FINAL REPORT

Multiple Benefits from Brassicaceous Cover Crops and Cover Crop Mixtures: Making Cover Crops Pay in the Chesapeake Bay Region

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Abbreviations: nitrogen (N); total soluble organic N (TSON); WREC (Wye Research and Education Center); CMREC (Central Maryland Research and Education Center); LESREC (Lower Eastern Shore Research and Education Center); Beltsville (USDA /ARS Wallace Agricultural Research Center); RCB (Randomized Complete Block), C:N ratio (ratio of carbon to nitrogen content in plant tissue).

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EXECUTIVE SUMMARY

Winter cover crops can substantially reduce nitrogen loading from cropland to the Chesapeake Bay. Cover crops are also known to reduce soil erosion and lessen runoff of sediment and phosphorus from cropland. However, these effects may not directly allow the farmer to recover the costs of growing cover crops. Therefore, despite research, promotion, and subsidy initiatives, adoption of cover cropping on Maryland farms remains too low to meet the State's environmental objectives.

This project focused on tap-rooted cover crop species in the Brassicaceae family, namely forage radish (*Raphanus sativa* L.), rapeseed or canola (*Brassica napus* L.) and mustards (all referred to herein "Brassicas"). The Brassica cover crops are relatively new to Maryland, but research elsewhere suggests their potential to provide a range of specific benefits to the farmer in addition to the societal benefits of reduced erosion and nitrogen loss. Cover crops in this family reportedly may be able to increase crop yields or reduce production costs by helping farmers overcome limitations due to soil compaction (replacing expensive and environmentally damaging deep tillage), recycling nitrogen to crops (reducing required N fertilizer purchase) nematode infestation (replacing fumigation) and weed competition (replacing some cultivation or herbicide application). Other beneficial effects, such as improved soil surface structure and formation of water-conserving mulch, were also expected, but are not unique to this family of plants.

The field research evaluated the degree to which Brassica cover crops can provide benefits to farmers as well as capture residual soil nitrogen in fall before it can leach to groundwater. The overall aim was to offer farmers sufficient direct economic benefits to encourage wider voluntary use of water-quality enhancing cover crops. During the course of the project the work focused increasingly on forage radish, one of the five Brassica cover crops originally included in the study. We early-on observed that forage radish offered a unique suite of characteristics that appealed to farmers, namely extremely rapid and deeply rooted growth in fall, vertical taproots that create large holes in the surface soil and smaller channels that deeply penetrate the subsoil, reliable frost killing in Maryland, and rapid residue decay which leaves little surface residue by spring planting time. Of all the Brassica cover crops studied, forage radish was the one most spontaneously adopted by farmers who had contact with our research.

The potential of the cover crops to reduce N leaching from cropland in the Mid-Atlantic Region was assessed by studying extractable mineral N ($NH_4 + NO_3$) N in the soil profile (upper 105 to 180 cm) as well as nitrate-N (NO_3-N) and total dissolved nitrogen (TN) in the soil porewater near the bottom of the root zone (75 to 120 cm) in plots cover cropped with forage radish, oilseed radish, rapeseed, rye and winter weeds (control) at two Maryland coastal plain locations, Central Maryland Research and Education Center (CMREC) and Wye Research and Education Center (WREC), from August 2003-May 2005. In addition, N uptake in the plant biomass was studied at these and several other locations and time periods. Rye was included in most studies as the current standard cover crop for comparison. The results show that rape and forage radish were as effective as rye at capturing residual N in fall. In fact, when averaged across sites both rape and forage radish exhibited significantly greater N uptake than rye. Rape had a similar pattern of N capture as rye in spring, but apparently released its N more rapidly and with less tendency to immobilize N if grown into the reproductive stage. Rape was, however, more difficult to kill than rye, either by tillage or by herbicide sprays. Among the cover crops studied, forage radish tended to show the greatest fall capture of N. In addition, in both laboratory incubations and field studies, forage radish and rape residues decomposed and released their N more rapidly than rye.

The rapid N release from the freeze-killed forage radish residues appeared to be agronomically advantageous, increasing early season N availability. The spring N boost was reflected in more rapid growth of subsequent corn and soybean crops and suggests that less N fertilizer might be necessary to grow corn after radish than corn after rye (a hypothesis not tested in the project). On the finer textured soil (Matapeake silt loam) there was no evidence that this released N was subject to leaching loss in spring. However, in one of the four site-years that leaching was studied (2004/2005 on the extremely sandy soils of CMREC) soil porewater data did suggest N was leaching before planting time in spring. The field conditions (high rainfall and N soybean residue) associated with this leaching, as well as lab incubation data, suggest that leaching would not be a problem where high carbon residues such as corn stubble were present from the previous crop. Based on our limited data, we recommend that a nitrogen-demanding crop be planted as early as possible in spring to re-capture the released N if forage radish is used as a cover crop on sandy soils containing high amounts of residual nitrogen. Fortunately, the radish cover crops allowed soil to warm more rapidly than soil under a living cover crop (rye or rape), thus allowing earlier planting.

The results also suggest that Brassica cover crops, especially forage radish, can provide sufficient other benefits to make them attractive for farmers to use, even without subsidies. The rapid N release for crops in spring just mentioned is a valuable effect that may save money on fertilizer and increase yields. Use of forage radish as a cover crop resulted in marked changes to the weed ecology, including a distinct suppression of horseweed (a troublesome weed that has developed resistance to glyphosate). Nearly complete early spring weed suppression by the forage radish may save the cost of a burn down herbicide application before spring planting. This effect, combined with the earlier soil warm-up in spring than observed with the other cover crops, may make no-till planting possible in organic farming systems that cannot use most herbicides. These options have already been adopted by some farmers, but need further research.

Among the reputed attributes of the Brassicas which first led us to propose this project was the ability to alleviate soil compaction by forming deep root channels through dense soil layers. Our previous studies had shown that such "biodrilling" opens small (< 1mm) root channels through compacted layers and that roots of summer crops can follow these channels to access the underlying subsoil layers. This effect was studied for soybean and corn at CMREC. Both crops sent more roots into the subsoil where forage radish had been grown than where rye or no cover had been used. In the last year of the project reporting period we initiated a new experiment in which we imposed compaction treatments. In this experiment we also determined that the number of forage radish roots reaching the subsoil was not affected by severe compaction, while the corresponding number of rye roots was drastically reduced. Taken as a whole, our field data, along with the experience of several collaborating farmers, suggests that forage radish has the potential to alleviate soil compaction and may be able to substitute for the use of deep ripping tillage.

None of the Brassica cover crops studied showed significant suppression of soybean cyst nematode or other plant parasitic nematodes at the Lower Eastern Shore Research and Education Center (LESREC). However, the cover crops at both LESREC and CMREC did have marked effects on the soil nematode community structure. For example, forage radish altered the community of beneficial nematodes in ways that favored the bacterial decomposition pathway and may have enhanced nutrient cycling. Although not formally a part of this research project, observations suggested that Brassica cover crops may be effective for soil phosphorus removal, and may influence mycorrhizal fungi and soil borne plant diseases.

In about half of the site-years in which good cover crop stands were established, cover crop treatments -- especially the forage radish -- resulted in significantly higher summer crop yields. The forage radish is an attractive investment for farmers who can get it planted sufficiently early in fall. Some dairy farmers have adopted forage radish after corn silage and report promising results. Our research suggests that the Brassicas offer new tools to capture N in certain situations. We are not suggesting that Brassicas can replace rye as the principle cover crop in grain rotations. Though rape can be planted later in fall than radish, both radish and rape need to be planted earlier than rye to be effective. Aerial seeding into maturing corn or soybeans in early September can be fairly reliable, but not as effective as drilling into an open field. The most practical situations for establishing radish may be in vegetable rotations and after corn silage harvest. Even where they can be conveniently established, we suggest rotating cover crops rather than using the Brassicas continuously year after year.

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SECTION I - BACKGROUND AND LITERATURE REVIEW

Cover crops are viewed by many scientists as an essential tool in managing farmland for long-term sustainability (Fageria et al., 2005 Sauve et al., 1998). A considerable amount of cover crop research was conducted in Maryland and the mid-Atlantic region during the past two decades. Most of this research focused on just a handful of cover crop species, mainly on cereal rye and hairy vetch, which were found to be well adapted to the region's climate and cropping systems. Most cover crop research in Maryland has been directed toward the use of these cover crops for capturing residual mineral nitrogen (N) before it can leach away in the fall (Coale et al., 2001; Shipley et al., 1992; Clark et al., 2007). Extensive research on Maryland's Eastern Shore has demonstrated the ability of a rye cover crop to greatly reduce the loss of N to groundwater from conventionally fertilized corn in no-till production systems (Brinsfield and Staver, 1992; Staver and Brinsfield, 1998). Relatively little has been done to demonstrate direct benefits to the farmer from the use of cover crops.

An easily quantified economic benefit of cover crops is their ability, under some conditions, to replace most or all of the fertilizer N needed for optimal production of corn or other nitrogen demanding crops. Legume cover crops can provide N for crop production by means of biological N-fixation followed by mineral N release when the cover crop residues decompose (Blevins et al., 1990; Holderbaum et al., 1990). In a somewhat non-realistic experiment on a continuous no-till corn system using a new site each of three years, a hairy vetch cover crop enhanced the efficiency of N fertilizer and increased profitability compared to using winter wheat or just corn stubble for winter cover (Hanson et al., 1993). However, most research has shown that it usually costs as much to grow and manage a hairy vetch cover crop as the value of the N fertilizer it saves, so profitability has not consistently been improved by using the legume cover crops for N (Frye et al., 1985; Shurley, 1987; Clark et al., 2007) and few large farms have adapted legume cover crops for their nitrogen supply to corn and other grain crops (Hoyt et al., 2004).

Farmers are generally unaware that cover crops have much more to offer than N fixation and environmental benefits to society. Under specific circumstances, certain cover crop species have been noted for their ability to provide rooting channels through compacted soils (Rosolem et al., 2002), prevent soil erosion (Sauve et al., 1998), capture leachable nutrients (Coale et al., 2001), increase organic matter and improve soil structure (Sauve et al., 1998), enhance biological diversity and activity (Mendes et al., 1999), and suppress weeds, nematodes, and pathogens (Grossman, 1993). We propose that if farmers can obtain the combined value of two or three such benefits, they will then regard cover crops as a profitable farming practice worth adopting, even without subsidies.

In recent years, evidence has been reported that Brassica cover crops have the potential, under appropriate conditions, to benefit farmers in multiple ways that, added together, may provide significant economic incentives for adoption of cover cropping. While Brassica cover crops may be adopted for their other benefits, Kristensen and Thorup-Kristensen (2004) noted that their rapid establishment and root growth in cool fall weather make the Brassicas especially well adapted to capture residual soluble nitrogen in the fall before this major water pollutant has a chance to leach below the root zone. They found that the forage radish rooted reached 1 m deep in the soil 25 days earlier in fall than was the case for winter rye. By early November they found roots of radish had reached 2.27 m while those of rye had reached 1.15 m. In an early Florida study (Volk and Bell, 1945), turnip reduced the volume of water leached between December and March by 46% and

[1] This report includes some excerpts from previous reports and from project publications listed on page 66.

combination of turnip with millet permitted 5.4 more inches of rain to fall before leaching occurred as compared to fallow soil. In a recent Canadian study (Isse et al., 1999), forage radish was the most effective cover crop studied for reducing the nitrate concentration in groundwater, bringing nitrates to less than 4 ppm compared to nearly 20 ppm under plots with no cover crop. Danish researchers (Thorup-Kristensen, 2001) found that deep rooting parameters of rye, ryegrass, and forage radish was closely correlated with nitrate uptake in deep soil horizons. Kristensen and Thorup-Kristensen (2004) and Thorup-Kristensen (2001) suggest that cover crop use of water reduces percolation available to carry away nitrates and that N uptake from the subsoil was more important to reduce N leaching losses than equivalent uptake from the surface soil.

The high N capture potential of Brassicas has also been studied in California (U of CA, 2001), where late November N content of cover crop root biomass was 58 kg/ha for oilseed radish and 19 kg/ha for rye. In California, Jackson et al. (1993) the N content (kg N/ha) of the above ground cover crop biomass in March was 70 for annual ryegrass, 116 for rye ('Merced'), 130 for phacelia, 145 for oilseed radish, and 170 for white mustard.

The low C: N ratio and rapid decay of Brassica cover crops suggest potential benefits from mixing Brassica cover crops with grasses (Meisinger et al., 1992; Weinert et al., 2002). Brassica cover crops are reported to have a similar capacity as rye to scavenge N (Sainju et al., 1998; Sainju and Singh, 1996; Justes et al., 1999; Vos and Van der Putten, 2001; Sieling et al., 1999; Stivers-Young, 1998). However, little was found in the literature regarding the N release rates of Brassica residues. Compared to rye, faster N mineralization from Brassica cover crop residues is expected because Brassica residues generally will have lower C/N ratios than that of rye when killed in spring. If N release from Brassica residues is rapid, the Brassica cover crops may overcome farmer concerns about competition for N between decaying cover crop residues and the cash crop. In early work in Denmark, Thorup-Kristensen (1994) suggested that N release from the Brassica cover crop residues may be more effective than from cereal rye residues. In that study, spring barley took up significantly more N by June when following forage radish (74 kg N ha^{-1}) and rape (68 kg N ha^{-1}) compared to rye (50 kg N ha-1). More recently, in a 4-year Georgia study, Schomberg et al. (2006) reported that the amount of N mineralized in 90 days (measured with in situ soil cores) was 1.3 to 2.2 times greater following black oat, crimson clover, and oilseed radish than following rye.

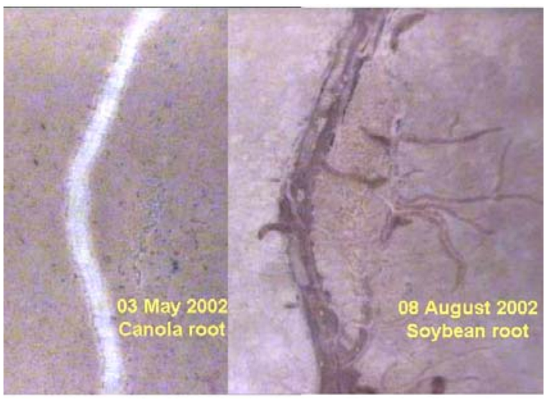

Figure 1 Minirhizotron images showing (left) a root of a Brassica cover crop (Canola) in a highly compacted Matapeake subsoil, and (right) a soybean root the following summer growing in the same root channel left by the Canola. From Williams and Weil (2004).

Subsoil compaction is a widespread problem in Maryland. According to United Soybean Board Director Glen Holland (a farmer from Pocomoke, MD), “unpredictable precipitation, excessive tillage and the use of heavy machinery over wet soils causes soil compaction for many farmers in this part of the country” (Hummel, 2002). Soil compaction restricts crop access to the water and nutrients stored in the deeper soil layers, resulting in serious yield losses, especially in dry years. In attempts to alleviate the

Figure 2 Holes left in a Glenelg soil after decay of winter-killed Forage Radish. Photo by R. Weil.

problem, farmers often resort to expensive deep ripping tillage. Reports from other parts of the world suggest that tap-rooted cover crops may be a less expensive, more environmentally friendly alternative to deep tillage for alleviating the effects of subsoil compaction (Yunusa and Newton, 2003). In California, Jackson et al. (1993) found that oilseed radish and other large taproot Brassica cover crops were more capable of loosening compacted soil than small grains. Brassica cover crops could be particularly suited for penetrating compacted soil because of their tap-rooted morphology (Materechera et al., 1992).

Researchers have hypothesized that roots growing in a wet season can create channels that roots of subsequent cash crops follow to grow through the compacted layer in summer when the soil is dry and hard (Cresswell and Kirkegaard, 1995). They termed this process "biological drilling" and the phenomenon was directly observed by Williams and Weil (2004) who used a minirhizotron camera to document cover crop roots making channels and soybean roots following those channels 4 months later (Figure 1). The cash crop can thus reach deeper water (and nutrient) resources (Unger and Kaspar, 1994). While there is little hard data on the effectiveness of Brassicas in penetrating compacted soils, preliminary observations in New York State suggest that, with good establishment and high biomass, white mustard has potential to "break through compacted soils" (Wolfe, 1998). Work in Brazil (Abreu et al., 2004) showed that "biological chiseling" (biodrilling) by Crotalaria roots had a greater effect on alleviating compaction (as measured by increased subsoil hydraulic conductivity) compared to mechanical chiseling.

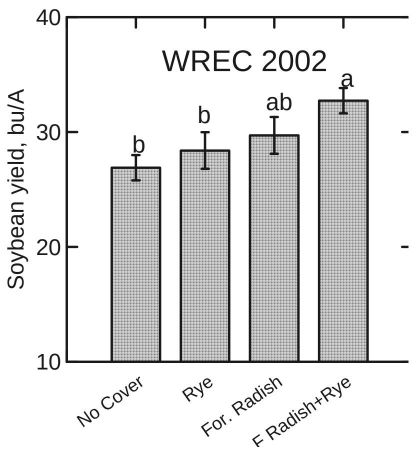

Figure 3 Effect of Forage Radish and Rye alone and in mixture on soybean yields at the Wye Research and Education Center, 2002. Deep ripping had no effect on yields. Williams and Weil (2004).

Prior to starting the current research, we had observed significant "biological" drilling in the surface soil where we planted a winter cover of forage radish on a no-till crop field that had been used the previous summer as a parking lot for nearly a hundred cars and trucks during a field day in wet weather (Figure 2). The large holes left by the decayed radish taproots might be expected to enhance rainwater infiltration and reduce runoff losses. Figure 3 shows results of a preliminary experiment conducted at WREC in 2002. The winter of 2001-2002 was the driest on record, and the soil profile never became as wet as is normal for the months of November-March. Therefore, the cover crop roots had relatively little opportunity to penetrate the compacted sub soil layer. Nonetheless, during the very dry summer of 2002, soybeans responded positively to the use of winter cover crops, especially the mixture of forage radish and rye (20% increased soybean yield). If a Brassica cover crop can alleviate the effects of soil compaction by "biological drilling", the farmer could save $18 to $30 /acre, the cost of custom deep ripping tillage, now in common use to counteract compaction (Johnson, 2001). If the farmer were considering the purchase of deep ripping equipment and a larger tractor to pull it, the savings would be much greater. This compares with cover crop seed costs of about $10 to $25 /acre.

Tissues of Brassica cover crops contain variable, but generally high levels of compounds known as glucosinolates (Carlson, 1987). When these plants are incorporated into the soil as a green manure, the glucosinolates can hydrolyze to produce isothiocyanates that exhibit fungicidal and nematicidal properties (Ettlinger and Kjaer., 1968). Rapeseed cover crops (*Brassica napus* and *B. campetris*) have been implicated in reducing densities of soil nematodes (Mojtahedi et al., 1991; Mojtahedi et al., 1993). For two consecutive years, planting Jupiter rapeseed in the fall and incorporating it in the spring as green manure limited *M. chitwoodi* damage on potato tubers in field experiments (Mojtahedi et al., 1993). In a California micro plot study, oilseed radish and white mustard were found to be effective trap crops for *Heterodera* (cyst) nematode (Gardner and Caswell-Chen, 1993). In a sugar-beet cropping system on loamy sand soils in Poland, sugar beet cyst-nematodes (*Heterodera schachtii*) were reduced by 40% after growing a white mustard cover crop, and by 41 - 48% after three oilseed radish cultivars. Work by Morra and Kirkegaard (2002) showed that soil pest control might be enhanced by selecting Brassica varieties containing high levels of glucosinolates and maximizing the maceration of the Brassica residues during soil incorporation in order to increase glucosinolate hydrolysis and subsequent release of the bio toxic isothiocyanates.

Kenworthy (personal communication, December 2002) estimated that 25% of Maryland's soybean acreage has yield-reducing infestations of soybean cyst nematodes. Nearly all Maryland cropland is infested with other parasitic nematodes (Sindermann et al., 1993). Root-knot nematodes (*Meloidogyne* spp.) can parasitize more than 2,000 species of plants including forage crops, small grains, fruits, vegetables, field crops, nursery crops, and turf grasses. This extremely wide host range makes them difficult to control by crop rotation. Nevertheless, on-farm research in Washington State showed that potato yields were not statistically different in an on-farm trial where nematodes were controlled by metham sodium fumigation or by use of a preceding white mustard cover crop (McGuire, 2001; Nowakowski and Szymczak-Nowak, 1998). Planting 'Jupiter' rapeseed in the fall and incorporating it in the spring as a green manure limited *M. chitwoodi* damage on potato tubers (Mojtahedi et al., 1993). Little such research has yet been done in Maryland, but preliminary results in Pennsylvania (Halbrendt, 1992) suggest that white mustard, black mustard, and rapeseed were generally as effective as commercial nematicides in suppressing dagger nematode in fruit crop systems. Recent research at the University of Maryland found some root knot and lesion nematode suppression by regularly rotating with sorghum sudangrass with susceptible vegetable, but that project did not study Brassica winter cover crops (Kratochvil et al., 2004).

Brassica species also contain phytotoxic (allelopathic) chemicals that can suppress weeds. While the exact mechanisms are not clear, and the effects differ widely among Brassica species and cultivars, numerous studies have shown that dramatic suppression of weeds can occur with Brassica cover crops. For example, incorporation of rape (Brassica napus) residue inhibited emergence and biomass of annual grassy weeds (Purvis et al., 1985). Research shows that the concentration and potency of the allelopathic compounds depend on environmental conditions and plant maturity at the time of cover crop kill. Petersen et al. (2001) evaluated the allelopathic potential of isothiocyanates (ITC) released by turnip-rape mulch and demonstrated strong suppression of germination in numerous weed species, including spiny sowthistle (Sonchus asper), smooth pigweed (*Amaranthus hybridus*), barnyardgrass (*Echinochloa crusgalli*), and blackgrass (*Alopecerus myosuroides*). They postulated that ITC interacted with weed seeds in the soil solution and as vapor in soil pores. In a Washington state study (Boydston and Vaughn, 2002), rapeseed incorporated just before flowering and one month before potato planting, reduced weed density by 73% in the middle of the potato growing season, and reduced weed biomass by 50% by the end of the season. The authors stated that the rapeseed provided commercially acceptable weed control without any other control measure in one of the two study years. Even more dramatically, a cover crop of rape and mustard in an Ohio field planted to foxtail and redroot pigweed reduced foxtail biomass production 93-98% (Holtz, 2001). Much research is yet needed to understand the effectiveness of weed control provided by various Brassicas cultivars in relation weed species, cover crop biomass, and method of kill.

Several studies have examined the effect of cover crops in the *Brassica* family on weed suppression with a range of results. Krishnan et al. (1998) found rapeseed and mustard green manure species to reduce the emergence and biomass production of kochia, shepherd's-purse, redroot pigweed, and green foxtail in subsequent soybean crops under both greenhouse and field conditions without negative impacts on soybean emergence or yield. Boydston and Hang (1995) found rapeseed cover crops to reduce weed biomass by up to 96% in subsequent potato crops compared to fallow treatments under field conditions. However, other studies reported no reduction in weed biomass following rapeseed and white mustard in green pea compared to rye and winter wheat control treatments. Haramoto and Gallandt (2005) report only small reductions in redroot pigweed following yellow mustard.

This variation in the effect of cover crops in the *Brassica* family to reduce weed seed germination may relate to its most commonly proposed mechanism. Plants in the *Brassica* family produce secondary plant metabolites called glucosinolates. When plant residues decompose and glucosinolates are broken down, they form toxic products that are believed to inhibit weed seed germination by reacting with seed enzymes. The most common breakdown products are isothiocyanates. Several review articles have been published dealing with glucosinolates and their potential to control weeds, disease, insects, and nematodes. Petersen et al. (2001) were able to relate the concentration of isothiocyanates released by turnip-rape mulch to germination inhibition of scentless mayweed, smooth pigweed, barnyard grass, and blackgrass in Petri dish experiments.

We could find only one paper in the literature dealing with weed suppression by forage or oilseed radish as a cover crop, Charles et al. (2006), who investigated a celery production system on a Houghton muck soil in Michigan. They reported that in each of three years, the radish cover crop produced the greatest dry matter in fall and reduced early season weed biomass by 98%. Two other cover crops in the study, hairy vetch and cereal rye, reduced early season weed biomass by about 70%. The Michigan authors concluded that cover crops can improve weed management, reduce fertilizer needs and increase celery yields on muck soils, especially where herbicides are not used.

SECTION II - HYPOTHESES AND OBJECTIVES

We proposed that cover crops in the Brassica family, if properly selected and managed, can provide the farmer specific benefits that increase farm profitability, while simultaneously providing the environmental benefits required by Maryland's Chesapeake Bay restoration efforts and avoiding the negative cover crop impacts on cash crop production that growers associate with some cover crops.

Research Hypotheses

1. Brassica cover crops, such as forage and oilseed radish, mustard and rapeseed, when grown alone or in mixtures with winter cereals, can provide nitrogen capture and soil moisture conservation benefits comparable to those provided by the "traditional" cereal rye cover crop.
2. The C/N ratio of Brassica tissues will be more stable with age and their decomposition more rapid than rye, especially if allowed to grow into late April or early May, therefore Brassica cover crops, alone or in mixtures, will release available N from their residues more in synchrony with the requirements of spring planted cash crops.
3. The deep growing tap roots of certain Brassica cover crops will penetrate compacted subsoil layers during the winter, when the soil is wet and soft, leaving channels that cash crop roots will follow during the summer when the compacted layers are relatively dry and very hard.
4. Because of the glucosinolate compounds in their roots and foliage, appropriate Brassica cover crops, alone or in mixture, will reduce plant parasitic nematode densities and crop infestations, thereby increasing cash crop yields.
5. Appropriate use of Brassica cover crops will suppress weeds through strong competition in fall and because they may produce compounds that suppress weed germination and growth.

Project Objectives:

1. Test hypotheses 1-5 and quantify the cover benefits described using field research plots at six sites.
2. Determine which species and mixtures can best deliver the specific benefits outlined in hypotheses 1-5.
3. Determine suitable agronomic practices for profitable, practical integration of Brassica cover crops and cover crop mixtures into major Maryland crop rotations.
4. Disseminate, through reports, newsletter articles and presentations at field days, information

on the initial results and on multiple benefits that farmers may obtain from cover crop systems under proper management.

SECTION III - MATERIALS AND METHODS

IIIA – FIELD EXPERIMENTS

Preliminary trials were begun in 2001/2002 at Wye Research and Education Center (WREC) and USDA Wallace Agricultural Center in Beltsville (BARC) under a Maryland Soybean Board grant. We began the project with a series of four field experiments, each repeated in at least two years. The location and soils at these four sites are described in Table 1. The main objectives and treatments associated with these experiments are described in Table 2. The original trial at WREC was continued, and three new "on-station" experiments were established under this project in fall 2003: one at Central Maryland Research and Education Center (the Hayden Farm or Beltsville Field Facility, CMREC), one at BARC and one at the Lower Eastern Shore Research and Education Center (LESREC, Salisbury, MD). In addition, in fall 2003, we collaborated with 3 commercial farmers to establish simplified, but still replicated, on-farm trials. The experiments conducted in fall 2003 were modified and expanded in fall 2004 to include two agronomic approaches to cover crop planting and to allow direct comparison of the Brassicas to rye (considered the standard cover crop in the region) at all four sites. The mustards never grew as well as the other Brassicas under our conditions and were dropped from most experiments. The rapeseed (rape) grew very vigorously, but proved difficult to terminate in spring. Rape was kept in most, but not all, of the experiments. Rye was originally included in only two of the studies, but was later added to most experiments to provide a common standard cover crop for comparison.

In Phase II, we brought these experiments to completion, and also established second, related experiments adjacent to the original experiments at LESREC, WREC and USDA Beltsville. Finally, we established several new experiments at USDA Beltsville and CMREC (Hayden) to focus on mechanisms underlying cover crop effects on weed suppression and interactions with soil compaction. Except for Exp. 1 at LESREC and some of the weed supression studies, each of the

Table 1 Description of field experiment site locations, soils, and cover crop seeding dates in 2003.

Facility Name	Location in MD (USA)	Soil series, phase and taxonomic classification	sand	clay	Org. matter		Soil acidity pH_{water}		Bulk density $g\ cm^{-3}$	
			mg g^{-1}							
			0-15 cm		0-15 cm	15-30 cm	0-15 cm	15-30 cm	0-15 cm	15-30 cm
BARC	Beltsville: 34°04' N; 72°92'W	Elkton silt loam (fine-silty, mixed, active, mesic Typic Endoaquult)	270	240	22	17	6.1	6.0	1.39	1.55
CMREC	Beltsville: 39°13' N; 76°86' W	Rosedale loamy sand (loamy, siliceous, semi active, mesic Arenic Hapludults) and Evesboro loamy sand (mesic, coated-lamellic Quartzipsamments)	780	60	14	6	5.5	5.6	1.45	1.65
LESREC	Salisbury: 38°36' N; 75°60' W	Hammonton loamy sand (coarse-loamy, siliceous, semi active, mesic, aquic Hapludults) and Galestown loamy sand (siliceous, mesic, psammentic Hapludults)	830	50	9	3	6.4	6.3	1.54	1.79
WREC	Queenstown: 39°13' N, 76°86' W	Mattapex silt loam (fine-silty, mixed, active, mesic Aquic Hapludults)	270	180	19	11	5.9	5.9	1.46	1.57

field experiments used a soybean-corn rotation. All experiments from 2003 to 2006 used the same cultivars, which were chosen to be glyphosate resistant to allow flexibility for weed observations early in the season. The soybean cultivar was 'NK/Syngenta S39Q4'. The corn cultivar was 'Pioneer' 34B62. Both cultivars were glyphosate resistant. Both crops were planted without N fertilizer or herbicide at planting time so that early season cover crop effects on weeds and N fertility could be observed. Weeds were controlled by over the top glyphosate spray (and N applied in the case of corn) at side-dress time, about1 month after planting.

The cover crops were no-till drilled into previous crop residues at CMREC and WREC, while a tilled seedbed was used at BARC and LESREC. The previous (2003) summer crops were potato and soybean at BARC, wheat at LESREC and CMREC and sweet corn at WREC, each being harvested before August, this allowing early planting of the cover crops into an open field. The cover crop treatments were planted in mid to late August (except the late planting at BARC). As soybean and corn crops are normally still green in August and early September when the Brassica cover crops need to be planted, some cover crop seeding in the fall of 2004 was planned to use broadcast over-seeding into the soybeans at leaf-yellowing. The latter seeding method was successfully used to establish good stands of Brassica in preliminary trials at WREC and Beltsville in fall 2002. This type of establishment was also tried in fall 2003 at a commercial scale by aerial seeding on two Farms in Kent County.

