ABSTRACT

Title	SPRING SEEDBED CHARACTERISTICS AFTER WINTERKILLED COVER CROPS
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Tillage is the common practice for seedbed preparation prior to early spring vegetables. To investigate the possibility of eliminating the need for spring tillage through the use of cover crops, spring seedbed characteristics after winterkilled cover crops forage radish (*Raphanus sativus* L.) and oat (*Avena sativa* L.) were monitored prior to and during growth of no-till and rototilled plantings of spinach (*Spinacia oleracea* var. Tyee) over four site years in Maryland's Coastal Plain and Piedmont regions. Results indicate that forage radish can facilitate no-till planting of spring vegetables in the mid-Atlantic without herbicides or fertilizer. Forage radish increases soil nitrate and sulfate in early spring and is best suited as a cover crop before the earliest planted main crops.

SPRING SEEDBED CHARACTERISTICS AFTER WINTERKILLED COVER CROPS

By

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Chapter 1 Background and General Research Approach

Background and problem definition

Cover crops can capture and recycle residual nutrients, add organic matter, reduce erosion, suppress weeds, fix nitrogen and, for certain species, alleviate soil compaction. Their environmental benefits are myriad, but cover crops can pose economic and logistical obstacles; for this reason, farmer adoption remains low (Snapp et al., 2005). Traditional cover crops in the Mid-Atlantic region, such as winter rye (*Secale cereale*), hairy vetch (*Vicia villosa*), and oat (*Avena sativa*) can delay soil warming and drying (Teasdale and Mohler, 1991), can be difficult to kill and incorporate, and can interfere with subsequent crop germination through allelopathy. Additionally, residues with a high C/N ratio can tie up nitrogen and other nutrients for the following crop. These concerns are most pronounced for the earliest planted vegetable crops such as spinach, lettuce, peas, potatoes, beets and carrots for which soil warming and drying and N availability are essential. With some exceptions, tillage remains the primary means of preparing a seedbed in the majority of vegetable production systems. Tillage is not only detrimental to soil structure and biota, it is expensive in terms of fossil fuels and time. The problem, therefore, is twofold: how can early vegetable production systems gain the environmental and agronomic benefits of cover crops without hindering early crop production, and is it possible to reduce or eliminate tillage before early spring vegetables?

Justification for research

Previous research with no-till (NT) agronomic crops has indicated that forage radish (*Raphanus sativus*—called radish in this review) may be able to provide an economically viable alternative to traditional cover crops (Weil and Kremen, 2007), but minimal radish research has involved vegetable production. No published research to-date has investigated early vegetable response to NT planting. Our understanding of nutrient dynamics in spring after radish is also limited, and with over 6000 ha of radish planted in MD in 2012 (MDA, 2013), a better understanding is needed not only for vegetable production, but for other cropping systems.

General research approach

Replicated field experiments over the course of four site years in Maryland's Coastal Plain and Piedmont regions investigated cover crop performance, spring vegetable performance, and spring nutrient dynamics. Although winter rye is the most common winter cover crop in MD and has been the alternative to radish in previous cover crop research, we chose to investigate oat along with radish because oat is the traditional winterkilling cover crop in this region and winterkilling is an important facet to facilitating spring planting. The research questions were divided into two connected but separate components. One question focused on vegetable crop performance after winterkilled cover crops and seedbed preparation technique (NT or rototilled), and the other question focused on nutrient (N and S) dynamics after winterkill and through the early spring period. Because a mechanistic understanding of processes as complex as emergence and crop response is difficult in a field experiment with so many factors, the research was more phenomenological than it is mechanistic. However, by monitoring climatic and soil conditions, some light may be shed on the mechanisms at work for certain responses.

Cover crop performance was quantified by measuring biomass, C, N, and S in late fall. Spring surface (0-20 cm and on some occasions to 30 cm) soil mineral N and S were measured approximately monthly from January through May. Vegetable response variables including emergence, yield, tissue N and S were measured in spring.

General research objectives and hypotheses

1. Quantify cover crop performance of radish and oat alone and in combination in terms of biomass production, N and S uptake.

   Hypothesis: Cover crops will be equal in biomass and N uptake. Radish will exceed oat in S uptake.

2. Measure and characterize spring surface soil mineral N and S dynamics after cover crop winterkill through the spring growing period.

   Hyphothesis: Mineral N and SO_4^{2-} will increase temporally and in magnitude in the order radish>radish-oat>oat>no cover.

3. Measure and quantify soil mineral N and S response to tillage.

   Hypothesis: Tillage will increase soil mineral N and S.

4. Compare spinach response among cover crop and tillage treatments.

   Hypothesis: Spinach emergence and yield will be greatest following radish and will not be negatively affected by NT planting.

5. Compare other vegetable crop responses to NT planting after radish to the standard practice of planting after tillage and no cover crop.

   Hypothesis: NT planting into radish will produce equal emergence and yield response as the standard practice.

6. Monitor soil moisture and temperature in the spring seedbed after cover crop winterkill.

    Hypothesis: Soil water content will be in the order oat>radish-oat>radish=no cover and daily high temperatures will be in the order no cover=radish>radish-oat>oat.

Chapter 2 Literature Review

This review addresses winterkilled cover crops used to facilitate early spring no-till (NT) vegetable planting. This cropping system/concept is new, and the literature on this topic is, therefore, sparse. This review includes a brief overview of cover crops, a more detailed synopsis of the literature on forage radish (*Raphanus sativus* L.), and a review of cover crop systems for no-till (NT) vegetable production. Weed dynamics, nutrient dynamics, soil temperature and moisture dynamics are key components of the early vegetable cropping niche, so this review pays special attention to how cover crops can modulate these aspects of the soil seedbed. The need to develop farming practices that enhance both environmental quality and farm viability underlies this work.

Cover crops

Cover crops can serve myriad environmental and agronomic functions that, in some ways, are epitomized by the three names commonly ascribed to them: cover crops; catch crops; and green manures (Dabney et al., 2010; Thorup-Kristensen et al., 2003). A single crop can be all three, and thus terminology can be confusing. Simple definitions can be deduced from the names themselves. Cover crops cover the soil, and can prevent erosion. Catch crops catch nutrients before they leach from the system and potentially enter the environment as pollutants; and green manures enhance nutrition of the subsequent cash crop (often through use of legumes and symbiotic N-fixation). The benefits of cover crops (the default term used in this review) can include weed suppression (Creamer et al., 1996; Kruidhof et al., 2008;

Stivers-Young, 1998; Teasdale et al., 2007; Weston, 1996), C addition to soil (Kuo et al., 1997; Sainju et al., 2002), alleviation of soil compaction via root channels (Chen and Weil, 2010; Williams et al., 2004), maintenance of soil moisture in droughty conditions (Teasdale and Mohler, 1993), and reduction of disease and pest incidence (Everts, 2002b; Larkin and Griffin, 2007; Muehlchen et al., 1990; Nicholls et al., 2000). In certain crop rotations, cover crops can detrimentally impact main crop production through allelopathic interference with cash crop germination (Kruidhof et al., 2009; Weston and Duke, 2003), immobilization of N (Snapp et al., 2005), hosting pathogens, and increasing pest pressure (Koike et al., 1996; Mirsky et al., 2012; Sumner et al., 1995).

The disadvantages of traditional, high-residue winter cover crops that make them ill-suited to early spring vegetable production include their effects on soil moisture and temperature, the difficulty killing and incorporating them, and the potential for nutrient immobilization by cover crop residues. Non-winterkilling, or persistent, cover crops such as winter rye (*Secale cereal* L.) and hairy vetch (*Vicia villosa* L.) continue to grow in spring and may need to be terminated several weeks before planting in order to avoid "pre-emptive" competition for soil nutrients (Dabney et al., 2010; Thorup-Kristensen et al., 2003). Termination at an early growth stage of grasses and many legumes cannot be achieved with mowing and requires either chemical means or incorporation. Excessive soil wetness in early spring can delay or interfere with field work for seedbed preparation and planting.; To minimize soil structural damage , tillage should be conducted while the soil water content is between 70 and 90 % of the soil's plastic limit (Dexter and Bird, 2001). Vegetable farmers, under extreme time constraints in spring, often till soil before it has adequately dried, leading to widespread compaction problems on vegetable farms (Wolfe et al., 1995). For vegetable farmers in California, the risk of disrupting the spring planting schedule because of the need to incorporate a cover crop is the biggest obstacle for replacing the typical winter fallow with a cover crop (Wyland et al., 1996). Even spring oat (*Avena sativa* L.), the traditional winterkilling cover crop in the mid-Atlantic, leaves high surface residue that acts as mulch. Although oat does not require termination, if left on the surface, the residue can keep the soil wet and limit soil warming (Teasdale and Mohler, 1993). The N fertilizer value of oat is considered negligible (Doran and Smith, 1991). Oat roots grown in pots and left to decompose in situ reduced net N mineralization compared to bare soil (Malpassi et al., 2000).

Cover crops can have negative as well as positive effects on plant nutrient availability. Incorporation of cover crop residues can decrease net (?) nutrient mineralization compared to bare soil (Baggs et al., 2000), limiting nutrient availability for the subsequent crop. A 2005 review discusses the complexity of N mineralization processes from organic residues such as cover crops, highlighting the multiple influences of the composition of the organic residue, soil temperature and water content, drying and wetting events, and soil characteristics (Cabrera et al., 2005). The authors underscore the impossibility of determining a C/N ratio or even a narrow range of C/N ratios that serve as a break-even point for N mineralization/immobilization from organic residue, suggesting that in some cases net immobilization may occur from residues with C/N ratios as low as 15 and net mineralization may occur from residues with C/N ratios as high as 40. To account for temperature and moisture effects on decomposition, some researchers have attempted to calculate decomposition days in NT cover crop systems according to air temperature and precipitation events (Ruffo and Bollero, 2003). The model does not take into account effects different residue may have on soil temperature and moisture, which are more influential on decomposition dynamics than air temperature and total precipitation. Continued research to parameterize models that can effectively predict N mineralization from cover crops may yield better results, but as of now, continued studies are necessary to document the actual decomposition dynamics of cover crops under field conditions.

Brassica cover crops

Asynchrony between main crop N demand and cover crop N mineralization poses both environmental and agronomic risks (Dabney et al., 2010), and has been one of the reasons behind an increased interest in Brassica cover crops (Weil et al., 2008). In a 2000 review of cover crops in the United States, “commonly” used cover crops included grasses (five species), legumes (seven species), and “other,” a category that included mustard species (*Brassica* spp.) and buckwheat (*Fagopyrum esculentum* Moench) (Lu et al., 2000). In a 2001 review, Brassica species were mentioned for their N-scavenging abilities (Dabney et al., 2001). By 2005, Brassicas were included as promising cover crop options alone and in mixtures to fill several niches (Snapp et al., 2005), and in 2010, Brassicas were included among grasses and legumes as one of three major categories of cover crops (Dabney et al., 2010). The change in academic publications to include Brassica species as a major cover crop group has paralleled a change in farmer-oriented publications. The popular handbook *Managing Cover Crops Profitably* mentioned Brassica species in the second edition published in 1998 (Clark, 1998), but focused on grass and legume species. The third edition in 2007 expanded to include a section on Brassicas and mustards (Chen et al., 2007). As an indication of farmer interest in Brassica cover crops, Tillage Radish (a brand of forage radish developed by a farmer-collaborator with the University of Maryland) was named “No-Till Product of the Year” in the *No-Till Farmer*, a distinction given by farmer votes. In 2012 in Maryland, over 6000 ha was planted in forage radish (MDA, 2013).

Several characteristics of Brassica cover crops have garnered attention among researchers and farmers. These include alleviation of soil compaction via creation of root channels (Chen and Weil, 2010; Williams et al., 2004), weed suppression (Charles et al., 2006; Haramoto and Gallandt, 2004; Kruidhof et al., 2008; Lawley et al., 2011; Lawley et al., 2012; Stivers-Young, 1998), N accumulation (Dean and Weil, 2009; Kristensen and Thorup- Kristensen, 2004; Stivers-Young, 1998; Thorup-Kristensen, 2001), biofumigation/pathogen suppression (Gimsing and Kirkegaard, 2006; Larkin and Griffin, 2007; Muehlchen et al., 1990), and S accumulation (Eriksen and Thorup-Kristensen, 2002). Despite a dramatic increase in research and understanding of Brassica cover crops, nutrient mineralization after Brassica cover crops is not well understood (Kremen, 2006). Because winterkilling is an essential facet of the early spring cropping niche, this review focuses on forage radish (*Raphanus sativus* var. *longipinnatus*) and the closely related oilseed radish (*Raphanus sativus* var. *oleiformis*), both referred to as “radish.” Other Brassicas, such as rape, do not winterkill and while they have similar growth patterns in fall (Dean and Weil, 2009; Thorup-Kristensen, 2001), they are not considered here.

The first reports in soil and agronomic literature of radish as a cover crop were from Brazil in the 1970s (Kemper and Derpsch, 1981). It is worth noting, however, that the effects of radish on loosening soil and suppressing weeds were observed by farmers in Japan and discussed in Fukuoka's seminal work on NT, low-input agriculture, *The One Straw Revolution* (Fukuoka, 1978). In Europe and North America, radish was investigated as a catch crop in the 1990s (Stivers-Young, 1998; Thorup-Kristensen, 1994) and initial results from Denmark showing radish's ability to capture more N than other cover crops spurred more research. Important key findings include the discovery that depletion of soil nitrate-N by cover crops is more a function of rooting depth than it is of root intensity, and the ability of radish to capture deep soil N is predicated on having adequate growing degree days, highlighting the importance of planting early in fall for optimizing N uptake (Thorup-Kristensen, 2001). Research in Denmark also showed the potential for deep soil S capture by radish and improved S availability to cash crops following a radish cover crop (Eriksen and Thorup-Kristensen, 2002; Eriksen et al., 2004).

Planting early in fall, provided adequate fertility and growing conditions, also allows for rapid canopy closure four to six weeks after planting. Although weed suppression was observed in New York in the 1990s (Stivers-Young, 1998), a mechanistic understanding of weed suppression by radish was elusive until a series of experiments in Maryland. This research found no evidence of allelopathy and strong evidence for light interception by the radish canopy that prevented weed seeds from breaking their dormancy in late fall and thus prevented the earliest spring weeds from emerging (Lawley et al., 2012). An earlier field experiment in the Netherlands had shown light interception to be a likely mechanism of weed suppression by radish, but had not ruled out allelopathy (Kruidhof et al., 2008). In Maryland, the planting window for radish to achieve near complete spring weed suppression ends around the first week of September (Lawley, 2010). According to the degree day calculations from Denmark (Thorup-Kristensen, 2001), the growing period between the end of August in Maryland and ~January when radish winterkills should provide more than adequate growth time for radish roots to reach below 1 m depth. Research on Maryland's Coastal Plain confirmed that radish depletes soil nitrate to the maximum depth measured of 180 cm in fall (Dean and Weil, 2009). It should be noted that this research did not measure roots in soil and it is possible that the depletion of deep soil nitrate is a result of nitrate capture higher in the soil profile. In the same field studies, spring soil mineral N measurements indicated early N mineralization from the radish cover crop (Dean and Weil, 2009; Kremen, 2006).

Kremen's unpublished thesis reveals the possibility of a small nitrate increase from radish as early as December or January, following winterkill, and then a later peak of soil nitrate concentrations in April-May (Kremen, 2006). Other field and lab research shows early N loss from radish cover crop tissue, even at low temperatures (3°C) generally considered limiting for substantial microbial activity (Magid et al., 2004; Thorup-Kristensen, 1994).

Direct release of nitrate from cover crop tissue, unrelated to mineralization processes, is possible. High nitrate release from radish cover crop tissue exposed to freeze-thaw cycles in a laboratory study was observed, though actual tissue nitrate content was not measured (Miller et al., 1994). Studies have reported radish tissue nitrate-N content to be as high as 32% of total tissue N (Fulkerson et al., 2007). Few studies, aside from Kremen (2006) have monitored soil mineral N throughout the late winter and early spring period. Instead, a single point-in-time measurement has been used to assess soil mineral N status (Isse et al., 1999; Stivers-Young, 1998), which does not capture likely temporal differences in cover crop decomposition.

Cover crop impacts on cycling of nutrients other than N have received little attention, but increased occurrence of crop S deficiencies globally (Haneklaus et al., 2008) raises the question of how cover crops could contribute to efficient S cycling (Eriksen, 2005; Eriksen, 2008; Eriksen and Thorup-Kristensen, 2002; Eriksen et al., 2004). Only two published studies have measured S content of radish cover crops and both have reported 7.7 g kg $^{-1}$ S (dry matter) resulting in 36 kg S ha^{-1} (shoots only) (Eriksen and Thorup-Kristensen, 2002) and 49 kg S ha^{-1} (whole plant) (Wang et al., 2008). Legumes, with high protein content, may have higher S content than Brassicas, but S mineralization from legume tissue is much slower than from Brassicas (Eriksen et al., 2004). The two mechanisms for S mineralization, the biochemical hydrolysis of sulfate-esters, and the biological mineralization through microbial use of organic C, may explain the different dynamics of S mineralization from cover crop tissue (Eriksen, 2005). Whereas Brassicas have high quantities of sulfate-esters such as glucosinolates that are readily hydrolyzed, legumes and grasses contain more S in protein and organic forms that require microbial decomposition. Capturing S and bringing it to the surface lessens the fall and winter leaching potential of sulfate, which like nitrate, is subject to leaching in predominantly negatively charged surface horizons. Loss of S from the soil surface can lead to S deficiencies in young seedlings or for shallow-rooted crops, especially in NT soils where sulfate has leached below the rooting zone (Hitsuda et al., 2005). As for N, it is desirable for S availability from cover crop decomposition to be synchronized with cash crop demand.

