly until May of each year, when they were removed to allow planting of the summer crop. Nutrient leaching was assumed to be minimal when cover crops were alive in fall and early winter; therefore, lysimeters were not installed until later in winter after the radish cover crops died and began to release nutrients. Lysimeters were installed to 75 cm depth at WREC1 and 90 cm at CMREC1 during February 2004. In February 2005, lysimeters were installed to 90 cm depth at WREC2 and 120 cm at CMREC2. To collect each sample, an 80- to 90-kPa vacuum was applied to the lysimeter with a hand pump, and pore water was collected over a 24- to 48-h period.

Laboratory Analyses

Nitrogen analyses were performed on plant, soil, and pore water samples. Nitrate-N and NH_4–N were extracted from soil using 0.5 mol L^{-1} K_2SO_4 (1:10 dilution). A copperized cadmium reduction column in a flow-injection autoanalyzer (Technicon Autoanalyzer II; Technicon Industrial Systems, Tarrytown, NY) was used for NO_3–N analysis (Technicon Industrial Systems, 1977) of soils. Ammonium-N was determined using an ammonia gas–selective electrode (Orion EA940; Thermo Electron, Waltham, MA) after addition of ionic strength adjusting solution that raised the pH to 13 (Banwart et al., 1972). Plant total nitrogen was analyzed using a combustion analyzer (CHN 2000; LECO, St. Joseph, MI) for samples (ground to pass 1-mm sieve). Soil pore water was analyzed for NO_3–N colorimetrically (Cataldo et al., 1975).

Statistical Analyses

The experiments at both sites used a randomized complete block design with four replications. Analysis of variance was calculated by SAS Proc Mixed (SAS Institute, 2005) for N in a given 15-cm increment of the soil profile, for the sum of all N in the sampled (0–105+ cm) profile, for pore water N on a given sample date, for plant dry matter, for plant tissue N concentration, and for plant N uptake. Block effects were treated as random variables, whereas cover crop treatments were considered fixed effects. Pore water N across sampling dates was analyzed using repeated measures ANOVA with time as the repeated variable using SAS Proc Mixed. Fisher's LSD with Tukey adjustment and orthogonal contrasts were performed to compare cover crops with one another and with the control. A p level <0.10 was considered significant because available time and equipment limited the number of deep soil cores obtainable to three per plot and because the consequences of a type II error were considered to be more serious than those of a type I error,

Results

Cover Crop Dry Matter and Nitrogen Uptake

Cover crop aboveground dry matter was similar among species at each site for each fall season (Table 1), except shoot dry matter, which was significantly lower for rye than for the Brassicas (orthogonal contrast, $p < 0.1$) in fall during the second year of the study. Among the Brassicas, forage radish had the greatest root dry matter. Only the large fleshy roots in the upper 15 cm of soil were measured. The dry matter ratio of the shoot to that of the fleshy root varied among and within Brassica cover crops and ranged from approximately 5:1 to 1:1. Approximately 10 to 50% of the forage radish fleshy root tissue was located above the soil surface (data not shown). Root and shoot tissues were easily distinguishable from one another by morphology and color. Root dry matter was not determined for rye.

Rape and rye shoot dry matter in spring did not differ significantly for any individual site-year (Table 2). Rape and rye shoot dry matter averaged 3900 kg ha^{-1} at CMREC2 and 2050 and 6350 kg ha^{-1} for WREC1 and WREC2, respectively, in spring. Rape root dry matter was 1532 and 2841 kg ha^{-1} for CMREC2 and WREC2, respectively. Rape root dry matter was not collected at WREC1 in spring. Dry matter was not sampled in spring for the forage radish because the plants died during the winter and rapidly decomposed throughout early spring.