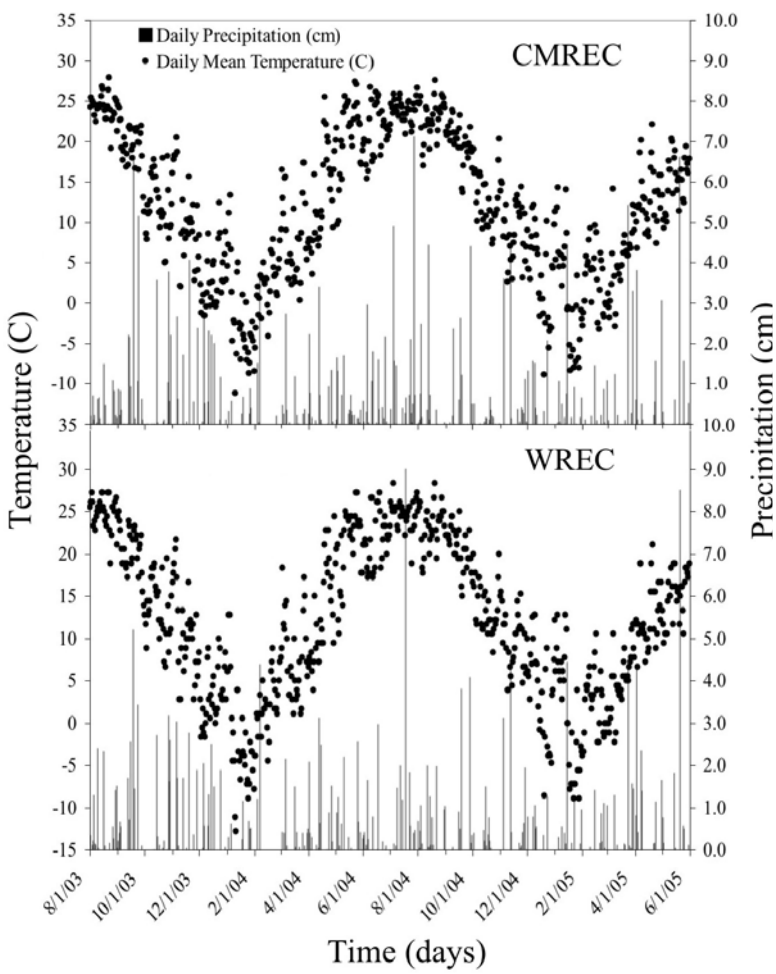

Figure 4 Daily mean temperature and daily precipitation at CMREC and WREC during the nitrogen release and leaching studies (1 Aug. 2003 through 31 May 2005).

Cover crop treatments, which varied among the experiments, included no-cover (winter weeds), rye alone, Brassica(s) alone, and Brassica(s) in mixture with 1/2 rate rye or with crimson clover. Brassicas to be evaluated included rapeseed (*Brassica napus,* cultivars 'Essex' and 'Humus'), forage radish (*Raphanus sativus, cultivar* 'Daikon'), oilseed radish (*Raphanus sativus, cultivar* 'Adagio'), and a mustard mix (*Brassica juncea+ Sinapis alba*). Each site had one or more of the following production limitations: subsoil compaction, parasitic nematode infestation, heavy weed pressure and/or high potential for nitrogen leaching. Nitrogen leaching was studied primarily at CMREC and WREC from 2003-2005 and the weather conditions for this period at those sites is shown in Figure 4. Neither of these sites had irrigation facilities. However, supplemental irrigation was used on several occasions at LESREC and USDA Beltsville where weed and nematode suppression were studied.

Experimental designs varied according to the objectives and logistical considerations. Baseline nematode, weed and compaction data obtained in fall 2003 were used in designing statistically efficient blocks, and these initial data were used as covariates to increase the power of some statistical analyses. For sites with suspected compaction, we created three-dimensional maps of soil bulk density, texture and/or penetration resistance to a depth of 45 cm. For sites suspected of harboring significant infestations of plant parasitic nematodes, maps of initial nematode densities were developed by transect sampling.

Table 1 Summary of field experiments conducted in the 2003-2006 growing seasons.

Site & Location	Site conditions	Cover crop treatments	Cover crop performance measures
BARC (USDA) Beltsville, MD	Severely compacted silt loam over clay; low levels of parasitic nematodes; heavy weed pressure. Irrigation is available.	Early and late plantings of forage radish, oilseed radish, rapeseed, mustard alone, forage radish with rye, no winter cover, and no-cover with deep subsoiling tillage in fall. Rye companion cover crop.	Compaction alleviation (root and water measures), weed suppression, moisture conservation, Nitrogen in biomass, soil profile and leachate.
CMREC (Hayden) Beltsville, MD	Moderate to severe subsoil compaction, loamy sand over sandy loam, moderate levels of parasitic nematodes.	Winter covers species: forage radish, oilseed radish, mustard, forage radish+ rye or no winter cover. Seeding methods: no-till drill, broadcast seeding; Kill methods: mow, herbicide, rolling chopper, disk incorporation.	Establishment, growth rate, fall and spring biomass, nitrogen in biomass, soil profile and leachate, kill efficiency, volunteering, residue decay rate, weed suppression.
LESREC (Salisbury, MD)	Very sandy soils, soybean cyst nematode infestation, compaction. Line source overhead irrigation is available.	Rapeseed (2 cultivars), Forage radish, Oilseed Radish, White & Brown mustard, each alone and in mixture with rye or clover, plus no cover, weed-free and rye-alone controls.	Nematode suppression, weed suppression, biomass, N-uptake, water conservation, biological pest control, N mineralization.
WREC Queenstown, MD	Severe subsoil compaction, silt loam over silty clay; moderate levels of parasitic nematodes.	Forage radish, oilseed radish, rapeseed, alone or in mixture with rye, rye alone, no winter cover, with or without deep subsoiling tillage in fall.	Compaction alleviation (root and water measures), nematode suppression, weed suppression, moisture conservation, Nitrogen in biomass, soil profile and leachate.
On-farm sites	Any two conditions: high nematodes, compaction, high leaching, susceptible weeds.	Two Brassica cover crops plus no-cover control, using 4 to 6 replications and farm machine scale plots.	Cover crops stand, spring biomass and N content; some nematode and weed counts, some subsoil water use.

The experiments described herein were conducted beginning in fall 2003 and continued, in some cases, through summer 2007, eventually providing some 16 site-years of data on cover crop performance and soil/cash crop response. Several studies are expected to continue as spin-off research through 2009. Details of each experiment are described below, followed by methods for analysis and sampling to evaluate the various hypothesized cover crop effects

<u>LESREC (Nematode and N cycling Objectives)</u>

<u>LESREC Exp. 1</u>

<u>Objectives:</u>

To screen a range of Brassica cover crop treatments (and the effects of mixing the Brassicas with a

Table 2. Cover crop combinations used as treatments in LESREC Exp. 1 in 2003-2004. This study focused mainly on nematode and nitrogen aspects of cover crops and cover crop mixtures.

	Non-Brassica Cover Crop		
	No non-Brassica	Rye	Crimson clover
Brassica Cover Crop	Treatment I.D. Number		
Mustard Mix	1	7	13
‘Essex Rapeseed	2	8	14
‘Humus’ Rapeseed	3	9	15
‘Daikon’ Forage Radish	4	10	16
‘Adagio’ Oilseed Radish	5	11	17
No Brassica Cover (weeds only)	6	12	18
No cover (weed free)	19		

legume or a winter cereal) for optimal agronomic performance, parasitic nematode suppression and N capture. The objective of including the nematode hosts, rye and clover, is to determine if the mulch benefits of rye and the N fixation benefits of clover can be realized without negating the Brassica nematode suppression.

<u>Treatments:</u>
There are 19 treatments as shown in Table 3: A factorial combination of 6 cover crops: {a mix of 2 types of Mustard (S*inapis alba* and B*rassica juncea*), 2 cultivars of Rapeseed (‘Dwarf Essex’ and ‘Humus’), Forage Radish, Oilseed Radish, and no-cover (weeds), and three species mixtures (alone or with cereal rye or with crimson clover)}. An additional control is a no-cover, weed-free treatment.

Experimental design
The experiment was set up with a factorial treatment structure, with 6 levels of Brassica cover crop and 3 levels of non-Brassica companion cover crop, and arranged in a randomized complete block design. The levels of Brassica cover crop included two cultivars of rapeseed (‘Humus’ and ‘Essex’), oilseed radish cv. ‘Adagio’, forage radish cv. ‘Daikon’ (also spelled Daikon), mustard mix (*S. alba and B. juncea*), and a no-cover control. The levels of non-Brassica cover crop included clover, rye, and no cover control. The treatments were replicated four times. A weed-free control (which was given an extra cultivation in fall to eliminate most winter weeds cover) was added to the 18 factorial treatments to give the 19 treatments shown in Table 3.

Primarily for logistical reasons and because of the availability of irrigation, the nematode suppression study originally planned for a field at Pemberton Park was established instead on Field #39 at the LESREC vegetable farm. Preliminary measurements were made using transects of soil samples to determine the spatial distribution of relevant soil properties for use in designing an effective blocking arrangement for this study (see Figure 17, page 32). Because no-till planting equipment was not available for use on this nematode-infested farm, and because tillage is still very common on the lower Eastern Shore, conventional tillage was used at this location throughout the project. The cover crop treatments were sown by seed broadcasting followed by cultipacking, cover crops were terminated by a combination of mowing and disk tillage, and then summer crops were sown with a conventional planter.

The experiment uses a randomized complete block plot design with four replications. Plots are 3 m wide (4 soybean rows) by 9 m long. The control treatments are no-cover (weeds), rye alone and no-cover (weed-free). Cover crops were killed near May 1 and soybeans (nematode susceptible variety) planted a week later as a test crop. Variables measured included: stand establishment, fall and spring ground cover, N capture and release, cover crop top and root biomass, soil nematode densities in fall, late spring and late summer (before harvest), spring and early summer weed cover, and soybean yields at maturity.

Cover crop seeds were broadcast by hand into bare tilled soil on 25 August 2003 and plots were then cultipacked to ensure good seed-soil contact. Seeding rates were 4.5 kg/ha mustard blend, 9 kg/ha rapeseed cultivars, 14.6 kg/ha radishes, 45 kg/ha for rye in combination, 126 kg/ha for rye alone, 34 kg/ha for crimson clover, and 17 kg/ha for crimson clover in combination. Cover crops were fertilized with 90 kg/ha N as ammonium sulfate and ammonium nitrate on 15 September 2003, to assure adequate nitrogen and sulfur nutrition for vigorous cover crop growth. A second application of 46 kg N/ha as ammonium sulfate was applied on 22 October.

Cover crop biomass in selected treatments was collected from 0.25 m^2 quadrats on 18 October 2003 and 28 April 2004. Cover crops were incorporated and killed with three passes of a disk harrow and a rear-mounted solid-wheel cultipacker on 28 April 2004. A soybean cyst susceptible, glyphosate tolerant soybean, cultivar 'NK/Syngenta S39Q4', was planted in 38 cm rows on 12 May 2004 at a seeding rate of 101 kg/ha. No further cultivation was performed after cover crop incorporation. To permit data collection on weed establishment, application of herbicide (N-(phosphonomethyl) glycine), at a rate of 0.96 L/ha active ingredient, was delayed until 15 June 2004. On 29 June 2004, a mixed fertilizer high in K was applied (36 kg N/ha, 22 kg P/ha, and 112 kg K/ha) in response to K deficiency symptoms on clover and low K levels on soil test reports.

On 15 September 2004 cover crop treatments for the second year were established by broadcasting seed into the standing soybean canopy (growth stage R7). Seeding rates were 50% higher than in 2003 to compensate for lack of soil incorporation. On 22 September, 59 kg/ha N as ammonium sulfate was broadcast onto these plots. On 18 October 2004 soybeans were combine-harvested over living cover crops. Grain subsamples were dried at 65˚C for determination of moisture content. Biomass was collected for winter-susceptible cover crops on 13 December 2004 from two 0.25 m^2 quadrats per plot. On 13 and 14 April 2005, the biomass was determined for winter-surviving cover crops and weeds and then plants were rotary mowed to 7.6 cm above the soil surface. All plots then received one pass of a chisel plow (15 cm deep) followed by 2 passes of a disk harrow with solid wheel cultipacker. On 10 May 2005 the plots were fertilized with 12 kg P/ha, 84 kg K/ha, 28 kg S/ha, 1 kg B/ha, tilled with two passes of the disk harrow, and sown with soybeans (same cultivar as previous year) in 38 cm rows at a rate of 500,000 seeds/ha. On 10 June 2004, herbicide (N-(phosphonomethyl) glycine) was applied at 0.62 L/ha active ingredient. In response to spider mite infestation, the pesticide cyhalothrin, lambda ((RS)-alpha-cyano-3-phenoxybenzyl 3-(2-chloro-3, 3, 3-trifluoropropenyl)-2,2,-dimethylcyclopropanecarboxylate) was sprayed at a rate of 0.03 L/ha active ingredient on 15 July 2004. Soybeans were harvested with a combine on 2 November 2005, nearly a month after maturity because of rain. Yield sub-samples were taken to the laboratory and dried at 65˚C for determination of moisture content.

LESREC Exp. 2.

Experiment 2 was located in the unused middle portion of the same field (#39) used for LESREC Exp. 1 and was also a randomized complete block design with plot size 3 x 9 m. Prior to planting, this area had been kept in fallow with repeated disking, since fall 2003. LESREC Exp. 2 included six cover crop treatments: mustard blend 'Caliente', rapeseed 'Essex', forage radish 'Daikon', oilseed radish 'Adagio', cereal rye 'Wheeler', and an unweeded control. On 27 August 2004, cover crops were broadcast seeded (same rates as in LESREC Exp. 1) into tilled soil and then cultipacked. A total of 100 kg N/ha as ammonium nitrate was broadcast by hand on 1 September and 22 September 2004 to assure vigorous cover crop growth and to allow evaluation of N uptake potential. Cover crop biomass was collected from 0.25 m^2 quadrats on 8-15 November 2004. Biomass collection of winter-surviving cover crops, and plot management was the same as in LESREC Exp. 1 in 2005 for the rest of the season, apart from planting of glyphosate tolerant corn 'Pioneer 34B62' on 9 May 2005 in 76 cm rows at a rate of 64,467 seeds/ha. Corn plots also received two applications of nitrogen at a rate of 67 kg N/ha on both 4 and 13 June. No herbicide was used until the glyphosate application on 4 June. Corn grain was harvested on 26 September 2004 with a combine.

WREC (Compaction alleviation and N capture and release objectives)
Site: Highly compacted, somewhat poorly drained soil (Mattapex silt loam) at University of Maryland's WREC.

WREC Exp. 1 design: Five cover crops grown alone (no cover, forage radish, oilseed radish, rapeseed and rye), and the mixture of forage radish + rye, plus two treatments with deep tillage (no-cover and rye), giving a total of 8 treatments. This treatment structure allowed the factorial comparisons of tillage x cover and of radish x rye treatment combinations (Table 4). Cash crops were a soybean /corn rotation that began in summer 2002 (soybean in 2002, 2004 and 2006, corn (sweet or dent) in 2003 and 2005). A randomized complete block design was used with four replications. Blocking was done taking into account soil spatial variability for compaction and drainage.

The site at WREC had a severely compacted subsoil layer at 20 and 40 cm soil depth, probably due to past field traffic and tillage mismanagement. This pattern of compaction is typical of much of Maryland cropland. Soil compaction at this site was spatially characterized using a recording cone penetrometer when the soil was uniformly wet.

WREC Exp. 2:
This experiment was initiated in fall 2004 on land adjacent to WREC Exp. 1. The experiment also used a corn/soybean rotation and a randomized complete block design with 4 replications. The corn in year 1 (summer 2005) was grown for silage and harvested in time for late August cover crop planting. Exp. 2 had only four treatments: 1) no cover crop; 2) rapeseed 'Essex'; 3) forage radish 'Daikon' and 4) rye 'Wheeler', all cover crops being drilled into crop residues in late August.

CMREC (HAYDEN FARM): Agronomic Practices, N Capture and Nematode Objectives
CMREC Exp. 1:
Objective regarding agronomic practices: To evaluate optimal sowing and killing methods for Brassica cover crops. Treatments: Winter cover species (5): forage radish, oilseed radish, mustard mix, forage radish + rye or no winter cover. Seeding methods (2): no-till drill, broadcast over-seeding; Kill methods (4) flail mow, herbicide (glyphosate), rolling stalk chopper, disk incorporation. Experimental design: Split block design with 4 replications; a factorial combination of cover crop species and kill methods as sub plots and seeding method as strip plots with re-randomization in each replication.
Summer cash crops followed a soybean/corn rotation beginning with soybean in summer 2004.

CMREC Exp. 2:
This experiment was initiated in fall 2004 using parts of the same field and the same four blocks as CMREC Exp. 1. Only the plots that had been used for broadcast seeding in fall 2003 were used. These plots were available because that seeding failed to produce a cover cop stand. The experiment used randomized complete block design with four replications and five

Table 3 Treatments included in WREC Exp. 1 on a compacted Mattapex silt loam. Bold treatment numbers are those used for N leaching studies. Gray shading indicates factorial treatment combinations for rye and radish.

Winter Cover	Tillage Applied: Completely No-till	Tillage Applied: Deep rip in fall†. No till planting.
	Treatment Combination No.	
Forage radish	**1**	--
Oil seed radish	2	--
Rapeseed (Canola)	**3**	--
Cereal rye	**4**	--
Forage radish + Rye	5	6
No cover (weeds)	**8**	7

cover crop treatments: 1) no cover crop, 2) forage radish 'Daikon', 3) oilseed radish 'Colonel', 4) rapeseed 'Essex', and 5) rye 'Wheeler' (in 2004) or 'common' (in 2005). Summer cash crops followed a soybean/corn rotation beginning with soybean in summer 2004.

Beltsville Experiments:
<u>Weed Suppression, Compaction Alleviation and N Capture objectives</u>
<u>Beltsville Exp. 1</u>
This experiment is a combination of two experiments originally proposed. It is located in the South Farm of USDA Beltsville Agricultural Research Center on a severely compacted, somewhat poorly drained Elkton silt loam. Extremely heavy and diverse weed pressure and severe compaction made this site appropriate for a combined compaction alleviation and weed supression objectives. Initially this experiment was also used to measure nitrogen uptake and profile depletion, but after finding high ammonium-N throughout the profile we investigated the history of the site, revealing excessive (~ 1000 Mg/ha) dairy manure applications in the 1980s, leading us to reject this site as inappropriate for N leaching studies.

This experiment used an incomplete factorial combination of 6 cover crop treatments (rapeseed, forage radish, oilseed radish and mustard, a rye-forage radish mixture, and no cover) and two planting dates (Table 5). In fall 2003, the planting dates were August 26 and September 10. For the cash crop in the following summer, the subplots were split between 10 weed-free and 10 unweeded sub subplot treatments. This gave a split-split plot design with four complete blocks; cover crops were the main plots, planting dates were the sub plots and weeding levels were the sub subplots in 2003-2004. The whole plot size was 12m x 30m. Sub subplots are 6m x 15m. A forage radish + rye mixture was planted instead of Mustard for the late planting (Table 5). Soybeans were planted in all plots the following May. In late May 2004, gypsum electrical resistance sensors were installed at 15 and 50 cm to monitor changes in soil water.

In the second year (2004-2005) the same plots were used but all were planted on 29 August 2004 with the sub plots being the presence or absence of rye as a mixed cover crop (Table 5). In fall 2004, the cover crops were interseeded into the standing soybean crop at first leaf yellowing using a hand spinner to simulate aerial seeding. The fall 2004 treatments are also shown in Table 5. Mustard, Rape, Forage Radish and a no cover control were included in a split plot design with half of each plot having rye (1/2 normal rate) included. For "aerial application" seed rates were increased to 8, 8, 18 and 120 lbs/A for Mustard, Rape, Radish and Rye, respectively.

Weed suppression and cover crop establishment were estimated by determinations of plant cover in late fall. Quadrats of the early-planted covers were harvested to determine dry matter and N uptake. Weed suppression potential was estimated by determination of plant cover in late fall.

Soil profile N was estimated from analysis of 15 cm increments of soil to 150 cm deep. Except for the surface increment of the no-cover plots, the mineral N content of the soil profile was low at the time of sampling and the cover crop treatment did not have a significant effect. It is possible that the bulk of the nitrate had already leached below the 150 cm depth of

Table 4 Treatments for Beltsville Exp. 1 on a compacted Elkton silt loam soil. Deep tillage was performed in fall 2003 and 2005.

Trt No.	Fall 2003Treatments	Fall 2004 Treatments
	Early seedbed & planting, 08/26/03	**Interseeded alone, 15/09/04**
1	Mustard mix	Mustard mix
2	Rapeseed	Rapeseed
3	Forage radish	Forage radish
4	No cover	No cover
5	No cover + deep tillage	No cover + deep tillage
	Late seedbed & planting, 09/10/03	**Interseeded, mixed with rye, 15/09/04**
6	Rapeseed	Mustard mix + Rye
7	Forage radish + Rye	Rapeseed + Rye
8	Forage radish	Forage radish + Rye
9	No cover	Rye alone
10	No cover + deep tillage	Rye alone + deep tillage

sampling by the mid-November sampling time.

Beltsville Exp. 2:
Because the 2004-2005 cover crops in the plots in the original experiment were to be interseeded into the standing soybean canopy at leaf yellowing, Exp. 2, a small new study, was established in the same field to allow us to continue to study the potential of the Brassicas when grown under optimal conditions. Exp. 2 consisted of a randomized complete block design with four cover crop treatments in plots 6 m wide by 15 m long: No cover, 'Essex' rapeseed, 'Daikon' forage radish, and 'Wheeler' rye.

The cover crop seed was drilled in mid to late August and the following spring the cover crops were terminated with glyphosate by the first week of May and soybean or corn planted as the plot in June 2005. The plots were instrumented with gypsum blocks to measure summer cash crop. One minirhizotron tube was installed in each soil water use at 15 and 50 cm depth. Cover crop dry matter production was measured in late October 2004, and crop grain yield was determined by a combine with yield monitor. Other measurements performed included installation of granular matrix electrical resistance sensors to monitor soil water content at 15 cm and 50 cm depths in the summer of 2005.

Beltsville Exp. 3:
A new study was established in fall 2005 in Field NE-11 consisting of five cover crop treatments in a randomized complete block design using 3 m x 15 m plot: No cover, forage radish, rye, rapeseed, and a mixed cover crop of forage radish + rye. The field was plowed and disked in summer 2005, but no-till managed thereafter. Soybean cultivar 'NK/Syngenta S39Q4' was planted on May 19 2006 in 16 cm rows. Minirhizotron tubes were installed to a depth of 36 cm in November 2005 for root observation in plots for the rye, rapeseed, no cover and forage radish treatments. Images were obtained on three dates in 2005-2006. Soil water at 15 cm and 50 cm depths was monitored during the period of June to August 2006 using 32 granular matrix electrical resistance sensors (Watermark sensors, Irrometer, Inc.) installed in 16 plots. The sensors were connected to 4 data loggers and read hourly. Cover crop dry matter production was determined on December 2005 by collecting two 0.25 m^2 quadrats per plot. Soybean yields were measured on October 16, 2006.

Beltsville Exp. 4:
In summer 2006 a new experiment was started in field NF2B to study the interactions between soil compaction and Brassica cover crops. Rather than simply observing cover crop effects on existing compaction conditions, this experiment imposed soil compaction treatments. The objectives were: (1) to evaluate effects of soil compaction on cover crop root penetration, (2) to determine effects of cover crops on the macro-porosity of compacted soil layers; (3) to quantify root penetration and subsoil water uptake of corn /soybean on compacted soils as influenced by winter cover crops. This field experiment used a 3 x 4 factorial treatment structure consisting of 3 compaction levels (none, medium and high) and 4 winter covers crop treatments (rye (*Secale cereale L.*), forage radish (FR, *Raphanus sativus* L), rapeseed (*Brassica napus*) and no cover). The three compaction treatments were created by driving a heavy front-end loader on soil irrigated to near field capacity. The entire plot area was wheel-trafficked by repeated passes: No Compaction – no pass; Medium Compaction –one pass (Wt: $1.19*10^4$ kg, force: $7.44*10^4$ Newtons) and Heavy compaction –two passes (medium compaction plus one additional pass with a load of 926 kg of gravel, force $8.02*10^4$ Newtons). The compaction treatments were imposed on August 18 and 21 2006. Prior to applying the compaction treatments, the whole field was moldboard plowed to 25 cm and deep ripped to 40 cm. After the compact treatments, the upper 7 - 8 cm was disk harrowed on 28 August 2006 to prepare a seedbed. The cover crops were drilled on the same day.

Bulk density was determined at 5 cm intervals by taking six 1.86 cm diameter cores per plot to 40cm depth and soil strength was determined at 5 cm intervals to 45 cm depth by making 10 insertions of a recording cone penetrometer (Spectrum Technologies, Inc.). On 8 and 11 December 2006, a hydraulic soil coring rig (Giddings Corp.) was used to collect three 6.4 cm diameter cores from the end of each plot to at least 55 cm depth. Each core was centered over a cover crop or weed plant, depending on the treatment. The cores were broken in the field at 5 cm intervals and live roots protruding from the upper and lower break surfaces were counted. The soil segments were then transported to the lab for collection of roots by washing and sieving procedures. On 1st November 2006, a golf course cup cutter was used to obtain 3 soil cores per plot from the upper 15 cm from which cover crop and weed roots were obtained by washing and sieving.

Beltsville Experiments 5-8, North and South farms-Weed Suppression

Forage radish cover crops were established specifically for the study of weed suppression effects in the fall of 2005 in two fields (North and South Farm) at the USDA Research Station in Beltsville, MD. Three weed supression experiments were conducted in both fields and one experiment was conducted in the lab using material collected from these fields. Cover crops were planted in late August and were first damaged by frost in late November. During unseasonably dry periods, plots were irrigated in the fall to ensure adequate cover crop biomass production and again in the spring to encourage weed germination and emergence. Due to a problem with volunteer hairy vetch in the no cover crop plots, the South Farm experiments were abandoned in spring of 2006. All results presented in this report are based on the results of the North Farm field. The experiments were modified and repeated in fall 2006, and will be continued beyond the funding period of this project in 2007, but the results from the second year are not available for the period of this report.

<u>Beltsville Exp. 5:</u>
This experiment was established to quantify the effect of forage radish cover crops on natural weed populations when compared to no cover crop treatments. Cover crops were planted at 13 lbs/ac. Natural weed populations were quantified from November till July (the experiment)? using percent cover ratings. Weeds were left to grow until July rather than plant a test crop so that changes in weed populations from forage radish cover crop treatments could be observed.

Figure 5 : Plant tissue extract preparation and germinated lettuce seeds.

<u>Beltsville Exp. 6:</u>
In January weed seeds were introduced into sub plots of Experiment 5 below the forage radish residue. Horseweed, lambsquarters, redroot pigweed, and green foxtail were chosen to be tested in the experiment because they have developed herbicide resistance in Maryland and because of the availability of seed lots with more reliable germination. Weed seed emergence was counted on a weekly basis from January through May to determine the length and degree of weed suppression achieved for each species following forage radish cover crops.

Beltsville Exp. 7:
In late November before the first damaging frost, a set of small 1 m^2 subplots was created to evaluate the effect of different amounts and types of forage radish residues. The residue treatments were applied by removing or adding plant material. Forage radishes shoots and tap roots were removed (fine roots still remained in soil) or added to see if they changed the degree or length of weed suppression. It was thought that the removal of forage radish residues just before they began to decompose would isolate the effect of weed competition during the cover crop growing season from the effect of plant chemicals released from decomposing residues (also known as allelochemicals). Percent cover ratings were used to rate the response of natural weed populations to forage radish residue treatments.

Beltsville Exp. 8:
This lab experiment was intended to examine the allelochemical effect of forage radish cover crop tissues, residues, and amended soil on seed germination and seedling growth. Plant, residue, and soil samples were collected from the forage radish and no cover crop treatments in Exp. 5 in January, March, and May. Plant tissues and residue samples were dried, ground and shaken with water to create extracts (Figure 5). Soils from the forage radish and no cover plots were sampled from the top 2 cm, sieved, and shaken with distilled water to create extracts. All extracts were diluted 1, 2, 5, and 10 fold, placed in Petri dishes with 50 lettuce seeds, and incubated for 48 hours at 25^{o}C (Figure 5). Lettuce seeds are a sensitive test species that is used as a standard in allelopathy studies. Percent seed germination as well as root and shoot length of ten seedlings were measured to determine if forage radish cover crops contained water soluble allelopathic compounds that inhibit or stimulate seed germination and growth.

SECTION IIIB -- EVALUATION METHODS FOR SPECIFIC COVER CROP EFFECTS

N Capture and release evaluations:
Four measures were taken to document the capture and release of nitrogen by the cover crops:
1) Cover crop dry matter was sampled in each experiment in late fall and again before the cover crops were killed in spring. Shoot and fleshy taproot material was harvested in two or three 0.25 m^2 quadrats for each replicate plot of selected treatments. The total N content of the dried and ground dry matter was determined by high a temperature combustion CHN elemental analyzer. Except for certain treatments at LESREC with crimson clover, it can reasonably be assumed that N in the plant reflects N removed from the soil and kept from leaching. The tissue C content and the C/N ratio were also determined to provide insights into the N mineralization-immobilization potential of the plant residues.

Figure 6 A large part of the fleshy taproot of forage radish may protrude above ground, making it difficult to compare biomass among cover crops. Photo shows foilage damaged by first frost in December.

1) Dry matter produced by all cover crops was measured in November, before winter kill occurred for the frost sensitive species. The biomass of the cover crops not winter killed was measured in late April, before tillage to kill and incorporate the covers. All cover crop biomass was determined by hand harvesting one 0.25 m^2 quadrat from each end of each plot. All shoot biomass was harvested from all cover crop cultivars. The tap root can be a major part of the biomass of the radish and rape plants, containing a large percentage

of the glucosinolates produced and nitrogen taken up by the plants. Also, up to half of the radish root biomass is often located above ground (see Figure 6). For these reasons, we harvested and measured the large fleshy tap root of these plants in addition to their shoot biomass. We did not harvest and measure the much smaller roots of the rye and clover plants. Once dried, all tissue samples were weighed, and selected samples were ground and analyzed for total C and N by LECO high temperature combustion, to determine the plant uptake of nitrogen. Because of the extremely diverse growth habits among the cover crops, comparisons were made using both total (tap root + shoot) and shoot dry matter.

2) The nitrate + ammonium extractable by 0.5 *M* K_2SO_4 were determined in the upper 105 to 180 cm of soil (in 15 cm increments) in selected treatments at Beltsville, CMREC (Hayden) and WREC to estimate the relative efficiency with which the various cover crop treatments have cleaned up the N in the soil profile. The cadmium reduction flow injection auto analyzer (Technicon Industrial Systems, 1977) and ion selective electrode (Banwart et al., 1972) methods were used to determine nitrate and ammonium, respectively. Precise core volume sampling allowed calculation of soil bulk density and therefore also total soluble N in the profile per hectare. At WREC, N capture was evaluated in November 2003 by measuring N in soil cores to a depth of 120 cm. In fall 2004, biomass samples were taken in mid-November, but deep soil coring was delayed by wet weather to January 2005. All deep soil cores were obtained using a drop-hammer driven, fully enclosed tube (Veihmeyer, 1929; deVera et al., 1980).

3) Nitrate-N concentrations in the soil pore water (leachate) were determined for selected treatments in all four experiments by sampling periodically during early spring (February or March-April) using 1-bar ceramic tip suction lysimeters set at 75 - 120 cm depth, depending on conditions in the profile. Each lysimeter was fitted with two flexible plastic tubes, one for applying the vacuum with a hand pump, the other for removing the sample under positive air pressure (Grossmann and Udluft, 1991).

4) Nitrate + ammonium-N was determined in the 0-15 cm and 15 – 30 cm layers of soil by sampling periodically in winter and spring after the kill date to estimate the mineralization-immobilization of plant available N. Precise number and length of cores was determined to allow calculation of soil bulk density and nitrogen content per unit land area (Kulmatiski and Beard, 2004). Extraction and analysis methods were as in #2, above.

5) A nitrate–N determination was done in mid-June on the upper 30 cm of soil to assess N release from cover crops and assess the resulting need for N fertilizer for the summer crop. This assessment was based on the Pre-Sidedress Nitrate Test (Magdoff et al., 1984;Heckman, 2002) that evaluates the N supplying power of a soil.

6) A 48-day laboratory incubation study was conducted to compare mineralization of shoot and root residues of forage radish, rape and rye. Contrasting soils—a silt loam from WREC and loamy sand from CMREC—were used to compare differences in C and N mineralization based on soil types when amended with different residues. A two-pool equation (exponential for the labile pool + linear for the recalcitrant pool) was used to fit curves to accumulative C mineralization data as well as identify differences in pool size values and rates of pool decomposition.