Cover Crops for No-till Vegetable Production

No-till agriculture has increased to over 40 million ha in North America (Derpsch et al., 2010),. Vegetable production continues to rely primarily on tillage for creation of a suitable seedbed, however, which can have deleterious effects on soil quality. One notable exception in the mid-Atlantic is the production of pumpkins grown in NT, cover crop systems, which reduces the need for costly fungicide applications and increases the marketability of the pumpkins because the cover crop residue prevents soil splashing onto the fruits (Everts, 2002b). Farmer adoption of this system for growing pumpkins has been high (>70% in Maryland) because it is not risky and reduces costs. Other NT systems for vegetables in the mid-Atlantic have been investigated for beans, tomatoes, potatoes, and broccoli (Abdul-Baki and Teasdale, 1997; Abdul-Baki et al., 1996; Morse, 1999a; Morse, 1999b; Teasdale and Abdul-Baki, 1998), but adoption of these systems is not widespread. Some possible constraints identified in these systems that may limit adoption include delayed maturity of cash crop (because of reduced soil temperatures), a need for greater fertilizer and herbicide inputs, and disease pressure (Hoyt et al., 1994). Poor aggregation and fast reversion to low soil porosity in intensively-tilled systems may also limit the ability to alternate between NT production and tilled production; the full soil quality benefits of NT practices often require several years of continuous NT to achieve (Derpsch et al., 2010).

All of the above-mentioned NT cover crop-vegetable systems rely on high-residue mulches for moderating soil moisture and temperature and, to some extent, for weed control. In most of the systems above, additional weed control is provided by herbicides and in one study that compared the yield between no-herbicide and herbicide treatments in NT tomatoes grown in cover crop mulch, the herbicide treatment had higher yields in two out of three site years (Teasdale and Abdul-Baki, 1998). Lack of appropriate herbicides has been identified as one of the barriers to NT adoption (Derpsch et al., 2010). High-residue cover crop mulch is ill-suited to early season vegetable production, which relies on rapid soil warming and drying. This mismatch may explain why the NT vegetable production systems researched to-date have centered on later-planted crops. An additional concern for certified organic growers lies in the reliance of many of these systems on herbicides for both cover crop termination/desiccation and weed control.

In order for NT practices to be applicable to early season vegetable production, the spring seedbed must undergo adequate soil warming and drying. Furthermore, organic farmers cannot adopt NT practices that rely on herbicides for weed control.

Conclusion.

Previous research on NT vegetable production is only marginally relevant to the early vegetable cropping niche, and a new paradigm is necessary. Early vegetable production is a cropping niche that has not benefitted much from advances in NT or cover crop research. The unique characteristics of radish as a cover crop, which include high N and S capture in fall, spring weed suppression, low surface residue in spring, and likely rapid N and S mineralization in spring, have opened the possibilities for a different NT cover crop paradigm that is, indeed, applicable for early NT vegetable production. Increased understanding of spring seedbed characteristics including soil temperature, moisture and nutrient mineralization patterns, along with field testing the response of various vegetable crops to NT planting, could open possibilities for implementing economically viable soil conserving practices on vegetable farms.

Chapter 3 Forage Radish Cover Crop Increases Soil Nitrate and Sulfate in Spring

Abstract

Winterkilled cover crops are advantageous because they do not require termination prior to spring planting. The traditional winterkilling cover crop in the mid-Atlantic is spring oat (*Avena sativa* L.), which can limit field work by keeping the soil wet and is not considered to have fertilizer value. Forage radish (*Raphanus sativus* var. *longipinnatus*) is a cover crop that has received attention for its N and S scavenging abilities in fall. Less is known of the nutrient dynamics in spring after forage radish winterkills. In order to investigate spring nutrient dynamics after winterkilled cover crops with and without spring tillage before and during the growing season of spinach (*Spinacea oleracea* var. Tyee), we conducted an experiment over four site years on Maryland's Coastal Plain and Piedmont regions. By mid-April, winterkilled forage radish had increased surface (0-20 cm) soil nitrate-N by over 30 kg ha^{-1}at both site years in the Piedmont soil, regardless of tillage. After tillage, nitrate-N content after forage radish was more than 50 % higher than bare soil. Forage radish increased soil sulfate-S by more than 9 kg ha^{-1} at all site years. Soil nutrients following a radish-oat biculture were generally similar to a forage radish monoculture, but there were exceptions.

Introduction

Cover crops can capture and recycle nutrients in temperate agricultural systems, but to maximize environmental and agronomic benefits, mineralization of captured nutrients must be synchronized with subsequent cash crop demand (Dabney et al., 2010; Meisinger et al., 1991; Thorup-Kristensen and Nielsen, 1998; Thorup-Kristensen et al., 2003). Forage radish and the closely related oilseed radish (*Raphanus sativus* var.*oleiformis*), both referred to as “radish” in this review, have prompted interest as “catch” crops because of their N-scavenging (Allison et al., 1998; Dean and Weil, 2009; Isse et al., 1999; Kristensen and Thorup- Kristensen, 2004; Stivers-Young, 1998; Stivers et al., 1993; Thorup-Kristensen, 2001; Wang et al., 2008), and S-scavenging abilities in fall (Eriksen and Thorup-Kristensen, 2002). Radish winterkills in regions that experience multiple consecutive days with temperatures reaching below approximately -7° C, although there are varietal differences. Winterkilling is advantageous for spring planting because it eliminates the need for mechanical or chemical cover crop termination prior to field work. The traditional winterkilling cover crop in the mid-Atlantic is spring oat, which can hinder early field work and soil warming in cold, wet springs. Residues with high C/N ratios can also immobilize nutrients for the succeeding cash crop, a factor that serves as a disincentive for farmer adoption of cover crops (Snapp et al., 2005).

Cover crop uptake of nitrate and sulfate from deep in the soil profile during fall prevents leaching losses during the winter when precipitation generally exceeds evapotranspiration. Despite well-documented nutrient uptake by radish in fall, data on nutrient dynamics in spring after radish is sparse. Because spring nutrient fluxes are largely microbially-driven and rapid, important changes can be missed even with frequent sampling (Thorup-Kristensen et al., 2003). Small changes in water potential also affect the dominant N cycling pathways (Bateman and Baggs, 2005; Linn and Doran, 1984). Therefore, cover crop decomposition under field conditions can be difficult to fully understand. Limited evidence from field experiments points to possible early mineralization of both N (Dean and Weil, 2009; Kremen, 2006; Schomberg et al., 2006; Thorup-Kristensen, 1994) and S from radish (Eriksen and Thorup-Kristensen, 2002; Eriksen et al., 2004), indicating that its use as a cover crop may be best suited to the earliest planted spring crops or in finer textured soils where spring leaching is relatively slow. In the mid-Atlantic, cold-hardy vegetables such as spinach are among the earliest planted crops. A more thorough understanding of soil nutrient status throughout spring after radish would facilitate development of cropping systems that maximize nutrient use efficiency.

Historically, cover crop research has focused on N because of its dual roles as the primary limiting nutrient for crops and a major contributor to eutrophication. Literature values on radish N uptake in fall range from as little as 18 kg N ha^{-1} in Ontario for a radish cover crop planted after wheat harvest (Vyn et al., 2000), to as much as 310 kg N ha^{-1} in a muck soil in Michigan used for vegetable production (Wang et al., 2008). More commonly, N uptake is 100-150 kg N ha^{-1} (Dean and Weil, 2009; Isse et al., 1999; Kristensen and Thorup- Kristensen, 2004; Stivers-Young, 1998; Thorup-Kristensen, 1994). Assuming no other limiting conditions, N uptake by radish appears to be a function of quantity and location of available N combined with growing degree days (d° C) available before termination. In Denmark, researchers found that radish roots had grown to 1.5 m after 1000 d °C (base 0°) and oat roots had only reached 0.9 m. However, radish required 301 d °C to reach 0.1 m whereas oat only required 200 d °C (Thorup-Kristensen, 2001). Early planting of radish in fall is essential to optimize root growth and N uptake. The literature data on biomass production and N uptake by radish are complicated by the plant's partially aboveground fleshy root; reported N uptake sometimes includes both root and shoot, sometimes just shoot, and sometimes it includes all aboveground N (which includes the shoot and the part of the root that protrudes aboveground).

Most studies that have measured soil mineral N in spring after a radish cover crop have done so at only one point in time and results have been mixed. Some research has reported no difference between soil mineral N content after radish and other cover crops (Isse et al., 1999; Stivers-Young, 1998) and some have reported an increase in mineral N from radish (Dean and Weil, 2009; Kremen, 2006; Schomberg et al., 2006; Thorup-Kristensen, 1994; Weil et al., 2008). If cover crops decompose at different rates, one sampling date will likely not capture temporal differences in cover crop N mineralization. Indications of early mineralization and leaching losses after radish were observed on a loamy sand soil in one of four site years in MD where a high N, low C environment was created before cover crop establishment by terminating a green soybean (*Glycine max)* crop. Porewater nitrate-N at 120 cm after radish and before soybean planting the following year increased from nearly 0 mg L^{-1} in February to 5 mg L^{-1} in mid- March and nearly 20 mg L^{-1} by mid-April (Dean and Weil, 2009). These data show the potential for leaching losses in early spring after radish under some conditions.

Laboratory studies support the hypothesis that N from radish may be available early in spring. Substantial N loss from forage radish residue can occur even at 3°C (Magid et al., 2001), and freeze-thaw cycles may lead to higher nitrate-N leaching from radish biomass than from ryegrass (*Lolium multiflorum* L.) or red clover

(*Trifolium pratense* L.) (Miller et al., 1994). Direct nitrate-N loss from cover crop tissue high in nitrate-N may be a cause, separate and in addition to mineralization, of some observed early and high nitrate-N concentrations in soil and porewater after cover crops. Few values have been reported for radish or other cover crop nitrate-N content, but luxury consumption can account for a large portion of total N uptake in non-N limited environments. Nitrate-N was 20 and 32% of total N of radish harvested for fodder in winter and autumn respectively in Australia (Fulkerson et al., 2007). In Denmark, nitrate-N was 9 and 12 % of total N of radish and oat cover crops respectively, harvested in November (Thorup-Kristensen, 1994).

Cover crop impacts on cycling of nutrients other than N have received little attention, but increased occurrence of S deficiencies globally (Haneklaus et al., 2008) raises the question of how cover crops could contribute to efficient S cycling (Eriksen, 2005; Eriksen, 2008; Eriksen and Thorup-Kristensen, 2002; Eriksen et al., 2004). Only two published studies have measured S content of radish cover crops and both have reported 7.7 g kg^{-1} S (dry matter) resulting in 36 kg S ha^{-1} (shoots only) (Eriksen and Thorup-Kristensen, 2002) and 49 kg S ha^{-1} (whole plant) (Wang et al., 2008). Capturing S and bringing it to the surface lessens the fall and winter leaching potential of sulfate, which like nitrate, is subject to leaching in predominantly negatively charged surface horizons. Loss of S from the soil surface can lead to S deficiencies in young seedlings or for shallow-rooted crops, especially in NT soils where sulfate has leached below the rooting zone (Hitsuda et al., 2005).

In addition to the similarities between nitrate and sulfate behavior in the soil environment, there is a synergism between N and S as nutrients. Excess N fertilization with inadequate S supply can decrease yields in crops as diverse as wheat (Salvagiotti et al., 2009) and spinach (Smatanová et al., 2004). Adequate S supply to crops increases the production of S-containing amino acids cysteine and methionine and bioactive plant compounds, increasing the nutritive value of crops (Jez and Fukagawa, 2008). Despite the recognized issue of S deficiency, current soil tests are imprecise at predicting S availability to crops. Pot studies have shown 0.01 M $Ca(H_2PO_4)_2$, 0.01M $CaCl_2$, and 0.016 M KH_2PO_4 extraction of S to be well-correlated with plant S uptake or added S (Hue et al., 1984; Ketterings et al., 2012a; Zhao and McGrath, 1994) and limited field studies have shown 0.01M $CaCl_2$ extraction of S to be correlated to alfalfa (*Medicago sativa* L.) response (Ketterings et al., 2012b). Sulfate leaching and sorption in subsoil layers complicates the prediction of plant availability from soil tests, which generally include only the surface 20 - 30 cm of soil.

In order to investigate the potential of a forage radish cover crop to supply N and S to an early planted spinach crop and to contribute to a more thorough understanding of nutrient dynamics in spring following winterkilled cover crops, we conducted an experiment over four site years in Maryland’s Coastal Plain and Piedmont regions. The objectives of this research were: to quantify N and S uptake of forage radish and oat separately and in combination; to characterize surface soil mineral N and S after cover crop winterkill through the early spring growing season of spinach in no-till (NT) and rototilled (RT) plantings; and to determine the plant availability of soil N and S using uptake by spinach as an indicator.

Methods and Materials:

Field experiments were conducted over the course of two years, 2011-12 and 2012-13, at Central Maryland Research and Education Center Clarksville and Wye Research and Education Center, referred to as CMREC 1 & 2 and WREC 1 &2. Site characteristics are given in Table 3.1 Site characteristics for field experiments at Central Maryland Research and Education Center, Clarksville (CMREC) and Wye Research and Education Center (WREC).Table 3.1and soil test measurements in Table 3.2.

The treatment structure was a 2x2x2 factorial with factors: radish (present or absent), oat (present or absent) and spring tillage (NT or RT). The experimental design was a randomized complete block split-plot design with four blocks per site. The four cover crop main plot treatments were: forage radish (FR), oat (OAT), radish-oat (RO), and no cover crop (NC). These main plots were split in spring into NT and RT subplots.

Table 3.1 Site characteristics for field experiments at Central Maryland Research and Education Center, Clarksville (CMREC) and Wye Research and Education Center (WREC).

	CMREC	WREC
Location	39˚ 15’ 12” N 76˚ 55’ 49” W	38˚ 55’ 10” N 76˚ 08’ 19” W
Physiography	Piedmont	Coastal plain
Soil Series	Glenelg	Mattapax
Taxonomy	Fine-loamy, mixed, semiactive, mesic Typic Hapludult	Fine-silty, mixed, active, mesic Aquic Hapludult
Surface texture	SiL (16 % clay)	SiL (11 % clay)

Table 3.2 Soil test (0-20 cm) results for Central Maryland Research and Education Center, Clarksville (CMREC) and Wye Research and Education Center (WREC).

	CMREC		WREC	
year	**2011-12**	**2012-13**	**2011-12**	**2012-13**
pH_{water}	7.0	5.7	5.9	5.4
Organic C (%)	2.8	1.5	1.4	0.82
N (g kg^{-1})	2.4	1.6	1.0	0.80
	--------Mehlich III extractable nutrients (mg kg^{-1})--------			
P	200	115	92	74
K	445	367	81	66
S	12	20	20	19
Mg	216	143	174	111
Ca	2409	1047	786	722
B	1.5	0.66	0.55	0.63

Means of four blocks presented (12 cores per block taken prior to experiment intitiation).

[†] Samples taken after compost application

[‡] Samples taken after poultry litter and calcitic lime application

To avoid residual effects, a new field was used at each of the two sites in the second site year, adjacent to the field used in the first site year. Both sites were managed according to organic certification rules (CFR) prior to and during the experiment. The WREC 1 field was in second year alfalfa prior to disking in July 2011. The WREC 2 field received 2.3 Mg ha^{-1} poultry litter (3-0.9-2.5 NPK) and 2.2 Mg ha^{-1} calcitic lime in July 2012. The CMREC 1 field had a sequence of rye and buckwheat cover crops prior to tillage in July 2011 and had a history of high dairy manure compost applications, though quantities were unavailable. The CMREC 2 field, which did not have a history of high compost applications, received 12 Mg ha^{-1} (wet) finished dairy manure compost in July 2012 (1.2-0.42-1.9 NPK on dry weight basis; C/N ratio 11.3).

All fields were disked prior to initiating the experiments. Cover crops were planted using a Great Plains NT drill (Great Plains Manufacturing, Salina, KS) at WREC and a John Deere NT drill (John Deere, Moline, IL). Both drills had 19 cm row spacing and were calibrated to plant 10 kg ha^{-1} radish and 72 kg ha^{-1} oat. The RO treatment had alternating rows of radish and oat and the seeding rate was half of the full rate for each. Main plots were 3.0 m wide by 23 m long. For spring tillage, a 1.5 m wide power take off rototiller was used for a single pass down the middle of the subplots, resulting in sub-plots in spring that were 1.5 m wide by 11 m long. The tillage depth was approximately 10 cm. Important field activity dates are presented in Table 3.3.

Table 3.3 Field activity dates at Central Maryland Research and Education Center, Clarksville (CMREC) and Wye Research and Edcuation Center (WREC).

	CMREC		WREC	
Field activity	**2011-12**	**2012-13**	**2011-12**	**2012-13**
Cover crop planting	August 24	August 24	August 22	August 23
Cover crop biomass sampling[†]	October 28	November 11 & 14	November 19	November 28
Fall rototilling (No cover only)	October 25	November 19	October 24	October 26
Winterkill/mowing	~January 10 (winterkill)	~ January 25 (winterkill)	February 28 (mowing)	March 4 (mowing)
Spring rototilling	March 12	March 11	March 12	April 3
Spring vegetable planting	March 13 &14	March 11	March 20	April 4
Weeding[‡]	April 14	April 22	April 7[§]	April 21
Spinach harvest(s)	May 22	May 10, 20	May 18	May 17

[†] CMREC 1 and WREC 2 weeds were sampled from NC plots prior to fall tillage. NC biomass was not sampled at WREC 2.