Within each fall season, concentrations of N in shoots at each site did not differ between the Brassicas and rye. However, compared with fall 2003, shoot tissue N concentrations averaged across all cover crops were nearly two times higher in fall 2004 (36 mg N g^{-1} compared with 19 mg N g^{-1}) after the large organic N addition from soybean residues in August 2004 (Table 1). Root tissue N also was higher in fall 2004 but varied between sites, with higher values at CMREC2 (28 mg N g^{-1}) compared with WREC2 (16 mg N g^{-1}). Nitrogen concentrations in rape and rye tissue were lower in spring (Table 2) with rape shoots (17 mg N g^{-1} N; average of WREC1 and WREC2, 26 mg N g^{-1} at CMREC2) containing greater N than rye shoots (15 mg N g^{-1}; no difference between sites). Rape roots at CMREC2 (14 mg N g^{-1}) were twice as concentrated in N as rape at WREC2 (7 mg g^{-1}) in spring 2005.

Nitrogen uptake by Brassica shoots at WREC2 was significantly greater than by rye shoots (orthogonal contrast; $p < 0.03$). Nitrogen captured in the sampled roots in fall 2004 was

Table 1. Dry matter and N uptake of plants sampled near maximum growth in fall 2003 (following corn) and 2004 (following soybeans) at University of Maryland Central Maryland Research and Education Center-Beltsville facility (CMREC) and Wye Research and Education Center (WREC). Root samples were of the main portion of the Brassica taproot.

	2003				2004			
	CMREC		WREC		CMREC		WREC	
Cover crop	Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Root
Dry matter, kg ha^{-1}								
Forage radish	4650a†	1443a	2433a	2920a	3758a	2235a	4343ab	3843a
Oilseed radish	4912a	1580a	1993a	1580a	3700a	996b	–	-
Rape	–	–	2987a	1100a	3135a	639b	5053a	1413b
Rye	–	–	1974a	–	2859a	–	3210b	-
N content, mg g^{-1} tissue								
Forage radish	21.4a	18.4a	18.6a	11.5b	39.3a	31.2a	36.0a	16.2a
Oilseed radish	20.0a	16.6a	18.8a	12.7a	39.3a	28.6a	–	-
Rape	–	–	16.8a	12.4ab	35.7a	24.5a	34.2a	15.1a
Rye	–	–	23.9a	–	39.4a	–	30.8a	-
N uptake, kg ha^{-1}								
Forage radish	99.5a	27.3a	44.2a	33.5a	148a	69.7a	155ab	60.6a
Oilseed radish	97.8a	26.5a	36.6a	19.8a	145a	28.5b	–	-
Rape	–	–	49.6a	13.6a	111a	15.7b	171a	21.2b
Rye	–	–	42.6a	–	112a	–	99.0b	-

† Lowercase letters indicate significantly different means for each site and year ($p < 0.1$).

more than three times as great in forage radish than in rape. As measured in spring, shoot N uptake was similar for rape and rye within each site (Table 2). Sampled rape root tissue captured 20.5 kg N ha^{-1} in spring 2005.

Few differences between Brassicas and rye in dry matter production, N concentration, and N uptake were statistically significant within each individual site-year of the study. However, when these variables were averaged and compared across the 3 site-years in which Brassicas and rye were grown, forage radish and rape shoots had greater dry matter production and captured more N than rye shoots in fall (Table 3), with forage radish and rape shoots producing 41% greater dry matter and capturing 46% more N than rye in fall. In spring, averaged over the same three site-years, rye had slightly more dry matter, but rape tissues had significantly higher N concentrations and therefore surpassed rye in total N uptake (Table 3).

Cover Crop Influence on Soil Mineral Nitrogen

Cover crops had no effect on extractable NH_4–N in the soil profile during the course of the experiment, with the exception of fall at WREC2, when rye plots had 77.4 kg ha^{-1} NH_4–N compared with the Brassica and control plots (86.4–94.8 kg ha^{-1}) (data not shown). Seasonal and fertilizer effects were evident on the soil NH_4–N content. Ammonium-N in the soil profile during the first year of the study decreased from fall 2003 to spring 2004 but increased from fall 2004 to spring 2005.