Nematode Evaluations for field experiments:

Research sites were assessed for pre-existing infestations. Soils were sampled for initial nematode populations in July 2003. Soil (and roots in some cases) were sampled at cover crop planting, at maximum cover crop growth in fall 2003, at about 1 month after cash crop planting and at cash crop harvest to assess short term and residual effects on nematode populations. Composite soil samples (10 cores, each 2 cm x 15 cm) were collected from the middle two crop rows of each plot in a systematic pattern. Soil cores were collected of a precise number and length to allow calculation of bulk density for each sample and expression of results on a per land area basis (which is more ecologically meaningful than the commonly reported soil mass basis). Samples in sealed plastic bags were kept on ice during transport to the Nematology laboratory where total soil mass, and water content were determined, and 250 cm^3 sub-samples of fresh soil were taken for wet vermiform extraction using a modified Baermann method (Hooper, 1986). Soil moisture content and field bulk density were measured and used to calculate results as nematodes per square meter in the upper 15 cm of soil. We identified and counted the extracted nematodes under a stereoscopic and/or compound microscope. All soil extractions were completed within 3 weeks of soil sampling. Total numbers of nematodes were determined from each treatment-replicate combination, and nematodes identified to trophic group (plant parasitic, bacteria feeding, fungal feeding, predatory) using esophageal and general characteristics (Yeates et al, 1993). This broad measure of community structure can help assess whether non-plant parasitic (generally beneficial) nematodes were affected.

Effects on Soil Nematode Ecology
In addition to the work on plant parasitic nematodes, analysis of grouped nematode taxa and community indices were used to study the effects of several of the cover crops on the total soil nematode community at two sites in Maryland with loamy sand surface soil textures (CMREC and LESREC). Soil properties were also used to explain effects. A secondary objective was to evaluate the influence of timing of cover crop termination versus cover crop type on nematode response parameters. Using the methods of Ferris et al. (2001) , the enrichment index (EI), channel index (CI), structure index (SI), bacterivore and fungivore maturity indices (BaMI, FuMI), and total community maturity index 2-5 (□MI25, MI25) were calculated to quantify the nematode community response to cover crops.

Lab procedure for Nematicidal Properties, Bioassay 1:
A 48-hour bioassay was conducted using lab-cultured *Meloidogyne* sp. There were three blocks and 19 treatments each consisting of root and shoot material of rapeseed ‘Essex’, mustard blend ‘Caliente’, forage radish ‘Daikon’, oilseed radish ‘Adagio’, and a biomass-free control, applied at two fresh plant tissue rates, 1% and 5% of sand weight. The experiment also included a non-Brassica plant tissue control of rye ‘Aroostook’ shoots at the same two tissue rates. Each assay unit was a plastic cylinder fit inside another cylinder (~3 cm diam.), with fine fabric (25 µm mesh) stretched across it (Zasada and Tenuta, 2004). Units were filled with 5 grams of coarse sand and color coded for treatment identification. Fresh plant material was chopped and then either 0.05 or 0.25 g fresh plant pieces were then mixed into 5.0 g of pre-weighed sand and poured into an assay unit. Three replications of both levels of biomass for root were prepared, followed by addition of a 1 ml aliquot of nematode slurry, before the shoot treatments for that plant type were prepared. Aliquots contained roughly 270 nematodes, based on the average of five aliquots. When each block of 19 treatments was completed, the units were placed into a large plastic Petri dish. The Petri dishes were then incubated at 25 ˚C. At 24.0 hours after addition of the nematode aliquot for each unit, the unit was transferred to a small Petri dish and filled with water so that the cloth suspended sand-biomass mixture was just touching the surface of the water. This resulted in immediate saturation of the pore matrix. A small semi-circle in the outer cylinder enabled nematodes which survived and passed through cloth to move into the Petri dish. After 48.0 hours, assay units were removed from the Petri dishes, and nematodes were counted in each dish within two days. Data for Bioassay 1 were analyzed as a percentage of the control. The mean number of surviving nematodes in the control was approximately the same as the mean number of nematode counts in the preliminary aliquot counts, so the results may be interpreted as similar to the percent of nematodes surviving out of the number added to the assay units.

Lab procedure for Nematicidal Properties, Bioassay 2:
In the second lab bioassay, plant material was collected from field blocks in Experiment 1 at

LESREC and the corresponding block number was maintained for the lab bioassay. The plant materials consisted of rapeseed 'Essex' and 'Humus' root and shoot material, and a biomass control of rye 'Wheeler' shoot, each at 25 g fresh plant material kg^{-1} dry sand weight. Essex is the rape cultivar most commonly used as a cover crop. Humus is a rape cultivar selected for anti-nematode properties. The nematodes used for this assay consisted of a mixed community which was sampled and extracted from the same field plots in which the Brassica plant material had been grown. After three days of refrigeration, 1 ml aliquots containing approximately 200 nematodes were added to each assay unit. Aliquots of the Brassica-derived nematode communities were added to assay units already containing the root or shoot of the corresponding Brassica cultivar, as well as to the rye shoot assay unit, and a biomass-free control assay unit. Thus the bioassay experiment had an unbalanced randomized block design, with eight replications for each distinct nematode community, and four replications for each type of plant tissue. There were 8 replications of the rye and biomass-free control. The same incubation procedures were followed as in Bioassay 1. The number of surviving nematodes were counted and identified as either plant parasitic or free living. In Bioassay 2, data were analyzed as two separate experiments (nematode communities from rapeseed 'Essex' and 'Humus' plots).

***Weed Evaluations*:**
The weed suppression potential of the experimental cover crops, effects on weed competitiveness, and shifts in weed species composition were assessed by line-intersect transect methods of estimating ground cover, by biomass determinations using 0.25 m^2 quadrates, and/or by duplicate visual scoring of plot ground cover and species dominance. Depending on the sites, weed suppression was estimated in late fall, early spring, at cash crop planting and in summer at 'lay-by'. Several of the Beltsville weed suppression experiments included a weeds-only (unweeded, no crop) control treatment and a set of weed-free control plots (hand weeded or sprayed during the cover crop growing season and beyond). This allowed a factorial analysis to evaluate cover crop impact on weeds and weed competition independent from direct effects of cover crops.

Compaction Alleviation Evaluations:
The initial compaction conditions were evaluated using bulk density (core method) and soil strength (cone penetrometer) data. However, unlike for tillage alleviation of compaction, biodrilling would be expected to facilitate crop root penetration of the compacted zone without changing the gross bulk density or cone penetration resistance. Therefore plant-centered methods were needed to evaluate the effects of the cover crops on soil compaction.

Effective crop rooting depth was estimated in summer by soil water use and recharge above and below the compacted zone. These changes in soil water content were monitored with buried electrical resistance moisture sensors. Where crop roots have been able to penetrate the compacted zone and have access to subsoil water, we expected to see more rapid and complete depletion of stored subsoil moisture. Monitoring water use both above and below the compacted zone was meant to allow us to detect the effects of "biological drilling" by cover crops on cash crop root access to subsoil moisture and distinguish this from the water conserving effects of cover crop residue surface mulch.

To monitor water use as a means of evaluating the potential of the cover crops to alleviate soil compaction via bio-drilling, soil water sensors were placed in selected treatments at 15 and 50 cm depths. Because of the large number of sensors (several hundred) required to monitor the plots with sufficient replication, time domain reflectometry (TDR, Topp et al., 2000) wave guide sensors and meters proved to be far too expensive; electrical resistance blocks were used instead. Four sensors were installed in each plot monitored, one set near each end of the plot. Four treatments were monitored for a total of 64 sensors per experimental site. During the first two years, the sensors used were gypsum resistance blocks (Delmhorst, Inc.) read with a hand meter factory calibrated to read in percent of available water remaining. We also calibrated the meter and sensors separately in samples of soil from 15 and 50 cm deep to be able to convert these meter readings to g water /g dry soil (a typical calibration curve is shown in Figure 34 on page 51). In subsequent work we used granular matrix resistance sensors connected to data loggers that obtain readings every hour (Watermark sensors and data loggers, Irrometer, Inc). The Watermark sensors which are factory calibrated to read in cbar (- kPa) soil water tension give data that are quite a bit more reproducible than that from the simple gypsum blocks (Cardenas-Lailhacar et al., 2005; Clint Shock, 2004; Spaans and Baker, 1992.

The second approach we used to evaluating compaction alleviation was direct observation and measurement of plant rooting. We measured plant roots above, within and below the compacted soil zone.

One method of root observation was the use of a minirhizotron camera which was purchased in collaboration with a colleague for about $30,000 of non-project funds. This fiber optic digital camera and precision mounting device is inserted into clear plastic tubes (5 cm diameter) that are semi-permanently installed in the soil, generally at a 45 degree angle (Ephrath et al., 1999; Liedgens and Richner, 2001). The camera device moves at 1.4 cm intervals and captures an image at each depth interval. The difficulty of installing a large diameter tube in a highly compacted soil limited the number of observations we could make, but we were able to install 16 tubes in one experiment to obtain replicated images. Roots were counted on the images and, for selected images, root length was determined using WinRhizo software (Blouin et al., 2007) which facilitates, but unfortunately cannot automate, the measurement of roots in soil images.

Fine roots (as opposed to large, fleshy storage roots) were also quantified by collecting large diameter (5 to 7.5 cm) soil cores with either hand driven equipment or hydraulic coring equipment (Giddings, Inc.) which became available in the last year of the project. Roots were counted in 5 cm increments of the soil cores by the core-break method (Bohm, 1979; Stone et al., 2001) which is relatively rapid and has the advantage of counting only living roots. Core break root counts were made to 45 cm depth using hand-driven equipment or to 60 cm depth using hydraulic equipment (the latter was available only in the last two years of the project).

For selected soil cores, root dry matter and length were determined after washing roots free of soil. Root determinations were generally made for cash crops (corn and soybean) in summer, but for selected experimental plots in fall 2006 roots were also measured for the cover crops.

SECTION IV -- RESEARCH RESULTS

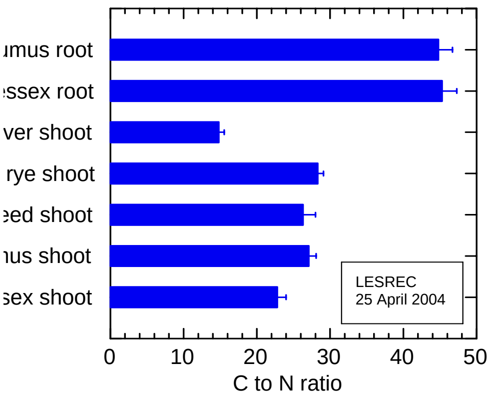

Figure 7 Ratio of C/N in tissue of fall sown cover crops just before killing in spring prior to planting soybeans. Humus and Essex are cultivars of rape.

Nitrogen cycling

Forage radish, oilseed radish, and rape were compared to rye, a popular cover crop in the region, with regard to nitrogen uptake N at three sites CMREC (Hayden), WREC and LESREC.

In late April 2004 at LESREC, the Rape (both Essex and Humus cultivars) shoot dry matter had about the same tissue C/N as did rye (23 to 29), but the C/N ratio in the rape roots was about 45 (Figure 7), high enough to cause N immobilization. The clover shoot dry matter, as expected, had a sigificantly lower C/N ratio (about 15) that would cause immediate N mineralization to occur. Perhaps because of the high root C/N ratios present, only the plots that had clover cover crops showed moderately high levels mineral nitrogen (15 to 20 mg/kg) in the upper 30 cm of soil collected in mid June (data not shown).

For cover crops sown in August 2004 (Table 6), the rapid growth of the Brassicas, especially the radishes, resulted in about 2 fold higher production than rye, if only shoot dry matter is considered, and 3 fold higher if the fleshy tap root is included. The Brassicas also produced about 5 fold higher dry matter than weeds (data not shown). Table 6 summarizes four site-years' data on the shoot biomass and nitrogen content (kg ha^{-1}) for rye and forage radish where both species were grown under the same conditions and N uptake was determined. By late November, the uptake of N in the foliage (not roots) of forage radish was 137 kg ha^{-1} as compared to 87 kg ha^{-1} for rye. Data for roots are not shown in Table 6. Rye roots, which are fibrous in nature and completely underground, were not measured in these experiments. However, the fleshy root of forage radish occurs partly aboveground, and is easily collected. It could be considered partly above ground tissue. The fleshy forage radish roots contained an average of 60 kg ha^{-1} N in 2003 at four field sites (BARC, WREC, LESREC, CMREC) and an average of 84 kg ha^{-1}N in 2004 at three field sites (WREC, LESREC, and CMREC).

In 2005 we completed the main soil field work for the project in the area of cover crop nitrogen

Table 5 Shoot biomass and nitrogen content (kg ha^{-1}) for rye and forage radish in the four site-years in which both species were grown under the same conditions and N uptake was determined. Data for roots are not shown here, but the fleshy root of forage radish and rape contained considerable additional N. Rye roots were not sampled.

Location/Year	Cover crop	Biomass in fall	N uptake in fall	Biomass in spring	N uptake in spring
WREC 2003-4	Forage Radish	7300	156	--	--
	Rye	5920	148	2533	47
WREC 2004-5	Forage Radish	4343	155	--	--
	Rye	3120	99	6221	86
CMREC 2004-5	Forage Radish	1943*	75	--	--
	Rye	1029	41	4659	75
LESREC 2004-5	Forage Radish	3647*	161*	--	--
	Rye	2221	61	3649	92
Overall means	Forage Radish	4308*	137*	--	--
	Rye	3072	87	4265	75

-- Data not collected

* The average value so marked is statistically greater ($p<0.05$) than the other value within the site-year pair.

capture and release. However, we are continuing to expand our data base on plant N uptake by these covers. In 2006 we completed analysis of the data from the deep soil cores and N mineralization samples taken in 2003-2005. Although the project is now completed, our research on N uptake is continuing. Our results continue to indicate that the Brassicas are capable of rapidly taking up large amounts of residual soil N in the fall if planted earlier than mid September. With tissue N concentrations ranging from 2.0 to 3.5% and dry matter ranging to more than 7,000 kg/ha by late fall, their potential for N uptake appears to be even larger than that of rye, which is the standard N capture cover crop in our region. At CMREC (Evesboro loamy sand), plant N uptake by late fall 2004 ranged from 151-214 kg N/ha in the Brassicas (shoot + fleshy root).

An important objective of our project is to evaluate the N leaching risk presented by winter-killed, decomposing forage radish in late winter and early spring months. The temporal patterns of N release for control and forage radish treatments during spring 2005 were nearly opposite from each other (see Figure 14, page 28). Nitrate in control plot porewater was highest on the first sample date in February and declined thereafter, indicating that our samples caught the tail-end of N leaching from the control plots. In the radish plots, the porewater was as low as under rye or rape for the first several sample dates, but began increasing in late March and reached high levels only in mid April, suggesting that N was conserved during the winter months, but released in early spring. This pattern was corroborated by the N mineralization study in the upper 15 cm of soil, and suggested that radish would make N available early in spring. This can be viewed as an advantage over rye (which is known for immobilizing N in spring) if the cover crop is followed by an early-planted crop such as corn or early vegetables. If planting is delayed until May on loam sand soils, significant N may be lost by leaching before the spring crop can capture it.

On a finer textured soil at WREC (Matapeake silt loam), the average shoot N uptake from November 2003 and January 2005 (deep sampling targeted for December 2004 was delayed by frozen soils until early January) ranged from 121-160 kg N/ha for the Brassicas and rye. Nitrate-N (0-105 cm) was 260 kg N/ha under control and 76-96 under forage radish, rape, and rye--a

Table 6 Mean biomass, tissue N concentration and N uptake by forage radish, rape and rye for the three site-years of the nitrogen leaching study in which all three species were planted in the same experiment. All cover crops were planted in late August to early September.

	Fall			Spring	
	Forage Radish	Rape	Rye	Rape	Rye
Dry Matter (kg ha^{-1})	3560 a†	3710 a	2571 b	4080 b	4470 a
N Content (g 100 g^{-1} tissue)	0.032 a	0.029 a	0.031 a	0.020 a	0.015 b
N Uptake (kg ha^{-1})	119 a	111 a	78.6 b	81.1 a	64.9 b

†Means followed by different small letters are significantly different, $p<0.05$

significant decrease. In March-April 2005, much more NO_3-N was measured in the porewater collected under the control plots than under all the Brassica and rye cover crops. Porewater NO_3-N under control averaged 4.3 mg/L over the sampling period while the cover crops averaged 0.2-0.7 mg/L.

Our work suggests that if planted by mid September, rape, forage radish and oilseed radish are at least as effective as cereal rye in capturing residual soluble nitrogen in the soil profile. In agreement with European studies published after the initiation of our project (Kristensen and Thorup-Kristensen, 2004; Thorup-Kristensen et al., 2003), the Brassicas appear to exhibit a very rapid and deep rooting habit that allows them to uptake large quantities of N from deep in the soil profile early in fall before the N can leach beyond their reach. For example, data from a highly permeable sandy soil near Beltsville, MD, suggest that within 7 weeks of planting, the Brassica cover crops can capture exceptionally large amounts of nitrogen that might otherwise leach to groundwater over the winter. When planted by September 1, good stands of forage radish or rapeseed cover crops produced up to 6,000 kg/ha dry matter containing over 140 kg/ha of nitrogen by mid-November.

The radish roots apparently reached deeper than 180 cm into the soil by late October. This depth of rooting is suggested by Figure 15 (see page 28) which shows a significant reduction in nitrate nitrogen at 180 cm in the soil profile where either forage radish or oilseed radish were growing. This was the only experiment in which soil conditions allowed us to sample as deep as 180 cm. This observation is in agreement with the recent literature from northern Europe (cited above) that suggests that forage radish is more effective than rye at capturing nitrogen from deep in the profile in fall. It should be kept in mind that the deeper the N is located in the soil, the more likely that it will leach to groundwater before spring crops can take it up. *Therefore, N captured in fall from deep in the profile probably is of greater environmental value than the same quantity captured from more shallow soil layers* (Thorup-Kristensen et al., 2003).

Table 7 Nitrogen uptake by forage radish cover crops grown on commercial farms without fertilization but on fields with histories of periodic organic amendment (manure or compost). Means ± S.E.

Location	*Cover crop planting date*	*Sample date*	*Shoot dry matter,*	*Root dry matter,*	*Shoot N conc.*	*Nitrogen uptake by shoots*
			kg/ha	*kg/ha*	*%*	*kg/ha*
Lancaster, PA-Groff farm, notill grain, hay, vegetables	16 Aug. 2004	14 Nov. 2004	4076±261	n.d.	2.96±0.02	121±9
White Hall, MD – Norman farm, organic vegetables	18 Aug. 2004	13 Nov. 2004	2710±42	2576±75	2.84±0.25	77±9
Galena, MD. Colchester farm, organic vegetables	09 Sep. 2005	18 Nov. 2005	4431±130	4124±126	3.02±0.2	142±5
White Hall, MD Magness farm, dairy, after corn silage	24 Sep. 2006	11 Nov. 2006	1483±539	n.d.	2.23±0.14	31±12
Lancaster, PA-Groff farm, notill grain, hay, vegetables	30 Aug. 2006	18 Nov. 2006	2109±227	1056±109	3.25±0.08	69±9

Like small grains, radish will not grow vigorously if surface soil nitrogen is very low. In low N soil, deep rooting suffers more than shoot growth. On sandy soils there is often a lot of N left deep in the profile while most has washed out of the surface horizon by fall. We have not applied any N to our fall radish plots on commercial farms (Table 8) and have had excellent biomass and N uptake on all but very sandy, unmanured soils in a strictly grain rotation. We have not conducted nitrogen rate fertilizer trials on the Brassica cover crops, however, our experience with virtual cover crop failures from N deficiency on some very low N sandy soils leads us to believe that where needed to ensure vigorous cover growth, a small nitrogen application is very likely to result in much improved nitrogen scavenging from the profile and therefore less N loss by leaching. In our experiment station research plots with low residual N we often fertilized the radish with N both to assure vigorous growth and enable the N uptake potential to be expressed. We believe that application of 20 to 30 kg N/ha as fertilizer in fall would be justified, if it is necessary in order to get the cover crops off to a rapid, deep rooting start that allows them to recover 100 to 200 kg N/ha from deep in the profile before it can leach completely below the potential root zone.

Table 8 presents productivity and N uptake data for forage radish planted in early fall by commercial farmers. The on-farm forage radish was planted without fertilization, but in most cases on fields with a history of manure or compost application. The data show that the N uptake was very large - in the same ballpark as that for our experiment station plots that did receive N fertilizer, attesting to both the impressive N uptake potential of the forage radish and to the large amount of N that can become available during the fall in many farm soils.

Table 8 Root and shoot dry matter production and nitrogen content of spring-planted cover crops.[1]

	Lewis 2005		*-------------------- CMREC 2005 ------------------*						*CMREC 2006*		*Overall means*	
	Dry matter		*Dry matter*		*Nitrogen Content*		*Nitrogen uptake*		*Dry matter*		*Dry Matter*	
Cover crop	*Root*	*Shoot*	*Root*	*Shoot*	*Root*	*Shoot*	*Root*	*Shoot*	*Root*	*Shoot*	*Root*	*Shoot*
Radish	98	793a	186a	1368a	1.55a	2.73a	2.9a	37.0a	253a	1983a	244a	1381a
Rape	n.d	294b	103b	902b	n.d.	n.d.	n.d.	n.d.	54b	484c	79b	506c
Rye	n.a.	n.a.	231a	676c	1.56a	3.31a	3.5a	22.6b	n.d.	1293b	231a	985b

[1] Covers at CMREC were no-till planted on loamy sand soils on 04 April 2005 and 31 March 2006. Nitrogen (33 kg N /ha) was applied to covers as urea-ammonium nitrate solution at planting. Covers were sampled and then sprayed with glyphosate on 04 June 2005 and 23 May 2006. Covers at Lewis farm (Caroline Co.) were no-till drilled on 28 March and 07 April 2005 and received no nitrogen. As there was no effect of planting date on final dry matter, values shown are means of both planting dates and 5 replications, as measured on 31 May 2005. Nitrogen in tissue was measured only for CMREC 2005 samples. Root data are for upper 15 cm soil. Means within a column followed by the same small letter are not different at P <0.05.

Table 9 summarizes project data for our trials in which cover crops were planted in early spring instead of fall. These studies were carried out because we received requests from grain farmers for information on spring planting of the Brassicas. They wanted to explore spring planting as a way to get around the difficulties of making the early fall planting date needed for best winter hardiness and performance of the Brassica cover crops. They wanted to know if it would make sense for them to plant the cover crops in late March/early April and kill them about two months later in late May before planting soybeans. As the data in Table 9 show, the aggressive growth seen for fall planted covers, especially for the radish, was not seen with spring planting. Both rape and radish flowered early on and produced relatively little foliage and even less root dry matter, even when fertilized. The N taken up at CMREC in 2006 barely equaled the N applied. The CMREC 2006 study also gave a good idea of root to shoot ratios for rye, rape and radish under these conditions. For the Brassicas, the shoot to root ratios were near 6:1, indicating far less root allocation than for the same species planted in fall (see for example table 8 in which the shoot to root ratios varied from near 1:1 to about 2:1).

We therefore conclude that early spring planting, as envisioned by some farmers, does not seem to be a viable option. Because of the relatively slow growth and especially small

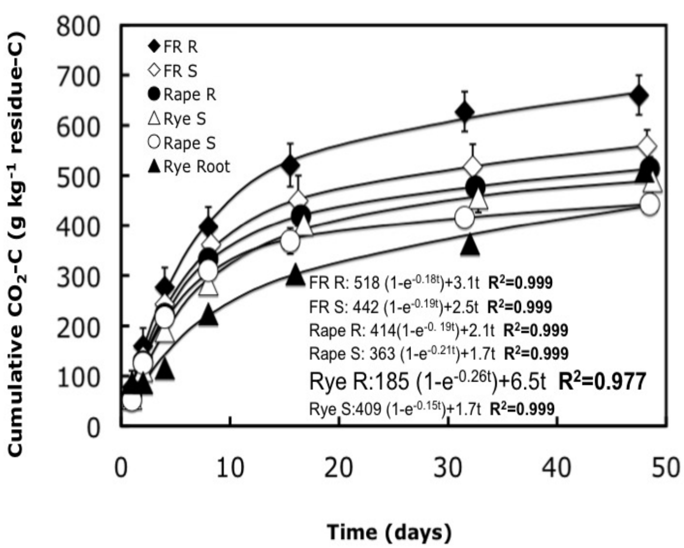

Figure 8 Cumulative CO_2 evolution (points=measured and lines=estimated) over time in an Evesboro loamy sand. Bars are SEM, n=4. Background CO_2 and CO_2 evolved from control soil have been subtracted from data.

proportion of root growth, there appears to be little chance that any compaction alleviation or weed suppression benefits could be realized from spring planted Brassicas, and the N uptake benefits were very modest and undoubtedly occurred too late to prevent most N leaching.

Residue decomposition lab study

In the laboratory incubation study (Figures 8-9) comparing the mineralization of residues of rye, rape and forage radish in two soils, evolution of C was rapid in both soils within 24 h following incorporation of plant materials into soil but declined thereafter, and the C evolution rate was low from day 16 to the end of the study (Figure 8 shows data for the Evesboro loamy sand). Average cumulative C mineralization from all materials was approximately 425 to 650 g kg^{-1} added residue C over the 48-day period. Rye roots (sampled from spring –planted rye) decayed the most slowly and radish roots and shoots (from fall planted radish) decayed most rapidly. The rates of CO_2 evolution from rape shoots and roots and rye shoots were in the middle.

Figure 9 shows the cumulative N mineralization. After 48 days in both soils, only the rape and radish shoot tissue (C/N ratios of 16 and 12) produced significantly more mineralized N than the unamended control soil. Between 10 and 37% of N added to soil with the forage radish and rape shoot residues was measured as soil mineral N on the last day of the incubation study. In contrast, the cumulative N mineralized from rye shoots and Brassica roots (C/N ratios > 21) was not significantly greater than from the unamended control soils. These data are in agreement with our observation in the field of greater N availability in spring following radish than following rye (see below).

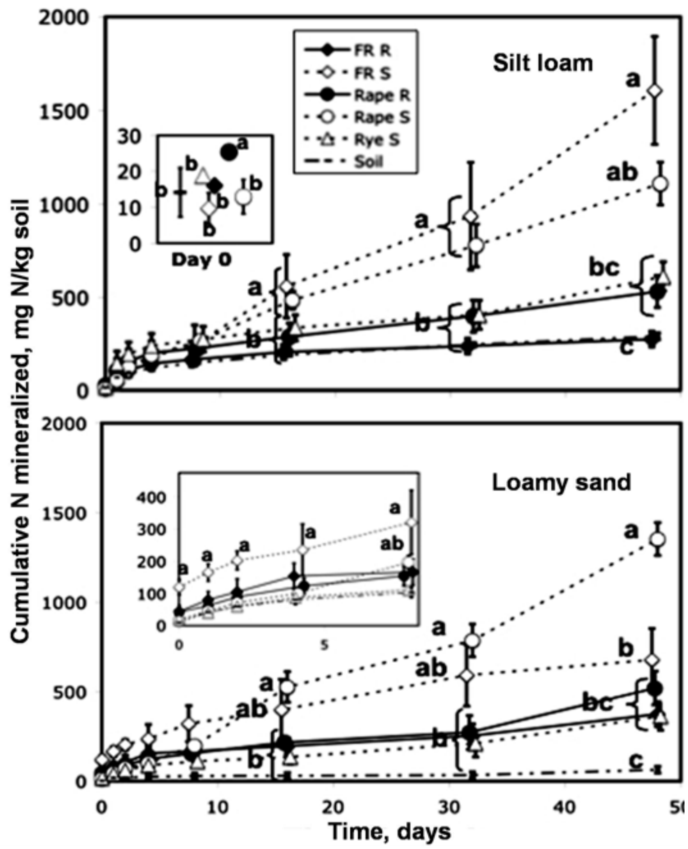

Figure 9 Cumulative mineral N (NH_4-N + NO_3-N) in amended Elton silt loam and Evesboro loamy sand soils. Error bars are SEM, n=4; n=8 for control soil. Within each day, means followed by the different letters are statistically different ($P \leq 0.05$, using Tukey-Kramer adjustment).

There may be environmental value in using radish or rapeseed to clean up the nitrate deep down in the soil profile in fall. Rye takes up very little N in the fall when planted at typical early October planting dates. Even when planted in late August/early September as in our studies, rye does not take up N as fast or from as deep in the profile as radish. In terms of environmental protection, a kg of N taken up from 2 m deep is worth much more than a kg taken up from 0.6 m deep because the deep N had much less chance of being used next season and much greater risk of leaching. Available data certainly appears to warrant including Brassicas – both radish and rapeseed –in cover crop programs for capturing nitrogen so long as the Brassicas are managed properly and established early -by mid-September in Maryland.

Nitrogen release in the field

In addition to reducing leaching losses (discussed below), cover crops that capture residual soil N in fall can also reduce fertilizer needs if N release by mineralization from cover crop residues is synchronous with N use by subsequent crops. The potential of forage radish (*Raphanus sativus* L.) and rape (*Brassica napus* L.), to act as N catch crops as well as to provide subsequent summer crops with inorganic N mineralized from their residues was compared to that of rye. Cover crop treatments (rye, forage radish, rape, forage radish + rye mixture and an unweeded no cover control) were compared in replicated experiments at three locations from 2003 to 2005. Each experiment used a rotation consisting of winter cover crop/soybean (*Glycine Max* L.)/winter cover crop/corn (*Zea mays* L.) in the fall of 2003 and 2004. Nitrogen uptake and dry matter production by cover crops and main crop seedlings (prior to any N side-dressing) were measured along with mineral N (NO_3-N and NH_4-N) and total soluble organic N (TSON) content of the soil at 0-15 and 15-30 cm depths.

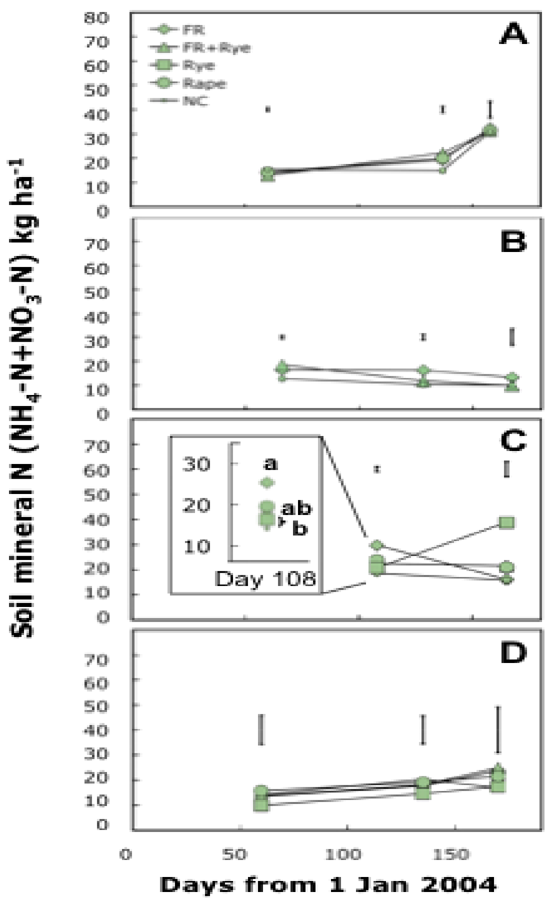

Figure 10 Soil mineral nitrogen (0-30 cm) in spring 2004 (Exp.1) at BARC (A) CMREC (B), LESREC (C) and WREC (D). Vertical bars are average SEM. Mean values with the same lowercase letter are not statistically different at (P<0.05).