‡Weeding with a hand-held hoe.

[§] In forage radish no-till and all rototilled treatments. Weeding in other treatments was not performed

Spinach (var. Tyee) was planted in spring using a three-row NT planter (Monosem Inc, Edwardsville, KS) with 38 cm row spacing at WREC 1, WREC 2 and CMREC 2. CMREC 1 was planted by hand with four rows and 30 cm row spacing. Depth of planting was approximately 1.5 cm. At WREC 1, NC RT was a complete crop failure because of seed corn maggots, so no spinach data were collected. The same year, NC NT, RO NT and OAT NT were not harvested because weed competition led to a complete crop failure. At WREC 2, OAT RT was not planted because the soil was too wet to till, so no spinach or soil data were collected

Cover crop biomass:

Cover crops were harvested from two 0.25 m^2 quadrats from each plot in late fall prior to expected winterkill, resulting in two subsamples per plot. The NC plots were rototilled in fall to reduce weeds in spring because herbicides are not permitted in organic agriculture and to simulate the common farmer practice of “winter fallow.” Weed biomass was harvested prior to fall tillage and therefore was not harvested on the same date as the rest of the biomass at CMREC 1 and WREC 2 (Table 3.3). In OAT and NC plots, above-ground shoots were harvested. For the plots containing radish, the whole radish plant (shoot and fleshy root) was pulled from the ground, the root and shoot separated, and the root was washed in the field to remove soil. Typically, approximately a quarter to a third of the fleshy root mass occurred aboveground. Subsamples of cover crops were dried in a forced-draft oven at 50-60˚ C until mass was constant. Each subsample was weighed and ground to < 2mm with a Wiley mill. Equal parts of the two subsamples from each plot were further ground using a coffee grinder to <1mm. These samples were analyzed for C, H and N (LECO CHN-2000 analyzer, LECO Corporation; St.Joseph, Michigan). Tissue NO_3^- -N was extracted 20:1 with deionized water shaken for 30 minutes on a rotary shaker and filtered with P2 grade filter paper (Fisher Scientific). Tissue NO_3^- -N was then immediately analyzed using a colorimetric salicylic acid method (Cataldo et al., 1975). S content was determined by digestion in nitric and hydrochloric acid and analysis by inductively couple plasma atomic emissions spectroscopy (A&L Eastern Labs, Richmond, VA).

At WREC 1, none of the cover crops winterkilled, and therefore they were mowed with single pass of a flail mower, which successfully killed the radish but resulted in approximately 10% regrowth of the oat. At WREC 2, approximately 15% of the radish in the FR and RO cover crops and approximately 5% of the oat in the RO and OAT cover crops did not winterkill and all plots were flail mowed to ensure cover crop termination.

Spinach samples:

Spinach tissue samples were analyzed for C:H:N, NO_3^- -N and S content using the same methods as described for cover crops. At WREC 1 and CMREC 1, whole plants were sampled and analyzed. At WREC 2 and CMREC 2, 30 mature leaves were sampled from different plants at harvest time and analyzed. At WREC 2, there was a single harvest, and at CMREC 2, there were two successive harvests for which tissue samples were analyzed.

Soil sampling and analysis:

Soil samples consisted of five cores (0-20 cm depth) from each plot that were taken using a ~2 cm diameter soil probe. Each core was divided by depth prior to being composited. On early sample dates, the increments were 0-2.5, 2.5-7.5 and 7.5-20 cm. On later sample dates, the increments were 0-7.5 and 7.5-20 cm. On some sample dates, samples to 30 cm were also taken. Cores were taken from random locations in each plot, excluding edges. In plots with radish, actual radish holes were not sampled. Soil samples were kept cool for transportation to the lab and then dried for 1-2 weeks in a forced draft oven at 50-60˚ C. They were then sieved to < 2 mm and gravel weight was recorded. Bulk density was calculated using the dry mass of the soil and volume of the five soil cores; a gravel correction was made when gravel was present assuming a density of 2.65 g cm^{-3}. Analysis of subsamples from each site to determine water content of the air-dried soil revealed that it was <1% for both sites. A single extraction was performed with 5.0 g soil and 25 mL 0.01 M $CaCl_2$, shaken at 120 rpm on a rotary shaker for 30 minutes. After shaking, samples were centrifuged for 15 minutes at 27,000 g. Nitrate-N and sulfate-Swere determined by ion chromatography on a Metrohm 850 Professional ion chromatograph fitted with a model 858 autosampler and a 150 x 4.0 mm anion separator column (Metrohm, Riverview, FL). Ammonium-N was determined with a modified indophenol blue microplate technique (Sims et al., 1995). Soil nutrient concentrations were calculated as a fraction of the air-dried mass or on per hectare as calculated using bulk density values.

Calculations

Growing degree days (d°C, base 0°C) for air temperatures were calculated as the sum of the average of minimum and maximum daily temperature for each day..

$$d°C = \sum \frac{daily\ max + daily\ min}{2}$$

If the average of the minimum and maximum daily temperature was below 0°C, it was considered 0.

Statistical analysis

All data were analyzed as a randomized complete block design (RCBD) using a mixed model in SAS 9.2 (SAS Institute, Cary, NC) with block as a random factor and cover crop as fixed factors. Data collected after the spring treatments, including spinach tissue and soil data, were analyzed as a RCBD-split plot with spring tillage as the subplot factor. If a multi-way factorial ANOVA showed significant interactions (*F* test=0.05 or less), only simple effects were compared. Interaction terms were removed from the model if the *F* test for interactive effects >0.4. Analysis of nutrient data by depth was performed using repeated measures. Treatment means were compared using an *F*-protected LSD ($p<0.05$). The program Pdmix800 was used to assign letters for treatment means (Saxton, 2003). Correlations were performed using SAS PROC REG function.

Results and Discussion

Cover crop performance

Extreme rain events at the time of planting occurred both years at WREC, with more than 20 cm of rain within four days of planting cover crops (Figs.1a and 1b). Total precipitation between fall planting and December 31 was 77 and 68 cm at WREC 1 and WREC 2 respectively, whereas the average for the previous ten years was 43 cm for that period. Despite the rain events coinciding with cover crop emergence, cover crop stands at WREC were comparable to cover crop stands at CMREC (Table 3.4), indicating that differences in cover crop performance between the sites (Table 3.5 & Table 3.6) were likely not a function of stand density.

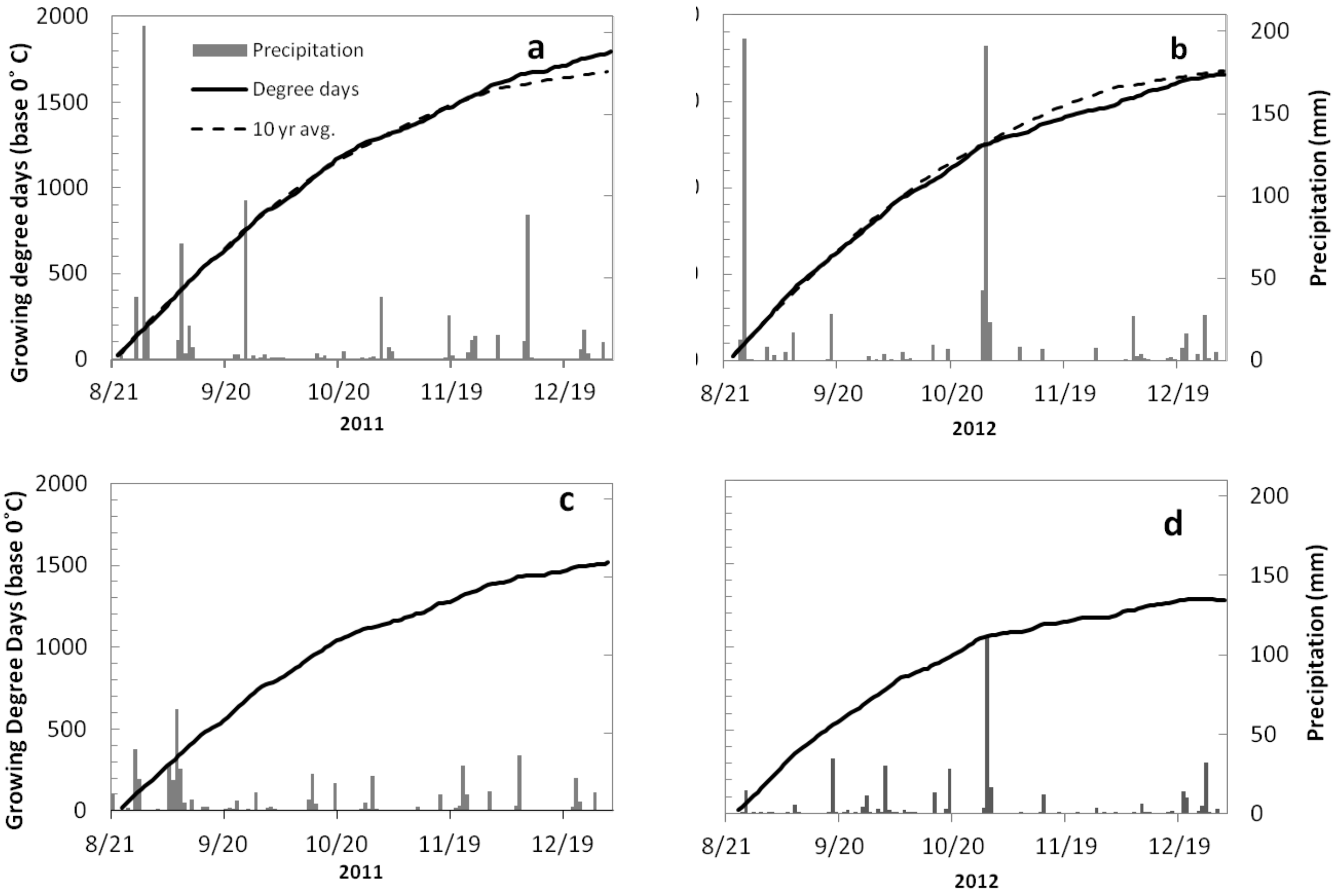

Figure 3.1 Cumulative growing degree days (base 0˚C) and precipitation at Wye Research and Education Center (top) and Central Maryland Research and Education Center (bottom).
Ten year average available for WREC only.

Table 3.4 Cover crop stands two-three weeks after planting at Central Maryland Research and Education Center, Clarksville (CMREC) and Wye Research and Education Center (WREC).

Cover crop treatment	CMREC		WREC	
	2011 (year 1)	**2012 (year 2)**	**2011 (year 1)**	**2012 (year 2)**
	------------------------Plants m^{-2}----------------------			
Forage radish	65 (17)	37 (7.0)	55 (4.5)	49 (5.0)
Radish-oat				
Radish	33 (8.3)	24 (3.1)	17 (4.4)	23 (5.0)
Oat	110 (21)	71 (22)	59 (4.5)	84 (11)
Oat	220 (24)	120 (14)	120 (8.0)	160 (17)

Numbers in parentheses are standard deviation of four blocks.

Radish is intolerant of wet growing conditions and limited oxygen. In addition to rainfall being more than 50% greater than average for both years, the soil is only moderately well drained. OAT and NC exhibited higher biomass and N uptake than FR at WREC 2 and RO had higher biomass production than FR at WREC 1 ((Table 3.5 & Table 3.6). At WREC 2, the presence of radish in the cover crop had a significant main effect of decreasing the shoot biomass by 0.98 Mg ha^{-1} (p=0.02) and the shoot N by 38 kg ha^{-1} (p=0.003). The NC biomass was harvested nearly a month before the cover crop biomass to accommodate fall tillage, and there is a possibility that this led to inaccurate comparisons of biomass and N content between the NC and cover crop treatments. The phenomenon of weeds outperforming cover crops in terms of biomass and N capture has been reported in other cover crop research, but the associated concerns of exacerbating weed pressure, especially for organic agriculture, likely outweigh the benefits of lower input costs and time (Baggs et al., 2000). The fall temperatures at WREC 1 and WREC 2 did not deviate much from the ten year average (Figure 3.1 Cumulative growing degree days (base 0˚C) and precipitation at Wye Research and Education Center (top) and Central Maryland Research and Education Center (bottom). Figure 3.1), and the d°C experienced both years is in excess of 1000 d°C required for radish to reach 1.5 m rooting depth in a sandy soil in Denmark (Thorup-Kristensen, 2001), indicating that temperature was not limiting.

The weather conditions in fall at CMREC during both site years (Figure 3.1) along with sufficient fertility created optimal growing conditions for cover crops. This is evident in the high biomass production and N capture both years (Table 3.5 & Table 3.6) We speculate that the higher N uptake at CMREC 2 than CMREC 1 (Table 3.6) was the result of compost application prior to cover crop planting, and could be indicative of the high potential for N loss if compost or manure is applied in fall without growing a cover crop. Similar differences in N uptake between years at the same sites were observed when FR was planted after corn (lower N uptake) in comparison to being planted after termination of a green soybean crop (higher N uptake) (Dean and Weil, 2009). Although weather data for the experiment years was recorded, historical weather data was not available for CMREC. The previous ten year average fall precipitation at a weather station located 23 km SE of CMREC was 48 cm; CMREC received 49 and 38 cm of precipitation in years 1 and 2 respectively, and in relatively evenly distributed rain events (Figure 3.1). Temperature data from nearby weather stations showed higher temperatures than CMREC's own weather station for the two site years, so historical temperature data is not included here.

Table 3.5 Fall cover crop performance at Central Maryland Research and Education Center, Clarksville, and Wye Research and Education Center. Cover crops were planted in mid-August and biomass harvested in late-October – November (Table 3.3).

	Cover crop treatment	**CMREC** 2011(year 1)	**CMREC** 2012 (year 2)	**WREC** 2011 (year 1)	**WREC** 2012 (year 2)
		-------------------------Mg ha^{-1}			-------------------------
Shoot biomass	Forage radish	3.8 ab	5.5 a	3.3 b	3.2 b
	Radish-oat	4.6 ab	6.0 a	5.6 a	6.2 a
	Radish portion	1.9	4.7	2.2	2.6
	Oat portion	2.7	1.3	3.4	3.9
	Oat	4.6 a	7.4 a	6.6 ab	7.7 a
	No cover-weeds	1.7 b	3.0 b	--	3.7 b
		-------------------------Mg ha^{-1}			-------------------------
Root biomass†	Forage radish	1.4 a	2.4 a	2.8 a	3.0 a
	Radish-oat	0.64 a	2.2 a	1.4 a	2.1 a

†Roots harvested for radish only and only in forage radish and radish-oat treatments.
Letters indicate significant differences between treatments within each site year, but not between site years (*F*-protected LSD, $p<0.05$).

Table 3.6 Total N and C/N ratio in cover crop tissue from Central Maryland Research and Education Center (CMREC) and Wye Research and Education Center (WREC).

		CMREC		WREC	
	Cover crop treatment	2011 (year 1)	2012 (year 2)	2011 (year 1)	2012 (year 2)
		--------------------------kg ha^{-1}--------------------------			
Shoot N	Forage radish (FR)	154 a	236 a	101 a	75 b
	Radish-oat (RO)	139 ab	246 a	131 a	103 ab
	Oat (OAT)	110 ab	204 a	129 a	126 a
	No cover-weeds (NC)	52 b[†]	115 b	--	129 a[†]
		--------------------------kg ha^{-1}--------------------------			
Root N	FR	37 a[‡]	75 a	50 a	42 a
(radish only)	RO	18 b	71 a	30 a	40 a
		----------------------------C/N----------------------------			
Shoot C/N ratio	FR	8.5 b	8.1 c	13 b	16 b
	RO (total)	16 a	9.5 b	23 a	30 a
	Radish portion	7.4	7.5	11	14
	OAT portion	22	16	30	43
	OAT	17 a	13 a	21 a	27 a
	NC (weeds)	13 a	10 b		12 b
		----------------------------C/N----------------------------			
Root C/N ratio	FR	13 a	16 a	22 b	27 b
(radish only)	RO	13 a	14 a	18 a	21 a

[†] NC biomass harvested two-four weeks before cover crop biomass to accommodate fall tillage.

[‡] p=0.056

Letters indicate significant differences between treatment means within each site year, but not between site years (*F*-protected LSD p<0.05, n=4).

Table 3.7 Nitrate-N as a fraction of total cover crop tissue N at Central Maryland Research and Education Center, Clarksville (CMREC) and Wye Research and Education Center (WREC).

	Cover crop treatment	CMREC 2011 (year 1)	CMREC 2012 (year 2)	WREC 2011 (year 1)	WREC 2012 (year 2)
		----------------------- NO_3^--N/Total N [‡]---------------------			
Shoot nitrate	Forage radish	0.31 a	0.20 a	0.095 a	0.040 c
	Ooat	0.33 a	0.21 a	0.085 a	0.13 a
	No cover	0.10 a[†]	0.11 b	--	0.078 b[†]
		----------------------------NO_3^--N/Total N[‡] --------------------------			
Root nitrate	Forage radish	0.43 a	0.35 a	0.19 b	0.16 a
(radish only)	Radish-oat	0.48 a	0.35 a	0.27 a	0.13 a

[†] NC biomass harvested two-four weeks before cover crop biomass to accommodate fall tillage.
[‡] at time of biomass harvest; biomass harvest was not immediately before winterkill
Letters indicate significant differences between treatment means within each site year, but not between site years (*F*-protected LSD $p<0.05$, n=4).