Cover crop treatments significantly reduced soil profile NO_3–N in fall (Fig. 3 and 4) compared with control plots, with significant effects in several depth increments to 1.0 m depth. Cover crops apparently took up nearly all the nitrate from the profile, whereas in the control plots large amounts of nitrate had moved down to between 60 and 90 cm in the profile. This bulge of nitrate was most pronounced in the sandy soil (CMREC). In fall 2003, two nitrate bulges were found in the profile at CMREC, the first peaking at approximately 100 cm and the second at approximately 180 cm. In the control plots, the first nitrate bulge extended between 60 and 120 cm and contained a total of 55 kg ha^{-1} of NO_3–N, almost matching the amount of N applied as fertilizer in August 2003 and demonstrating how great the leaching potential is of this sandy soil. The second bulge, extending from 165 cm downward, was most likely comprised of N still moving downward from fertilizer applied to wheat the previous spring (Fig. 3). By spring in 3 of 4 site-years, soil NO_3–N in the upper profile (0–60 cm) had increased in control, forage, and oilseed radish plots, and plant uptake by rape and rye continued to maintain low soil profile NO_3–N (Fig. 3 and 4).

Brassica and rye cover crop plots contained significantly less soil NO_3–N than did control plots at CMREC (Fig. 3 and 4). In fall, radishes were able to take up more N and deplete the soil profile of NO_3–N more efficiently than rape and rye. As the radishes decomposed, mineral N was released into the surface soil (0–60 cm) during the spring, where it could be available for the following crops. Rape and rye continued to capture and store N throughout the spring. Control plots lost N from the soil profile throughout fall and spring, presumably by leaching.

Table 2. Dry matter and N uptake of plants sampled near maximum growth in spring 2004 and 2005 at Univ. of Maryland Central Maryland Research and Education Center-Beltsville facility (CMREC) and Wye Research and Education Center (WREC). Root samples were of the main portion of the rape taproot.

	2004		2005			
	WREC		CMREC		WREC	
Cover crop	Shoot	Root	Shoot	Root	Shoot	Root
Dry matter, kg ha^{-1}						
Rape	2630a†	–	3140a	1532	6470a	2841
Rye	2530a	–	4660a	–	6220a	–
N content, mg g^{-1} tissue						
Rape	16.2a	–	26.6a	14.2	18.1a	6.89
Rye	15.0b	–	16.1b	–	13.9b	–
N uptake, kg ha^{-1}						
Rape	41.3a	–	84.3a	21.5	118a	19.6
Rye	37.8a	–	73.2a	–	83.7a	–

† Lowercase letters indicate significantly different means for each site and year ($p < 0.1$).

Table 3. Shoot dry matter production, N content, and N uptake of two Brassica crops (forage radish and rape) compared with rye over 3 site-years.

	Fall			Spring	
	Forage radish	Rape	Rye	Rape	Rye
Dry matter, kg ha^{-1}	3560a†	3710a	2570b	4080b	4470a
N content, mg g^{-1} tissue	32.0a	29.0a	31.0a	20.0a	15.0b
N uptake, kg ha^{-1}	119a	111ab	78.6b	81.1a	64.9b

† Lowercase letters indicate significantly different means ($p < 0.1$).

Nitrate in Soil Pore Water

Nitrate in soil pore water sampled from cover crop plots varied between sampling years at CMREC, but low concentrations were maintained throughout each spring at WREC. In spring 2004, NO_3–N concentrations in subsoil pore water samples were low (<2 mg L^{-1}) and were unaffected by crop treatments at either site (Fig. 5). In spring 2005, subsoil pore water NO_3–N concentrations at CMREC2 were markedly affected by the cover crop treatments (Fig. 5). At CMREC2, when pore water sampling began on 5 Feb. 2005, pore water NO_3–N in all the cover crop plots was significantly lower than in the control plots. Thereafter, pore water NO_3–N in the CMREC2 control plots followed a declining trend, whereas that in the forage radish plots increased during March and April. In the rape and rye plots, pore water NO_3–N was low (0.06–0.25 mg L^{-1}) for all sample dates. The spring 2005 pore water NO_3–N levels at WREC2 were similar to those at CMREC2 except that the levels in the forage radish plots were not increasing and averaged 0.602 mg L^{-1} throughout the sampling period. Rape and rye plots at WREC2 averaged 0.052 mg L^{-1} of pore water NO_3–N, whereas that in the control plots was much higher, averaging 3.94 mg L^{-1}.