Fall and spring N uptake by Brassica cover crops ranged from 100 to 250 kg N ha^{-1} (roots and shoots combined, see above discussion) and equaled or exceeded that of rye at all sites in both study years. We observed no effects of cover crops on soluble organic nitrogen in the surface soil in either field season (data not shown). Except for a single date at one site, we did not observe any cover crop treatment effects on inorganic N levels in the upper 30 cm soil in spring 2004 (Figure 10). The relatively low mineral N levels (generally less than 20 kg N/ha in the upper 30 cm) were probably due to microbial immobilization stimulated by the high C/N ratio in the corn residue present in spring 2004. By contrast, the soybean residue present in spring 2005 had a much lower C/N ratio and as a result higher mineral N levels were observed in the upper 30 cm of soil. More importantly, in this lower carbon environment, the cover crop residues did have some marked effects on soil mineral N. On most sample dates from February to April 2005, soil NO_3-N concentrations in forage radish plots were higher than those in rape, rye and no cover plots. The higher mineral N levels in the radish plots probably reflect the fact that the rye and rape were still alive, while rapidly decaying radish residues (but no living plants) were present in the radish treatment plots. In May and June 2005, following the termination in April of the rye and rape cover crops, soil NO_3-N concentration following rape generally exceeded that following rye. Compared to rye or no cover, Brassica residue decay increased early June dry matter and N content of V6 stage corn or seedling soybean plants at most sites (data not shown).

Modest amounts of N from decomposing forage radish tissues were observed in surface soils as early as February or March when this cover crop was frost killed in December. Rates of N mineralization accelerated considerably with warming temperatures in the period from March-June.

Significantly more N as nitrate from the forage radish cover crop was available for uptake by following main crops in early May (see data points at ~day 140 in Figures. 11-13) and mid-June (data points at ~day 160) than from rye (killed in April at early-boot stage). Heavy rain preceded soil sampling in early April 2005 (~day 100). The dip in surface soil nitrate levels at CMREC in April 2005 corresponded to a sharp rise in leaching water nitrate levels in the subsoil (see Figure 14, below). These data illustrate the greater risk of nitrate leaching from early mineralized N in a very sandy soil compared to a finer textured soil (Figures 14-16). The low soil nitrate levels in spring 2004 suggest that much of the N taken up by the Brassicas (and rye) in fall was probably immobilized as microbes decayed the high C/N ratio residues from the previous corn or wheat crops along with the lower C/N residue of the cover crops. Only in the plots with spring-killed crimson clover (at LESREC Exp. 1) was there a significant increase in soil mineral N in the upper 30 cm by mid June compared to the no-cover crop controls (data not shown). In the 2004-2005 cover crop seasons, the soil system was less carbon dominated because of the use of a soybean green manure before planting the cover crop the previous fall. This relatively high N, low C soil environment allowed net N mineralization from the cover crop residues. The Brassicas decomposed and released N more rapidly than the rye, according to both field (Figures 11-14) and lab incubation (Figure 9) measurements.

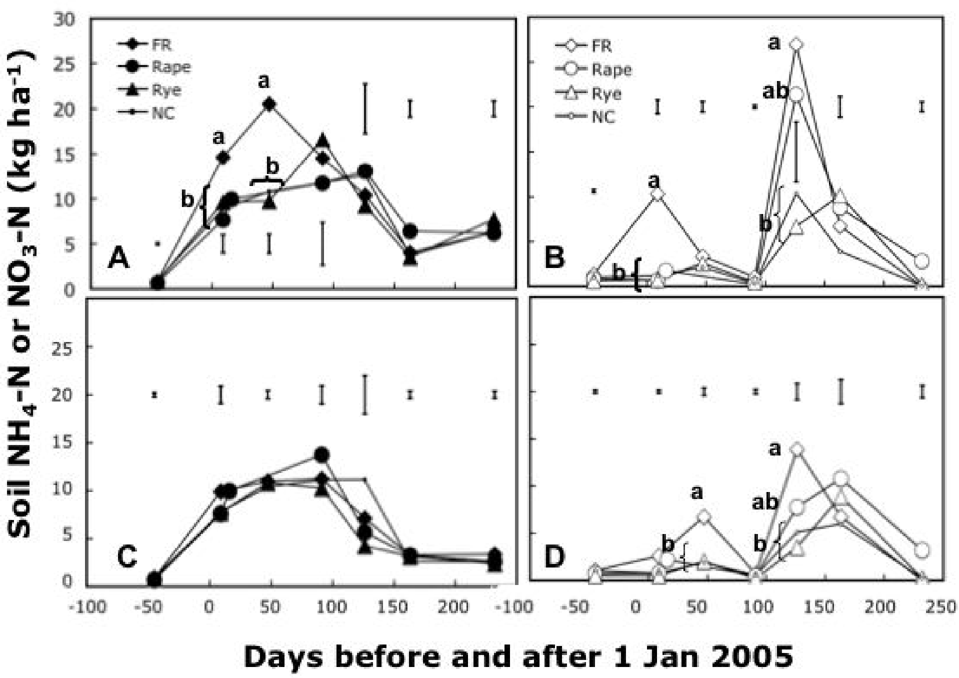

Figure 11 Ammonium (left) and nitrate (right) at 0-15 cm (A, B) and 15 to 30 cm (C, D) depths in loam sand soil at LESREC.

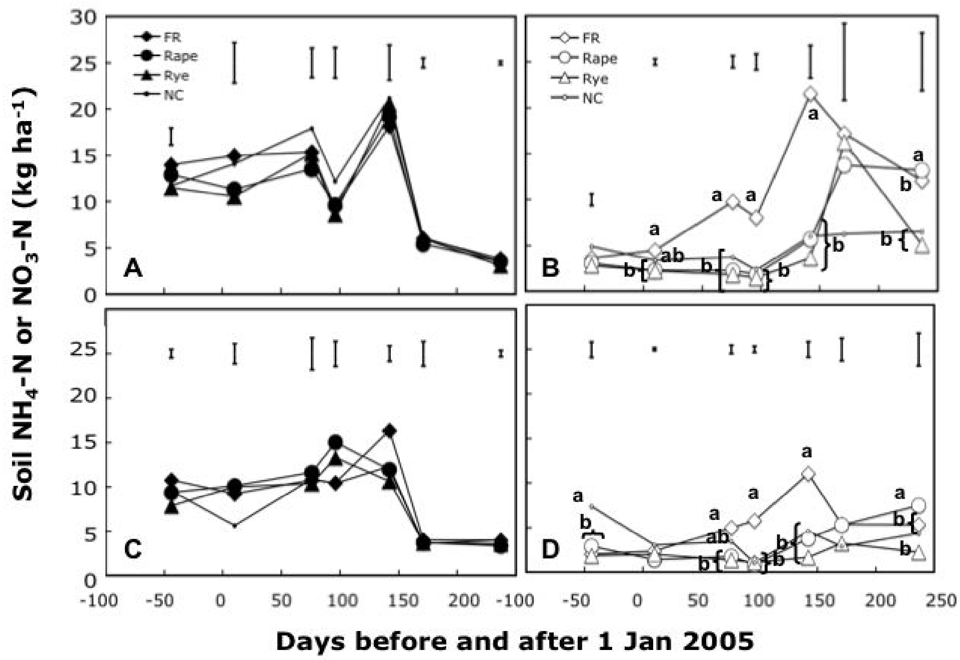

Figure 12 Ammonium (left) and nitrate (right) at 0-15 cm (A, B) and 15 to 30 cm (C, D) depths in silt loam soil at WREC.

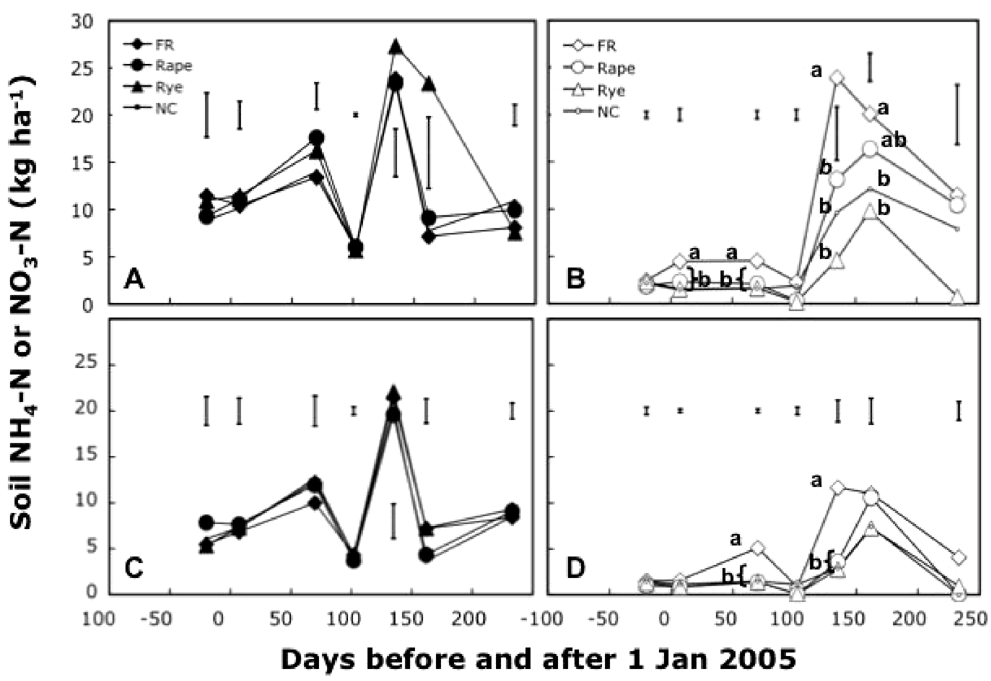

Figure 13. Ammonium (left) and nitrate (right) at 0-15 cm (A,B) and 15 to 30 cm (C,D) depths in loam sand soil at CMREC.

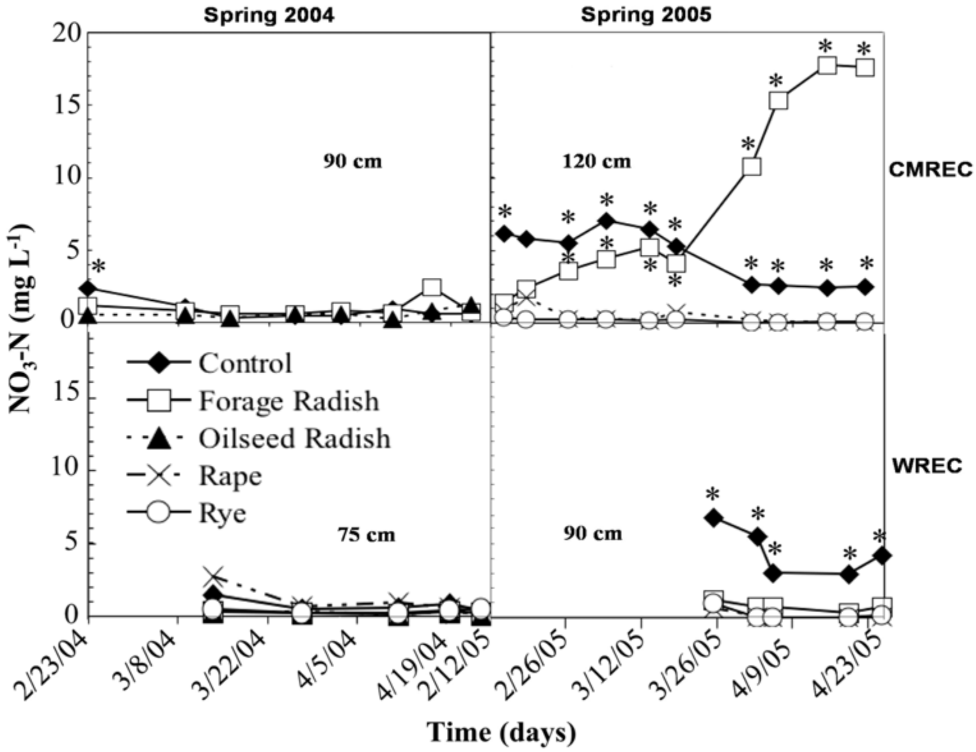

Figure 14 Nitrate-nitrogen in subsoil porewater at CMREC and WREC in the spring of 2004 and 2005. Means from four lysimeters per treatment in spring 2004, and eight lysimeters per treatment (two per plot, 4 plots sampled) in spring 2005. Lysimeters were installed to the depth indicated and sampled approximately weekly on the dates indicated. An asterisk (*) denotes significantly greater means than smallest mean for that site-date, $p<0.1$.

Nitrate-N in leaching water sampled from soil pores

Porous ceramic cup tension lysimeters were also installed at depths of 75-120 cm to monitor NO_3-N in soil porewater at CMREC and WREC.

In spring 2004, NO_3-N concentrations in subsoil porewater samples were very low (< 2 mg L^{-1}) and were unaffected by cover crop treatments at either site (Figure 14, left side), except that on the earliest sampling date in 2004 at CMREC (February 23), the no-cover control plots had slightly, but significantly higher nitrate levels in the porewater. It is possible that early leaching took place and that cover crop may have had effects prior to this first sampling date. Based on a simple model that used the average monthly concentrations and assumed that no surface runoff took place, evaporation and precipitation data suggest that approximate leaching losses for March 2004 (2.22 kg NO_3-N ha^{-1} mo^{-1}) were less than those for April 2004 (5.01 kg NO_3-N ha^{-1} mo^{-1}) at CMREC1. WREC1 had similar leaching losses in April and March (3.01 kg ha^{-1} mo^{-1}).

In spring 2005, subsoil porewater NO_3-N concentrations were markedly affected by the cover crop treatments (Figure 14). At CMREC2, when porewater sampling began on 5 February 2005, porewater NO_3-N in all the cover crop plots was significantly lower than in the control plots. Thereafter, porewater NO_3-N in the control plots followed a declining trend while that in the forage radish plots increased during March and April. In the rape and rye plots, porewater NO_3-N was low (0.06-0.25 mg L^{-1}) for all sample dates. During the spring on coarse textured soil, porewater NO_3-N concentrations in plots with freeze-killed cover crop (forage radish) were greater than in control plots or plots with overwintering cover crops (rape and rye). On fine textured soil, all cover crops provided a similar decrease in porewater NO_3-N concentration compared to control. At CMREC, the soil porewater N (sampled with suction lysimeters at 120 cm) under rape and rye averaged over 10 sampling dates in February-April 2005 was 0.28 and 0.13 mg NO_3-N/L whereas the control and forage radish had significantly greater concentrations at 4.4 and 6.8 respectively. The spring 2005 porewater 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 averaged 0.052 mg L^{-1} of porewater NO_3-N while that in the control plots was much higher, averaging 3.94 mg L^{-1}. Therefore, we recommend that on coarse textured soils, freeze-killed Brassica cover crops should be followed by an early-planted spring main crop.

Nitrate-N remaining in the soil profile
Soil samples from the soil surface to depths of 105 - 180 cm were obtained in fall and spring (2003-2005) for NH_4-N and NO_3-N analyses. The depth of soil core sampling for a given site varied according to soil conditions at that site. Brassica and rye, compared to a weedy fallow control, caused similar decreases in soil profile NO_3-N in fall and spring throughout the sampled profile. Cover crops had no effect on extractable NH_4-N in the soil profile during the course of the experiment (data not shown), with the exception of fall at WREC2 when rye plots had 77.4 kg ha^{-1} NH_4-N compared to the Brassica and control plots (86.4-94.8 kg ha^{-1}). Ammonium-N in the soil profile during the first year of the study decreased from fall to spring 2004, but increased from fall 2004 to spring 2005.

Cover crop treatments significantly reduced soil profile NO_3-N in fall (Figures 15 and 16) compared to control plots, with significant effects in several depth increments to 1.0 m depth. By spring, soil NO_3-N in the upper profile (0-60 cm) had increased in forage and oilseed radish plots (especially in 2005) while plant uptake by rape and rye continued to maintain low soil profile NO_3-N (Figures 15 and 16).

Although in fall, all cover crop plots had significantly less soil NO_3-N than control plots due to N uptake by the growing plants, during the spring, control and radish plots had greater soil NO_3-N concentrations than rape and rye, as the later cover crops continued to grow and capture nutrients. In the spring samples for three of the four site-years, NO_3-N concentrations in the upper 60 cm of the soil profile were greater in forage radish plots than in the rape or rye plots, and in one site year, greater than in the control plots. We ascribe these higher NO_3-N concentrations to N released from radish tissue by mineralization between the time of freeze-kill in late December and the time of soil sampling in April-May. These data are in agreement with most of the data we obtained on mineral N in the surface soil layer (Figures 11, 12, 13). The increased spring soil NO_3-N concentrations in radish plots was most pronounced and deeper in the profile in the second year than in the first, possibly because January 2005 was considerably warmer and wetter than January 2004 (Figure 4). The rapid appearance of NO_3-N in the surface soil of radish plots could be an advantage from the viewpoint of providing early N fertility for spring-planted main crops. Overwintering non-legume cover crops, such as rye, can reduce N availability to the following crop if termination occurs when their C/N ratio has increased above 25/1. However, the data from spring 2005 shows that on a very sandy soil (CMREC), NO_3-N concentrations in 120 cm deep porewater increased dramatically by early April, so some of the N released would probably have been lost to leaching before the roots of even a very early-planted main crop like corn or potato could capture it. Weinert et al. (2002) noted a similar early N release from a freeze-killed mustard cover crop on irrigated sandy soils in Washington State.

Overall Nitrogen Cycling Conclusions

This research demonstrated that forage radish and rape performed as well or better than rye as N cycling cover crops. Our data suggest that N in freeze-killed, decomposing forage radish residues may be at some risk for leaching in excessively drained very sandy soils during late winter and early spring. The Brassica cover crops cleaned up the nitrate in the soil profile in fall as well as rye (Figures 15, 16). In fall 2003 at CMREC we were able to obtain soil cores to 180 cm and document that the two radish cultivars caused significant reductions in nitrate levels as deep as 150 to 180 cm (rye plots were not sampled in that site-year). However, the winter killed radishes began to release mineral N from root and shoot decomposition in early spring. This early N release is of agronomic advantage compared to the N immobilization often caused by rye in spring. However, to avoid N leaching in spring, we would suggest two methods for retaining and/or reusing the N conserved by the forage radish cover crop: (1) following the forage radish cover crop with the planting of a nitrogen-demanding cash crop in April, or (2) fall-planting of forage radish as a mixture with an over-wintering cereal cover crop (rye or oats). Since low levels of nitrate in leaching water in all treatments in Exp. 1 (spring 2004) lead to inconclusive results on using the forage radish and rye mixture as a way to conserve N mineralized from forage radish residue in late winter/early spring, additional investigation into this mixture is warranted. Our farmer collaborators have successfully grown combinations of forage radish with rye or oats by drilling the two species in alternate rows. However, we do not have deep profile N data for those on-farm plots.

Even with the potential risk for inorganic N leaching following the winter-kill of forage radish, in Exp. 2, the forage radish cover crop consistently provided the greatest N availability to main crops in spring, indicating that a substantial portion of N from forage radish residues can be retained in surface soils until it can be used by subsequent main crops. In summary, our finding that greatest N release in spring comes from forage radish, followed by rape and then rye, is consistent with research conducted in northern Europe (Thorup-Kristensen et al., 2003). Peak nitrogen release from forage radish residues in May could coincide with the acceleration of corn N uptake beginning about 1 month after planting in early April. Other questions not addressed by this research include the possible inhibition of nitrification by glucosinolate degradation products from decomposing rape and forage radish residues. Also not studied were possible effects on nitrification and denitrification by the high amount of calcium recycled to the surface soil environment through the high-Ca content of Brassica cover crop residues.

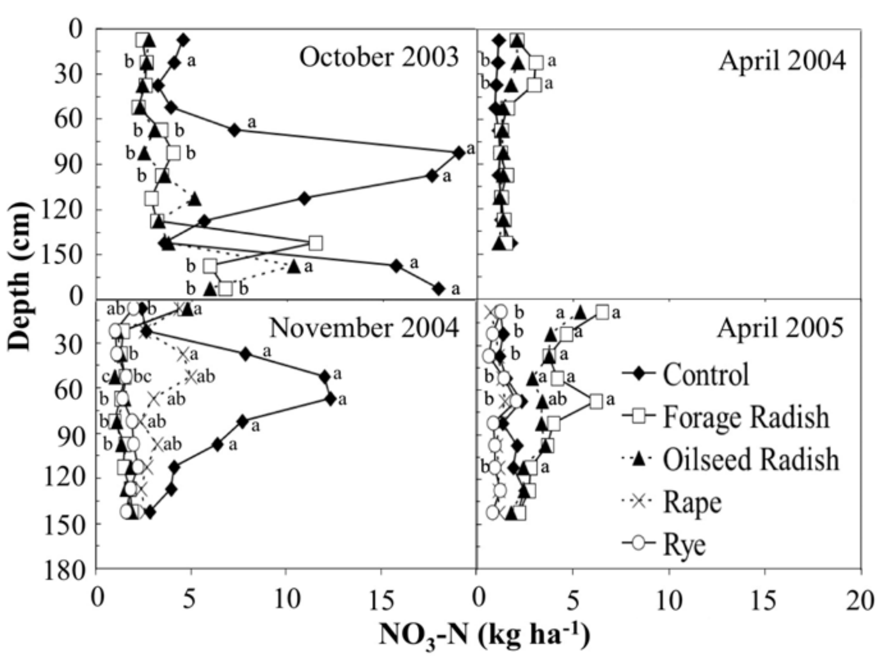

Figure 15 Soil nitrate-nitrogen amounts for each 15 cm depth increment sampled at University of Maryland Central Maryland Research and Education Center-Beltsville facility (CMREC) from October 2003-April 2005. Loamy sand soils. Small letters indicate significantly different means within a depth, $p<0.1$.

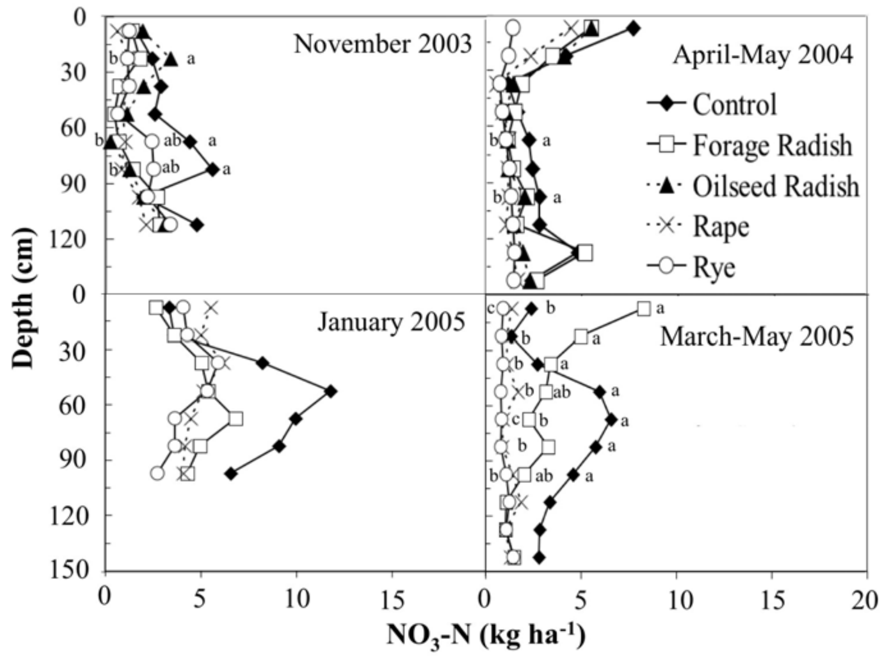

Figure 16 Soil nitrate-nitrogen for each 15 cm depth increment sampled at University of Maryland Wye Research and Education Center (WREC) from November 2003 through May 2005. Silt loam surface soil over silty clay loam subsoil. Small letters indicate significantly different means within each depth, $p<0.1$.

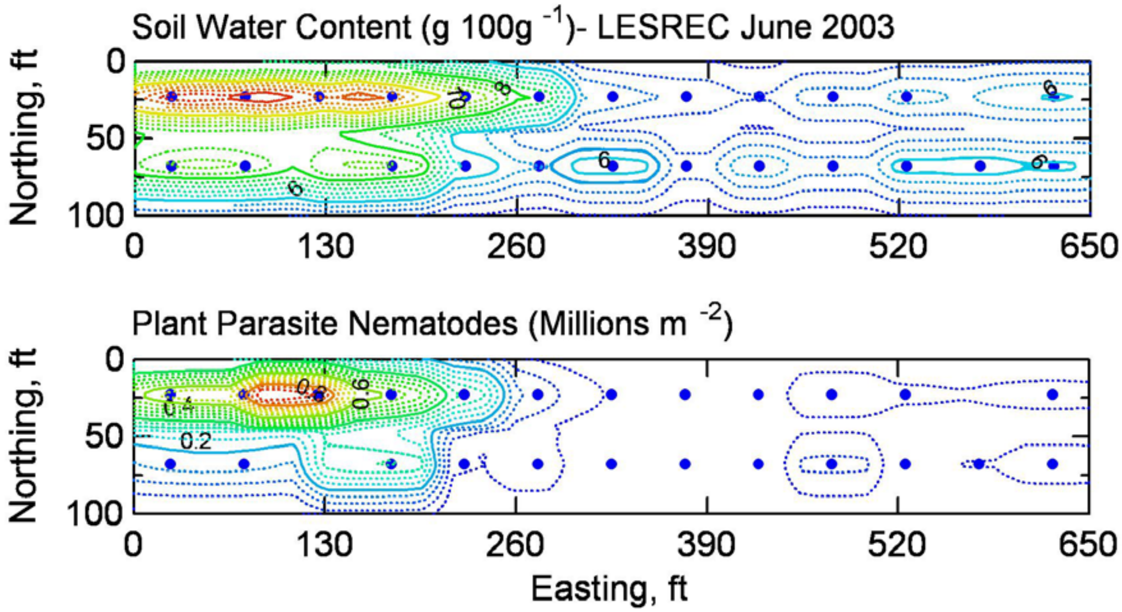

Figure 17 LESREC field 39 (containing LESREC Experiments 1 and 2) showing the spatial distribution of soil water (upper) and total parasitic nematode density (lower) in the 0-15cm deep soil layer prior to laying out and sowing cover crop plots. The filled circles show the transects of sample points used with Kriging to make the maps.

Effects on Soil Nematodes

Suppression of plant parasitic nematodes

Soil nematodes in grain crop agroecosystems were studied in three experiments, LESREC Exps.1 and 2 and CMREC Exp. 1. The hypothesis tested was that glucosinolate-containing Brassicaceous cover crops would suppress plant-parasitic nematodes. Cover crops tested included mustard blend (*Brassica juncea and Sinapis alba*) 'Caliente', rapeseed (*B. napus*) 'Essex', rapeseed (*B. napus*) 'Humus', oilseed radish (*Raphanus sativus*) 'Adagio'/'Colonel', and forage radish (*R. sativus*) 'Daikon'. These were combined with rye (*Secale cereale*) 'Wheeler' and crimson clover (*Trifolium incarnatum*) in LESREC Exp. 1. Soybean cyst nematode (*Heterodera glycines*) was studied by monitoring the active second juvenile stage individuals (J2). A survey of J2 *H. glycines* and soil properties showed an uneven distribution of the nematode and soil water content in the experimental field prior to establishing the experiments (Figure 17). This information was used to design an efficient blocking arrangement in the field, and as covariate data for later analysis.

The abundance of *Heterodera glycines* increased more than ten-fold over the two years in which susceptible soybeans were grown; it was not suppressed by Brassicaceous cover crops (Figure 18). Dolichodoridae (known as awl nematodes) declined over the two years in all treatments of the same experiment. Rye had opposite effects on Dolichodoridae in two experiments. Nematodes in the family Trichodoridae are commonly called "stubby-root" nematodes, because feeding by these nematodes can cause a stunted or "stubby" appearing root system (Crow, 2004). Trichodoridae nematodes were 2-4 times higher in mustard plots than in other Brassicaceous treatments during cover crop growth and 1.8 times higher than in oilseed radish plots during the entire two years, in Exp. 1. In two of the three experiments, rye favored high abundances of Trichodoridae in June. Combination of Brassicaceous cover crops with rye and clover decreased *H. glycines* J2 abundances, and/or increased soil moisture, or increased non-parasitic nematode abundances on one or more sample dates (e.g., Table 10). In laboratory bioassays, all cover crop tissues reduced survival of *Meloidogyne incognita* (root knot nematodes) or *H. glycines* J2 compared to unamended controls. Rapeseed biomass production (mg/kg soil) in 2005 in field Exp. 1 was lower than the minimum amount needed for suppression in the bioassay. Radish biomass production in 2005 was high enough to create residue to soil ratios as high as those that suppressed *H. glycines* J2 in the bioassay. The failure to observe suppression in the field by radish cover crops may have been related to the freeze-termination of this cover crop at a time when cold soil temperatures depress nematode activity. Future Brassicaceous biofumigation studies in Maryland should target high value horticultural production systems that allow for more intensive and flexible management of cover crops.

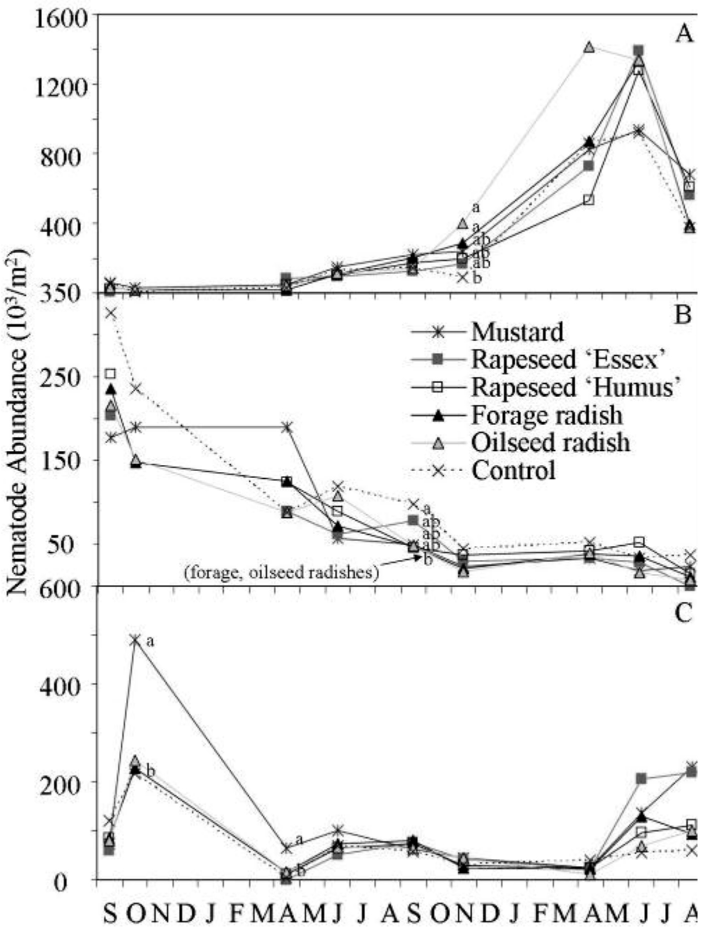

Figure 18 Abundance of *H. glycines* juveniles (J2) (A), Dolichodoridae nematodes (B), and Trichodoridae nematodes (C) in LESREC Exp. 1 from September 2003 to August 2005. Radish and mustard were winter-killed in mid to late December, while rapeseed and weeds (controls) were terminated by incorporation in mid to late April. September 2003 represents pre-treatment populations. Note that y axis scales vary. Some treatments were not sampled in October 2003 or April 2004. Means with the same letter do not differ at ($P < 0.10$) (HSD)

<u>*Effects on Heterodera glycines and soybean yields*</u>

Heterodera glycines juveniles (J2) increased in abundance dramatically over the two years of susceptible soybean, whether or not Brassica winter cover crops were grown (Fig. 18A; Table 11). Among the five Brassicaceous cover crop alone treatments and the control, oilseed radish ($P < 0.03$) and forage radish ($P < 0.09$) had higher abundances of *H. glycines* J2 compared to the control across dates in the second experiment year, though significant differences were only detected on the November sample date (Fig. 18A). Main effect means of *H. glycines* J2 abundances were significantly higher in forage and oilseed radish compared to treatments without Brassica cover crops on only one sample date -in June 2005. Egg densities were not measured in this study. Higher *H. glycines* J2 populations in radishes on one date may not be more problematic than populations in other treatments, if egg production was equivalent or less.