Root data are presented for radish roots only and only in the FR and RO treatments. The FR data highlight the variability in root:shoot partitioning by radish; while it cannot be statistically verified because of different biomass sampling dates, it appears that the radish plants at WREC had a higher root/shoot ratio (Table 3.5), which is characteristic of N-stressed plants (Reynolds and Thornley, 1982). Because of the higher root/shoot ratio, 33-36 % of total FR N was in root tissue at WREC whereas at CMREC, only 19-24 % of total FR N was in root tissue. As is typical of roots compared to shoots, FR root at both sites had higher C/N ratios than FR shoot (Table 3.6). A combination of root chemical composition and physical protection in soil contributes to a higher general recalcitrance of root material compared to shoot material (Puget and Drinkwater, 2001; Rasse et al., 2005). Radish roots may not be comparble in some ways to other plant roots because of their morphology (large, fleshy taproot), and chemical composition. The influence of root/shoot ratio on N and C cycling after radish deserves further investigation and future research on radish as a cover crop should distinguish between root and shoot biomass production and N capture.

Harvesting the major portion of the radish taproot is generally not difficult, but harvesting oat and other cover crop roots can be prohibitively laborious. Even harvesting and washing the roots does not provide information on root effects on the soil environment through root sloughing and root exudates (Dabney et al., 2010). The oat shoot data alone provide limited information, but may give some indications of below-ground dynamics. For example, at WREC, the C/N ratio of oat shoots in the RO treatment tended to be higher than in the pure OAT treatment, and the C/N ratio of radish roots was lower than the pure FR roots for both years (Table 3.6). There is also a trend that radish shoots in RO had lower C/N ratios than pure FR shoots. These trends are evident at CMREC, but of much smaller magnitude. If the oat shoot C/N ratio in RO at WREC is an indication of N-stress, it is likely that the root/shoot ratio of oat in RO was higher than in OAT. This is speculative, but could be important for understanding interactions and competition between Brassicas and grasses in cover crop mixtures under different conditions. The radish-oat interactions at WREC were likely influenced by wet growing conditions and by the N-limited environment.

Despite many investigations of nitrate capture by cover crops, few studies have actually measured the tissue nitrate content of cover crops. The prevailing assumption seems to be that the vast majority of captured nitrate is reduced and assimilated into plant tissue, which must then undergo ammonification and nitrification to return as nitrate to the soil. To the best of our knowledge, the direct release of nitrate-N from winterkilled cover crop tissue has only been investigated in a laboratory study of freeze-thaw cycles, though in the study tissue nitrate-N was not measured (Miller et al., 1994). Tissue nitrate-N at time of biomass harvest was over 20 % of total FR, RO, and OAT N at CMREC both years (Table 3.7). Biomassharvest was nearly two months before complete winterkill, however, and these values likely do not represent the nitrate-N content at the time of winterkill. Despite differences in total N uptake between site years at CMREC, the shoot nitrate-N on a per ha basis was identical for FR (47 kg ha^{-1}) and similar for OAT (36 and 43 kg ha^{-1} nitrate-N) at CMREC 1 and CMREC 2. At WREC, where the plants had lower N content, nitrate-N was a lower percentage of total N, exceeding 20% only in radish roots in the RO treatment at WREC 1 (Table 3.7). These values for tissue nitrate-N are within the range reported in other studies (Fulkerson et al., 2007; Thorup-Kristensen, 1994), but more data are needed on tissue nitrate-N content at the actual time of winterkill.

Spring Mineral N dynamics

Nutrient capture in fall is a high environmental priority, but nutrient availability in spring is more agronomically important. In this regard, despite the fact that OAT was the only cover crop treatment that had among the highest N capture in fall (Table 3.6), FR outperformed other cover crop treatments at all site years for the spring period monitored. The timing of observed increases in soil nitrate-N after FR in March and April is in line with previous research in the mid-Atlantic (Dean and Weil, 2009; Kremen, 2006). The parallel between increasing air temperatures and higher surface soil (0-20 cm) nitrate-N at CMREC 1 and 2, which had notably different temperature patterns (Figure 3.2), provides strong evidence to support greater nitrification after FR, not direct release of nitrate from cover crop tissue, as the primary mechanism responsible for increases in surface soil nitrate-N, though the possibility of direct release cannot be excluded. At CMREC 1 by March 5, the cumulative d° C (air temperature) since January 1 had reached 229. At CMREC 2 on March 5, the cumulative d° C was only 97, and didn't reach 230 until April 8. A parallel between temperature and soil nitrate-N is not evident at WREC because the cover crops were still living until they were mowed, which coincided with changes in temperature (Figure 3.3).

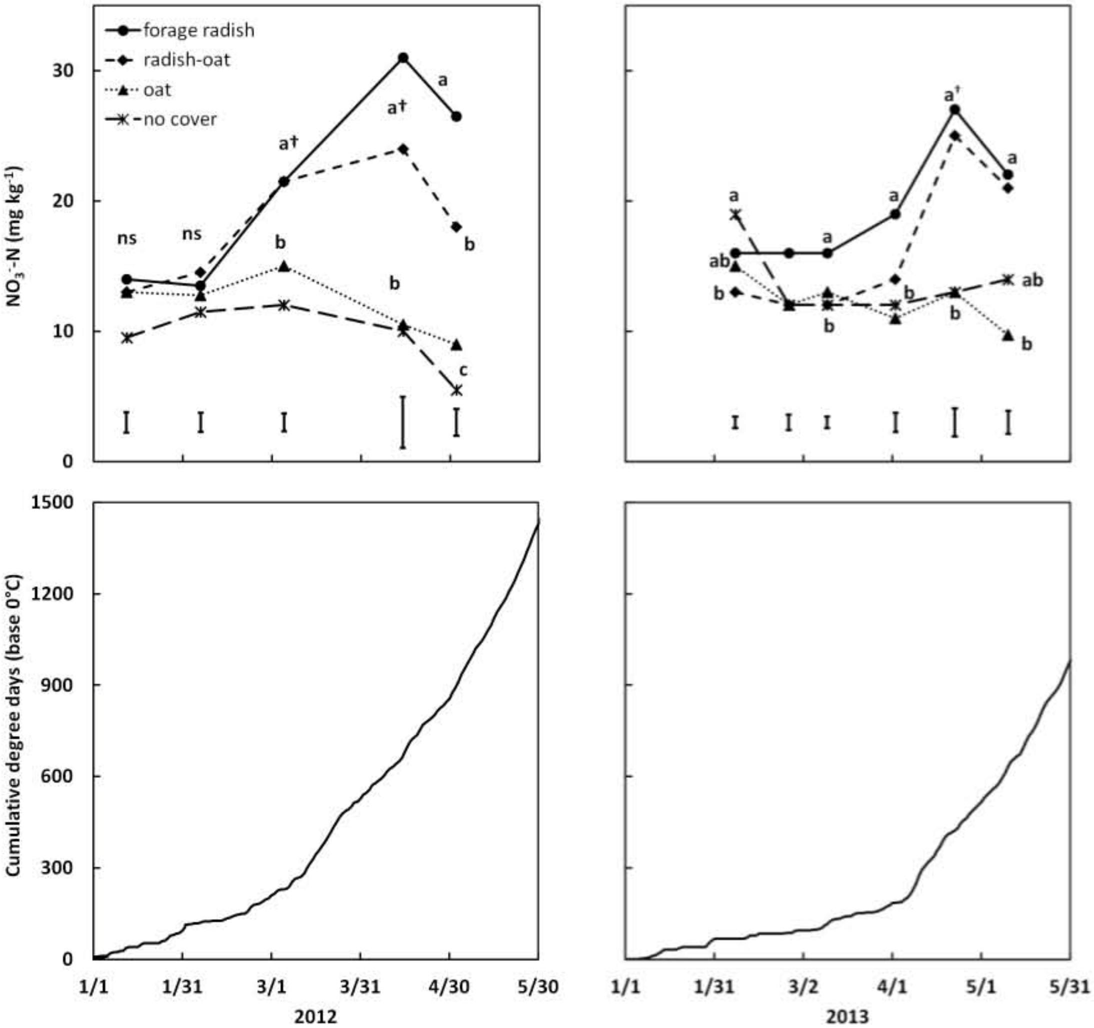

Figure 3.2 Soil NO_3^--N in no-till plots (0-20 cm) after four fall cover crop treatments (top) and cumulative degree days (base 0°C air temperature) (bottom) at Central Maryland Research and Education Center, Clarksville in 2012 and 2013.

Bars are one standard error of the mean (n=4). Letters represent significant differences of means (*F*-protected LSD, $p<0.05$) on individual sample dates only. Cover crops died in January both years.

†sample dates on which there were no significant interactions and radish main effect was significant

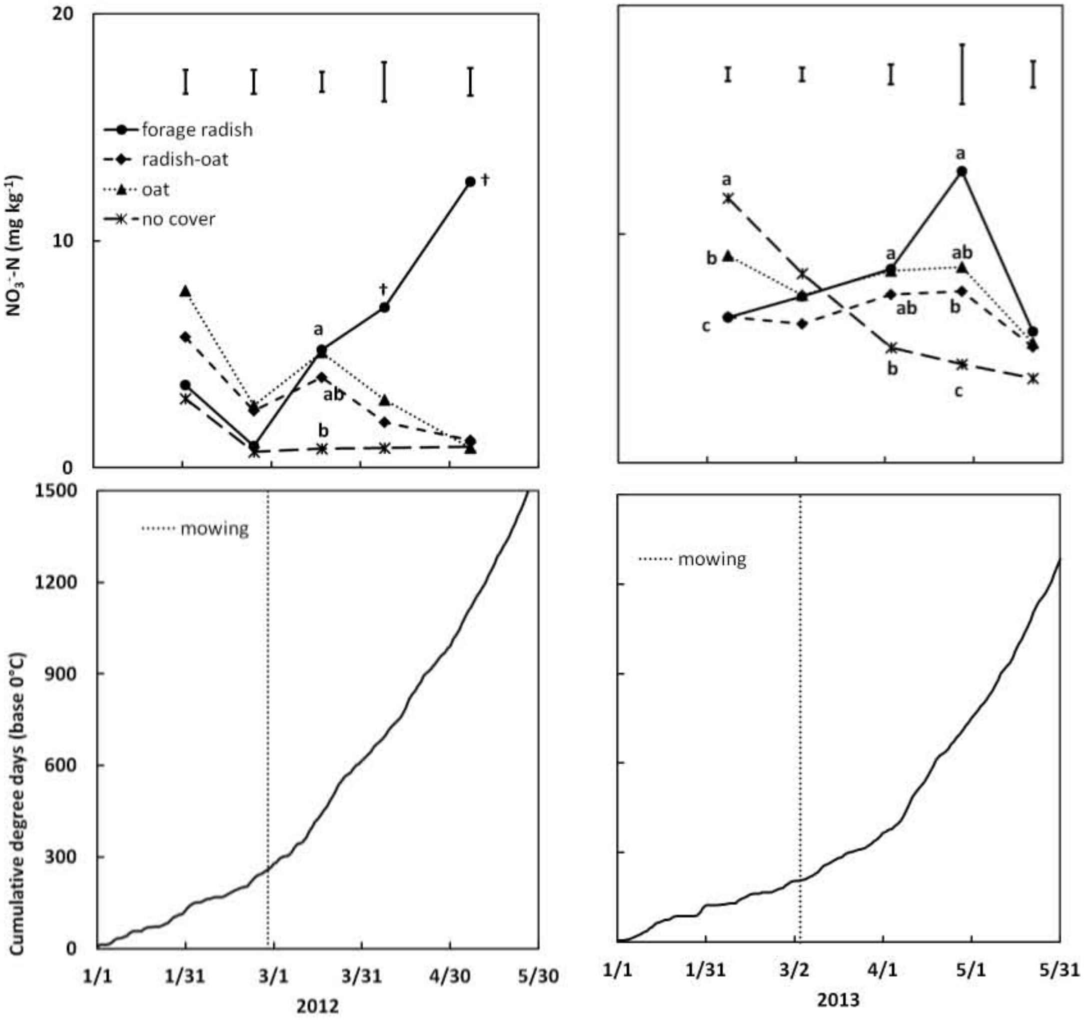

Figure 3.3 Soil NO$_3^-$-N in no-till plots (0-20 cm) after four fall cover crop treatments (top) and cumulative degree days (base 0˚C air temperature) (bottom) at Wye Research and Education Center in 2012 and 2013

Bars are one standard error of the mean (n=4). Letters represent significant differences of means (*F*-protected LSD, $p<0.05$) on individual sample dates only. Cover crops were mowed both years because of incomplete winterkill.

†letters are not given because FR was the only treatment that was weeded; NO3- in other treatments may have been affected by weed uptake.

Several independent and related variables influence nitrification including residue composition, soil temperature and moisture, drying and wetting events, and soil characteristics (Cabrera et al., 2005). Different cover crops can modify the soil moisture and temperature regimes (Teasdale and Mohler, 1993) in addition to adding residue with variable composition. Laboratory studies under controlled environments have shown higher rates of decomposition from Brassicaceous plant material than from monocots (Magid et al., 2004), even when initial C/N ratios were comparable. Precipitation patterns differed between CMREC 1 and CMREC 2 (Figure 3.4) neither was above average. Nitrification is extremely sensitive to water and oxygen content in soil (Bateman and Baggs, 2005; Linn and Doran, 1984), and lower than average precipitation at CMREC 1 may have either increased or decreased nitrification rates. It is challenging to determine mechanistically the reason for increased nitrification after FR, but it is likely a combination of all of the factors discussed.

At CMREC 1, soil nitrate-N (0-20 cm) after RO was closer to FR than it was to OAT; the main effect of radish on soil nitrate-N was significant on March 5 and April 14 (Figure 3.2). At CMREC 2, RO paralleled OAT and NC until April 22, when radish had a significant main effect on soil nitrate-N (Figure 3.2). The difference between the site years is more likely a function of weather conditions than residue composition, as the C/N ratios of FR and RO were closer to one another at CMREC 2 than CMREC 1. The data from CMREC provide inconclusive results about whether mixing radish and oat delays nitrification, which might be desirable to minimize N leaching losses. The similar soil nitrate-N concentrations throughout the period monitored at CMREC 1 and 2 between NC and OAT only indicate that net nitrification/immobilization between the two treatments was comparable, but do not give any indication of gross N cycling.

At WREC, there was no main effect of radish on soil nitrate-N on any sampling date either year. In contrast, soil nitrate-N after RO tended to be lower than after OAT (Figure 3.3). At WREC 1, the RO, OAT, and NC plots were not weeded, and although the data are presented in Figure 3.3for all treatments, statistical comparisons between the treatments for the last two sampling dates are not valid because of the high likelihood that weed uptake of nitrate affected soil concentrations. The C/N ratio of shoot tissue may be able to explain part of this trend because while the combined C/N ratio was the same in RO and OAT, the individual components differed (Table 3.6). Regardless of the mechanism, the agronomic implications of the interaction between radish and oat in RO under these specific conditions are important for predicting cash crop response and fertilizer requirements. Nitrogen or oxygen-limited growing conditions in fall may dramatically change the proportion of biomass produced by each component and the respective C/N ratios, affecting decomposition dynamics in spring. Most previous research into bi- and polycultures has been with grass-legume mixes, but as interest in cover crop mixes grows (Creamer et al., 1997; Dabney et al., 2010; Groff, 2008; Rosecrance et al., 2000), and interest in Brassica cover crops grows (Dabney et al., 2010; Snapp et al., 2005), understanding the interactions when Brassicas are included will become more important. Adjusting seeding rates and ratios in cover crop mixtures could optimize the cover crop performance for the desired niche; this research only investigated a single seeding rate for the mixture.

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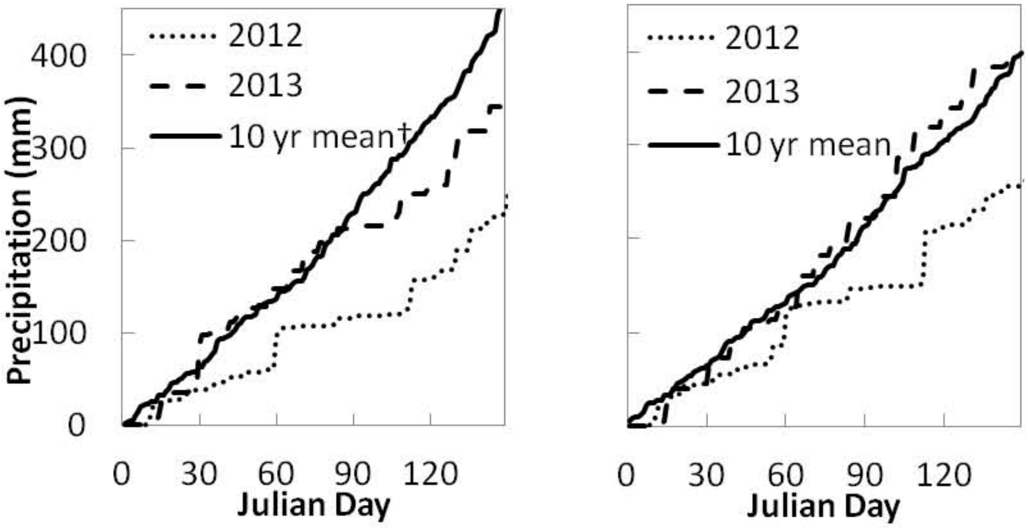

Figure 3.4 Cumulative precipitation January-May at Central Maryland Research and Education Center, Clarksville (CMREC) (left) and Wye Research and Education Center (right).
†Historic weather data not available for CMREC site. Previous ten year data taken from a weather station 23 km SE.