Discussion

Cover crop growth cycles were inextricably coupled to N cycling in the soil. As expected, crops that did not die in winter continued to capture NO_3–N from soil. The crops that died in winter decomposed and released N back into the soil. Following mowed soybeans, the cover crops captured larger amounts

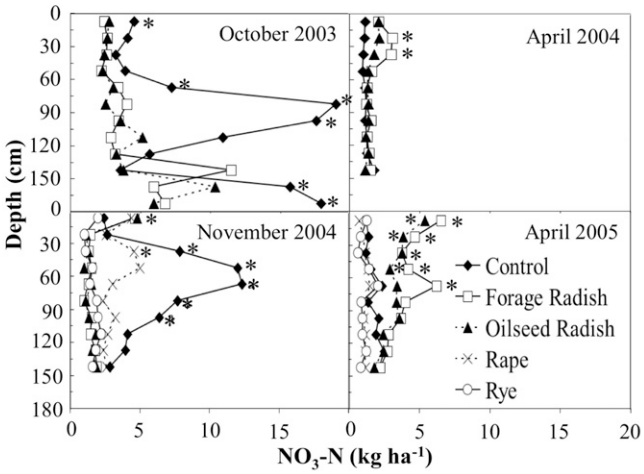

Fig. 3. Soil nitrate-nitrogen amounts for each 15-cm depth increment sampled at University of Maryland Central Maryland Research and Education Center-Beltsville facility from October 2003 through April 2005. *Significantly greater means than smallest mean within a depth increment ($p < 0.1$).

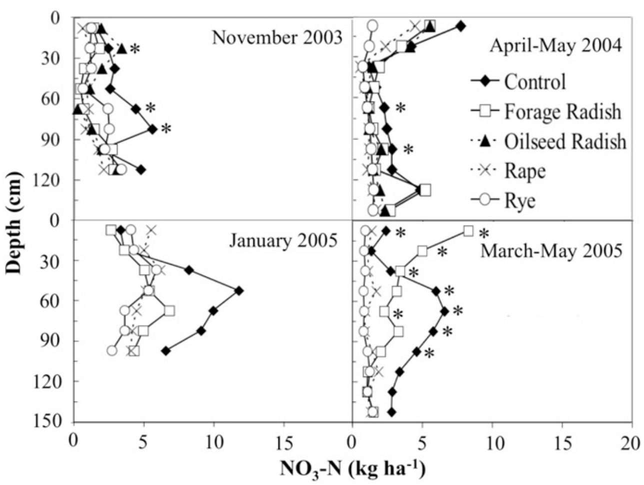

Fig. 4. Soil nitrate-nitrogen for each 15-cm depth increment sampled at Univ. of Maryland Wye Research and Education Center from November 2003 through May 2005. *Significantly greater means than smallest mean within a depth increment ($p < 0.1$).