Cysts were counted on several dates. There were no treatment effects on cyst abundances in 2004 (mean=139 ± 13 103/m2) or in 2005 (mean=78 ± 8 103/m2). The lower abundance of *H. glycines* J2 across treatments in August (compared to June, Fig. 18A), is probably a temporal effect on J2 activity in soil rather than a decrease in reproductive potential, because soils in August were warm (mean measured temperature =25 ˚C) and dry (8.4 g water/g dry soil) and there was no rain or irrigation for six days prior to sampling. Considering the more than ten-fold increase in H. glycines J2 over the two years, this study agrees with other recent studies that suggest Brassica cover crops do not decrease *H. glycines* reproductive potential either during cover crop growth or after green manure incorporation (Miller et al., 2006;Warnke et al., 2006).

Combination of Brassica cover crops with rye and crimson clover, however, resulted in lower *H. glycines* J2 abundances in June samples in both years. Rye suppressed *H. glycines* J2 abundance compared to Brassica cover crops (main effect means) by 38% ($P < 0.09$) in June 2004 and 57% ($P < 0.0001$) in June 2005 (Tables 10, 11). Clover main effect means for *H. glycines* J2 populations were 43% lower compared to Brassica main effect means in June 2005 (Table 11). However, neither rye nor clover alone was different from the weedy control plot alone in either year (simple effect means; Table 10).

Table 9 Effects of cover crop treatments on *H. glycines* populations at LESREC (Exp 1) on June 12, 2004. Cover crops were killed in January by freezing or in mid-April by tillage incorporation. Raw means of 4 replications.

Non-Brassica Cover Crop Factor	Mustard 'Caliente'		Rapeseed 'Essex'		Rapeseed 'Humus'		Forage Radish 'Daikon'		Oilseed Radish 'Adagio'		No Brassica		Non-Brassica Main Effect Means	
	nematodes x 10^3 m^{-2} ± SE													
None	151	a	98	a	100	a	106	a	115	a	133	a	117	A
Rye	82	a	123	a	7.4	a	93	a	14	a	112	a	72	B
Clover	160	a	74	a	18	a	59	a	81	a	58	a	75	AB
Brassica Main Effect Means	135	A	96	A	42	A	86	A	75	A	101	A		

[a] Simple effect means followed by the same letter do not differ at P<0.10.
[A] Main effect means followed by the same letter do not differ at P<0.10.

There were no treatment effects on soybean yield in 2004, however main effect means of soybean yield were 59% and 25% higher in rye (1851 kg/ha) than in the control (1166 kg/ha, $P < 0.001$; Brassicaceous cover crops alone + weedy control) or crimson clover (1480 kg/ha, $P < 0.10$), respectively in 2005. Low yields across treatments in 2005 (1503 kg/ha), compared to 2004 (3579 kg/ha), can be explained by only 10 cm total precipitation, including irrigation, during pod-fill in August and September, followed by high rainfall in October (20 cm), which delayed harvest and caused some bean rot.

Some yield loss, however, may be attributable to damage from *H. glycines* (Fig. 19A).

Table 10 Effects of winter cover crop treatments on nematode abundances in LESREC Exp. 2 in June and August during the corn cash crop season of 2005.

Cover Crop[a]	***H. glycines* J2**		**Trichodoridae**		**Dolichodoridae**		**Non-parasitic**	
	nematodes x 10^3/m^2 ± SEM							
	Jun	Aug	Jun	Aug	Jun	Aug	Jun	Aug
Mustard	14 ± 6 a	0 ± 0 b	83 ± 37 b	418 ± 127 a	10 ± 6 a	91 ± 72 a	2,110 ± 405 b	969 ± 175 a
Rapeseed 'Essex'	2 ± 2 a	0 ± 0 b	118 ± 58 ab	350 ± 128 a	0 ± 0	35 ± 11 a	3,261 ± 393 b	1,535 ± 341 a
Forage Radish	20 ± 9 a	6 ± 2 ab	112 ± 95 b	277 ± 59 a	6 ± 4 a	86 ± 41 a	2,792 ± 439 b	1,218 ± 214 a
Oilseed Radish	22 ± 9 a	17 ± 13a	29 ± 17 b	317 ± 122 a	0 ± 0	30 ± 10 a	2,293 ± 269 b	929 ± 104 b
Rye	27 ± 12a	8 ± 4 ab	276 ± 63 a	105 ± 38 a	0 ± 0	5 ± 2 a	5,831 ± 158 a	1,673 ± 96 a
Weedy Control	6 ± 4 a	4 ± 4 ab	67 ± 41 b	292 ± 58 a	11 ± 7 a	24 ± 18 a	2,125 ± 359 b	773 ± 55 b

Small letters indicate significantly different means within a depth, p<0.05

Nonlinear regression of soybean yield and *H. glycines* J2 suggests that yield decreases exponentially with increasing abundance of *H. glycines*. This supports current management recommendations in Maryland to take preventative measures if one cyst is found per 250 cm^3 of soil (Sardanelli et al., 1983). While the trend appears to be primarily a difference in years, reduced yields in the same plots in block 1 where *H. glycines* J2 populations were high in both years (Figure 19), suggest that the nematodes contributed to significant yield reductions in 2005. In both years, *H. glycines* J2 abundance in June was negatively correlated with yield (2004 r=-0.451, P < 0.0001; 2005 r=-0.436, P < 0.0001). Overall, more significant treatment effects on *H. glycines* J2 and yield were detected in 2005 than in 2004, possibly as a result of weather, accumulated cover crop effects on soil properties, increased root density in continuous soybean, or as a function of higher nematode densities, possibly already at equilibrium (Chen et al., 2001).

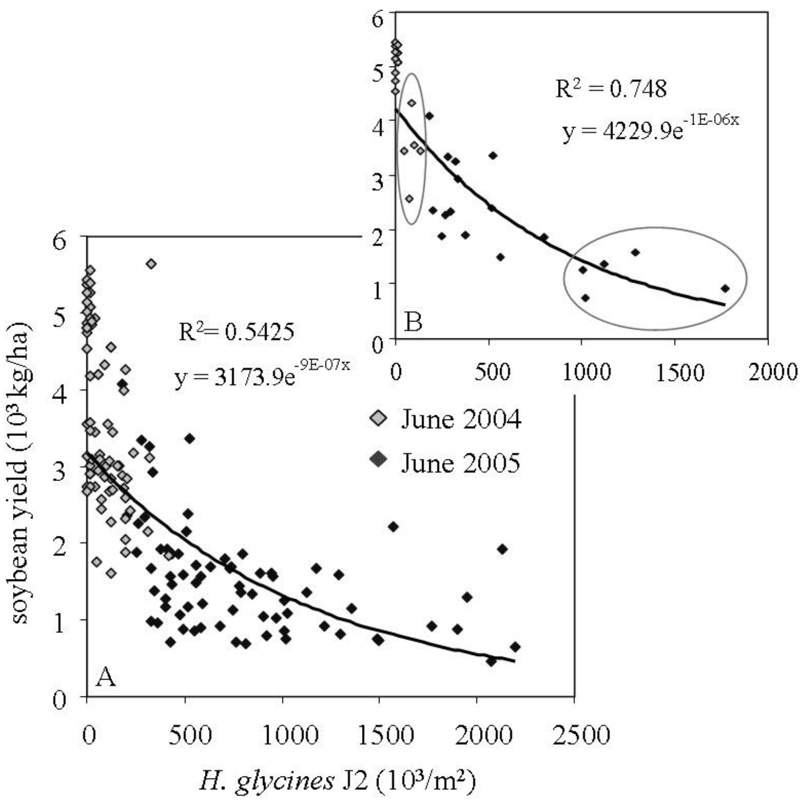

Figure 19 Nonlinear regression of *H. glycines* J2 and soybean yield in LESREC Exp. 1 in June 2004 and 2005 (A) and in only block 1 (B). Circles indicate the same plots in 2004 and 2005.

Bioassay 1

Bioassay results suggest that a rate of 50 g kg^{-1} plant material is an effective rate for nematode control (Figure 20A-D). Assuming incorporation to a 15 cm depth and 90 g water g^{-1} dry matter and 85 g water g^{-1} dry matter for radishes and rapeseed/rye moisture contents, respectively, the equivalent biomass production needed for nematode suppression in the field was 5,000 kg and 7,500 kg dry matter ha^{-1} for radishes and rapeseed/rye, respectively. Oilseed radish leaf tissue, however, suppressed *Meloidogyne* sp. by 57% compared to the unamended control at a rate of only 10 g kg^{-1} or 1,000 kg dry matter ha^{-1} (P < 0.0036) (Figure 20A). These rates were achieved in the field studies. Interaction with soil properties, incomplete hydrolysis of glucosinolates, differing sensitivities of nematodes observed in this study, or insufficient penetration of the soil during winter may explain the general lack of effects on plant parasitic nematodes by radishes.

Root tissue was generally more suppressive than shoot tissue, within an amendment application rate. Rapeseed root suppressed *Meloidogyne* sp. at the lower rate (1500 kg dry matter ha^{-1}) by 86% compared to the unamended control ($P < 0.0007$). This supports studies showing higher glucosinolate concentrations in rapeseed roots than shoots (Eberlein et al., 1998; Gardiner et al., 1999). Few studies have reported oilseed or forage radish root and shoot glucosinolates contents.

Suppression of *Meloidogyne* sp. with rye shoot at the 5% rate may be a result of hydroxamic acids (McBride et al., 2000; Zasada et al., 2005) or may indicate that oxygen was depleted during decomposition of the plant material. *Meloidogyne* was not present in our field experiments and may be more sensitive to Brassicaceous decomposition products than the genera observed in this study.

Bioassay 2

Rapeseed cultivars 'Essex' and 'Humus' were similar in their suppressive effect on *H. glycines* in bioassay 2 (Figure 21A,B). Nematodes used in this experiment were extracted from LESREC Exp. 1 field plot soil in April 2005, from the rhizosphere of the rapeseed cultivar corresponding to that of the tissue amendment. Lower abundances of *H. glycines* in the rapeseed 'Humus' control (unamended) (Figure 19B) may indicate some degree of suppression by 'Humus' during growth of that cover crop. Equal suppression of *H. glycines* by all amendments may indicate a general plant tissue effect, such as oxygen depletion, rather than specific chemical fumigation. Use of plant tissue known to be non-allelopathic, instead of rye, as the non-Brassica control might have made a better comparison. Rapeseed roots suppressed non-parasitic nematodes as much as *H. glycines*, but shoots did not. Bioassay results show that even in ideal conditions, Brassicaceous cover crop tissue has potential for only partial suppression of *H. glycines*. Non-plant parasitic nematodes were most sensitive to rapeseed root amendment (Figure 21C, D).

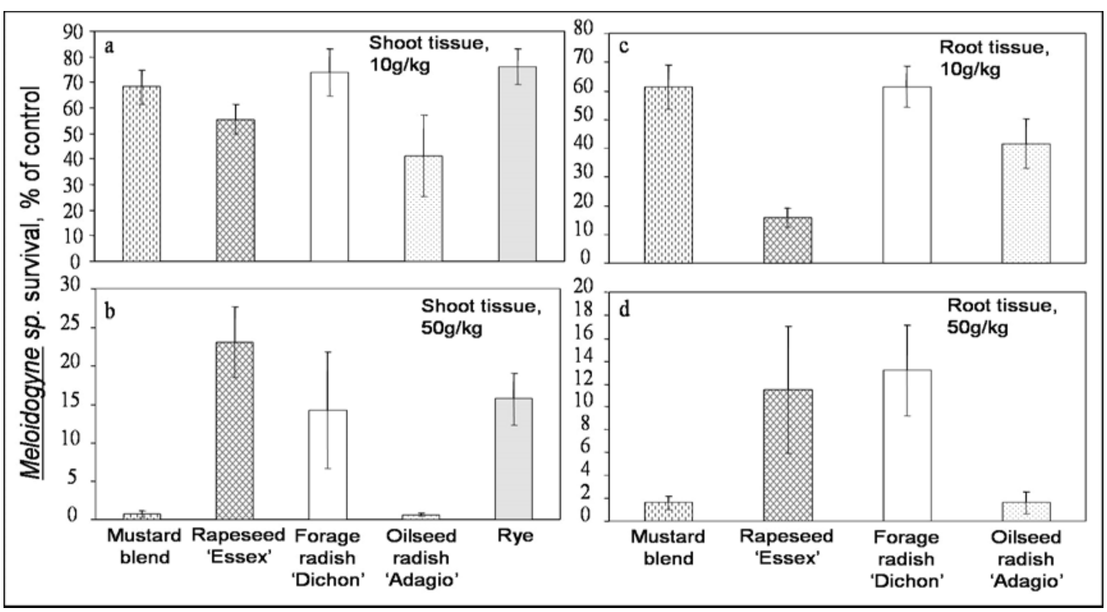

Figure 20 Results of lab bioassay to assess the nematode suppression effects of decay products from cover crop leaf tissue. Known populations of root-knot nematodes were added to wet sand containing varying amounts of chopped leaves or roots from selected cover crops. Mixing 10 g tissue/kg sand (upper panels) of fresh oilseed radish leaves into sand cultures killed 60% of the nematodes initially added. Using a higher rate of oilseed radish leaves (50 g tissue/kg sand, lower panels) killed almost all of the nematodes. The other Brassicas and rye had significant, but smaller, levels of action against the nematodes.

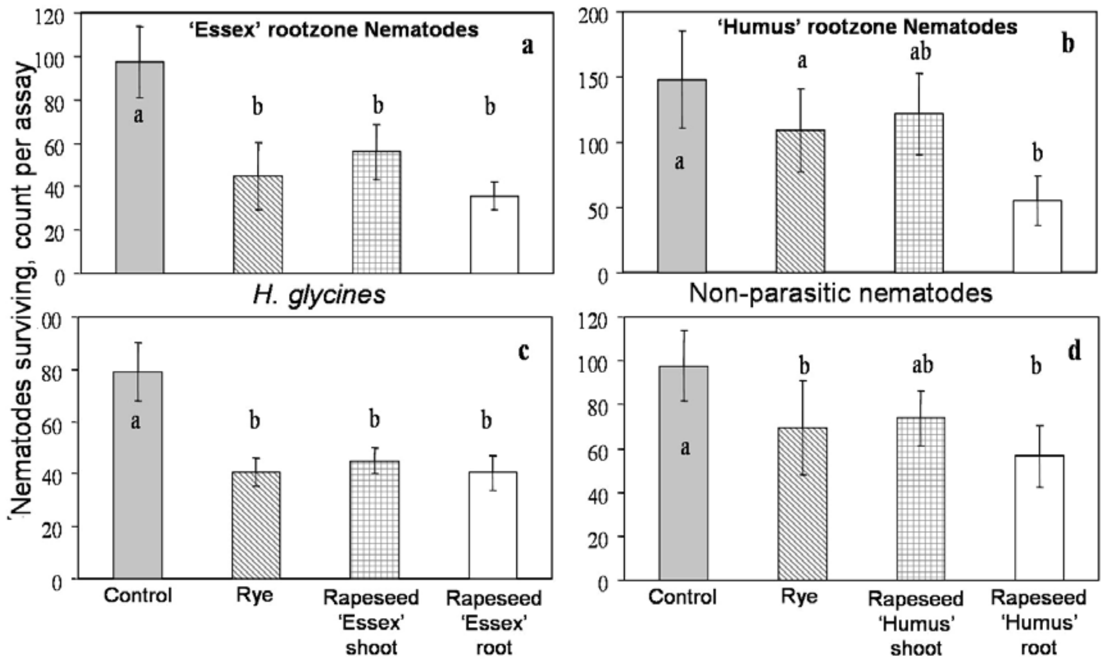

Figure 21 Effects of cover crop tissues on survival of *H. glycines* (a, c) and non-parasitic nematodes (b, d) in Bioassay 2. Nematodes used in the bioassay were mixed communities extracted from field plots growing rapeseed 'Essex' (a, c) and rapeseed 'Humus' (b, d) and then treated with corresponding macerated rapeseed tissue at a rate of 25 g/kg dry sand. Nematodes were incubated in 3 cm diam. plastic cylinders with the sand/fresh plant biomass mixture for 24 hours before contact with water (48 hours) enabled them to move out of the cylinder. Means represented with the same letter are not significantly different at $P < 0.10$ (HSD) (n=4).

Effects on Soil Nematode Ecology

In addition to the work on plant parasitic nematodes, analysis of nematodes grouped by function and indices of nematode community structure were used to study the effects of several of the cover crops on the total soil nematode community in three field experiments (LESREC Exps. 1 and 2 and CMREC Exp. 1) with loamy sand surface soils. Soil properties were also studied in relation to the observed effects. Nematodes provide a relatively simple way to assess the soil biological condition because they occupy every level of the food web and are easy to extract from the soil. Since nematode community dynamics reflect combined soil chemical, physical and biological properties over time, nematode community analysis offers insight into how particular agricultural tools, such as cover crops, may be managed to optimize their impact. The objective of this study was to determine the effects of Brassica and rye cover crops on the nematode community, via analysis of nematode genera, trophic group and community indices. A secondary objective was to evaluate the influences of the timing of cover crop termination versus the cover crop type on nematode response parameters. As these research objectives went beyond those of the funded project, the results will be only briefly summarized in this report.

The enrichment index (EI), channel index (CI), structure index (SI), bacterivore and fungivore maturity indices (BaMI, FuMI), and total community maturity index 2-5 (□MI25, MI25) were calculated (as described in Gruver, 2007 and Ferris et al., 2001) to quantify the nematode community responses to cover crops. In summer 2004 at CMREC (Hayden farm), the oilseed radish had a large positive effect on beneficial (non-parasite) soil nematodes (Figure 22). Plant parasitic nematode populations were small, and unaffected by the cover crops. Forage radish plots were not analyzed for nematodes in that site-year.

Nematode genera identified were similar among the three experiments. Total nematode abundance ranged between 1.9 and 2.7 billion/m^2 in Exp. 1; 1.5 and 3.2 billion/m^2 in Exp. 2; and 1.3 and 1.8 billion/m^2 in Exp. 3 (data not shown). Large populations of dormant (dauer) bacterivore Rhabditidae nematodes were found in radish cover crop plots four to nine months after radish winter freeze-kill, and EI values were higher in radish plots than in control plots in 2005 experiments, six months after radish was killed by freezing. Spring-terminated cover crops favored fungivore decomposition channels, evidenced by high CI values. Large abundances of the plant associate (facultative hyphal feeder), *Coslenchus*, in rapeseed and rye plots contributed to this effect. Despite repeated agronomic disturbances such as tillage, N applications, and herbicide treatments, SI, BaMI, FuMI, and MI25 values were frequently higher in winter-terminated cover crop plots compared with spring-terminated cover crop plots. Dauer larvae and EI effects appeared to be associated with cover crop type, while changes in the fungivore activity and maturity of the community appeared to be associated with the timing of cover crop termination.

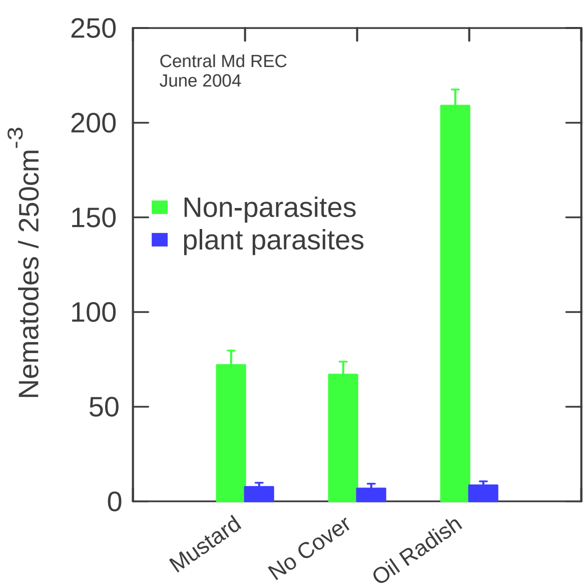

Figure 22 Beneficial (non plant parasitic) nematode populations in June 2004 after oilseed radish, mustard or no cover the previous fall.

On a sandy soil under no-till management near Beltsville, Maryland, frost killed radish cover crops (‘Daikon’ and ‘Colonel’) increased bacteria-eating nematodes while rye (‘Wheeler’) and rapeseed (‘Essex’) cover crops killed by herbicide in spring increased the proportion of fungal feeding nematodes. The unweeded control plots without cover crops tended to have nematode communities with characteristics in between those of the two cover crops effects. The Enrichment Index, which indicates a greater abundance of opportunistic bacteria – eating nematodes, was 23% higher in soils that had Brassica cover crops (Radish 'Daikon' and 'Colonel' and rapeseed 'Essex') than the unweeded control plots. These results, averaged over samples taken in November when the covers were growing, in June about a month after spring cover crop kill, and in August while corn was growing, suggest that the cover crops, living or dead, increased bacterial activity and possibly enhanced nitrogen cycling through the food web.

Weed suppression effects

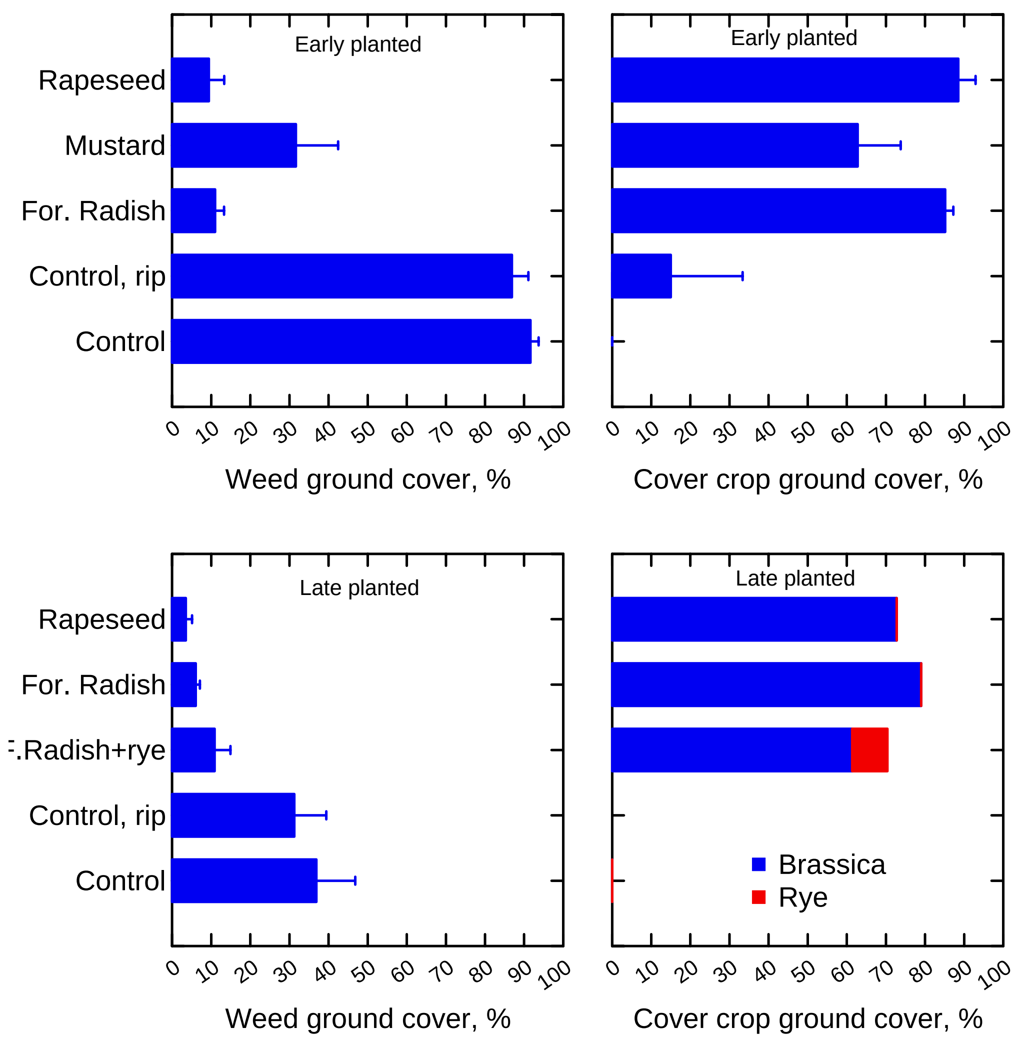

Figure 23 Ground cover (%) by weeds and cover crops in Beltsville Experiment 1 as affected by cover crop treatment and two planting dates, early (August 13, 2003) and late (Sept. 10, 2003).

Early cover crop planting (by September 1) appears to be critical for rapid ground coverage and significant weed suppression by the Brassicas, unless weeds are controlled at the time of the later cover crop planting date (Figure 23).

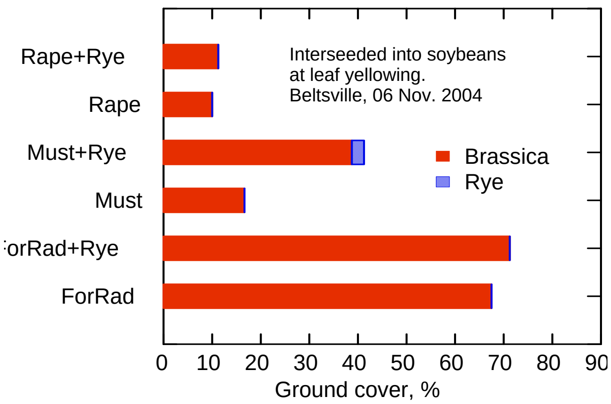

Figure 24 November 2004 ground cover data, Beltsville Exp. 1. Must= mustard.

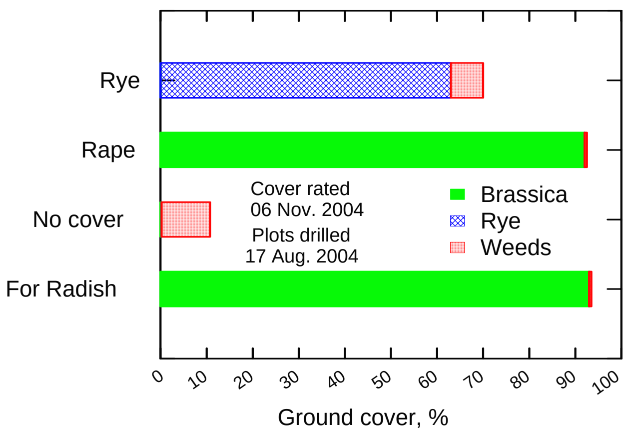

Figure 25 Percent ground cover by weeds and cover crops on 6 November 2004 in Beltsville Exp. 2 as affected by cover crop treatment drilled August 17, 2004. The no-cover control was sprayed with glyphosate once in September.

Our weed suppression research focused mainly on the forage radish because of the rather remarkably weed-free conditions observed following this cover crop. Although forage radish winter-kills leaves little residue, we have observed it to consistently leave the ground virtually weed-free through the winter and early spring. In response to this observation, several dairy farmers in Maryland and Pennsylvania have already successfully no-till planted directly onto the virtually weed-free and almost completely decomposed forage radish residue *without any burn down herbicide*. Anecdotally, they report that stands were actually better and early growth more vigorous for corn planted into radish without burn down herbicide than planted into herbicide killed small grain cover crop (or killed weeds with no cover crop).

Because the Beltsville site was the wettest of the four sites, the soybeans showed rank growth and heavy lodging, and matured later than expected. These factors made it very difficult for interseeded cover crops to establish. On 6 November 2004 vegetative cover was scored in the interseeded plots (Figure 24). Relatively little cover (5 to 35%) was provided by the Mustard, Rape and interseeded Rye. However the Forage Radish, whether sown alone or with Rye, provided a significantly greater 55 to 65% ground cover.

In early November 2004 ground cover in Beltsville Exp. 2 with August drilled cover crops (Figure 25) was very high. The results showed that the forage radish and rape plots had more than 90% cover while the rye plots had only 70% cover and the unplanted no-cover control plots averaged about 10% ground cover by weeds (glyphosate was applied just prior to drilling the cover crop seed in August).

Weed suppression research for the period of January 2005 to August 2005 attempted to quantify the observed effects of *Brassica* cover crops, in particular forage radish. This was primarily done using ground cover ratings and plant counts in plots of cover crops planted in fall 2004. In order to test the hypothesis that weed suppression is due to allelochemical release from *Brassica* cover crops (especially forage radish), a greenhouse study was designed to determine if the cover crop treatments influenced the weed seed bank in the soil. A growth chamber experiment was also set up to determine if lettuce and weed seed germination would be inhibited by the presence of chemicals in forage radish residue or a combination of soil and residue.

Effect of cover crop treatment on percent soil cover and weed density

Winter cover crop plots were rated for percent ground cover in March and May of 2005 and for weed density in May of 2005 to determine the degree of weed suppression following different cover crop treatments. Four replicated experiments that included forage radish, rapeseed, rye, and no cover treatments (USDA Beltsville Exp. 2, CMREC (Hayden) Exp. 1, WREC Exp. 2, and LESREC Exp. 2 are all described in the material and methods section, above. Data were normalized with a square root transformation for analysis. Analysis was performed using the mixed procedure of SAS. Figure 26 shows the back-transformed data as means of all four locations.

In both March and May, percent weed cover was highest in the no cover treatment but there was no difference between the three cover crop treatments ($\alpha = 0.05$). Despite the fact that forage radish was dead and mostly decayed, it was able to achieve weed suppression in March comparable to that of the living rye and rapeseed. However, percent exposed soil was highest in the forage radish plots in both March and May ($\alpha = 0.05$). No difference in weed densities was found in May of 2005. At this time the corn crop was in the two leaf stage and it appears that there was no longer any difference in weed suppression among cover crop treatments. Weed control (glyphosate) was applied *only after* these data were collected.

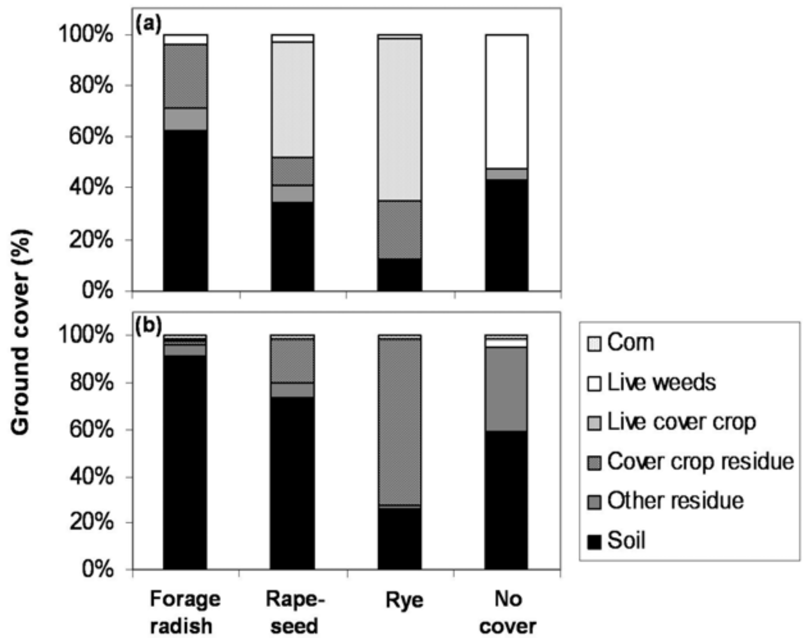

Figure 26 Effect of winter cover crop treatment on percent soil cover in mid-March (a) and mid-May (b) 2005. Data are means of four locations (LESREC, CMREC, WREC and USDA Beltsville).