Tillage effects on soil nitrate-

On all five post-spring tillage sampling dates at CMREC 1 and CMREC 2, tillage increased soil nitrate-N content. In four out of five sampling dates, main effects of both tillage and radish on soil nitrate-N content were observed. The increase in nitrate-N as a result of radish in the cover crop was more than 50% greater than the increase that was observed from tillage on these four sample dates (Table 3.8). The first harvest at CMREC 1 was May 10, at which time the effects of radish and tillage on soil nitrate-N were still present, even though spinach had taken up more N from radish plots than non-radish plots (see spinach results in Chapter 4). Although it is common for tillage to increase nitrification, previous research has shown the impacts of tillage on net N mineralization to be greater in bare soil than when cover crops are incorporated (Baggs et al., 2000). In other words, cover crops increase N immobilization compared to bare soil. This does not appear to be the case in any of the four site years in this study.

Table 3.8 Increases observed in soil nitrate-N (0-20 cm) on post-tillage sampling dates as a result of tillage and radish in cover crop at CMREC 1 (2012) and CMREC 2. (2013)

Sample date	Tillage effect[†]	p value	Radish effect[‡]	p value
	kg NO_3^--N ha^-		kg NO_3^--N ha^{-1}	
April 14, 2012	14 (5.6)	0.03	33 (7.2)	0.003
May 2, 2012	23 (2.8)	<0.0001	§	§
April 2, 2013	4.8 (1.9)	0.03	18 (2.5)	<0.0001
April 22, 2013	21 (3.4)	<0.0001	34 (4.4)	<0.0001
May 10, 2013	8.4 (3.8)	0.05	27 (5.7)	0.001

†Tillage effect= NO_3^--N with tillage (rototilling) - NO_3^--N (no-till)
‡ Radish effect= NO_3^--N with radish- NO_3^--N without radish
§a significant radish*oat interaction precluded a radish main effect.
Numbers in parentheses are SEM. (n=16 for tillage, n=8 for radish).

Table 3.9 Total soil nitrate-N (0-20 cm) on post-tillage sampling dates at WREC 1 (2012) and WREC 2 (2013)

Sample date	Forage Radish		Radish-Oat		Oat		No cover	
	No-till (NT)	Rototilled (RT)	NT	RT	NT	RT	NT	RT
				NO_3^--N (kg ha^{-1})				
April 8, 2012	21 bc	29 ab	--[†]	37 a	--	20 bc	--	14 c
May 7, 2012	37 a	34 a	--	35 a	--	22 b	--	9.3 c
April 27, 2013	40 a	44 a	22 ab	38 a	25 ab	--[‡]	13 b	23 ab
May 21, 2013	17 b	39 a	15 b	32 a	16 b	--	11 b	14 b

[†] data not included because RO, OAT, and NC NT plots were not weeded in 2012
[‡] OAT RT not planted because soil was too wet to till at planting

Tillage generally increased soil nitrate-N at WREC, but missing data complicate interpretation (Table 3.9). Unlike the RO NT at WREC, which generally had comparable or slightly lower soil nitrate than OAT NT, the RO RT was equal to FR RT on all sampling dates. The reasons for this are not obvious.

Nitrate variation with depth

On nearly all sampling dates, nitrate-N concentrations varied with depth in addition to cover crop treatment, and these differences were generally more pronounced for FR. An extreme example occurred on April 8 at WREC 2, when the nitrate-N concentration in the upper 2.5 cm of FR NT was 28 mg kg^{-1}, far greater than the nitrate-N concentrations in 2.5-7.5 cm and 7.5-20 cm, which were 4.2 and 3.8 mg kg^{-1} respectively ($p<0.05$). Such a pronounced stratification of nutrients either did not occur or was not captured in any other site year, but differences in nitrate-N concentration with depth were significant on all but the February 6 sampling date at CMREC 1 (Figure 3.5). By April 14 at CMREC 1, treatments with radish had higher nitrate-N in the surface 0-20 cm than 20-30 cm, whereas treatments without radish had lower overall nitrate-N and the concentration was no higher in the surface 20 cm than from 20-30 cm (Figure 3.5).

Samples to 30 cm were not taken in at CMREC 2, but concentrations in FR were 4.5, 10, and 9 mg kg^{-1} nitrate-N greater in the upper 7.5 cm of FR than in 7.5-20 cm on March 10, April 2, and April 22 respectively ($p<0.05$). By May 10, nitrate-N concentrations were not affected by depth. In OAT, nitrate-N concentrations did not vary with depth on any of the sampling dates from Feb 7 to May 10.

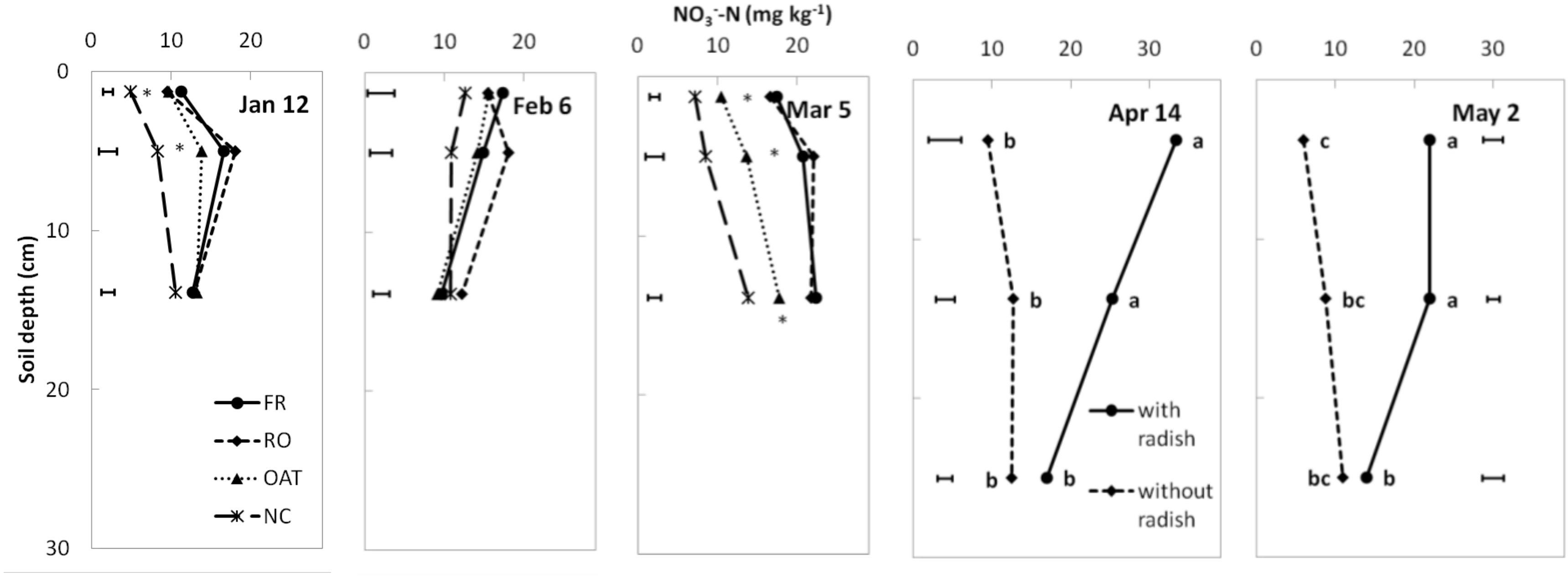

Figure 3.5 Soil NO$_3^-$ -N concentrations at Central Maryland Research and Education Center, Clarksville in 2012 after fall cover crop treatments (no-till only).

Depths sampled were 0-2.5, 2.5-7.5, and 7.5-20 cm on January 12, February 6 and March 5 and 0-7.5, 7.5-20 and 20-30 cm on April 14 and May 2.

Simple means presented on first three sample dates because of interactions. On April 14 and May 2, main effect of radish in the cover crop was significant.

Different means separated by an asterisk ($p<0.05$)

Letters represent different means, taking into account repeated measures for depth ($p<0.05$).

FR=forage radish RO=radish-oat OAT=oat NC=no cover

Soil ammonium

In general, neither cover crop nor tillage treatments affected ammonium-N concentrations, but a trend in all site years showed an initial decrease in ammonium-N concentrations in late winter and early spring followed by an increase in ammonium-N in early to mid-April (Figure 3.6). Similar to nitrate-N, ammonium-N was either concentrated in the upper 7.5 cm or there was no difference between the depths sampled. Consistent differences in ammonium-N with depth occurred at CMREC 2 (Figure 3.7). Surface soil temperatures are generally higher and cover crop residue was located on the surface, so these results are not surprising. Some evidence of an early flush of ammonium-N was obtained with a shallow surface sample (0-2.5 cm) immediately after cover crop winterkill at CMREC 2 when the ground below 2.5 cm was still frozen (Figure 3.8). This was the only sampling time when cover crop had a significant effect on ammonium-N concentrations and when ammonium-N was the dominant mineral form of N in the soil as measured by a 0.01M $CaCl_2$ extraction. Ammonium-N concentrations using 2M KCl were approximately 1.5 times greater than extracted by 0.01M $CaCl_2$ but results using the two extractants were highly correlated (R^2=0.98) for a limited subset that was analyzed (Appendix 2) and research has shown 0.01M $CaCl_2$ to be a reliable extractant for ammonium (Houba et al., 2000). A similar phenomenon of high ammonium-N concentrations immediately after winterkill was not observed at other site years, but samples were not taken so close to time of winterkill. However, soil nitrate-N data provide evidence that OAT at least partially winterkills and begins to decompose with less severe winter temperatures than radish. At WREC 2, where radish did not completely winterkill, OAT had higher soil nitrate-N concentrations in the surface soil (0-7.5 cm) than FR and RO when radish was still living (Table 3.9).

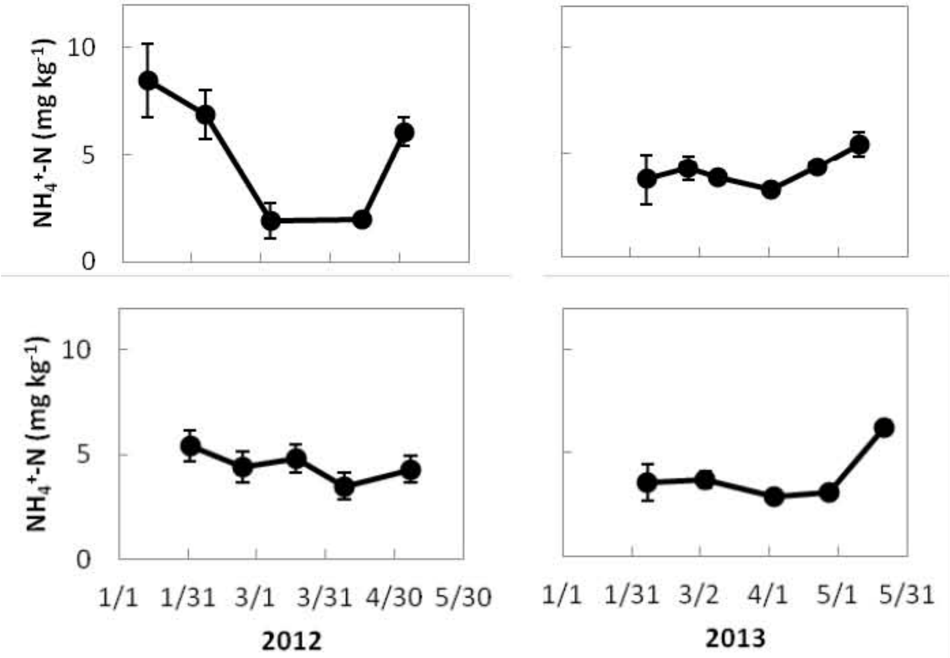

Figure 3.6 Soil NH_4^+-N (0-20 cm) for all cover crop and tillage treatments at Central Maryland Research and Education Center, Clarksville (top) and Wye Research and Education Center (bottom) in 2012 and 2013.

No treatment differences were observed. Bars are standard error of the mean.

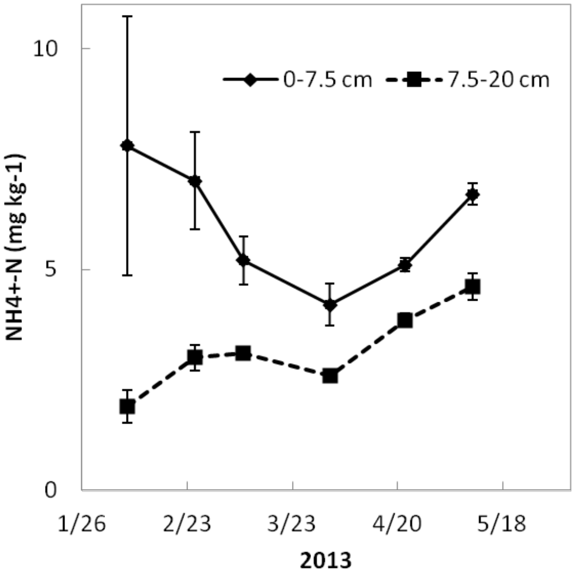

Figure 3.7 NH_4^+-N concentrations at Central Maryland Research and Education Center, Clarksville in 2013 for forage radish, radish-oat, and oat treatments (no-till only).

No cover is not included because of difficulty accurately dividing into depth as a result of fall tillage. Depth was the only : significant factor at all sampling dates. Depth was significant at all dates (*F*-protected LSD, $p<0.05$). Bars are standard error of the mean (n=12**).**

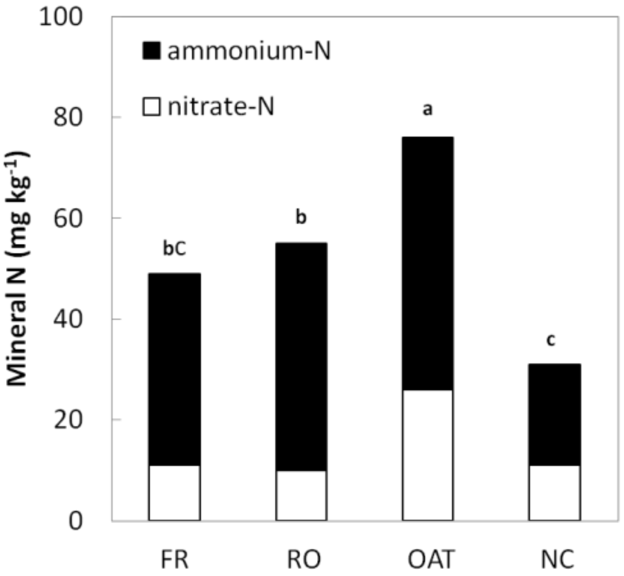

Figure 3.8 Mineral N in surface soil (0-2.5 cm) on January 28, 2013 at Central Maryland Research and Education Center, Clarksville soon after cover crop winterkill (n=4).

Letters represent treatment differences for total mineral N content (*F*-protected LSD, $p<0.05$). Average standard error of the mean for mineral N=5.6.

FR=forage radish RO=radish-oat OAT=oat NC=no cover crop

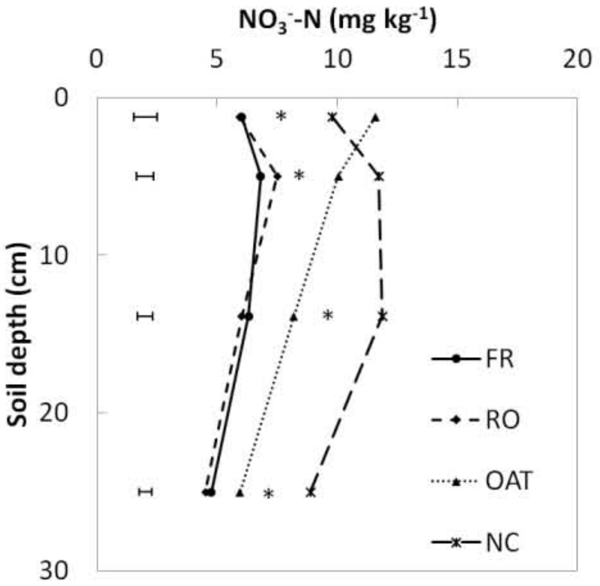

Figure 3.9 Soil NO_3^--N concentrations at Wye Research and Education Center on February 7, 2013.

* difference in treatment means (*F*-protected LSD, $p<0.05$) for each depth.

Bars are one SEM

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Soil sulfate

Sulfur capture by forage radish was predominantly a function of total biomass production; the S content of forage radish shoots did not vary much between site years, with a minimum of 7.8 g kg^{-1} and a maximum of 8.2 g kg $^{-1}$ (dry matter). Oat S content ranged from 1.8 g kg^{-1} to 3.1 g kg^{-1}; the maximum was in CMREC 2, the fall following a compost application (Table 3.10). Both sites had comparable Mehlich III-extractable S (Table 3.2) in the Ap horizon, considered “medium” for the mid-Atlantic region. It is not surprising, therefore, that the S content of cover crops was very similar all site years. Results cannot be extrapolated to a truly S-deficient soil. Previous reports of radish S content have been nearly identical to this study, under different conditions of a sandy soil in Denmark and a Histosol soil in Michigan (Eriksen and Thorup-Kristensen, 2002; Wang et al., 2008).