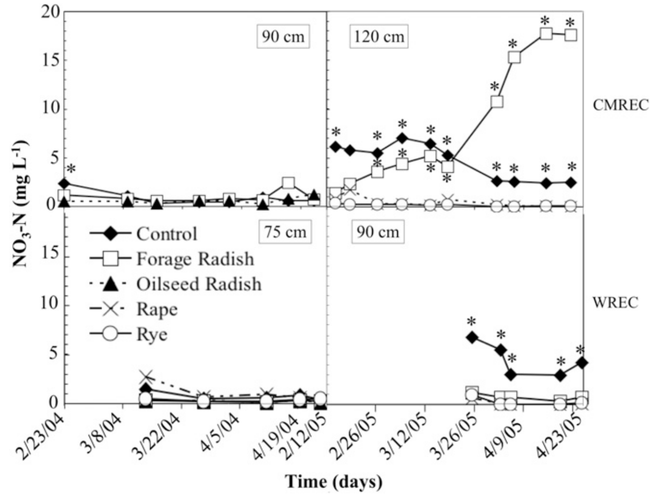

Fig. 5. Soil pore water nitrate-nitrogen at University of Maryland Central Maryland Reerach and Education Center-Beltsville facility (CMREC) and Wye Research and Education Center (WREC) in the spring of 2004 and 2005. Means from four lysimeters per treatment in spring 2004 and eight lysimeters per treatment (two per plot, four plots sampled) in spring 2005 are shown. Lysimeters were sampled weekly. Depth of lysimeter placement was 90 and 120 cm at CMREC and 75 and 90 cm at WREC in spring 2004 and 2005, respectively. *Significantly greater means than smallest mean for each date sampled ($p < 0.1$).

of N from the soil. The increased spring soil NO_3–N concentrations in radish plots were more pronounced and deeper in the profile in the second year than in the first year (Fig. 3). The mean temperature in January was 3°C warmer in 2005 than in 2004, probably increasing the rate of mineralization of the large supply of tissue and soil organic matter N. The higher January precipitation in 2005 (8.5 and 9.1 cm at WREC2 and CMREC2, respectively) would have increased the percolation rate and leaching of N compared with January 2004 (4.1 and 3.4 cm precipitation at WREC2 and CMREC2, respectively). The early appearance of NO_3–N in the surface soil of radish plots could be an agronomic advantage by providing early N fertility for spring-planted main crops. A soil profile depletion of available N by winter cover crops can be a problem for the N nutrition of the following main crops—a process termed "preemptive competition "by Thorup-Kristensen et al. (2003). Overwintering nonlegume cover crops, such as rye, can also reduce N availability to the following crop by microbial immobilization if termination occurs when their C/N ratio has increased above 30/1. However, on highly permeable, sandy soils, early N release from cover crop tissue may be problematic from an environmental standpoint. The data from spring 2005 show that on the sandy soil at CMREC2, NO_3–N concentrations in 120-cm-deep pore water increased dramatically in forage radish and control plots by early April. It is likely that much of this NO_3–N would have been lost to leaching from this soil before the roots of even an early-planted main crop could capture it. Weinert et al. (2002) noted a similar early N release from a freeze-killed mustard cover crop on sandy soils.

Tissue N concentrations were similar among the cover crops and between sites within each year. This is in agreement with Lainé et al. (1993) and Thorup-Kristensen (2001), who reported similar shoot tissue N concentrations for Brassicas and rye. However, tissue N concentrations for all covers were quite different between the 2 yr of our study. The high N environment induced by applying green soybean residues in 2004 resulted in much higher cover crop shoot N concentrations in that year (31–39 mg g^{-1}) than in the first year (18–22 mg g^{-1}) in which the covers were planted into relatively high C/N ratio corn residues. Although rye roots were not sampled in this study, in a follow-up study now underway (Guihua Chen and Ray Weil, personal communications, June 2008) biomass (to 15 cm depth) for rye roots was similar, and N concentrations (12.3 ± 0.24 mg g^{-1}) were only slightly lower than for forage radish roots (15.4 ± 0.54 mg g^{-1}) and rape roots (14.8 ± 0.38 mg g^{-1}) grown under the same conditions. In this study, rape roots (to approximately 15 cm depth) ranged from 22 to 30% of total shoot+root dry matter, a value comparable to the 24 to 29% reported by Lucas (2004) for rye roots measured just before cover crop termination in spring. Therefore, we believe it is likely that roots of rape and rye in our study contained similar amounts of N. Forage and oilseed radishes were much more variable in dry matter partitioning, with 23 to 62% of total dry matter as roots, which may in part be due to the highly variable size of the fleshy taproot of the radishes.