Effect of forage radish residue on seed germination

The purpose of this experiment was to quantify the effect of forage radish residue on seed germination. The materials collected for the experiment included forage radish residue, intact soil from beneath forage radish residue, and both soil and forage radish residue. These materials were collected in March of 2005 from four replications of winter cover crop experiments at four locations (Beltsville, CMREC (Hayden), WREC, and LESREC). A thin layer of these materials was placed over moist filter paper in Petri dishes, each with 50 seeds of a particular species. The dishes were then incubated in a growth chamber at 25^{o}C for 7 days. Seeds of lettuce, lambs quarters, and redroot pigweed were used in the incubation.

Percent germination of seeds in the experiment was corrected for the germination percentages of the seed lots of lettuce, lambs quarters, and redroot pigweed used which were 83, 93, and 99 %, respectively. Data collected for materials from each location was combined for analysis. The analysis was performed using the mixed procedure of SAS. The statistical model accounted for variation between sampling locations and the blocking of the experiments from which the samples were collected. The data were normalized using a square root transformation prior to analysis. The data presented in Figure 27 is back transformed.

Percent germination of all seed species was at least 20% lower than their respective germination tests for all material types (data not shown). Significant differences in percent germination among treatments and seed species were found but there was no significant interaction. Unexpectedly, soil + residue from the forage radish plots had the highest percent germination and soil from no cover control crop plots with no forage radish residue had the lowest percent germination (Figure 27). We speculate that the decayed forage radish may have released nitrates, a compound long known (Steinbauer and Grisby, 1957) to signal germination for some weed seeds.

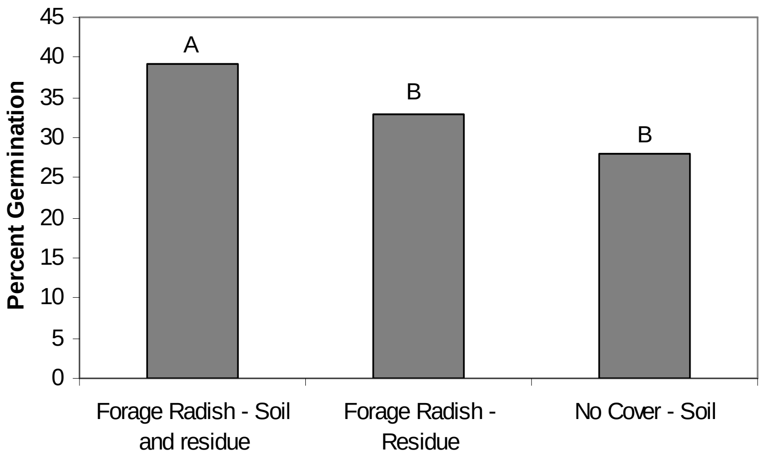

Figure 27 Seed germination in soil or cover crop residue. Means from four locations and of lettuce, lambs quarters, and redroot pigweed seeds. Columns with the same letter are not significantly different ($\alpha = 0.05$).

<u>Effect of cover crops on weed seed germination</u>

The objective of this experiment was to quantify the effect of cover crops on the weed seed bank in the soil. It was hypothesized that allelochemicals released by cover crops would kill weed seeds and reduce weed seed germination. Soil samples were collected in March of 2005 from four blocks of Beltsville Exp. 2 and LESREC Exp. 2. The Beltsville site was no-till while the LESREC site was conventionally tilled. Cover crop treatments included forage radish, rapeseed, rye, and no cover. Soil samples were spread out over trays of a fine sand material and watered to keep the soil moist. These trays were laid out in a completely randomized design on benches in a greenhouse. Germinating weed seedlings were counted once a week for a period of four weeks.

Emergence data from each location were analyzed separately because of differences in tillage between the two sites from which the soil had been sampled. The statistical model accounted for variation among blocks in the field experiments from which the samples were collected. The data were square root transformed prior to analysis. Average germination counts were expressed on a per cm^3 of soil basis. The data presented in Figure 28 is back transformed.

Average germination counts were less than 1 plant per cm^3 for all cover crop treatments at both locations. It was expected that weed seedling emergence would be lowest following forage radish. This trend was observed in the samples from LESREC, where weed seedling emergence was highest in the no cover treatments (Figure 28, upper). However, this trend was not seen in the samples from Beltsville. At this location, weed seedling emergence was highest following forage radish (Figure 28, lower). As nitrates have been long known to stimulate the germination of many seeds (Hendricks and Taylorson, 1974; Steinbauer and Grisby, 1957), we speculate that the apparent stimulation in germination may have been due to higher levels of nitrate from the release of N by the decaying forage radish residues (see above). Although once these effects were observed in these studies, it was too late to obtain a meaningful measure of the nitrate content of the soil. We are currently conducting studies aimed at monitoring the nitrate fluctuations and their impact on weed seed germination following forage radish cover crops.

In all our experiments, we have observed that radish winter cover crops suppressed weeds from the time they were planted in late August until some time in April. In our 2005-2006 weed suppression studies, during April, henbit and chickweed emerged in the forage radish plots, while horseweed emerged in no cover plots. Horseweed was suppressed following forage radish cover crops for the duration of the experiment but the mechanism to explain why this suppression occurred is still unknown. Our 2006-2007 experiments (which carry on beyond the project grant period reported on here) will also include test crops (corn and potato) that are planted in early April to determine if suppression of horseweed following forage radish cover crops will remain effective after the soil is disturbed during seeding.

Since after every good stand of radish we have observed the soil to be weed free at planting time in early spring, it was hypothesized that forage radish might provide weed control in two ways: 1) it might suppress weeds by severe competition during the rapid growth of the cover crop in the fall, 2) during the decomposition of forage radish residue over the winter months, allelochemicals might be released that prevent weed seeds from germinating.

As just mentioned, in the 2005-2006 and 2006-2007 seasons, forage radish cover crops suppressed weeds from the time they were planted in late August until mid- to late-April in two experiments in Beltsville, MD. Horseweed (*Conyza canadensis*) resistant to glyphosate is the newest type of resistant weed in Maryland. It was first reported in 2002 (Ritter, 2005). In these experiments, forage radish successfully suppressed horseweed (*Conyza canadensis*) suggesting that it may be a new integrated management tool for herbicide resistant horseweed in the Mid-Atlantic region. Understanding the mechanism of forage radish weed suppression will be critical to predicting how effective forage radish will be in suppressing horseweed in other locations and under different environmental and management conditions.

Although spring germination of horseweed was suppressed by forage radish cover crops, no such suppression of lambsquarters, pigweed, or green foxtail was observed at the Beltsville site in 2006. Post-project experiments are being conducted in 2007-2008 at other sites to confirm the results of this experiment, especially in fields where horseweed is known to be a problem. Experiments that tested the effect of forage radish cover crops on the natural weed seed bank in the field were more successful than those using planted weed seeds or lab experiments. Continuing research spun off from this grant is on sites selected to have a known history of weeds that are of interest, rather than depending on introducing weed seed.

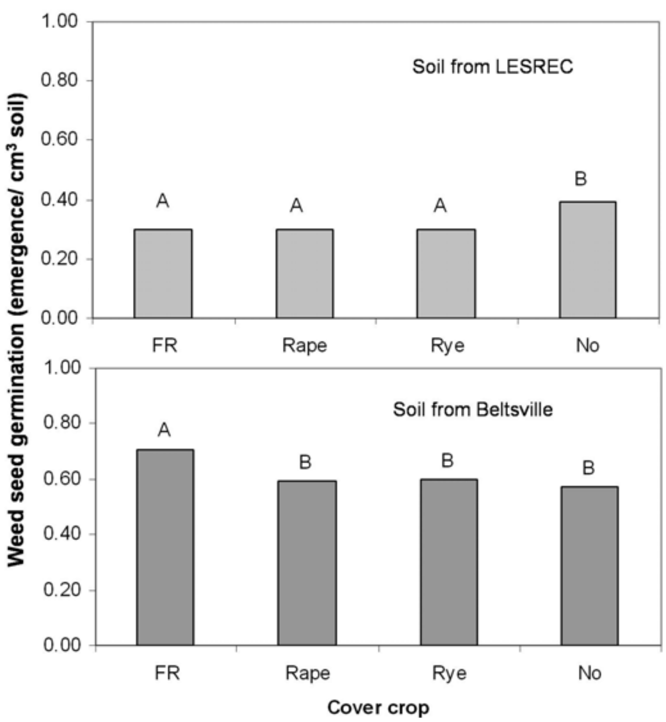

Figure 28 Effect of cover crops on weed seedling germination in soil from LESREC and Beltsville. Columns with the same letter are not significantly different ($\alpha = 0.05$).

Experiments designed to understand the mechanism of forage radish weed suppression were conducted and were described above as Beltsville Experiments 7 and 8. Although these first year studies were not considered conclusive because of the small plot size, our results showed that adding or removing forage radish residues had no effect on weed suppression. In spring 2007 (after this grant period had ended) data from larger plot experiments showed the same thing. In growth chamber studies, forage radish tissue, residue, and soil extracts had no effect on lettuce seed germination and had little effect on lettuce seed root and shoot growth. Therefore, we conclude that our data strongly suggest that radish suppresses spring weeds by smothering in fall, rather than by allelopathy during residue decomposition. However, the mechanism for horseweed suppression in spring is still unclear, hence our continuing research into that aspect.

The length and scope of forage radish weed control

Forage radish suppressed weed growth in the fall when the cover crop was growing and in the spring as the residues decomposed when compared to no cover treatments (Figure 29, Table 12). In April, henbit and chickweed were the first weeds to emerge in forage radish treatments (Figure 29c, Figure 30 and Table 13). These two winter annual weeds had previously dominated the no cover treatments in January and March, suggesting that their emergence had been delayed by the forage

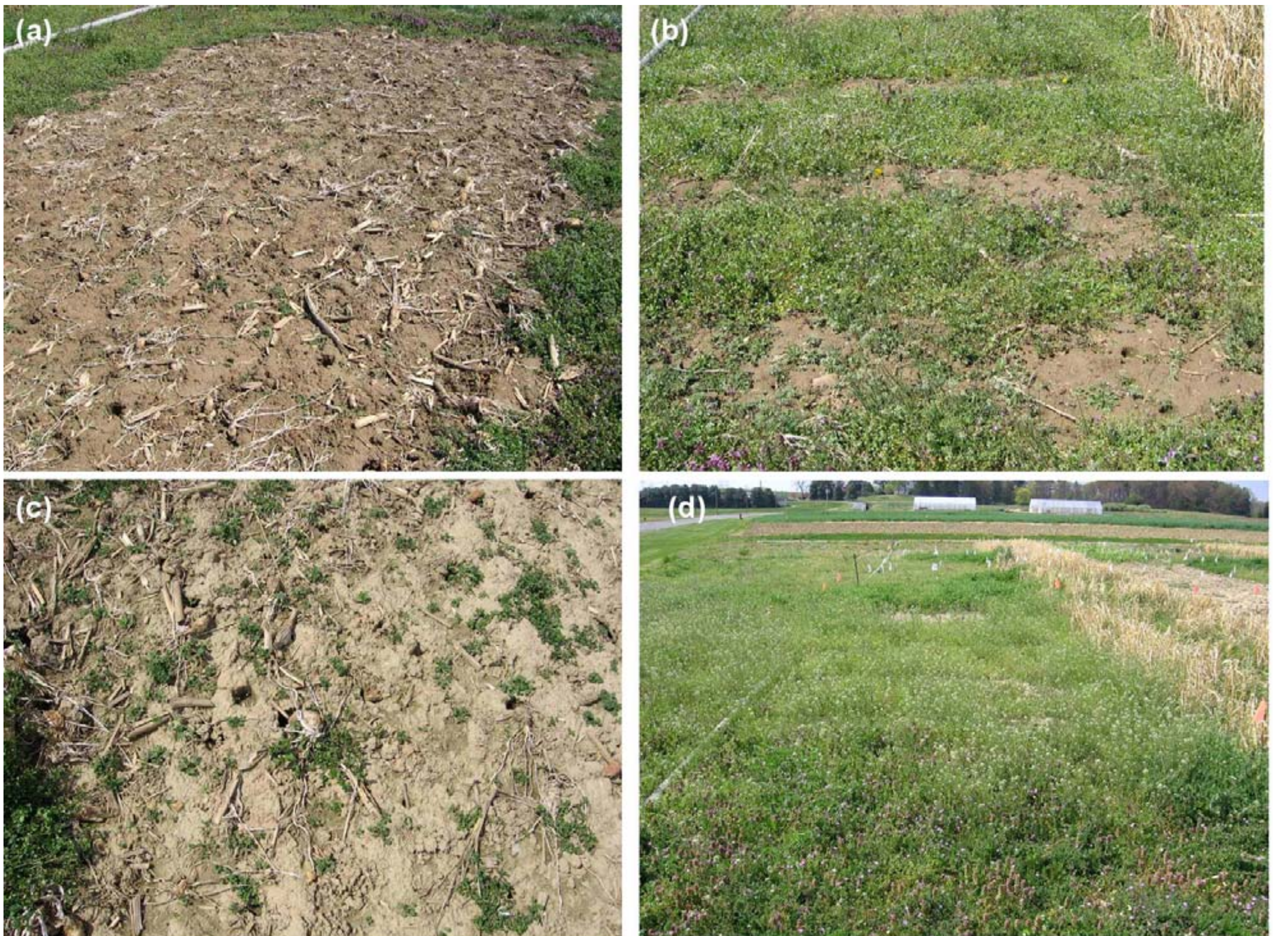

Figure 29 On April 4th there were no weeds in the forage radish plots (a) and many weeds in the no cover crop plots (b).By April 13th henbit and chickweed began to emerge in the forage radish plots (c). In the no cover plots chickweed and speedwell dominate and horseweed had begun to emerge (d). Photos by Y. Lawley.

radish cover crop. While henbit was the dominant weed in the forage radish plots, horseweed began to emerge in the no cover plots in April (Figure 29d, Table 14). Percent ground cover ratings for weeds in the no cover plots decreased relative to the forage radish plots later in May and June as weeds (especially horse weed) grew tall and shaded soil surface. Henbit began to die out in the forage radish plots by mid-June to early July, however no horseweed germinated in the forage radish plots. It is not known if forage radish had an allelopathic effect on the horseweed that prevented it from germinating or if the canopy of henbit created an unfavorable environment for horseweed germination.

One hypothesis was that forage radish would suppress winter annual weeds better than it would suppress summer annual weeds. Forage radish was observed to delay the emergence of winter annual weeds relative to no cover and oat treatments rather than inhibit them from germinating. By delaying the emergence of winter annuals, summer annual weeds were also delayed from emerging. If the emergence of these summer annual weeds (which are harder to control) could be pushed past a critical weed free period for a summer crop, this might give the summer crop a competitive edge.

Figure 30 On 9 May 2006 henbit dominates forage radish plots (left) while horseweed dominates no cover plots (right).

Figure 31 Researchers and extension personnel observe radish residue experiment in which some researchers removed radish roots and / or shoots from plots and added them to others. November 27, 2006 field day, Beltsville, MD. Results were obtained in spring 2007, after the grant reporting period.

Table 11 Mean percent ground cover through the 2005/2006 growing season in the Beltsville North Farm Experiment

	Mean percent ground cover (%)				
Month/ Cover Crop	Live cover crop	Cover crop residue	Other residue	Soil	Total weeds
November					
Forage Radish	100a	-	0a	0a	0a
No Cover	-	-	0a	60b	40b
January					
Forage Radish	0a	67a	0a	33a	0a
No Cover	-	-	0a	40a	60b
March					
Forage Radish	0a	34a	0a	66a	0a
No Cover	-	-	3b	13b	84b
April-early					
Forage Radish	0a	16a	6a	67a	11a
No Cover	-	-	0b	10b	90b
April-late					
Forage Radish	0a	9a	2a	52a	37a
No Cover	-	-	0a	6b	94b
May					
Forage Radish	0a	0a	0a	0a	98a
No Cover	-	-	0a	24b	76b
June					
Forage Radish	0a	0a	0a	15a	85a
No Cover	-	-	32b	28b	40b
July					
Forage Radish	0a	0a	43a	40a	17a
No Cover	-	-	20b	38a	42b

Table 12 Mean percent ground cover through the 2005/2006 growing season in the Beltsville North Farm Experiment

Month/ Cover Crop	Mean percent ground cover (%)								
	Total weeds	Chick weed	Hen -bit	Horse-weed	Speedwell Sp.	Shepherds Purse	Galin-soga	Pig-weed	All grasses
November									
Forage Radish	0a	-	-	-	-	-	-	-	-
No Cover	40b	-	-	-	-	-	-	-	-
January									
Forage Radish	0a	0a	0a	0a	0a	0a	0a	0a	0a
No Cover	60b	40b	19b	0a	0a	0a	0a	0a	0a
March									
Forage Radish	0a	0a	0a	0a	0a	0a	0a	0a	0a
No Cover	84b	61b	10b	0a	16a	0a	0a	0a	0a
April-early									
Forage Radish	11a	0a	0a	0a	7a	0a	0a	0a	0a
No Cover	90b	67b	0a	4a	12ab	6b	0a	0a	0a
April-late									
Forage Radish	37a	0a	30a	0a	4a	7a	0a	0a	0a
No Cover	94b	60b	5b	4a	6a	12a	0a	0a	0a
May									
Forage Radish	98a	0a	63a	0a	17a	0a	0a	0a	0a
No Cover	76b	0a	0b	24b	10a	0a	0a	0a	0a
June									
Forage Radish	85a	30a	61a	0a	0a	0a	0a	0a	0a
No Cover	40b	0b	0b	27b	0a	0a	0a	0a	0a
July									
Forage Radish	17a	0a	0a	0a	0a	0a	10a	3a	10a
No Cover	42b	0a	0a	33b	0a	0a	5a	1a	5a

Note: Letters indicate significant difference (α=0.05) within a column for each month

Beltsville Experiment 6: Effect of forage radish cover crops on weeds of interest

This experiment was more controlled than Beltsville Experiment 5 because it dealt with weed seeds that had been planted under forage radish residue (Figure 32). Other weeds from the natural seed bank were frequently removed to decrease their interference with the introduced weeds. Weeds began to emerge in these plots in April (Table 14). Lambsquarters and pigweed emerged in larger

Figure 32 Seedlings of pigweed, green foxtail, lambsquarters, and horseweed (from left to right) germinated in May from planted seeds. Photo by Y. Lawley.

numbers than horseweed and green foxtail in both the no cover and forage radish treatments. As green foxtail and horseweed emergence was poor in both forage radish and no cover plots, the results may reflect poor seed rather than any effect of forage radish. In contrast to experiment 5, forage radish in experiment 6 had a stimulatory effect on pigweed and lambsquarters emergence compared to no cover treatments.

In Beltsville experiment 6, lambsquarters and pigweed began emerging well before these weeds were germinating from the natural weed seed bank in Experiment 5. Lambsquarters was never observed to germinate in forage radish plots of Experiment 1 and pigweed began only in July to germinate in both forage radish and no cover treatments. Some of the differences observed between Beltsville Experiments 5 and 6 may have been due to mechanical weeding that was done in these plots to facilitate weed emergence counts. Differences may also have resulted from the placement of weed seeds on the soil surface in close contact with the forage radish residues that could alter the temperature and/or nutrient environment these seeds experience relative to Experiment 1.

An occasional horseweed seed (2 per m of row) did emerge in the forage radish treatment from Beltsville Experiment 6, while no horseweed seeds from the natural weed seed bank emerged in Beltsville Experiment 5. While the number of seeds emerging was so low as to be inconclusive, it is possible that the canopy of henbit present in Experiment 5 played a role in preventing the emergence of horseweed, rather than an allelopathic suppression of horseweed forage radish.

Table 13 Mean weed emergence from planted weed seeds over 2005/2006 growing season in the Beltsville North Farm Experiment

		Mean weed emergence in a 1 m row					
Cover Crop	Weed	January	February	March	April	May	Total
Forage Radish	Green foxtail	0	0	0	2	1	67
	Horseweed	0	0	0	0	2	2
	Lambs quarters	0	0	0	290	98	401
	Pigweed	0	0	0	87	84	202
No Cover	Green foxtail	0	0	0	6	1	70
	Horseweed	0	0	0	0	1	2
	Lambs quarters	0	0	0	32	87	138
	Pigweed	0	0	0	4	45	77

Figure 33 Moving forage radish residues in November 2005. Forage radish shoots and tap roots removed (left). Doubling forage radish residues (center), placing forage radish roots and shoots in no cover plots (right). Photos by Y. Lawley.

Beltsville Experiment 7: Effect of forage radish residues on weed suppression

Increasing cover crop residues did not increase weed suppression in forage radish treatments (Table 15). Neither removing forage radish shoots, doubling forage radish residues, nor adding forage radish roots to the soil from a no-cover plot had a significant effect on weed suppression (Figure 33, Table 15). Thus the results of this experiment fall short of explaining the relative contributions of forage radish roots and shoots to weed suppression, as well as the relative effect of fall competition and the release of allelochemicals from decomposing residues. These results may be due to the large edge effect in the small plots that were used as well as the orientation of the residues that were added to the plots. It may be necessary to use larger plots to detect significant differences in weed emergence due to the patchy distribution of weeds.

Table 14 Effect of removal or addition of forage radish root and shoot residues on percent weed cover in the 2005-2006 Beltsville North Farm Experiment.

		Percent weed cover		
Cover Crop	Residue Treatment	Mid-Feb.	Mid-April	Mid-June
Forage Radish	roots and shoots	0a	43a	85a
	roots and no shoots	0a	18a	73a
	roots and double shoots	0a	29a	76a
	no shoots and no roots	0a	25a	63a
No Cover	forage radish shoots	43a	95a	100a
	forage radish roots and shoots	36a	98a	99a

Note: Letters indicate significant difference (α=0.05) within a cover crop treatment and month

Beltsville Experiment 8: Effect of forage radish extracts on lettuce seed germination and growth

Forage radish plant tissue, residue, and soil extractions influenced lettuce root and shoot lengths rather than lettuce seed germination. Extracts of forage radish root and shoot tissues harvested in November inhibited lettuce root and shoot growth relative to the distilled water control (Table 16). This inhibition did not occur when using extracts of forage radish residues collected in March. Extracts of soil collected below forage radish residues in March increased lettuce root and shoot length while extracts from soil samples collected below forage radish residues in May had no effect on shoot or root length (Table 17).

Table 15 Effect of aqueous plant extracts dried and ground plant tissues collected in November and March from the Beltsville North Farm Experiment on mean shoot and root length of 'Great Lakes' lettuce.

		January				March			
Plant Extract	Dilution	Shoot		Root		Shoot		Root	
		Mean	StDev	Mean	StDev	Mean	StDev	Mean	StDev
Water Control	1	7.0	1.4	1.2	0.4	8.6	2.4	1.8	0.4
Forage radish root	1	0.0	0.0	0.0	0.0	1.9	1.4	0.8	1.0
Forage radish root	1:1	0.5	0.5	0.2	0.4	9.1	5.9	1.3	0.6
Forage radish root	1:5	2.8	1.1	1.1	0.3	17.1	3.5	1.7	0.5
Forage radish root	1:15	5.7	1.3	1.2	0.4	20.3	4.0	1.7	0.6
Forage radish shoot	1	0.0	0.0	0.0	0.0	6.0	4.7	1.2	0.5
Forage radish shoot	1:1	0.8	0.5	0.3	0.5	10.7	3.9	1.3	0.6
Forage radish shoot	1:5	3.1	1.3	0.9	0.4	18.8	5.9	1.4	0.5
Forage radish shoot	1:15	5.6	1.8	1.5	0.6	21.4	26.9	1.4	0.5

Table 16 Effect of aqueous soil extracts collected in March and May from the Beltsville North Farm Experiment on mean shoot and root length of 'Great Lakes' lettuce.

Soil Extract	Dilution	March				May			
		Shoot		Root		Shoot		Root	
		Mean	StDev	Mean	StDev	Mean	StDev	Mean	StDev
Water Controls	1	7.4	1.6	1.7	0.5	7.7	2.7	1.9	0.3
Forage radish soil	1	19.4	3.5	1.9	0.5	14.3	3.0	1.7	0.5
Forage radish soil	1:1	17.2	4.5	2.0	0.4	11.7	2.8	1.6	0.6
Forage radish soil	1:5	15.1	4.3	2.0	0.4	8.9	2.3	1.8	0.4
Forage radish soil	1:15	14.0	4.1	1.8	0.4	9.4	2.4	1.7	0.5
No cover soil	1	14.8	3.5	1.7	0.5	14.8	4.0	2.1	0.4
No cover soil	1:1	15.0	5.1	1.6	0.6	12.9	3.1	2.1	0.4
No cover soil	1:5	12.7	4.0	1.8	0.4	12.2	3.7	2.0	0.4
No cover soil	1:15	10.9	3.5	1.8	0.4	9.5	3.2	2.0	0.3

Conclusions regarding weed suppression by forage radish:

Forage radish winter cover crops suppressed weeds from the time they were planted in late August until April. In April, henbit and chickweed emerge in the forage radish treatments, while horseweed emerged in no cover treatments. Horseweed was suppressed following forage radish cover crops for the duration of the experiment but the mechanism to explain why this suppression occurred is still unknown. Future experiments should also include test crops that are planted in April to determine if suppression of horseweed following forage radish cover crops remains effective after the soil is disturbed during seeding.

Although horseweed was suppressed by forage radish cover crops, no suppression of lambsquarters, pigweed, or green foxtail was observed at Beltsville in 2006. Experiments should be conducted at other sites to confirm the results of this experiment, especially in fields where horseweed is known to be a problem.

Experiments that tested the effect of forage radish cover crops on the natural weed seed bank in the field were more successful than those using planted weed seeds or lab experiments. Future research sites should be selected that are known to have a history of weeds that are of interest rather than introducing them.

Experiments designed to understand the mechanism of forage radish weed suppression were not conclusive. Adding or removing forage radish residues had no effect on weed suppression in the small plot experiment. An experiment that uses larger plots should be used to confirm the findings of this small plot experiment. Forage radish tissue, residue, and soil extracts had no effect on lettuce seed germination and had little effect on lettuce seed root and shoot growth. Germinating seeds in soil collected from forage radish plots may be a more biologically meaningful way to conduct bioassays to test for effects on seed germination and growth. Understanding the mechanism of forage radish weed suppression will be critical to predicting how effective forage radish will be in suppressing horseweed in other locations and under different environmental and management conditions.

Farmers in Maryland wanting to take advantage of forage radish cover crops to suppress weeds should plan their crop rotations so that early seeded crops and crop varieties can be planted in April following forage radish cover crops. This study may be the first to indicate that forage radish could be used to manage horseweed without herbicides. This is encouraging given the difficulty of killing horseweed using herbicides and the increasing occurrence of herbicide resistant horseweed in Maryland.

Compaction alleviation effects

Soil compaction reduces productivity and profitability to some degree on nearly every farm in the mid-Atlantic region. It does so mainly by limiting root penetration and elongation, thus reducing plant access to water stored in the subsoil. Subsoil compaction also promotes surface runoff and ponding after heavy rain, increasing the potential for crop damage and loss of nutrients to streams. Tap-rooted Brassica cover crops may have the potential to help ameliorate soil compaction problems, especially in no-till farming, by creating root channels and altering soil structure by the addition of organic matter and protection of the soil surface. We hypothesized that roots of cash crops following a radish cover crop will more rapidly and frequently penetrate compacted soil than where a rye cover crop or no cover crop was grown. To test the above hypotheses, two types of field studies were conducted: the first imposed cover crop treatments on existing soil compaction conditions (CMREC Exp. 2 and Beltsville Exp. 3) while the second type of experiment imposed compaction treatments in a factorial combination with cover crop treatments (Beltsville Exp. 4).

Alleviation of subsoil compaction was one of the first research goals when our group began studying the Brassica cover crops. We hypothesized that the cover crop roots would penetrate compacted subsoils in fall and winter when the soil was wet and relatively soft, and that these cover crop roots would leave channels that the summer crop roots could follow to traverse the compacted zone when it was dry and very hard. This process has been termed "bio-drilling." Documentation of possible ameliorative effects of cover crops on soil compaction presents a research challenge. The normal approach to evaluating the effect of tillage or traffic on soil compaction does not apply because the traditionally used measures of soil compaction, bulk density and penetration resistance are not expected to be influenced by the root bio-drilling mechanism hypothesized. The root channels formed by biodrilling are likely to be small enough (~ 1mm) that their presence would not be detectable by penetrometer measurements. Nor would traditional bulk density measurements be affected since the opening of large pore spaces (channels) by root action would of necessity further compact the soil adjacent to the channels.

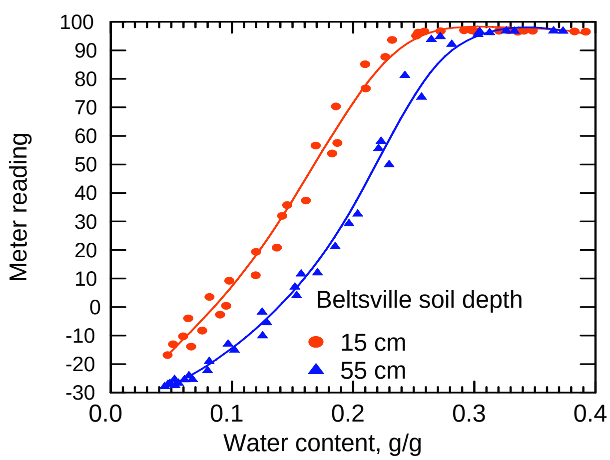

Figure 34 Calibration curve for gypsum block soil water sensors for surface and subsoil horizons at Beltsville.

Therefore we decided to measure the effects on compaction alleviation in terms of water use by crops and crop rooting patterns. This makes sense because the main reason that soil compaction is a problem is that it restricts crop root growth, especially downward into subsoil layers where water and nutrients can be accessed during times of drought stress. The main advantage of improved deep rooting, then, is that it should give crops more access to subsoil moisture. Plants especially need access to subsoil water during dry, hot periods during the summer that create high transpiration demand.

Because direct root measurements in compacted soils is extremely difficult and labor intensive, our first approach to measuring the effect of biodrilling was to monitor soil water above and below the compacted layer. We hypothesized that biodrilling by cover crops would allow more roots to access the subsoil and therefore the crop would use subsoil water more rapidly than where there was no biodrilling. The situation is complicated by the likelihood that the root channels can also serve as pathways for rapid preferential flow of percolating rainwater causing the subsoil to recharge more rapidly after a rainfall event. Therefore, effective biodrilling might result in greater or smaller subsoil water content at any given time, making soil water data interpretations somewhat uncertain.

We monitored soil water content above (A horizon) and below (B Horizon) the compacted plow pan as a means of studying the "bio-drilling" effects of fall cover crops. We expected to see A horizon water content respond rapidly to rainfall events and drying periods, but to be moderated significantly by plant residue mulch. We expected to see subsoil water depleted only during longer dry periods during which A horizon water would be mostly used up. We expected that increased crop rooting in the subsoil would result in greater use of subsoil water during such periods. We also expected that channels from biodrilling might allow more rapid recharge of subsoil water after rain events.

To monitor how cover crops influenced the ability of summer crops to obtain subsoil moisture, during 2004-2005 we installed almost 200 soil moisture sensors consisting of concentric electrodes embedded in gypsum blocks (electrical resistance blocks). We installed the soil water sensors at 15 cm (above the 25 to 40 cm deep compacted layer) and 50 – 55 cm (below the 25 to 40 cm deep compacted layer). The blocks respond to the soil water potential (or tension) by soaking up water from the soil as the soil becomes moister. As the soil dries, it draws water out from the blocks. The water in the blocks, which is effectively a saturated $CaSO_4$ solution due to the gypsum matrix, controls the electrical conductivity or the resistance to the passage of a known current between two concentric metal mesh cylindrical electrodes embedded in the gypsum.