Table 3.10 Sulfur capture of fall cover crops at Central Maryland Research and Education Center, Clarksville (CMREC) and Wye Research and Education Center (WREC).

Response variable	Cover crop treatment	CMREC		WREC	
		1	2	1	2
Shoot S		--------------------------kg ha^{-1}--------------------------			
	Forage radish	31 a	43 a	26 a	26 ab
	Radish-oat	22 b	39 a	25 a	30 a
	Oat	8.5 c	17 b	12 a	18 b
	No cover-weeds	4.3 c	9.3 b		26 ab
Root S		--------------------------kg ha^{-1}--------------------------			
	Forage radish	9.3 a	18 a	19 a	24 a
	Radish-oat	4.8 a	17 a	10 a	18 a

Letters indicate significant differences between treatment means (n=4) within each site year, but not between site years (F-protected LSD p<0.05)

Radish increased soil sulfate-S concentrations immediately after winterkill or termination by mowing (Figure 3.10) in all site years. The increase in sulfate-S from radish was equivalent to 9-12 kg S ha^{-1} (0-20 cm) when measured in mid to late April at CMREC 1 and 2 and WREC 1. At WREC 2 on April 27, the radish effect was modulated by the presence of oat in the cover crop mix such that the FR had 16 kg ha^{-1} more sulfate-S than OAT and NC (p<0.0001) and 8.6 kg ha^{-1} more sulfate-S than RO (p=0.0008). Tillage had no effect on sulfate-S either year at CMREC or at WREC 2, but tillage decreased sulfate-S at WREC 2 by 5.6 kg ha^{-1} as measured on April 8 (p=0.03).

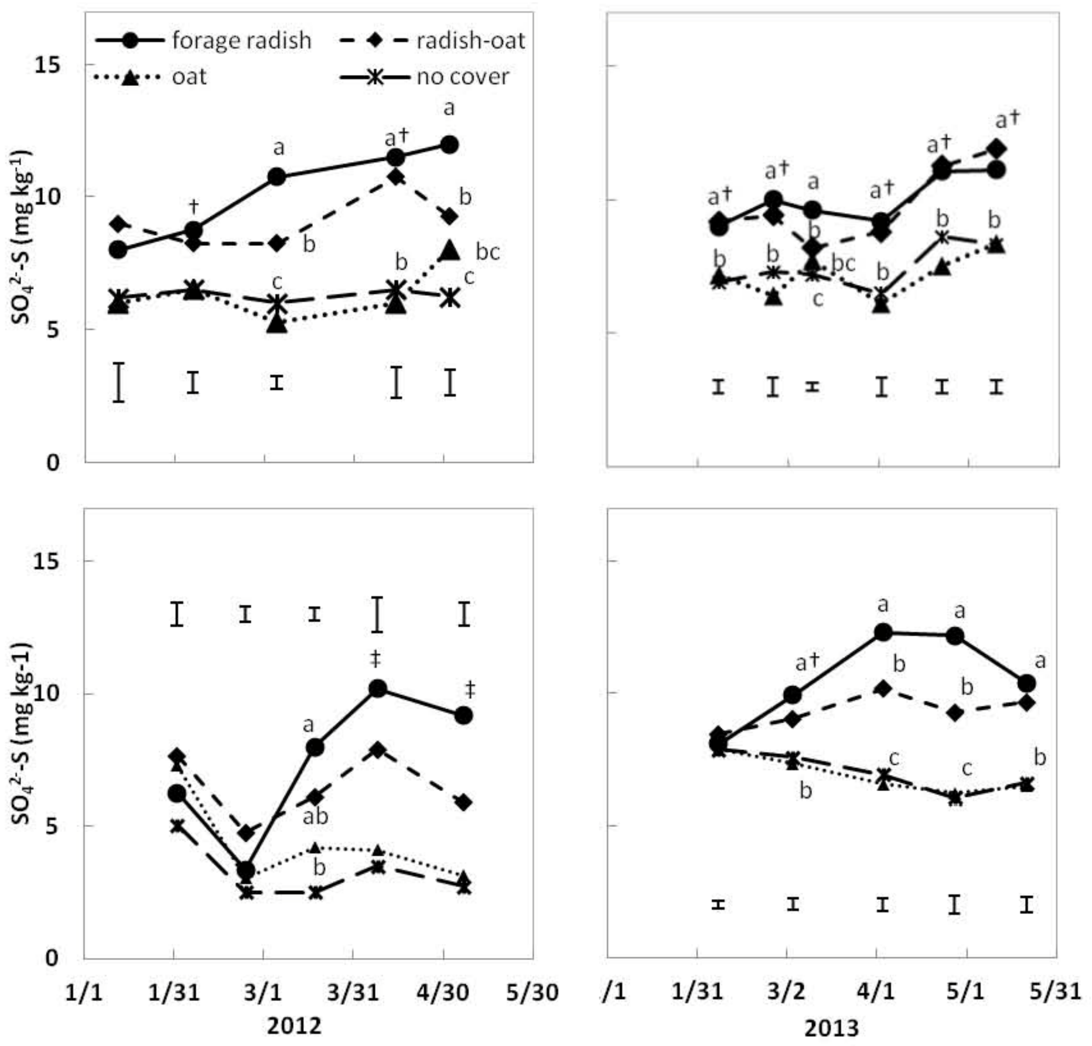


Figure 3.10 Soil SO_4^{2-}-S concentrations (0-20 cm) at Central Maryland Research and Education Center, Clarksville (top) and Wye Research and Education Center (bottom) 2012 and 2013 after four cover crop treatments in no-till plots.

Bars are average standard error of the mean (n=4).

†sample dates on which there were no significant interactions and radish main effect was significant

†letters are not given because forage radish was the only treatment that was weeded; NO3- in other treatments may have been affected by weed uptake.

S mineralization can be both biochemical and biological. In an incubation study using isotopic dilution, Eriksen (2005) concluded that initial S mineralization from cover crop residue is likely driven by biochemical hydrolysis of organic sulfates, not a microbial need for C. Brassicas contain high levels of glucosinolates, which are subject to such hydrolysis. If the primary mode of initial sulfate mineralization is biochemical, it would be expected that sulfate levels in soil would increase upon cover crop termination, regardless of temperature. The data support this hypothesis, with higher soil sulfate-S in FR and RO immediately after winterkill/mowing (Figure 3.10). Subsequent S mineralization may be microbial, accounting for continued increases in sulfate-S with time. Unlike soil nitrate-N, soil sulfate-S at WREC was higher in RO than OAT, but lower than FR, despite the fact that total S uptake was equal between FR and RO (Table 3.7). This can be explained by the radish S in RO undergoing hydrolysis while the oat S remained C-bound. Lower soil sulfate-S in RO than FR was also observed on two sample dates at CMREC 1, but the total S uptake in RO was less than FR that year. Legume cover crops can have high S content, but S mineralization from legume residue is slow (Eriksen et al., 2004). Our data show that including radish in a cover crop can increase surface soil sulfate in early spring through May, providing a tool for addressing sulfur deficiencies. Because of rapid and early N mineralization, using radish to address S deficiencies should only be considered where early spring N is also desirable.

Spinach uptake of N and S

Spinach yield results are discussed in full in Chapter 4. Differences in yield were likely influenced by large differences in emergence and resulting stand counts in addition to availability of nutrients at CMREC 1 and WREC 1 and 2. At CMREC 2, stand counts were comparable among treatments. Differences in stand counts make both percent N and S in spinach tissue and total uptake data potentially unreliable indicators of plant availability of N and S. Even with this confounding factor, there is strong evidence that radish and tillage increased N availability (Table 3.11) and radish increased S availability (Table 3.12) in spring. Literature data on spinach S content is sparse. In a pot experiment looking at N and S fertilization of spinach, the no S treatment had S content as low as 2 g kg^{-1}, which was yield-reducing. Sulfur fertilization, along with N fertilization, increased the S content to 5 g kg^{-1} and increased the cysteine and methionine content (Smatanová et al., 2004). Our spinach S content ranged from 3.2 to 4.7 g kg^{-1}(Table 3.12). Interactions between cover crop and tillage factors were present for all but the second harvest of spinach leaves at CMREC 2, when radish was the only significant factor for spinach S content. This was the only site year for which successive spinach harvests were made from the same plants and therefore we cannot extrapolate too far. However, the fact that the difference in spinach S content became more clear on the second harvest may mean that S did become limiting by the time of the second harvest in the treatments without radish.

Table 3.11 Spinach N content and total N uptake after cover crop and tillage treatments at Central Maryland Research and Education Center, Clarksville (CMREC) and Wye Research and Education Center (WREC) in 2012 (1) and 2013 (2). Whole plants were harvested and analyzed unless otherwise noted.

Harvest site	**Simple effects (all treatment means)**								**Main effects (no interactions)**			
	Forage radish		**Radish-oat**		**Oat**		**No cover crop**		**Radish**		**Spring tillage**	
	No-till (NT)	**Rototilled (RT)**	**NT**	**RT**	**NT**	**RT**	**NT**	**RT**	**With radish**	**Without Radish**	**NT**	**RT**
	----------N (% of spinach dry matter)----------											
CMREC 1[†]	4.5 abc	4.3 bcd	4.0 cd	4.9 a	4.2 cd	4.8 ab	3.7 d	4.4 abc			4.0 b	4.6 a
CMREC 2a[‡]	5.2 ab	5.3 a	5.1 ab	5.3 a	4.7 e	4.9 cd	4.8 d	5.2 ab				
CMREC 2b[§]	4.5 bc	4.8 a	4.4 bcd	4.7 ab	4.0 e	4.3 de	4.1 de	4.2 de	4.6 a	4.1 b	4.2 b	4.5 a
WREC 1[¶]	3.8 b	4.4 a	--[¶]	4.2 a	--[¶]	4.1 ab	--[¶]	--[¶]				
WREC 2	3.5 c	4.4 a	3.3 c	4.0 b	3.2 c	--[#]	--[#]	3.5 c				
	----------N (kg ha^{-1} uptake in harvested spinach shoots) ----------											
CMREC 1	71 a	86 a	19 bc	13 c	15 c	13 c	5.9 c	37 b				
CMREC 2a	23 a	18 b	18 ab	17 b	9.8 cd	10.4 c	5.7 d	16 b				
CMREC 2b ’	18 a	16 a	17 a	16 a	11 b	11 b	8.6 b	9.5 b	17 a	10 b		
WREC 1	22 ab	45 a	--[¶]	34 a	--[¶]	7.2 b	--[¶]	--[¶]				
WREC 2	10 b	19 a	6.6 bc	16 a	2.6 c	--[#]	--[#]	2.8 c				

Letters represent treatments with different means (F-protected LSD $p<0.05$) (n=4).

[†] Only tillage was significant main effect, though simple means are presented

[‡] First harvest of mature leaves.

[§] Second harvest of mature leaves

[¶] No cover crop failure from seed corn maggots. Radish-oat and oat no-till crop failure from weed competition.

[#] Oat rototilled not planted because of conditions too wet for tillage; NC NT crop failure.

Table 3.12 Spinach S content after cover crop and tillage treatments at Central Maryland Research and Education Center, Clarksville (CMREC) and Wye Research and Education Center (WREC) in 2012 (1) and 2013 (2). Whole plants were harvested and analyzed unless otherwise noted.

Harvest site	**Simple effects (all treatments means)**								**Main effect (no interactions)**	
	Forage radish		**Radish-oat**		**Oat**		**No cover**		**Radish**	
	No-till (NT)	**Rototilled (RT)**	**NT**	**RT**	**NT**	**RT**	**NT**	**RT**	**With radish**	**Without radish**
	-----------------------------S (g kg^{-1} of spinach dry matter) -----------------------------									
CMREC 1	4.4 ab	4.7 a	3.9 bcd	3.7 cd	4.4 ab	3.4 d	3.7 bcd	4.0 bc		
CMREC 2a[†]	4.2 ab	3.8 d	4.0 abc	3.9 cd	4.1 abc	4.0 bcd	4.0 bcd	4.3 a		
CMREC 2b[‡]	4.2 a	4.0 ab	4.1 ab	4.0 ab	3.9 ab	3.8 ab	3.7 b	3.7 b	4.1 a	3.8 b
WREC 1[§]	3.6 a	4.3 a	--	4.2 a	--	3.9 a	--	--		
WREC 2¶	4.1 b	4.5 a	3.8 bc	4.1 b	3.2 d	--	--	3.5 d		

Letters represent treatments with different means (F-protected LSD p<0.05) (n=4).

[†] First harvest of mature leaves

[‡] Second harvest of mature leaves

[§] NC crop failure from seed corn maggots. RO and OAT NT crop failure from weed competition

¶OAT RT not planted because of conditions too wet for tillage; NCNT crop failure.

The relatively even spinach stand densities at CMREC 2 (see Chapter 4), allowed for valid correlation analysis between concentrations of nitrate-N in the soil and in spinach tissue. Soil nitrate-N on April 22 was well correlated with spinach tissue nitrate-N for the two successive harvests (Figure 3.11). Total tissue N was also well correlated with tissue nitrate-N and $\log_{10}$ tissue nitrate-N for the first and second harvests, respectively (Figure 3. 12). These data suggest that nitrate uptake was a function of soil nitrate and that nitrate assimilation was proportional to the plants' needs, as would be expected (Steege et al., 1999).

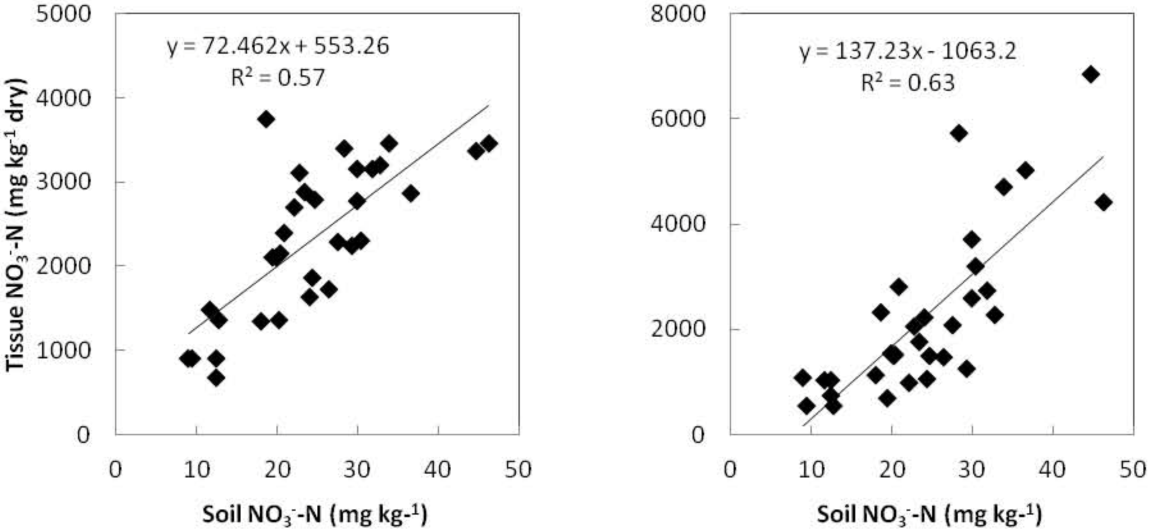


Figure 3.11 Soil NO_3^--N on April 22 (0-20 cm) correlation with spinach dry tissue NO_3^--N from May 10 (left) and May 20 (right) successive harvests at Central Maryland Research and Education Center, Clarksville in 2013.
(note different axes).

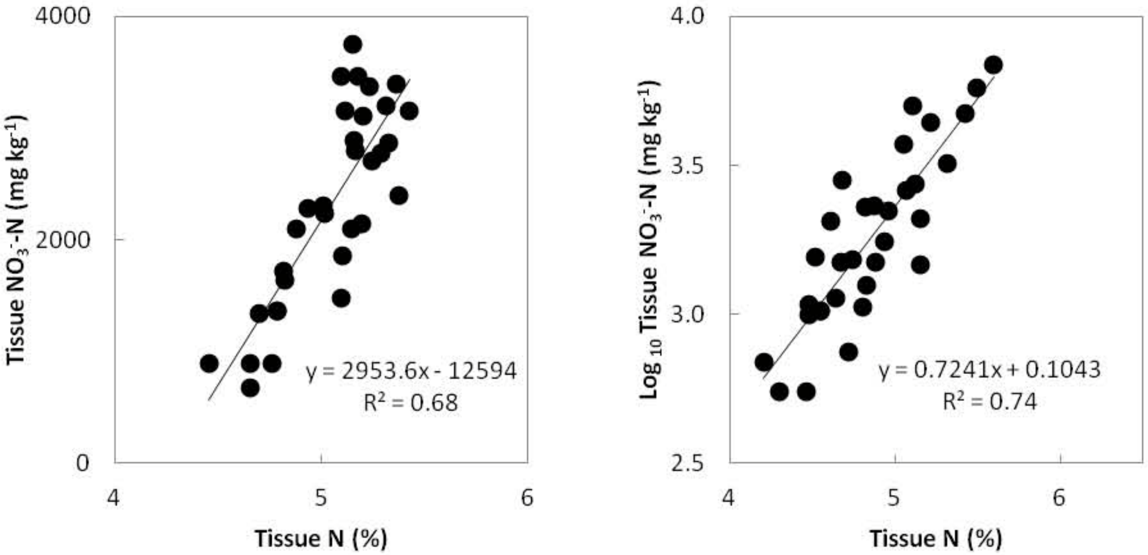


Figure 3. 12 Spinach tissue N correlation with tissue NO_3^--N on May 10 (left) and log10 tissue NO_3^--N on May 20 (right) at Central Maryland Research and Education Center, Clarksville, in 2013.
($P<0.0001$ for slope and intercept for both).