The Brassicas exhibited considerable flexibility in growth and the potential to take up large quantities of soil N in fall. The N uptake capabilities were especially evident in the N-rich soil environment following soybeans. Thorup-Kristensen (1993) also noted that N uptake by cover crops increased with increasing amounts of soil mineral N. This result is in contrast to the data of Schroder et al. (1996), who reported that the mass of N captured by rye shoots was related to fall temperatures but not to N availability.

We speculate that microbial immobilization of N stimulated by the presence of high C/N corn stover and wheat stubble combined with relatively low precipitation in spring 2004 caused the soil pore water to be lower in nitrate N in spring 2004 than in spring 2005. Likewise, spring soil mineral N measurements suggest that very little net mineralization of plant tissue N occurred between fall 2003 and spring 2004 at CMREC1 compared with the control plots, possibly due to microbial immobilization in conjunction with corn residue decomposition and low precipitation. Soil pore water data confirm that little NO_3–N was present in subsoil pore water during spring 2004, which is a marked contrast to pore water collected during spring 2005 at CMREC2 (Fig. 5).

Changes in mineral N in the finer textured soil at WREC2 differed from those at CMREC2. Finer textured soils are able to retain a greater amount of N than coarse soils like those at CMREC, as also observed by Beaudoin et al. (2005) in France. Elevated NO_3–N concentrations in pore water were not evident for the WREC forage radish plots, and soil NO_3–N amounts found in the upper 120 cm of the soil profile were consistent over the study year, although the location of highest concentration changed from fall to spring (Fig. 4). Increases in mineral N in the CMREC2 radish plots from fall to spring corresponded to approximately 64% of the N uptake of radish in fall. Increases in soil N in WREC2 radish plots were lower than in CMREC2 plots and corresponded to only 5% of the forage radish uptake at the time of spring sampling.

As compared with winter fallow, the Brassica cover crops and rye demonstrated significant potential for decreasing the quantities of NO_3–N lost from plant–soil ecosystems by leaching. However, certain species may be suitable only for specific sites and crop rotations. Rape and rye continue to capture and retain soil N into the spring and would be appropriate to use on coarse- and fine-textured soils with main crops planted in May or June. However, the release of N from decomposing forage and oilseed radish tissues in spring may cause high NO_3–N concentration in the subsoil pore water of very coarse textured soils (Fig. 5). In sandy soils, pore water N concentrations may be >10 mg NO_3–N L^{-1} as biological activity increases with warming spring weather and precipitation washes N deeper into the soil. Therefore, we recommend that an early-planted, N-demanding crop should be used after the freeze-killed radish cover crops on coarse textured soils.

Conclusions

All cover crops examined in this study decreased soil mineral N losses compared with winter weed control plots by storage of N in plant tissues throughout the fall and early winter. Plant N uptake by the Brassicas was greater than or equal to rye during fall, and average rape N uptake surpassed rye N uptake during spring. In early spring on the highly permeable sandy soil, subsoil pore water in radish plots was higher in NO_3–N than in the rape or rye plots, most likely because the radish was freeze-killed and was decomposing while the rape and rye were growing and taking up N.

Additional research is needed to determine the optimal agronomic management of these new cover crops in various types of cropping systems in the region. One of the agronomic limitations for the Brassica cover crops is the need for early planting. Farmers in the mid-Atlantic region have successfully planted Brassica cover crops after harvest of such crops as corn silage, small grains, and sweet corn. For use in the widespread corn grain–soybean rotations, more risky broadcast seeding into standing crop canopies may be an option.