Wires from these electrodes were positioned above the soil surface so they could be attached periodically to a meter to obtain soil readings indicative of the soil moisture at the two depths. We used a Delmhorst meter (KS-D1 Digitak Soil Moisture Tester) made specifically for the model GB-1 Gypsum Soil Blocks. This meter is factory calibrated to read near 95-98 when the soil is at field capacity (about 10 kPa tension) and near zero when the soil water tension is near the wilting coefficient (Delmhorst Instrument, 2003). When the soil was very dry, readings were as low as minus 30. We checked each individual block for a consistent reading under saturation.

We also calibrated blocks in duplicate pots of soil material obtained from 15 cm depth (A horizon) and 55 cm depth (B Horizon) from each field site in which gypsum blocks were used in the field experiments. A typical set of calibration curves (which we fit to polynomial functions with $R^2 > 0.98$)

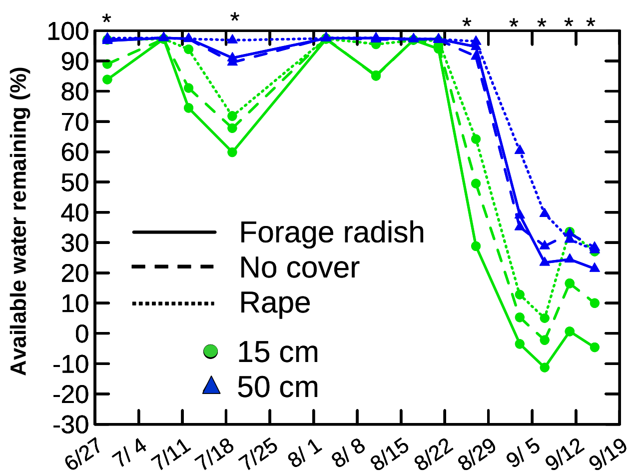

Figure 35 Soil water above and below the plow pan (as indicated by gypsum block meter readings) in Beltsville Exp.1 during the 2004 soybean growing season. Asterisks (*) denote dates with significant differences among cover crop treatments. Means of 8 sensors. Silt loam to silty clay loam soils

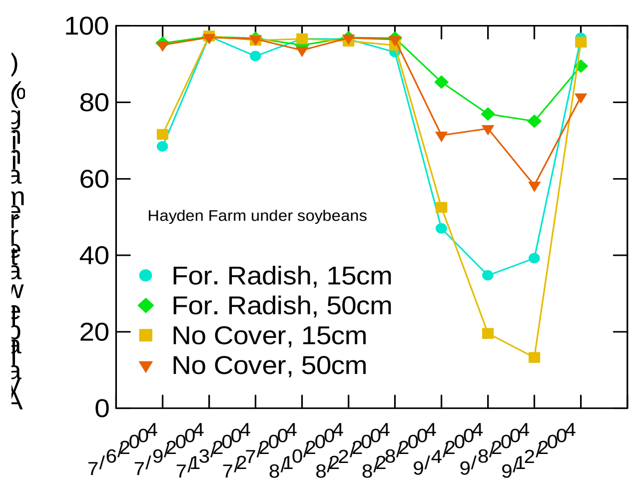

Figure 36 Soil water above and below the plow pan (as % of maximum water holding capacity) measured by gypsum block sensors in CMREC Exp.1 during the 2004 soybean growing season. Loamy sand soils.

relating gypsum block meter readings to gravimetrically measured soil water content are shown in Figure 34 for the soil in Beltsville Exp. 1. However, since relative soil water is the variable of interest, we analyzed and present the gypsum block data in this report as raw meter readings to avoid adding additional error and to maximize sensitivity.

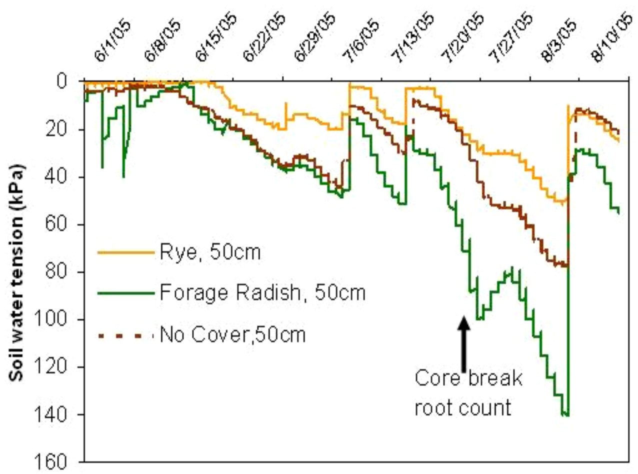

Figure 37 Soil water tension at 50 cm depth under corn growing after three winter cover crop treatments. Arrow indicates the date on which the core break root count data shown in Figure 39 (left) were obtained. CMREC Exp. 2. Greater tension = drier soil. Means of 4 Watermark sensors.

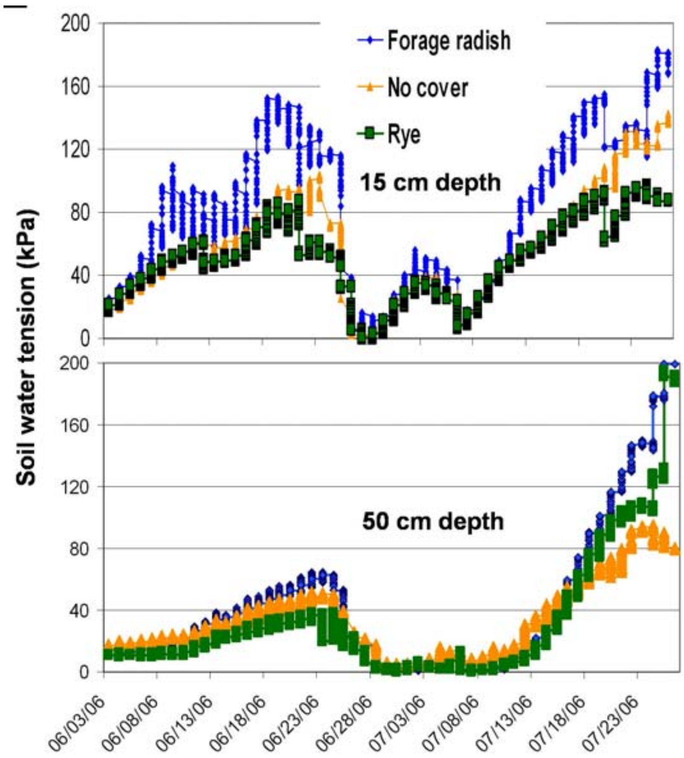

Figure 38 Soil water tension during a dry spell in July 2006 in Beltsville Exp. 3 (higher values = drier soil) at 15 cm (silt loam) and 50 cm (silty clay loam) depths. The crop was soybeans. More rapid subsoil (50 cm) drying in the plots that previously grew forage radish suggests that the soybean crop is better able to utilize the subsoil water in those plots. More rapid drying at 15cm may be due to less residue cover after radish. Means of 8 Watermark sensors.

The data suggest that the sensor array installed was capable of closely reflecting soil water use by the summer crops and replenishment by rain. Although conditions caused relatively little water stress during summer 2004, the gypsum resistance blocks distinguished differences in mean summer subsoil water potential among the cover crop treatments at two of the three sites monitored. The gypsum block data clearly shows that the surface soil dried more rapidly during dry periods and wetted much more rapidly after rain events than did the subsoil (Figures 35 and 36). However cover crop effects were not easily detected, partly because of the lack of severe moisture stress and partly because of the limited number of readings that could be taken with the hand held meter.

Some difference in subsoil and surface soil water content during late summer was observed following radish compared to the no-cover crop plots, but the exceptionally ample and well distributed rainfall during most of summer 2004 did not allow for extensive depletion of subsoil moisture that might have maximized these effects. Two moderate drought stress periods did occur, first in early July and then from late August and until substantial rain events between September 8 and 12. During these periods water was lost more rapidly from the surface soil in the radish treatment plots than in the no cover or in the rye treatment plots (Figure 35), probably because the radish plots had almost no water conserving mulch from either weed or cover crop residues. No significant effects were detected in the rate of subsoil water depletion.

In 2005 and 2006, we replaced most of the gypsum block sensors with Watermark granular matrix resistance sensors. Not only were the Watermark sensors more sensitive to changes in soil moisture, they could also be wired to multi-channel data loggers that recorded hourly temperature-corrected readings directly as kPa soil water tension. This capability, combined with some extended dry periods, allowed us to obtain data that more clearly showed how summer crop soil water use was influenced by cover crop treatments (Figures 37 and 38).

Figure 37 presents data from the 50 cm depth of the sandy soil at CMREC Exp. 2 during the period 01 June to August 16, 2005 during which corn was growing on the plots. In early June the subsoil for all treatments was in the same range of low subsoil moisture tensions (a few erratic peaks are from one sensor which had a loose connection). Subsequently, when the weather became hot and evapotranspiration demand increased, the subsoil moisture tension increased (that is, the soil dried out) more rapidly in the forage radish treatment plots than in the rye or no-cover plots. In

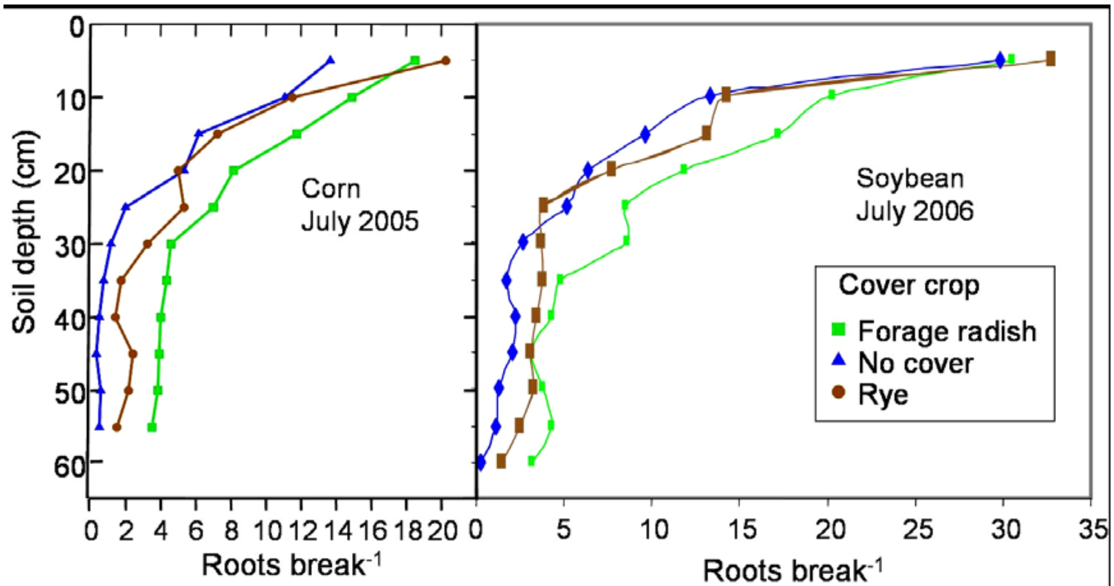

Figure 39 Vertical distribution of summer cash crop roots at CMREC Exp. 2 (corn, *left* and soybean, *right*) in soils planted to forage radish, rye or no cover crop the previous fall. In both years, the summer crop had significantly more subsoil roots following forage radish, compared to following either the rye cover crop or no cover. Loamy sand soil at Beltsville Field Facility, Central Maryland Research and Education Center. Means of 12 cores.

the forage radish plots, the subsoil moisture also rebounded more dramatically after each of the four rain events, including one event (7/27/05) that caused no reduction of moisture tension in the rye and no-cover treatment plots. These patterns of water depletion tend to support our hypothesis of greater subsoil rooting by corn following the forage radish cover crop. In addition, it appeared that the cover crop biodrilling also opened channels by which rain water could more rapidly recharge the subsoil. The differences in soil water content could not have been due to water use by the cover crops themselves because all plots were uniformly completely recharged with water at both depths at several times during the soybean growing season.

Due to the rapid decomposition of the winter-killed residues, the surface of forage radish plots was almost devoid of residue or weed cover by late March, while rye cover crop plots were densely covered with residues all spring and summer because the rye was not killed until April and the rye residues decomposed much more slowly than did radish residues. The difference in surface residue cover is likely to have influenced the water content of the surface soil layer (0-15 cm) by decreasing evaporative losses compared to those occuring following the radish cover crop. This residue cover effect probably explains why the soil water content at 15 cm depth during the rainless, drought stressed period of July 20 to 26, 2006 differed among the cover crop treatments in the order of rye-treated plots > FR-treated plots > NC-treated plots (Figure 38).

During the same July 20-26 period, soil at 50 cm depth (Figure 38) dried faster in the forage radish plots than in the no-cover or rye plots, but surface soil evaporation could not be a direct cause. Rather, we interpret the greater subsoil water depletion to indicate that during a critical time for the soybean growth, plants in forage radish-treated plots used more subsoil water than those in rye- or no cover treatment plots. During subsequent dry periods, the soil at 50 cm was drier than the measurement limit of the sensors (data not shown), but the soybeans in forage radish treatment plots showed fewer foliar water stress symptoms than those in rye or no cover treatment plots. This observation suggests that the soybean roots in the forage radish plots had access to more subsoil water deeper than 50 cm. Our preliminary conclusion is that cover cropping with forage radish has the potential to help ameliorate the effects of soil compaction on agricultural land and give crop root better access to subsoil moisture. These results also suggest that a mixed cover crop that combined both rye and forage radish might combine the benefits of both to result in the highest crop yields and least soil erosion.

Although the soil water depletion data were apparently sensitive to cover crop effects, the complex patterns of water depletion and recharge in two soil layers made it difficult to interpret the implications regarding the effects of cover crops on summer crop rooting depths.

Figure 40 The first pass of a **c**ompaction treatment being applied to Beltsville Exp. 5 in August 2006. The entire surface of a plot receiving the treatment was trafficked. Photo by R. Weil.

We realized that direct measurement of crop roots would be a desirable complimentary data set. However, the measurement of plant roots in the field is notoriously difficult and intrusive. During our preliminary research prior to obtaining the project grant, we arranged to use a state of the art minirhizotron fiber-optic camera capable of imaging roots *in situ* repeatedly over time. We were successful in obtaining images of soybean roots following the channels made by Brassica cover crops and these data were published in 2004. Later in 2004, we had the opportunity to collaborate with several colleagues in the purchase (using non-project funds) of a state-of-the art minirhizotron camera apparatus.

Installing the minirhizotron observation tubes in compacted soils proved very difficult, so we were limited to one or two tubes per plot in selected plots, and in most cases the depth was limited to 75 cm. While we captured thousands of root images, obtaining quantitative root data with the minirhizotron camera has proven to be quite challenging and difficult to interpret. To obtain more unequivocal data, we eventually resorted to measuring root growth directly using deep soil cores.

Therefore, we also approached the problem by using large (~9 cm diameter) soil cores and the core-break method (Bohm, 1979) to measure plant root distribution. Root counting by the core break technique gave results that were less time consuming, less variable and more repeatable than root length measurements based on images of roots taken with a minirhizotron camera or on roots washed from soil cores. With the core break root counting method we were able to show that corn

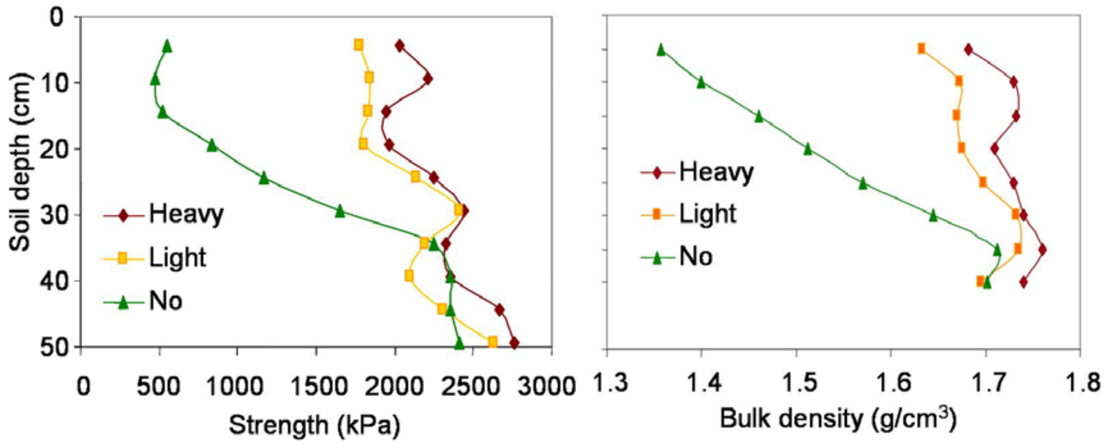

Figure 41. Soil strength (*left*) and bulk density (*right*) in the upper 50 cm of soil after application of compaction treatments on sandy loam soil in early August 2006. The B horizon with higher clay content begins at about 30 cm.

in mid summer 2005 grew about twice as many roots below the compacted plow pan of a Galestown loamy sand where a rye cover crop was used as compared to where no winter cover had been grown. Moreover, nearly 10 times as many summer crop roots were able to penetrate the plow pan where the forage radish had been grown as compared to the no cover plots (Figure 39, *left*). The cover crop treatments were repeated in the fall of 2005 and, during summer 2006, soybeans were grown on the plots. The soybean roots, like the corn root in the previous year, were much more numerous where the crop had been preceded by the forage radish cover crop than where either a rye cover crop or no cover crop had been used (Figure 39, *right*). The second greatest number of deep roots occurred in the rye cover treatments. The fewest deep roots occurred in the no-cover crop control plots. In contrast to the deep roots, shallow roots (above the plow pan) of both corn

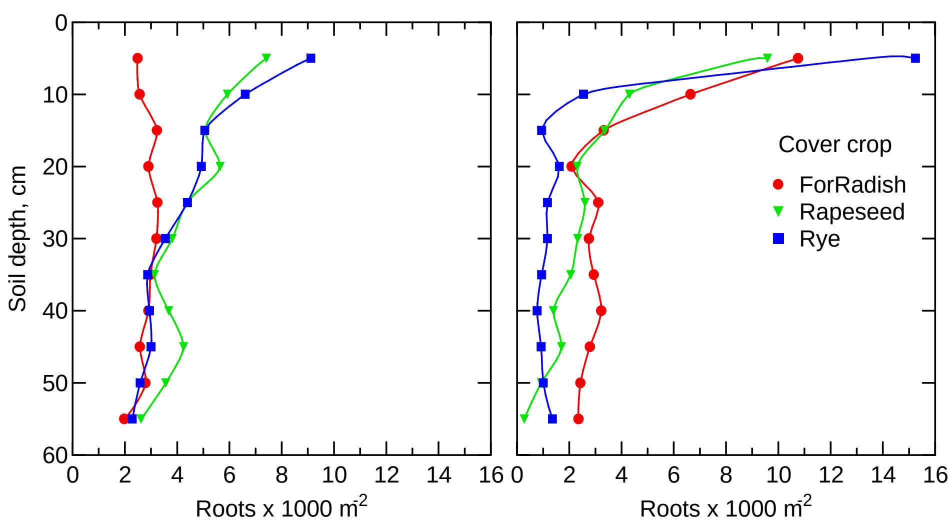

Figure 42. Cover crop rooting density in November 2006 as influenced by soil compaction. Root data are for (*left*) no compaction and (*right*) heavy soil compaction. The compaction treatment caused all three cover crops to increase their rooting in the surface soil layer (0-8 cm) which was loosened by tillage after the compaction treatment. Unlike rye and rapeseed, forage radish roots in subsoil (30 -65 cm) were not significantly reduced by compaction. As a result, in the 30 to 55 cm layer of the compacted soil, the radish produced 2 or 3 times as many roots as did rapeseed and rye, respectively.

and soybean were most abundant in the rye cover crop treatment.

In 2006 we also initiated a compaction experiment in which we applied compaction treatments by driving a heavy front end loader over a loam soil near field capacity (Figure 40). The loader made either no pass (uncompacted), a single pass (light compaction, Wt: $1.19*10^4$ kg, force: $7.44*10^4$ N) or two passes, (heavy compaction, the second pass with 926 kg gravel in the loader, force: $8.02*10^4$ N). The compaction treatments resulted in severe surface soil compaction down to about 35 cm depth (Figure 41) and simulated the kind of compaction that harvest and manure spreading machinery often causes on commercial farms during wet weather. After the compaction treatments were applied, the whole field was disked to about 8 cm and rye, rapeseed and forage radish cover crops were drilled.

All three cover crops (and the weeds in the control plots) responded dramatically to the severe compaction levels even though the upper 8 cm had been loosened. Root and shoot biomass were both dramatically influenced. Large soil cores were taken to 60 cm depth using hydraulic equipment. These cores were utilized for core-break root counts and root washing. The compaction treatment caused all three cover crops to increase their rooting in the surface soil layer (0-8 cm) which was loosened by tillage after the compaction treatment. Unlike rye and rapeseed, forage radish roots in subsoil (30 -65 cm) were not significantly reduced by compaction (Figure 42). As a result, in the 30 to 55 cm layer of the compacted soil, the radish produced 2 or 3 times as many roots as did rapeseed and rye, respectively. The experiment is continuing beyond the grant period, with corn planted on these plots in spring 2007.

Phosphorus availability and redistribution.

Because they are non-hosts for mycorrhizae, Brassicaceous plants are known to have evolved other mechanisms for accessing soil phosphorus. For example, in a recent study by Zhang et al. (1997), root exudates were collected from radish and rapeseed in P-sufficient and P-deficient nutrient solutions. In radish, the dominant acids were tartaric, malic and succinic acids; the production of these increased between 15 to 60 times under P deficient conditions. In sand culture with either $Ca(PO_4)_2$ or $AlPO_4$, radish used P from $AlPO_4$ much better than from $Ca(PO_4)_2$, but the opposite was true for rapeseed. These results help to explain why radish is preferentially used in China on acid soils and rapeseed on calcareous soils.

In our preliminary investigations, we found that after three years of cover crops in a corn-soybean rotation with *Brassica* species, that soil test P by Mehlich 3 extract increased between

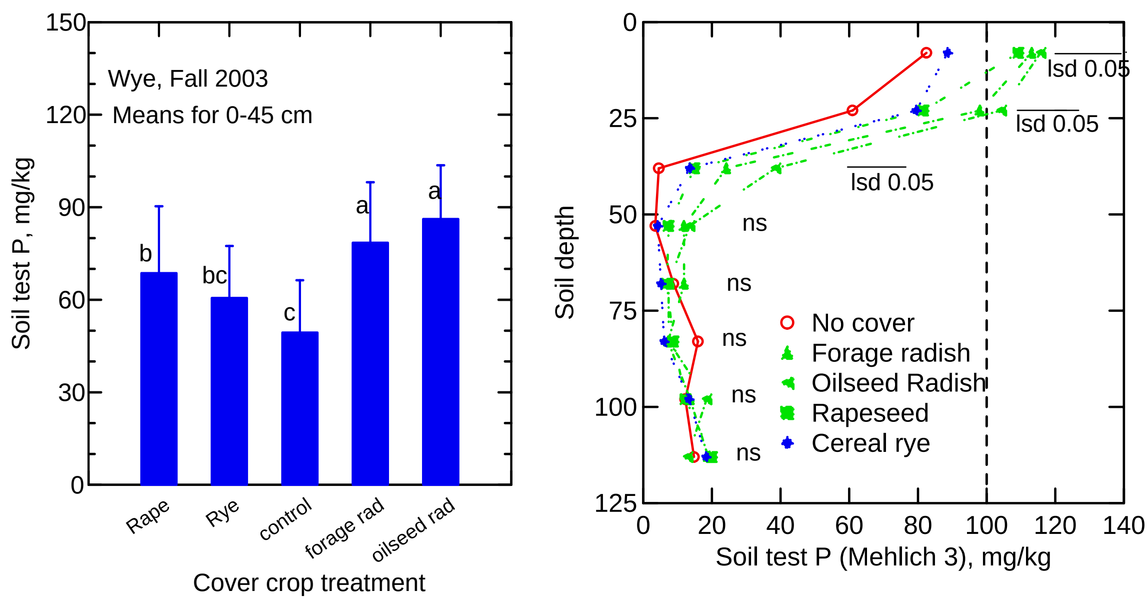

Figure 43 Soil phosphorus (Mehlich 3 extractable) as affected by 3 years of cover cropping with rape, rye or radishes. (*Left*) Means of soil test P for upper 45 cm of soil. (*Right*) Soil test P changes with depth to 105 cm in the same soil. Data for samples taken in fall 2003 on plots growing cover crops but receiving no P since fall 2001.

40% and 80% compared to no cover cropping (Figure 43). The forage radish plots were significantly higher in P in the A horizon than were either the rye plots or the no cover plots. The fact that the increased P occurred as deep as 45 cm suggests that the increase was not due simply to vegetative pumping that left high P residue on the soil surface. We hypothesize that unique radish root exudates may have mobilized P in the upper soil layers. The increased soil test P is also due in part to the fact that the radish cover crops can accumulate between 30 and 40 kg/ha P in their biomass before freezing in winter (see Figure 44) . We also observed that forage radish tissue concentration and total uptake of P greatly exceeded that of other agricultural plants, including other Brassica cover crops. These data suggest the need for further study on the potential of the forage radish to improve low phosphorus soils by making P more available. Just as important for Maryland, research should evaluate the potential of forage radish cover crops to accelerate the remediation of soils excessively high in phosphorus by presenting the opportunity to harvest 40 kg P/ha each year in addition to the P removed in normal cash crop harvest (such as the 20 to 30 kg P removed by a crop corn or soybeans).

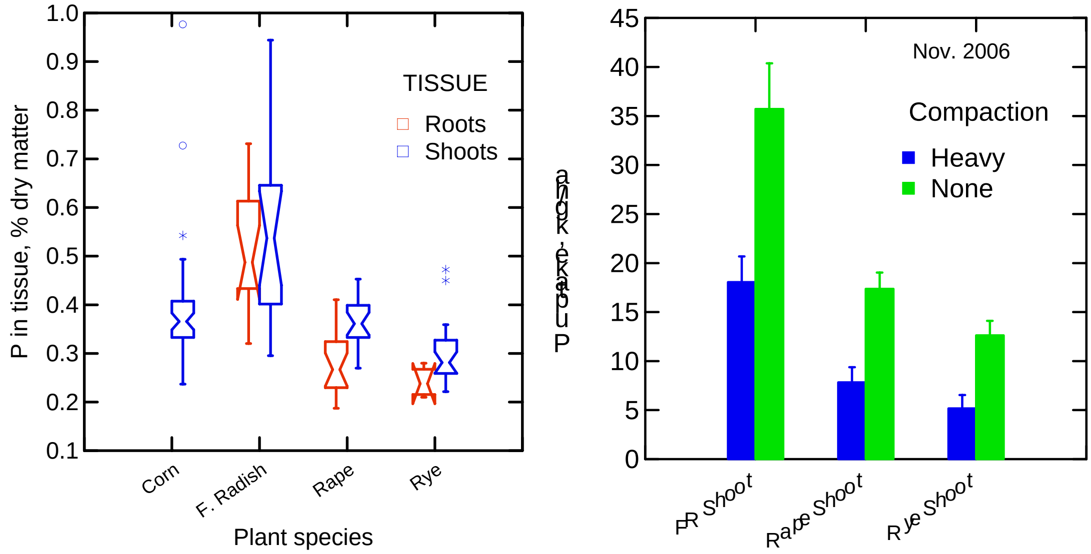

Figure 44 (*Left*) Forage radish tissues tend to contain much higher phosphorus concentrations than other crops collected over many site years (N=152). The notch in each box plots indicates the 95% confidence interval around the mean. (*Right*) Compared to other cover crops, radish showed a greater potential to remove P from either compacted or uncompacted soil in Beltsville Exp. 5. Soil test P was medium to high (not excessive) in the soil depicted at right.

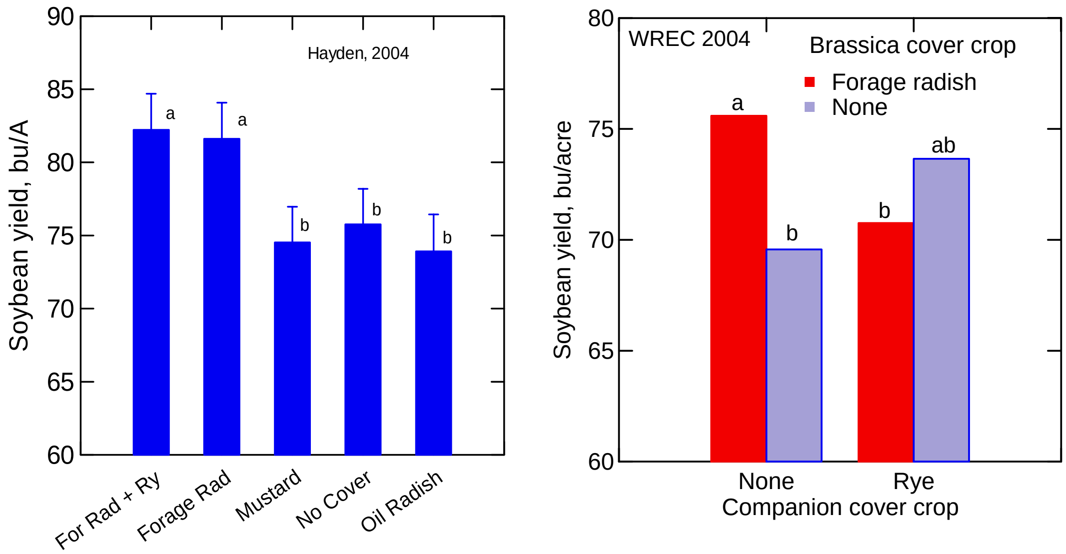

Figure 45 (*Left*) Soybean yields CMREC Exp.1 in 2004 as affected by previous cover crop treatment. Cover crops were terminated with glyphosate or by frost. (R*ight*) Soybean yields at Wye in 2004 as influenced by the factorial combination of and Forage Radish cover crops.

Effects on crop yields

In four of eight site-years with good cover crop stands, the use of radish cover crops resulted in significant corn or soybean yield increases compared to plots which had no cover crop. The largest increase was in soybean yields in CMREC Exp. 1 (Hayden farm) in 2004 (Figure 45, *left*) where the cover crop treatments had a marked and obvious influence on soybean growth and yield. Early in the soybean growing season, the cover crop kill/residue handling method also had a significant effect (Figure 46) giving a significant interaction such that soybean seedlings were largest if they followed a forage radish cover that was killed by disking, possibly because of an acceleration of N mineralization which would benefit young soybeans before their N-fixation capacity was fully developed. In mid-season, there were significant canopy height effects measured such that the soybeans in both radish cover crop treatments were about 15 cm taller, regardless of cover crop kill method, than the soybeans in the mustard or no cover plots (data not shown). This growth difference carried through to soybean grain harvest only for the forage radish treatments (because of low germination rye seed, there was very little rye in the forage radish + rye treatment). The result was a 7 bushel/acre advantage for the soybeans following forage radish or forage radish + rye cover crops (Figure 45, left), even though the forage radish died in late December 2003 and left almost no surface residues in spring 2004. We are not sure what the reason was for this positive effect of the forage radish cover crops, but we measured increased soil water (due to better infiltration because of biodrilling?), increased beneficial nematodes (see section above) and increased early season nitrate-N in these plots. We also observed, but did not measure, several patches of soybeans with severe symptoms of a root rot, possibly Rhizoctonia or Fusarium. We

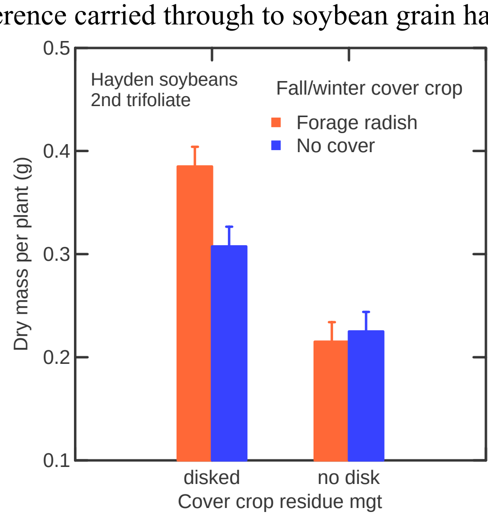

Figure 46 Early soybean growth advantage following tillage incorporation of winterkilled forage radish.

saw these symptoms in no-cover and mustard plots, but not in forage radish plots.