Spinach appears to be an ideal crop to take advantage of the early N mineralization from FR, but spinach is shallow-rooted and obtains 80% of its nutrients from the surface 15 cm of the soil (Schenk et al., 1991). To maximize nutrient use efficiency, it may be advantageous to plant a deep-rooted crop after a shallow-rooted crop (Thorup-Kristensen, 2006) to capture any residual N.

Conclusions

Forage radish biomass production and N capture is strongly influenced by growing conditions. In wet conditions, biomass production and N capture by OAT and even volunteer weeds may exceed that of radish, but under optimal growing conditions, FR can capture more than 200 kg N ha^{-1} in shoots alone. Despite lower total N capture by FR than OAT under wet fall conditions, FR consistently increased surface soil nitrate-N in spring (March-May). Radish mixed with oat yielded less predictable spring nutrient dynamics and under some conditions, the mixture of RO may reduce net N mineralization in spring compared to pure OAT. Further research investigating the interactions between Brassicas and other cover crop families should consider the influence of root/shoot partitioning and root composition on fall cover crop performance and spring nutrient cycling. To elucidate all pathways of cover crop contributions to soil nitrate, tissue and soil samples closer to the time of winterkill should be taken. The high nitrate content of cover crop tissue may have greater implications for colder climates when cover crops die earlier in their growth. In climates where winterkill of cover crops is not guaranteed, such as parts of the mid-Atlantic, radish may be a suitable cover crop for early spring crops even though it requires termination because mineralization begins rapidly and termination by both chemical and mechanical means is possible. In addition to rapid N mineralization in spring, radish increased surface soil sulfate levels immediately after winterkill and this increase persisted into May. Radish and other Brassica cover crops may be a tool to maximize S cycling efficiency.

Chapter 4 Forage radish cover crop can facilitate no-till spring vegetable planting without herbicides in the mid-Atlantic, USA

Abstract

Using cover crops and reduced tillage practices prior to early spring vegetables in the mid-Atlantic is difficult because traditional high residue cover crops can hinder spring field work and cash crop growth. A field study was conducted over four site years in Maryland's Piedmont and Coastal Plain regions to determine the feasibility of no-till (NT) planted early vegetables after winter cover crops. Seedbed conditions and vegetable crop performance were monitored after forage radish (*Raphanus Sativus* L.) (FR), a low-residue winterkilled cover crop, oat (*Avena Sativa* L.), the traditional winterkilled cover crop in the region, a combination of radish and oat (RO), and a no cover crop control (NC) before and after planting into no-till (NT) and rototilled (RT) soil. In three out of four site years, NT planting after FR was the highest or among the highest yielding treatments for spinach (*Spinacia oleracea* var. Tyee), with yields as high as 19 Mg ha^{-1} fresh weight. Provided adequate cover crop growth leads to sufficient weed suppression and soil physical conditions without tillage are suitable for crop growth, a FR cover crop can eliminate the need for tillage in spring prior to early vegetables.

Introduction

Cold, wet soils and weeds can be problematic for early spring vegetable production in cool, humid climates such as the mid-Atlantic, USA. Tillage is the most common practice to create a warm, dry, and weed-free seedbed, but tillage makes the soil susceptible to erosion and contributes to compaction when performed before adequate soil drying (Wolfe et al., 1995). Cover crops protect soil from erosion in winter and provide additional environmental benefits including nutrient capture. However, many traditional winter cover crops (e.g., winter rye (*Secale cereale* L.), hairy vetch (*Vicia villosa* L.), and oat exacerbate planting and crop establishment problems in spring because they are difficult to kill and/or incorporate. If not incorporated, they keep the soil cool and wet (Teasdale and Mohler, 1993). Some cover crops release allelochemicals, which can interfere with early crop establishment as well as weed seed germination (Creamer et al., 1996; Kruidhof et al., 2009). Additionally, cover crops with high C/N ratios can immobilize nutrients, reducing their availability for the subsequent cash crop. These disadvantages of cover crops serve as disincentives that have limited cover crop adoption by farmers generally (Snapp et al., 2005). Practices such as cover crops and reduced tillage systems to enhance soil quality must be convenient to implement and economically advantageous to achieve widespread adoption (Jackson et al., 2004; Mallory et al., 1998; Weil and Kremen, 2007). In order to facilitate, rather than hinder, early spring production, a cover crop that does not keep soil cool and wet and does not immobilize N in spring is necessary, and in order to eliminate tillage in spring, a warm enough, dry enough, and weed-free seedbed must be created via an alternate mechanism.

Special considerations for organic and small producers

A special issue in *Renewable Agriculture and Food Systems* (RAFS) devoted to “conservation tillage strategies in organic management systems” (Volume 27 Issue 1, Dec. 2012) (Carr et al., 2012) reveals persistent themes in the development of NT organic systems (primarily grains) including: (i) difficulty with weed management; (ii) inadequate N availability or poor synchronization with cash crop demand;

(iii) timing of cover crop termination; and (iv) planting equipment constraints. These themes highlight some of the important differences between NT, as it is commonly practiced (with herbicides and chemical fertilizers), and NT organic systems; whereas both weeds and insufficient nutrient availability can be controlled or supplemented by chemical means in conventional production, neither herbicides nor synthetic fertilizers are permitted in certified organic agriculture. The primary weed suppression mechanism in the organic systems discussed in the RAFS issue above and in all NT organic systems research-to-date of which we are aware is a high-residue cover crop mulch, generally from a mechanically terminated cover crop. For early spring vegetables, a warm and dry seedbed is necessary, precluding the use of such mulches. Without the use of herbicides, weed suppression must come from a different mechanism. To address crop nutrient needs, many organically approved fertilizers and amendments do not have immediately available nutrients, making cover crop decomposition and nutrient synchronization with cash crop demands all the more essential for effective cover crop-based systems in organic agriculture.

No-till vegetables

Like NT organic systems research, research-to-date on NT vegetables, both organic and conventional, has focused on the use of high-residue cover crop mulches. Because of the limitations already discussed for high-residue mulches in spring, the focus has been on later-season crops like pumpkins, tomatoes, beans and broccoli (Abdul-Baki and Teasdale, 1997; Herrero et al., 2001; Morse, 1999b). For these crops, NT direct seeding and transplanting into cover crop mulch has proven to be an effective technique to manage plant disease, crop quality, and environmental impacts. Mulch limits loss of soil moisture in droughty conditions and regulates the daily temperature fluctuations (Hoyt et al., 1994; Teasdale and Mohler, 1993), which can decrease need for irrigation but also delay maturity (Hoyt et al., 1994). In a highly successful example of NT vegetable production, 70% of conventional pumpkins grown in Maryland are produced using a NT-cover crop system, which reduces the need for fungicide applications (Everts, 2002a). NT cover crop mulch systems for tomatoes have been investigated with mixed results. One study in the mid-Atlantic found a NT hairy vetch mulch system to be more economically risky than a plastic mulch (Wu et al., 2002) but another study in the same region found a NT hairy vetch mulch system to be the least risky and most profitable (Kelly et al., 1995). These mixed results indicate the importance of perceived risk in farmers' decision making about which systems to use. The risk of NT may be greater for organic producers, for whom use of herbicides is not allowed. In cover crop mulch systems for NT tomatoes with and without herbicides in the mid-Atlantic, the no-herbicide treatments had lower yields in two out of three years (Teasdale and Abdul-Baki, 1998), demonstrating the potential yield loss from weed competition in NT systems without herbicides.

We were unable to find any peer-reviewed research on NT early spring vegetables after cover crops, but one unpublished research project described on-farm trials in Virginia evaluating "frost-killed" cover crops for early vegetable production (Schonbeck, 2006). This author reported higher yields of spinach after a radish cover crop compared to a grain-legume mix cover crop, and higher pea emergence and yield after NT planting.

Forage radish

Radish grown for centuries throughout Asia as a vegetable, such as daikon (meaning “big root” in Japanese), is similar to those that have been adopted for use as cover crops. Fukuoka, who pioneered the concept of NT farming without chemicals for many crops, including vegetables, noted that daikon can successfully compete with winter and early spring weeds. As the daikon grows, it “penetrate(s) deeply into the soil, adding organic matter and opening channels for air and water circulation” (Fukuoka, 1978). Researchers in Brazil in the 1970s trialed 50 cover crop types and selected radish as one of the eight most promising cover crops for its beneficial effects on soil and subsequent crop production (Kemper and Derpsch, 1981). Both the weed-suppressing and root-penetrating aspects of FR have been further investigated by recent research, confirming Fukuoka’s observations with data. The unusual weed suppression by forage radish was observed in New York in the 1990s (Stivers-Young, 1998) and the mechanism thought to be light interception (Kruidhof et al., 2008). Further research in Maryland showed that fast canopy closure (four to six weeks after planting in late August) and light exclusion prevents initiation of annual weed seed germination in late fall and therefore eliminates early spring weeds (Lawley, 2010; Lawley et al., 2012). Research in Maryland showed that radish roots can penetrate compacted soil layers (Chen and Weil, 2010) and subsequent crops can then take advantage of root channels created by a radish cover crop (Williams et al., 2004). Weed suppression and physical effects on soil by radish comprise two of the characteristics that suggest its potential use as a cover crop before NT vegetables.

The third characteristic of radish that indicates its potential utility for early vegetables is high N content and possible early mineralization. Research in Europe and the mid-Atlantic has found that radish captures N from deep within the soil profile. In Denmark, where “fodder” radish has been studied extensively for use as a catch crop to reduce environmental contamination from agricultural nutrients, researchers found that radish roots reached over 2.4 m deep, reducing NO_3^- concentrations at that depth and capturing more N (157 kg N ha^{-1}) than both rye and Italian ryegrass (Kristensen and Thorup- Kristensen, 2004). In Maryland, USA, radish reduced NO_3^- concentrations down to 1.8 m depth and captured over 200 kg N ha^{-1} in some site years (Dean and Weil, 2009). Studying N dynamics in spring is notoriously more difficult than studying N uptake in fall because transformations are microbially-mediated, can be rapid, and the interactions between cover crop, soil, and climate are complex (Thorup-Kristensen et al., 2003). Spring N availability following cover crops is more important for vegetable performance than fall N uptake. Ideally, N mineralization from a cover crop will be synchronized with cash crop N demand (Dabney et al., 2001; Dabney et al., 2010; Thorup-Kristensen et al., 2003). N dynamics following radish are poorly understotod, but some results point to rapid and early mineralization in spring (Dean and Weil, 2009; Kremen, 2006; Magid et al., 2001). For legume cash crops like pea, N availability in early spring may not be as essential, but for other crops such as spinach N fertilizer recommendations are in the order of 150 kg ha^{-1}, though even efficient plants may use only two-thirds of the added N (Schenk et al., 1991).

We hypothesized that a fall-planted radish cover crop could replace spring tillage before early vegetables by providing a warm, dry, and weed-free seedbed with adequate N supply. Our objectives were to evaluate spring vegetable crop performance after NT and RT planting following (i) forage radish (FR), (ii) oat (OAT), (iii) a combination of the two (RO), and (iv) a no cover crop control (NC). We monitored relevant soil conditions including mineral N content, moisture, and temperature to help provide a mechanistic understanding of the crop performance in these systems and the potential implications for farmers.

Materials and Methods

Two experiments were conducted at two field sites in the Maryland Coastal Plain and Piedmont regions in 2011-12 (year 1) and 2012-13 (year 2): Central Maryland Research and Education Center-Clarksville (CMREC) and WREC Research and Education Center (WREC). Both sites had been under organic management for over three years and were maintained according to USDA organic rules (CFR, 2013) for the duration of the experiments.

Experiment 1

Experiment 1 investigated cover crop and tillage effects on soil characteristics and spinach production. The treatment structure was a 2x2x2 factorial with factors: radish (present or absent), oat (present or absent) and spring tillage (NT or RT). The experimental design was a randomized complete block split-plot design with four blocks per site. The four cover crop main plot treatments were: forage radish (FR), oat (OAT), radish-oat (RO), and no cover crop (NC). These main plots were split in spring into NT and RT subplots.

To avoid residual effects, a new field was used at each of the two sites in the second site year, adjacent to the field used in the first site year. Site and soil characteristics are presented in Table 4.1 and Table 4.2. The WREC 1 field was in its second year of alfalfa prior to disking in July 2011. The WREC 2 field received 2.3 Mg ha^{-1} poultry litter (3-0.9-2.5 NPK) and 2.2 Mg ha^{-1} calcitic lime in July 2012. The CMREC 1 field had a sequence of rye and buckwheat cover crops prior to tillage in July 2011 and had a history of high compost applications. The CMREC 2 field, which did not have a history of high compost applications, received 12 Mg ha^{-1} (wet) finished dairy manure compost in July 2012

Table 4.1 Site characteristics for field experiments at Central Maryland Research and Education Center, Clarksville (CMREC) and Wye Research and Education Center (WREC)..

	CMREC	**WREC**
Location	39˚ 15’ 12” N 76˚ 55’ 49” W	38˚ 55’ 10” N 76˚ 08’ 19” W
Physiography	Piedmont	Coastal Plain
Soil Series	Glenelg	Mattapax
Taxonomy	Fine-loamy, mixed, semiactive, mesic Typic Hapludult	Fine-silty, mixed, active, mesic Aquic Hapludult
Surface texture	SiL	SiL

. All fields were disked prior to initiating the experiments. Cover crops were planted using a no-till drill with 19 cm row spacing at rates of 10 kg ha^{-1} (FR) 72 kg ha^{-1} (OAT). The RO treatment had alternating rows of radish and oat and the seeding rate was half of the full rate for each. Main plots were 3 m wide by 23 m long. For spring tillage a 1.5 m wide power take off rototiller was used for a single pass down the middle of the RT subplots, resulting in sub-plots in spring that were 1.5 m wide by 11 m long. Approximate depth of tillage was 10 cm..Important field activity dates are presented in Table 4.3

Table 4.2 Soil test results for field experiment sites at Central Maryland Research and Education Center, Clarksville (CMREC) and Wye Research and Education Center (WREC) in Maryland, USA.

	CMREC		WREC	
Year	2011-12	2012-13[1]	2011-12	2012-13[2]
pH_{water}	7.0	5.7	5.9	5.4
Organic C (%)	2.8	1.5	1.4	0.82
	--------Mehlich III extractable nutrients (mg kg^{-1})--------			
P	200	115	92	74
K	445	367	81	66
S	12	20	20	19
Mg	216	143	174	111
Ca	2409	1047	786	722
B	1.5	0.66	0.55	0.63

[1] Samples taken after compost application

[2] Samples taken after poultry litter and calcitic lime application

Spinach was planted in spring using a three-row no-till planter (Monosem Inc, Edwardsville, KS) with 38 cm row spacing at WREC1 and 2 and CMREC 2. CMREC1 was planted by hand with four rows and 30 cm row spacing. Depth of planting was approximately 1.5 cm. At WREC 1, NC RT was a complete crop failure because of seed corn maggots, so no spinach data were collected. The same year, NC NT, RO NT and OAT NT were not harvested because weed competition led to a complete crop failure. At WREC 2, OAT RT was not planted because the soil was too wet to till, so no spinach or soil data were collected

Experiment 2

A separate experiment to investigate response of vegetable types to NT planting and cover crop was planted in a randomized complete block split plot design. The cover crop/tillage treatments (main plots) were: FR NT, FR RT, and NC RT. The plots were split with vegetable type as the subplot. The vegetables were: spinach, lettuce (*Lactuca sativa* var. Coastal Star), pea (*Pisum sativum* var. Sugar Snap), and kohlrabi (*Brassica oleracea* var. Kolibri). Pelleted lettuce seed was used. At CMREC

1, only two vegetable types were planted (spinach and lettuce). These vegetables were planted in the same manner as described for spinach in Experiment 1, although the depth for pea planting was adjusted to 2.5 cm. No cover crop biomass or soil data was collected from Experiment 2.

Cover crop biomass

Cover crops were harvested in Experiment 1 from two ¼ m^2 quadrats from each plot in late fall prior to expected winterkill, resulting in two subsamples per plot. The NC treatment was rototilled in fall to reduce weeds in spring and to simulate the common farmer practice of "winter fallow." Weed biomass was harvested prior to fall tillage (Table 3). For the OAT and NC plots, above-ground shoots were harvested. For the plots containing radish (FR and RO), the whole radish plant (shoot and fleshy root) was pulled from the ground, the root and shoot separated, and the root was washed in the field to remove soil. Typically, approximately a quarter to a third of the fleshy root mass of the radish plant occurred aboveground. Data are presented as shoot biomass and root biomass. Subsamples of cover crops were dried in a forced-draft oven at 50-60˚ C until mass was constant. Each subsample was weighed and ground to < 2mm with a Wiley mill. Equal parts of the two subsamples from each plot were further ground using a coffee grinder to <1mm. These samples were analyzed for C, H and N (LECO CHN-2000 analyzer, LECO Corporation; St. Joseph, Michigan).