The choice of cover crop should take into consideration the timing of N release in relation to the N demands of the subsequent crop and the impact of soil texture on the susceptibility of NO_3–N to leaching in fall and spring. The forage radish, a brassicaceous cover crop that freeze-kills in the mid-Atlantic region, releases N from plant tissues early in spring. Although this early N availability may provide an agronomic advantage for the summer crop, significant amounts of NO_3–N may be lost to leaching if a main crop is not planted early enough to recapture this N. Early planting of a subsequent summer crop is especially important to minimize spring leaching losses in coarse-textured, well- to excessively drained soils. Rape, which continues to capture soil NO_3–N until terminated in spring, may be a more appropriate choice of cover crop on coarse-textured soils when the summer crop will not be planted until late spring.

Acknowledgments

This study was partially funded by the Maryland Center for Agroecology, USDA NE-SARE program (grant LNE03-192) and by the Maryland Soybean Board. The authors thank Julie Hill for technical assistance in the lab and field.

References

Banwart, W.L., M.A. Tabatabai, and J.M. Bremner. 1972. Determination of ammonium in soil extracts and water samples by an ammonia electrode. Commun. Soil Sci. Plant Anal. 3:449–458.

Beaudoin, N., J.K. Saad, C. Van Laethem, J.M. Machet, J. Maucorps, and B. Mary. 2005. Nitrate leaching in intensive agriculture in northern France: Effect of farming practices, soils, and crop rotations. Agric. Ecosyst. Environ. 111:292–310.

Cataldo, D.A., M. Haroon, L.E. Shrader, and V.L. Youngs. 1975. Rapid colorimetric determination of nitrate in plant tissue by nitration of salicylic acid. Commun. Soil Sci. Plant Anal. 6:71–80.

Chesapeake Bay Program. 2004. Innovation in agricultural conservation for the Chesapeake Bay: Evaluating progress and addressing challenges. Scientific and Technical Advising Committee publication 04-003. Chesapeake Research Consortium, Inc., Edgewater, MD.

Coale, F.J., J.M. Costa, G.A. Bollero, and S.P. Schlosnagle. 2001. Small grain winter cover crops for conservation of residual soil nitrogen in the mid-Atlantic coastal plain. Am. J. Alternative Agric. 16:66–72.

Devera, E.R., B.P. Simmons, R.D. Stephens, and D.L. Storm. 1980. Samplers and sampling procedures for hazardous waste streams. Environmental Protection Agency-600/2-80-018. USEPA, Cincinnati, OH.

Fageria, N.K. 2007. Green manuring in crop production. J. Plant Nutr. 30:691–719.

Feyereisen, G.W., B.N. Wilson, G.R. Sands, J.S. Strock, and P.M. Porter. 2006. Potential for a rye cover crop to reduce nitrate loss in southwestern Minnesota. Agron. J. 98:1416–1426.

Fisk, J.W., O.B. Hesterman, A. Shrestha, J.J. Kells, R.R. Harwood, J.M. Squire, and C.C. Sheaffer. 2001. Weed suppression by annual legume cover crops in no-tillage corn. Agron. J. 93:319–325.

Isse, A.A., A.F. Mackenzie, K. Stewart, D.C. Cloutier, and D.L. Smith. 1999. Cover crops and nutrient retention for subsequent sweet corn production. Agron. J. 91:934–939.

Jackson, L.E., L.J. Wyland, and L.J. Stivers. 1993. Winter cover crops to minimize nitrate losses in intensive lettuce production. J. Agric. Sci. 121:55–62.

Kristensen, H.L., and K. Thorup-Kristensen. 2004. Root growth and nitrate uptake of three different catch crops in deep soil layers. Soil Sci. Soc. Am. J. 68:529–537.

Lainé, P., A. Ourry, J. Macduff, J. Boucaud, and J. Salette. 1993. Kinetic parameters of nitrate uptake by different catch crop species: Effects of low temperatures or previous nitrate starvation. Physiol. Plant. 88:85–92.

Lucas, S.T. 2004. Evaluation of labile soil carbon test for prediction of soil productivity response to organic matter management. M.S. thesis. Univ. of Maryland, College Park, MD.