At LESREC in 2004, all cover crop treatments produced higher soybean yields compared to no cover crop, but differences among the cover crops treatments at that site were variable and mainly related to soil moisture. The two replications with the Hammonton (Aquic Hapludults) soil averaged 60 and 68 bu/acre while the two replications on the Galestown loamy sand (Psammentic Hapludults) soil averaged only 39 and 46 bu/acre. Furthermore, if the treatments were grouped into those with substantial residue in spring (dry matter>2000 kg/ha) and those with little to no residue (namely the winter killed mustard, forage radish and oilseed radish and the weed-free plots), the difference was highly significant, with the high residue plots yielding 55±2 bu/A and the low residue plots yielding 46±3 bu/A.

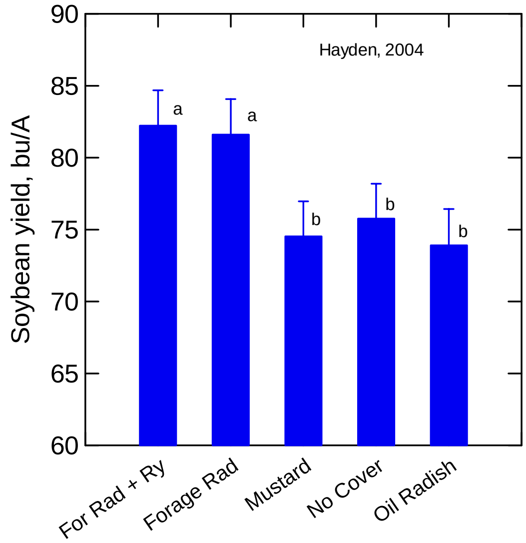

Figure 47 No-till corn grain yields in 2005 as influenced by winter cover crop planted in fall 2004 at CMREC (Hayden farm).

At WREC Exp. 1, soybean yields were also high in 2004, averaging over 5,000 kg/ha (over 70 bu/A). Although there was a significant block effect (lower yields in the more poorly drained blocks), cover crop treatment had little consistent effect on yields. If only the factorial combination of forage radish and rye alone or together are considered in the ANOVA, the interaction effect of yield was significant (P=0.05) with forage radish increasing yields compared to no cover if rye was absent. Forage radish had no effect if rye was present (Figure 45, *right*).

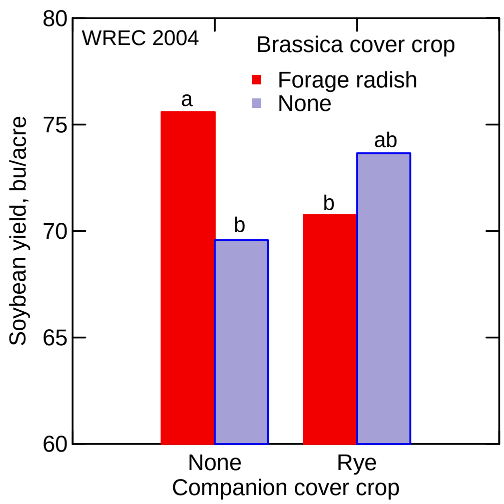

Figure 48 Corn yields for Beltsville Exp. 1 in which the bare soil following radish cover crop allowed liquid N to splash onto corn foliage causing sever fertilizer burn. No other cover crop effects on yield were observed.

Soybean yields at Beltsville Exp. 1 were also very high in 2004, averaging 73 bu/A. There were no differences among cover crop treatments and no effect of the deep ripping performed for some treatments the previous fall (August 2003).

In 2005, corn was grown for grain or silage in the four main experiment station locations. At CMREC Exp. 2, the mean corn silage yield was 14,145±414 kg/ha dry matter and cover crop treatments had no significant effects, except that cob moisture content was slightly higher for the rye cover crop treatment and lowest for the forage radish cover crop treatment. In CMREC Exp. 1, corn was harvested for grain. Since the mow and roll cover crop kill methods were dropped from the experiment, only the no-till plots (cover crops killed by herbicide and corn no-till planted) were considered and corn grain yields were significantly higher in the forage radish treatments than in any other cover crop treatment (Figure 47).

At Wye in 2005 (WREC Exp. 2) corn silage yields were similar to those at CMREC, averaging 13,144±711 kg/ha dry matter with cover crop treatments having no significant effect. At LESREC (Exp. 2) corn was grown for grain and yields averaged 140±3 bu/acre. Cover crop treatments had no effects on corn grain yields, but early in the season (mid-June) corn plants had significantly more dry matter (g/plant) in the rapeseed treatments than in the forage radish, rye or no cover treatments. This early effect was thought to be due to rapid N mineralization from the incorporated rapeseed residues and the possible leaching in these very sandy soils of N released much earlier from forage radish residues (see section of N release from residues, above). At Beltsville Exp. 1 in 2005, corn grain yields averaged 122±3 bu/acre with no cover crop effects, except as the cover crop residues influenced foliar burn from splashing of side dressed liquid fertilizer. Because of their complete suppression of early weeds and rapid decay of their residues, the forage radish plots were nearly bare at the time of side-dressing and the plants were severely burned by splashing that did not occur on all other plots where cover crop or weed residues covered the soil surface (Figure 48). Beltsville Exp. 2 grew corn for silage and yields averaged 12,435±734 kg/ha dry matter with no effects of cover crop treatments.

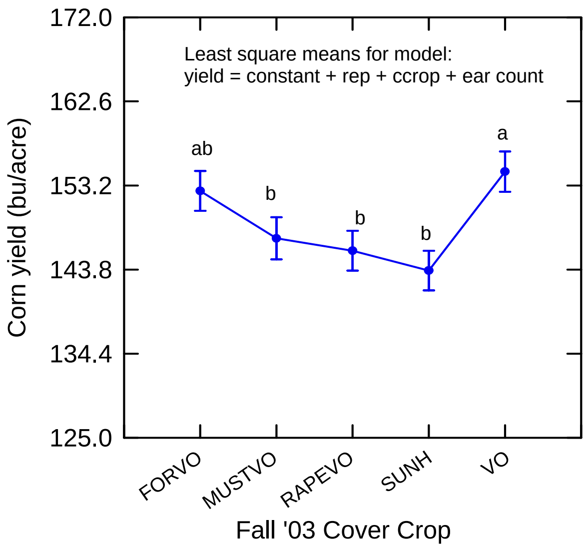

Figure 49 Comparison of corn yields following various cover crop mixtures at Cedar Meadow Farm. Lancaster, PA. FORVO=forage radish+ vetch + oats; MUSTVO=mustard+ vetch + oats; RAPEVO=rapeseed+ vetch + oats; SUNH= sunhemp; VO= hairy vetch + oats.

On farm yields

In 2004, corn was grown in a replicated experiment on Cedar Meadow Farm run by Steve Groff in Lancaster, PA in which we compared 3-species mixtures of various Brassicas mixed with hairy vetch + oats to the farmer's control practice of the 2-species mixture of vetch + oats. Corn yields (Figure 49) were highest in the 2-species vetch and oats (which produced the most total cover crop dry matter, data not shown) and the 3-species forage radish +vetch+oats, compared to the other 3-way mixtures. Soybeans were grown in 2005 in a replicated experiment on Cedar Meadow Farm in which we compared forage radish to mixed cover crops of forage radish + oats and vetch + oats. The vetch+oats was his standard treatment for comparison and a no-cover crop control was not included. The mean soybean yield was 3747 kg/ha with no significant difference among cover crop treatments.

In addition, several farmers reported yield increases of corn grain after radish cover crops in unreplicated, but large scale, strip comparisons. While data on nitrogen uptake suggest that an increased supply of this nutrient in spring was involved with the observed higher yields following the radish cover crops at several sites, other mechanisms such as deeper rooting cannot be ruled out.

Agronomic practices for cover crops

Cover crop establishment by interseeding

"Aerial seeding" Brassica cover crops into standing grain crop canopies at soybean leaf yellowing or corn dry down time is an approach we investigated to better fit Brassica cover crops into standard soybean-corn rotations. Growth of the interseeded Brassicas was usually severely limited by shading until the corn or soybeans were harvested. Planting the cover crops in early spring is another approach we examined (see cover crop biomass production results, above).

Figure 50 Combining soybeans on plots "aerially seeded" with Brassica cover crops at soybean leaf yellowing.

For the fall 2004 cover crop treatments in CMREC Exp. 1 we used two means of establishment: drilling in August (optimal conditions) and broadcasting into standing soybeans at leaf yellowing. The August drilled covers produced excellent stands and large biomass. The interseeded stands were less uniform and slower to grow (Figure 50), but their growth accelerated after the soybeans were harvested, achieving nearly 2,000 kg dry matter/ha by mid November, 2004 (Figure 51). Dry matter for rye was similar to that of the radishes within a seeding method. Nitrogen content of these covers was not determined.

On farm trials to evaluate aerial seeding.

To enable us to provide additional practical agronomic recommendations on planting these covers, in addition to the simulated aerial seeding into soybeans on the four research station experiments,

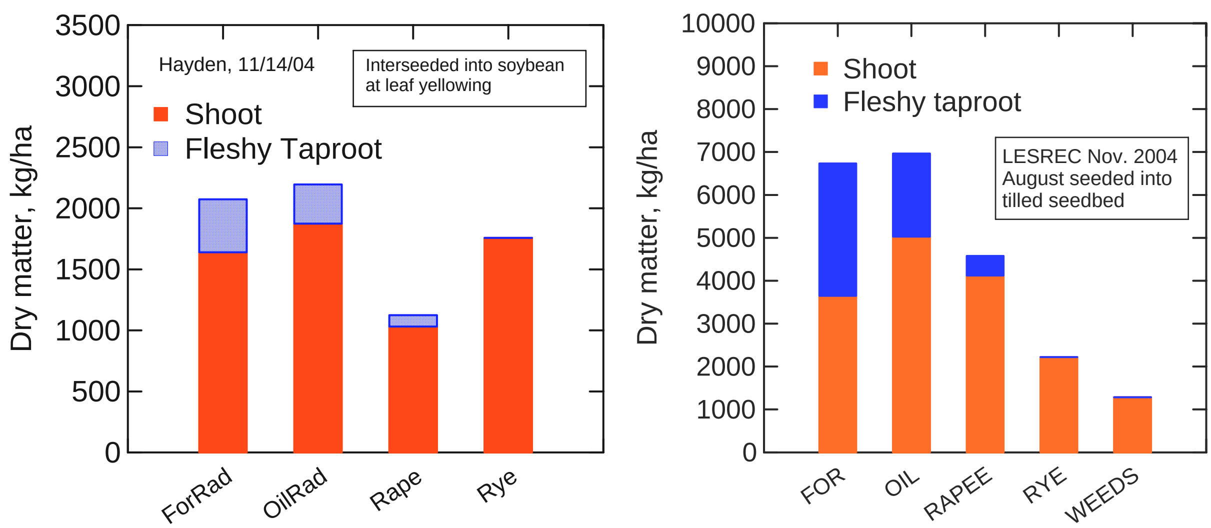

Figure 51 Dry matter of interseeded cover crops November 2004 in CMREC Exp.1 (*left*) and LESREC Exp.1 (*right*).

we also put out several on-farm trials on the Eastern Shore. Two of these farms participated in a preliminary trial of the aerial inter-seeding concept and cooperated to fly on forage radish seed mixed with oats to obtain the minimum bulk spread per acre. Each farm had three 100ft wide x 300 ft long strips flown onto standing corn in mid-August.

While there were problems with even seed distribution due largely to use of a poorly suited bulking agent (oat seed) and herbicide carry over, the trial did show that good Brassica cover crop stands could be established by this method. Figure 52 shows that the shoot and root dry matter produced in these aerially interseeded strips was similar to the simulated aerial interseeding at LESREC and at CMREC (Figure 51, left). The poorest growth occurred at the Susen Farm where radish seedlings appeared to suffer from late corn harvest (shading). In the Susen Farm field the radish suffered damage from residual herbicide effects, most likely from "Callisto" (mesotrione, a synthetic plant-derived product for control of broadleaf weeds in corn) and /or atrazine used at spring corn planting. The root growth was especially affected by contact with the herbicide in the soil. However, despite the herbicide damage there, the Susen Farm strips had the best stand count of about 6 to 7 radish plants/ft^2, enough within the ideal range for the cover crop. King's Grant Farm received about 1/10 inch of rain immediately after seeding and then no rain for 10 days, so the stand there was not as good (only 3 plants/ft^2), but the radishes that established there grew very well with characteristic thick, vigorous taproots.

The project gathered information on important

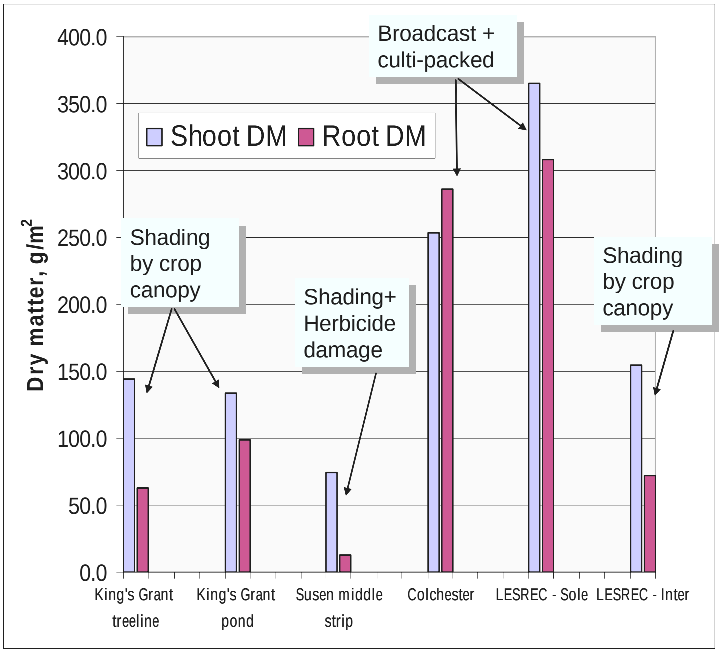

Figure 52 Shoot and root (fleshy taproot) dry matter of forage radish cover crop in mid November 2004. For King's Grant and Susen Farms in Kent County, MD, forage radish was aerially inter-seeded into standing corn. For LESREC-Inter seed was spun into soybeans at leaf yellowing. At Colchester Farm (Kent County) and LESREC Exp.2 (LESREC-sole), forage radish was broadcast on open ground and cultipacked a a sole cover crop. Relative root growth was much lower in the interseeded plots due to initial shading. (lbs/A = 11.2 x g/m^2)

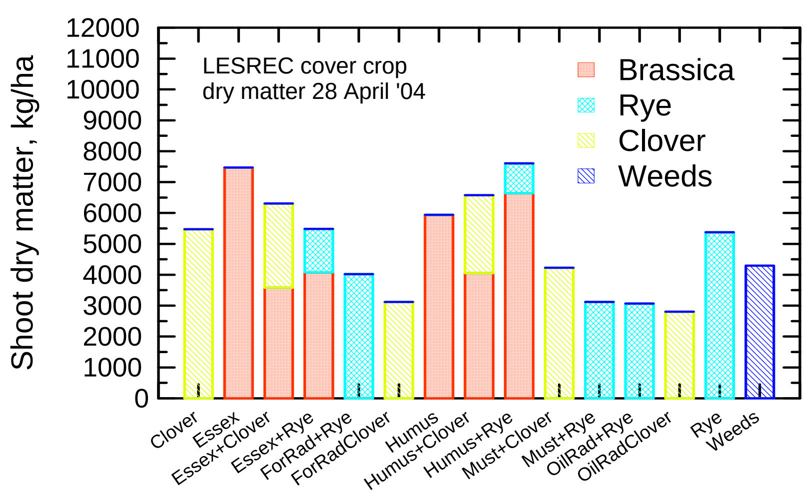

Figure 53 Dry matter at time of spring cover crop incorporation in 2004. Dry matter production by winter killed cover crops (radishes and mustards) is not shown.

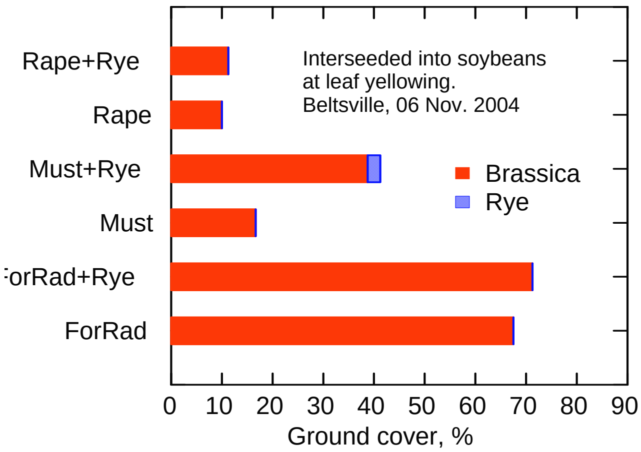

Figure 54 Ground cover by Brassica cover crops alone or with ½ normal rate of cereal rye seed. Covers were interseeded into soybeans on 13 Sept. 2004, soybeans were harvested on 15 Oct. and covers were rated on 06 Nov. 2004.

agronomic practices, such as suitable seeding rates, soil conditions, soil fertility, and planting dates. The trials in fall 2004 and 2005 showed promise for achieving good stands by interseeding forage radish either into corn in late August or into soybeans in mid September, however the biomass and root to shoot ratio of the interseeded Brassica was considerably lower than when drilled into an open field (compare root data in Figure 51, left and right). Interseeded radish cover crop N recovery was substantial, but may not be as great or from as deep in the profile as for the drilled cover, and the potential for compaction alleviation and weed suppression may be much lower. Farmers with diverse cropping systems that include vegetables such as early harvested sweet corn have been able to fit the Brassica cover crops into their systems, but establishing the Brassica cover crops early enough in the fall to obtain maximum benefits has proven difficult in grain farming systems.

Several farmers in northern Maryland and southern Pennsylvania adopted the forage radish after corn harvested in late August for silage, and reported excellent stands. We are evaluating the latter option in experiments begun in fall 2006.

Mixed Cover Crops

The dry matter produced by the end of April in the various cover crop treatments in LESREC 2004 is shown in Figure 53. The greatest dry matter was produced by the two rape cultivars, alone or in combination with rye or clover. The next largest dry matter production was by sole rye or sole clover. Intercropping rye or clover with the Brassicas greatly reduced the rye dry matter, and to a lesser extent, the clover dry matter. The control plots allowed to grow weeds after mid-August tillage produced about as much dry matter as either rye or clover.

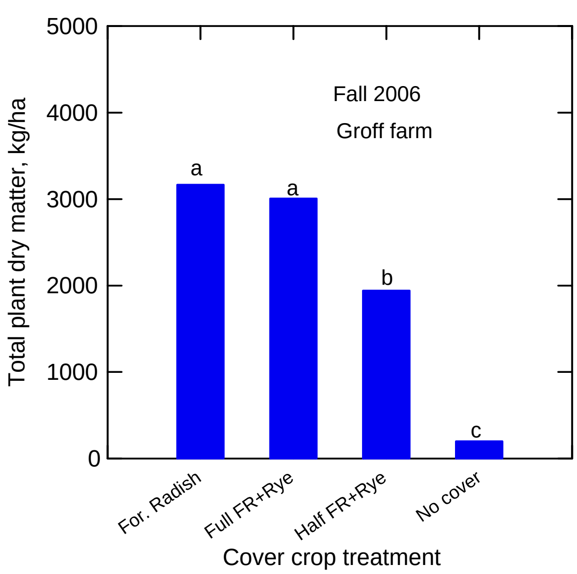

Figure 55 Plant dry matter in November 2006 from forage radish planted alone or mixed with rye in alternate drill rows, at full or half seeding rates.

Root production by the Brassicas is of particular concern for several reasons, including the potential for bio drilling and the incorporation of glucosinolates under no-till production. Intercropping with clover or rye appeared to have opposite influences on the shoot to root ratio in the two rape cultivars. Mixed cover cropping with clover significantly increased the Rape shoot/root ratio, possibly because nitrogen supplied by the clover stimulated shoot growth and reduced the plant's need to invest in root production. The opposite could have occurred because of competition by rye that would have reduced the available N supply.

Mixed cover crops were studied at two experiment station locations and on several commercial farms. LESREC Exp. 1 included 10 different 2-species mixtures established by broadcast mixed seed and cultipacking. Two rapeseed cultivars, two radish cultivars and mustard were grown alone or mixed with either crimson clover or rye. Figure 53 shows the dry matter production by the mixture components in spring just before cover crops were killed in preparation for soybean crop planting. Rye produced about 5,300 kg/ha dry matter when grown alone, but only 1,000 to 1,400 when grown mixed with rape. Rye produced 3-4,000 kg/ha dry matter when mixed with Brassica species that winterkilled, leaving them free from competition during spring growth. However, we observed that the rye (and clover) present in spring was growing mainly in the gaps in the Brassica canopy left by uneven hand broadcasting of the cover crop seeds in fall.

WREC Exp.1 included one treatment with a rye-forage radish cover crop mixture, and in every year that produced a significant cover crop effect, that mixture gave the highest cash crop yield. However, when growing conditions in the fall are good (warm, moist but well aerated soils, early planting date and good nitrogen supply) the radish can be competitive such that very little rye survives to grow in spring. Collaborating farmer, Steve Groff, noticed this problem in our 2003 mixed cover crop plantings on his farm and decided to modify his drill to plant the rye and radish seed in separate rows to give the rye more space to establish. Even better rye performance was achieved with two rows of rye drilled for every row of radish. However, even with alternate row drilling in fall 2006, adding 60 kg/ha of rye seed resulted in no significant increase in fall dry matter production compared to drilling just the 10 kg/ha of forage radish (see Figure 55). The main reason Groff uses the rye is to provide living or residue cover to protect against erosion in spring and early summer on his steeply sloping soils, but we also believe the rye will reduce N leaching in spring and reduce evaporation of surface soil water during the summer.

SECTION V:
Conclusions/Recommendations for Management of Brassica Cover Crops

Our experience and data suggest that the Brassicas offer new tools to capture N in certain situations. We are not suggesting that Brassicas can replace rye as the principal cover crop in grain rotations. Though rape can be planted later in fall than radish, both radish and rape need to be planted earlier than rye to be effective. Aerial seeding into maturing corn or soybeans in early September can be fairly reliable, but not as effective as drilling into an open field. The most practical situations for establishing radish may be in vegetable rotations and after corn silage harvest. Even where they can be conveniently established, we would not suggest using the Brassicas continuously year after year. Rather we suggest rotating cover crops. One reason to rotate cover crops is that the Brassica may reduce the potential for beneficial mycorrhizal fungi to colonize summer crops. Our tentative recommendations for growing Brassica cover crops include:

1. As with any new practice, it is best to start small, either by using part of a field or by using test strips.
2. Drill forage radish seed at a rate of 8 to12 lb/A or broadcast and cultipack at 15 to 20 lbs/A. For rape use 4 lb/A drilled or 8 lbs/A broadcast.
3. Forage radish needs some available N in the surface soil to get off to a vigorous start, so unless the field has a history of legumes, manure applications or less than complete fertilizer utilization (for instance, because of drought), a small (15-20 lbs/acre) application of N may be called for at radish planting.
4. Even in the warmest parts of Maryland, freeze kill was complete for forage radish in every year of our study. The date and extent of freezekill will depend on the severity of the winter and/or your location. For a forage radish cover crop to be completely freezekilled, air temperatures need to fall below 25 ^{o}F for several nights.
5. Since freeze-killed radish residues disappear quickly, the inclusion of a winter grass such as rye in a cover crop mixture may be desirable to supply surface cover and N uptake in early spring.
6. For a cover crop mixture of radish and rye, drill in 8 lb/A forage radish + 60 lb/A rye. For best results modify the drill so it seeds a pattern of 2 rows of rye (from large seed box) and 1 row of radish (from small seed box).
7. Spring oats or sorghum/sudangrass can be seeded with forage radish to supply more surface residue and N immobilization, while still allowing freezing weather to terminate the cover crop.
8. Brassica cover crops should be established as early as possible, but no later than late September. Broadcast over-seeding into standing corn or soybeans in late August/early September has been successful, but the resulting cover crop will have a less vigorous root system.
9. Winter-surviving cover crops can be killed in the spring, by mowing followed by double-disking or by using a full rate of glyphosate. A second application may be needed for rapeseed. Experiments with just mowing or rolling-crimping have showed these methods to be inadequate to kill rapeseed. Cover crop kill in spring should be accomplished before seeds mature on the cover crop.

Seed Availability

Rape seed is widely available at about $1.20/lb. Forage radish is not a common cover crop in the mid-Atlantic region, so seed availability and price (about $2.20/lb in 2007) may be an issue, although as a result of our research project, local commercial seed production began in 2006. It is best to call seed suppliers a few months prior to planting time to check on availability. Two sources[2] we have used are: 1) Steve Groff in Lancaster, PA (www.Cedarmeadowfarm.com) and Labon Inc. in Boucherville, Quebec Canada, (www.labon.net).

SECTION VI – DISSEMINATION

Public attention:

Partly because of our presentations of concepts and results at several farmer meetings, interest in the Brassica cover crops has been quite high among Maryland farmers. *The Delmarva Farmer* newspaper wrote a positive story about the 2004 Maryland Center for Agroecology grants which largely featured our cover crop project. Excerpts of the story follow:

From : Bourgeois, R. 2004. More cover crops part of solution to clean up Bay. *The Delmarva Farmer*, Easton, MD [on line at http://www.americanfarm.com/TopStory5-11-04b.html].
The hope is to use cover crops on 75 percent of Maryland's row-crop acres by 2010.
Ray Weil, University of Maryland professor of soil science, said many farmers have seen little economic benefit from planting cover crops, because it costs as much to grow the crops as the value of the nitrogen fertilizer that is saved. But, Weil said, nitrogen fixing and environmental benefits are not the only advantages offered by cover crops. "Theory holds that roots growing in a wet season can create channels that roots of subsequent cash crops follow to grow through the compacted layer in summer when the soil is dry and hard," Weil said. Soil compaction restricts access to stored water and nutrients in deeper soil layers, which can result in yield loss, especially in dry years. Compaction can also occur with excessive tillage and from the use of heavy machinery on wet soils. Weil said that while there has been little research in Maryland, in Pennsylvania white and black mustard and rapeseed (canola) have been as effective as commercial nematicides in suppressing dagger nematodes in fruit-crop systems. He said Brassica cover crops have been shown to contain chemicals that suppress weed growth, but more research is needed in understanding more about weed control related to weed species, cover crop biomass and method of crop kill. Various cover crops, he said, can provide rooting channels through compacted soil, prevent erosion, capture leachable nutrients, increase organic matter, improve soil structure, enhance biological diversity and activity, and suppress weeds, nematodes and disease pathogens. Weil conducted studies in collaboration with commercial farmers at sites with pronounced soil compaction, nematode, leaching and weed problems. Studies used fields with no winter cover as well as those with rye, Brassicas, canola, forage radish, oilseed radish, mustard and turnips."

Penn State Extension has picked up on our cover crop work, as evidenced by the extension article on the forage radish:
Duiker, S. 2005. Forage radish, a new cover crop [Online]. Available by Pennsylvania State University - Field Crop News -Vol. 05:14 http://fcn.agronomy.psu.edu/2005/fcn0514.cfm#forage (posted November 18, 2005; verified December 10, 2005).

In 2005, The New Farm, a popular on-line farm magazine, wrote a story about our on-farm radish cover crop work with farmer Steve Groff (Bowman, 2005.
Groff likes what the fall-planted radishes do to open up soil and attract earthworms, but he needs something to provide soil cover after April 1, when the winter-killed succulent radish biomass has largely disappeared.

[2] Mention of a particular product or company is solely for reader convenience and does not imply endorsement over others by the University of Maryland.

University of Maryland soil scientist Ray Weil is working with Groff and others to find the cropping mixes that make the best use of the soil-penetrating abilities of the radish to break up soil compaction. In the fall of 2004 (year three of this experiment cycle), he alternated the rows of the cereal and root crop to give the oats a chance to grow. That worked well, and is his practice again this fall (year four). Groff reports his other uses of radishes: "Where I'm planting radishes into high-residue situations, such as sweet corn stalks, I plant only radishes as the corn stalks don't break down as quickly in the spring. This fall I've planted radishes with hairy vetch/rye and with crimson clover."

"Radish ripper" idles steel

Groff is perfecting a technique he pioneered last year to alleviate compaction in the farm driveways that provide in-season access through his vegetable fields: "I put four, 7.5-inch rows of radish over each wheel track and planted the middles and edges with hairy vetch and rye. I call this my 'radish ripper,'" he says. "I tested the concept last year and the radishes seemed to alleviate most of the compacted driveways. I planted over 5 acres of driveways so far and the ripper/stripper [implement] is still in the shed!"

As a result of a presentation by Weil at the Southern Shore Agronomy day in 2006, the Salisbury Daily Times reported the following in a lead story (Mitchell, 2006):
It's one meeting packed full of information that farmers don't like to miss.
"I find it helpful," said Somerset County farmer Gary King.
At the annual meeting, King learned things he's never thought of before.
"When dealing with cover crops and reducing compaction, they showed us new crops to use, like radishes," he said. "I've never dreamed of that before. It's a great idea."
Richardson said cover crops that can reduce compaction and nutrients will be a big help this spring.

Because of our poster presentation at the 13th World Congress of Soil Science in Philadelphia in 2006, we were invited to write a "perspectives" paper on integrated approaches to cover crop research The paper (Weil and Kremen, 2007) was peer reviewed and published in the Journal of the Science of Food and Agriculture, a leading international journal published in UK.

Outreach Efforts at Dissemination of Results:

In December 2004 we participated in the annual College of Agriculture and Natural Resources Agricultural Extension In-Service Training where we presented ideas on covers and how they can be investigated by farmer research and scientist research done "on-farm". Some 20 extension personnel participated in this session.

In January 2005 we held two sessions in the annual Farming for Profit and Stewardship conference put on by Future harvest and Maryland Cooperative Extension: one on the Brassica cover crops themselves and the other on the potential for farmer cover crop research. The response at both was excellent, with 65 farmers requesting further information or asking to collaborate on research on their farms. Among the participants at the farmer research session, 52 farmers submitted answers to a questionnaire, of which 43 (87%) said they currently use cover crops to some degree.

On May 23, 2005 we conducted an evening field day (twilight tour) at CMREC Beltsville facility

(Hayden Farm) with 39 attendees, about half being farmers and half extension and research or industry personnel.

On February 16, 2006 the P.I. (Weil) made a presentation on *Cover Crop to Alleviate Soil Compaction* at the Southern Shore Agronomy Day in Princess Anne, Maryland. Over 50 farmers were in attendance.

On November 27, 2006 we presented a cover crops field day at the USDA research farm in Beltsville in conjunction with Future Harvest. Twenty researchers, extension educators and farmers attended. A fact sheet is being revised to include the new weed suppression information.

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