Meisinger, J.J., W.L. Hargrove, R.L. Mikkelson, J.R. Williams, and V.W. Benson. 1991. Effects of cover crops on groundwater quality. p. 57–63. *In* W.L. Hargrove (ed.) Cover crops for clean water. Soil and Water Conservation Society, Ankeny, IA.

Pionke, H.B., W.J. Gburek, and A.N. Sharpley. 2000. Critical source area controls on water quality in an agricultural watershed located in the Chesapeake basin. Ecol. Eng. 14:325–335.

SAS Institute. 2005. SAS Release 9.1. SAS Institute, Cary, NC.

Sainju, U.M., and B.P. Singh. 1997. Winter cover crops for sustainable agriculture systems: Influence on soil properties, water quality, and crop yields. Hortic. Sci. 2:21–28.

Schroder, J.J., W.V. Dijk, and W.J.M. De Groot. 1996. Effects of cover crops on the nitrogen fluxes in a silage maize production system. Netherlands J. Life Sci. 44:293–315.

Shipley, P.R., J.J. Meisinger, and A.M. Decker. 1992. Conserving residual corn fertilizer N with winter cover crops. Agron. J. 84:869–876.

Staver, K.W., and R.B. Brinsfield. 1998. Using cereal grain winter cover crops to reduce groundwater nitrate contamination in the mid-Atlantic coastal plain. J. Soil Water Conserv. 53:230–240.

Technicon Industrial Systems. 1977. Technicon autoanalyzer ii, Industrial Method no. 487-77a. Technicon Industrial Systems, Tarrytown, NY.

Thorup-Kristensen, K. 1993. The effect of nitrogen catch crops on the nitrogen nutrition of a succeeding crop: I. Effects through mineralization and pre-emptive competition. Acta Agric. Scand. Section B 43:74–81.

Thorup-Kristensen, K. 1994. The effect of nitrogen catch crop species on the nitrogen nutrition of succeeding crops. Fert. Res. 37:227–234.

Thorup-Kristensen, K. 2001. Are differences in root growth of nitrogen catch crops important for their ability to reduce soil nitrate-N content, and how can this be measured? Plant Soil 230:185–195.

Thorup-Kristensen, K., J. Magid, and L.S. Jensen. 2003. Catch crops and green manures as biological tools in nitrogen management in temperate zones. Adv. Agron. 79:227–302.

Thorup-Kristensen, K., and N.E. Nielsen. 1998. Modeling and measuring the effect of nitrogen catch crops on the nitrogen supply for succeeding crops. Plant Soil 203:79–89.

Veihmeyer, F.J. 1929. An improved soil sampling tube. Soil Sci. 27:147–152.

Vos, J., and P.E.L. Van Der Putten. 1997. Field observations on nitrogen catch crops: I. Potential and actual growth and nitrogen accumulation in relation to sowing date and crop species. Plant Soil 195:299–309.

Vos, J., and P.E.L. Van Der Putten. 1998. Field observations on nitrogen catch crops: II. Root length and root length distribution in relation to species and nitrogen supply. Plant Soil 201:149–155.

Vos, J., and P.E.L. Van Der Putten. 2004. Nutrient cycling in a cropping system with potato, spring wheat, sugar beet, oats, and nitrogen catch crops: II. Effect of catch crops on nitrate leaching in autumn and winter. Nutr. Cycling Agroecosyst. 70:21–31.

Weinert, T., W.L. Pan, M.R. Moneymaker, G.S. Santo, and R.G. Stevens. 2002. Nitrogen recycling by nonleguminous winter cover crops to reduce leaching in potato rotations. Agron. J. 94:365–372.

Weil, R., and A. Kremen. 2007. Thinking across and beyond disciplines to make cover crops pay. J. Sci. Food Agric. 87:551–557.

Williams, S.M., and R.R. Weil. 2004. Crop cover root channels may alleviate soil compaction effects on soybean crop. Soil Sci. Soc. Am. J. 68:1403–1409.