At WREC 1, none of the cover crops winterkilled, and they were mowed with single pass of a flail mower, which successfully killed the radish but resulted in approximately 10% grow back of the oat. At WREC 2, approximately 15% of the radish in the FR and RO cover crops and approximately 5% of the oat in the RO and OAT at WREC did not winterkill, and all plots were flail mowed.

Soil sampling and analysis

In Experiment 1 only, soil samples consisted of five 0-20 cm cores from each plot that were taken using a 2 cm diameter soil probe. Cores were taken from random locations in the central 5 m of each plot, except that in plots with radish, the actual radish holes were avoided because they change the surface level and therefore depth of the soil. Soil samples were kept cool for transportation to the lab and then dried for 1-2 weeks in a forced draft oven at 50-60˚ C. They were then sieved to < 2 mm and gravel weight was recorded. Bulk density was calculated using the dry mass of the soil and volume of the five soil cores; a gravel correction was made when gravel was present assuming a particle density of 2.65 g cm^{-3}. Porosity was calculated using bulk density and the same particle density. (Analysis of subsamples from each site revealed that water content of the air-dried soil was <1% for both sites). A single extraction was performed with 5.0 g soil and 25 mL 0.01 M $CaCl_2$, shaken at 120 rpm on a rotary shaker for 30 minutes. Samples were centrifuged for 15 minutes at 27,000 *g*. Nitrate-N content was determined with ion chromatography (Metrohm) and NH_4^+-N was determined with a modified indophenol blue microplate technique (Sims et al., 1995). Soil nutrient concentrations are presented as a fraction of the air-dried mass

Emergence and yield data

For both experiments, initial emergence data for spinach, lettuce, peas, and kohlrabi was measured by counting three 0.5 m sections of the middle row. For plots with harvestable crops, a stand count at harvest maturity was also done. For Experiment 1, spinach harvest for yield data at CMREC 1 and WREC 1 and 2 consisted of a single harvest of whole plants. At CMREC 2, two successive harvests of mature spinach leaves for all blocks were made and a third harvest of mature leaves was done for a single block (work was interrupted by a severe lightning storm, and the spinach quickly bolted in the following days). At WREC 1 and 2, 6 m of the middle row was harvested for yield data. At CMREC 1 and 2, 4 m of the middle row was harvested.

For Experiment 2, lettuce yield was measured by harvesting whole heads from 4 m of the middle row (CMREC 1 and 2, WREC 1). Qualitative observations were made of other vegetables. Dried spinach tissue was analyzed for C and N on a LECO CHN-2000 analyzer (LECO Corporation; St. Joseph, Michigan).

Weed ground cover was estimated using a visual estimation method from the end of the plot.

Table 4.3 Field activity dates at Central Maryland Research and Education Center, Clarksville (CMREC), and Wye Research and Education Center (WREC) in Maryland, USA.

	CMREC		WREC	
Field activity	**2011-12**	**2012-13**	**2011-12**	**2012-13**
Cover crop planting	August 24	August 24	August 22	August 23
Cover crop biomass sampling[1]	October 28	November 11 & 14	November 19	November 28
Fall rototilling (NC only)	October 25	November 19	October 24	October 26
Winterkill/mowing	~January 10 (winterkill)	~ January 25 (winterkill)	February 28 (mowing)	March 4 (mowing)
Spring rototilling	March 12	March 11	March 12	April 3
Spring vegetable planting	March 13 &14	March 11	March 20	April 4
Weeding[2]	April 14	April 22	April 7[3]	April 21
Spinach harvest(s)	May 22	May 10, 20, &23 (1 block)[4]	May 18	May 17
Lettuce harvest	May 23	May 30	May 25	--

[1] CMREC 1 and WREC 2 weeds were sampled from NC plots prior to fall tillage. NC biomass was not sampled at WREC 2.

[2] Weeding with a hand-held hoe.

[3] In forage radish no-till and all rototilled treatments. Weeding in radish-oat no-till, oat no-till and no cover no-till not performed.

[4] A lightning storm prohibited harvesting from other three blocks.

Soil moisture and temperature monitoring

Decagon 5TE and GS3 combined capacitance and thermistor sensors (Decagon Devices, Pullman, WA) were installed in the middle 5 m of the cover crop plots to monitor volumetric water content and temperature at 5 cm below the soil surface in late fall, prior to cover crop winterkill. A shallow hole was dug at a location chosen randomly by tossing a trowel. If the hole clearly contained a solid radish root, the sensor was inserted so as to avoid the root itself. The sensors were installed into undisturbed soil on the side of the dug hole. The 5TE sensors were installed with the sensors oriented horizontally, but the prongs oriented vertically. The GS3 sensors were installed with the needles horizontal. In a given block, only one model of sensor was installed. Average temperature and water content were logged hourly using EM50 dataloggers (Decagon Devices, Pullman, WA). To calculate growing degree hours (base 8°C), the sum of hourly temperatures was calculated. If the hourly temperature was <8°C, it counted as 0. If the hourly temperature >8°C, it counted as (temp-8°C).

Plastic limit

The lower plastic limit was determined using four replicates of field moist soil taken in January that was wetted evenly and repeatedly rolled into a 3.2 mm threat until the soil no longer held together. The gravimetric water content was determined at this point (McBride, 2002).

Statistical analysis

Data were analyzed using a mixed model in SAS 9.2 (SAS Institute, Cary, NC) with block as a random factor. Data collected after the spring treatments (tillage or vegetable species), including emergence, yield, and soil data, were analyzed as a split plot with spring tillage as the subplot factor. If a multi-way factorial ANOVA showed significant interactions (F test=0.05 or less), only simple effects were compared. Interaction terms were removed from the model if the F test for interactive effects >0.4. Treatment means were compared using an F-protected LSD ($p<0.05$). Repeated measures were used to compare harvest 1 vs. harvest 2 in the case of CMREC 2. The program Pdmix800 was used to assign letters for treatment means (Saxton, 2003). Correlation analyses were made using SAS PROC REG.

Results and Discussion

Experiment 1 cover crops

Cover crop performance and compostion varied across site years. Detailed results are given in Chapter 3 and summarized here to provide context for the spring vegetable and soil data. In both site years at CMREC, shoot biomass production and shoot N uptake was equal among FR, RO and OAT (NC was less both years). The maximum shoot biomass production was 7.4 M ha^{-1} (OAT) at CMREC 2 and the maximum shoot N content was 246 kg N ha^{-1} (RO) at CMREC 2. In both site years at WREC, FR had lower shoot biomass production than RO and at WREC 2, the FR shoot biomass (3.2 Mg ha $^{-}$1) was less than OAT and equivalent to NC (weeds). The shoot N uptake was generally lower at WREC than at CMREC, with a minimum of 75 kg N ha $^{-1}$ (FR) in at WREC 2 and a maximum of 131 kg N ha^{-1} (RO) in fall 2011. The poorer FR performance at WREC appeared to be related to restricted soil drainage at that site. Precipitation between cover crop planting and Dec. 31 was 77 and 68 cm at WREC 1 and WREC 2 respectively, whereas the previous 10 year mean for that period was 43 cm. Quantitative measurements of fall ground cover during cover crop growth were not made, but it was observed that by the first week of October of each year at CMREC, there was no visible bare ground in the FR treatment, whereas at WREC both years, patches of bare ground were visible in all cover crop treatments.

Soil temperature and moisture

Soil moisture limited field work at WREC 2, delaying spinach planting beyond the point the air temperature began to increase, and the OAT RT treatment was never planted because the soil was deemed too wet to till. This judgment was validated by determination of the gravimetric water content of soil samples at that time, which showed the water content in OAT (and RO, which was tilled and planted) to be above 90% of the plastic limit (Figure 4.1 Soil gravimetric water content (0-20) cm on April 3, 2013 prior to spring tillage and planting with respect to range of plastic limit appropriate for tillage at). It has been suggested that for most soils, 70-90% of the plastic limit is the water content at which tillage will not cause major structural damage to soil and will create a suitable seedbed for planting (Dexter and Bird, 2001). The 10 year weather data for WREC showed that WREC 1 spring precipitation was below average, whereas WREC 2 was average both in timing and quantity of precipitation (Figure 4.2). This suggests that wet and potentially field-work limiting conditions are probable this time of year for comparable soils.

Forage radish creates a drier seedbed in spring than OAT, potentially allowing earlier field work operations. Data from continuous monitoring of volumetric water content at 5 cm support the conclusion that FR allows for more rapid soil drying after rainfall than OAT (Figure 4.3). However, the high water content of NC as measured by the sensors is in disagreement with the soil samples that show NC and FR had equivalent water content. The cover crop treatment plots had comparable bulk densities so the conversion between volumetric and gravimetric water content should not have altered the results. The sensors were measuring volumetric water content at 5 cm depth, whereas the soil samples were 0-20 cm, and this may account for the discrepancy.

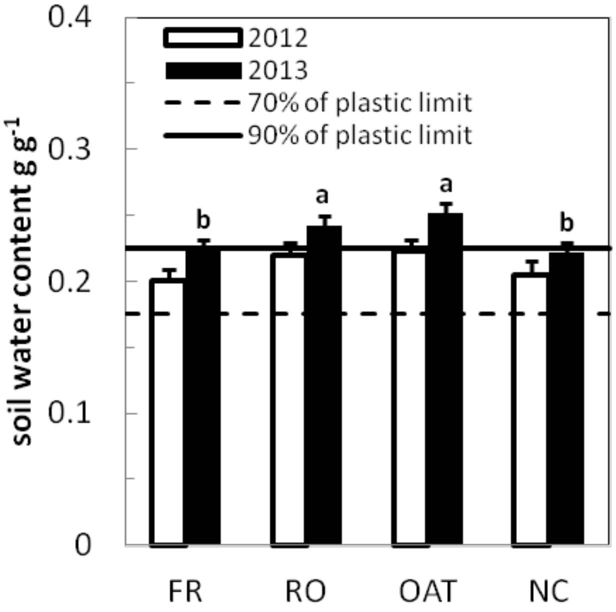


Figure 4.1 Soil gravimetric water content (0-20) cm on April 3, 2013 prior to spring tillage and planting with respect to range of plastic limit appropriate for tillage at Wye Research and Education Center in 2012 and 2013.

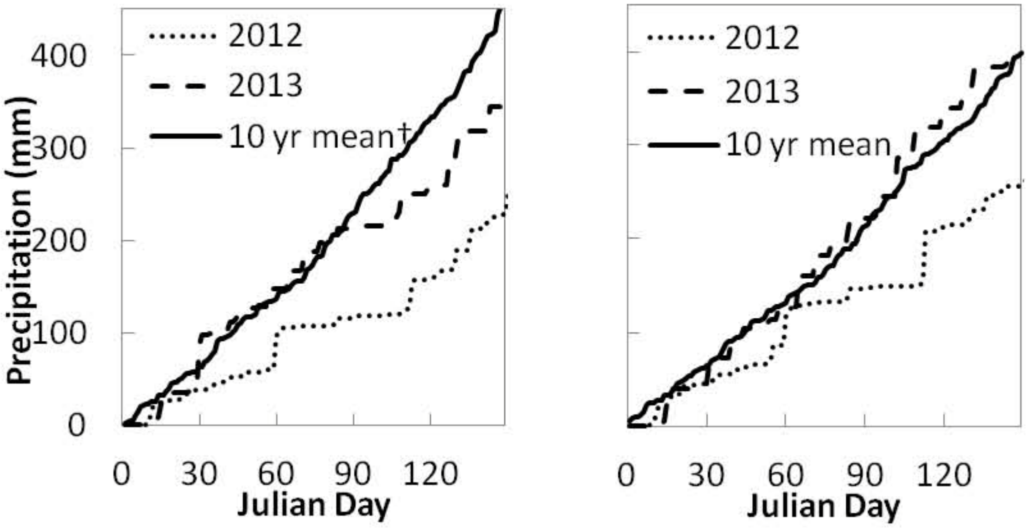


Figure 4.2 Spring precipitation at four site years in Maryland, USA. Central Maryland Research and Education Center, Clarksville (CMREC) (left), and Wye Research and Educatin Center (right).

† Historic weather data unavailable for CMREC. Data from weather station 23 km SE of CMREC.

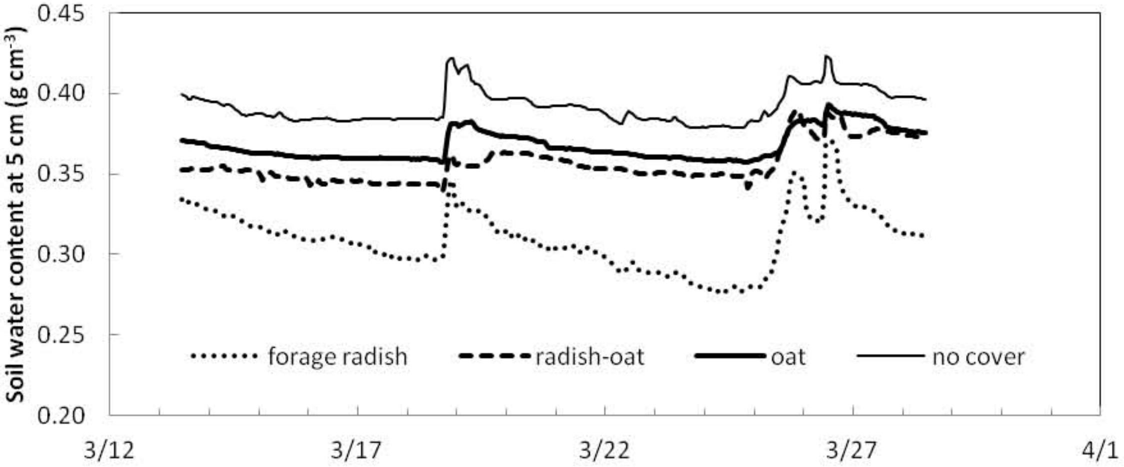


Figure 4.3 Average (n=3) volumetric water content at 5 cm depth after cover crop treatments and before spring planting at Wye Research and Education Center, 2013.

Dryer conditions and more rapid soil drying after FR than OAT was also evident at CMREC, though field work was not hindered in either spring season by soil wetness (Figure 4.4). Whereas the RO treatment at WREC more closely paralleled the water content of OAT, at CMREC, FR and RO were more closely aligned. The lower volumetric water content in the NC plots is a function of lower bulk density in these plots because of fall tillage, and, therefore, cannot be extrapolated to mean the gravimetric water content was actually lower. We speculate that in the treatments with radish, surface water tends to flow down the radish holes instead of being lost as runoff.

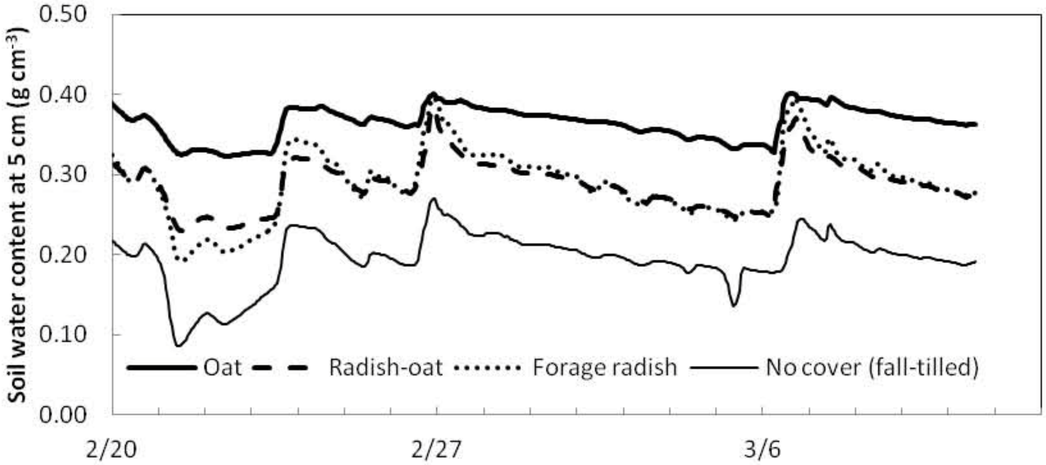


Figure 4.4 Average (n=5) volumetric water content at 5 cm depth after cover crop treatments and before spring planting at Central Maryland Research and Education Center, Clarksville, 2013.

As has been noted and discussed by other authors, mulch moderates the amplitude of daily soil temperature changes in addition to maintaining higher soil moisture (Moody et al., 1963; Teasdale and Mohler, 1993; Wierenga et al., 1982). This phenomenon was evident in daily temperature fluctuations at both WREC (Figure 4.5) and CMREC (6a) during early spring. The higher daily temperatures amounted to 20% more cumulative growing degree hours (base 8°C) in FR, RO and NC NT than OAT NT by April 22. The NC RT soil accumulated 16% more growing degree hours than FR, RO and NC NT, showing that tillage does create a warmer seedbed (Figure 4.7). Generally, the concept of growing degree days is applied to air temperature and not soil temperature, but soil temperature can be dramatically different from air temperature and may exert a stronger influence on plant growth, especially for germination, emergence and early growth stages (Ritchie and Nesmith, 1991; Wierenga et al., 1982). Soil temperatures generally exhibit wider fluctuation closer to the surface (Wierenga et al., 1982). The depth of our sensors, 5 cm, was deeper than seed placement. The temperature at seed depth may have had greater fluctuations than at 5 cm, but likely followed the same pattern of higher maximum daily temperatures with less residue. These data highlight the importance of management practices, including cover crops and tillage, on soil temperature and show that FR does not act in the way high-residue cover crops do to keep soil cool.

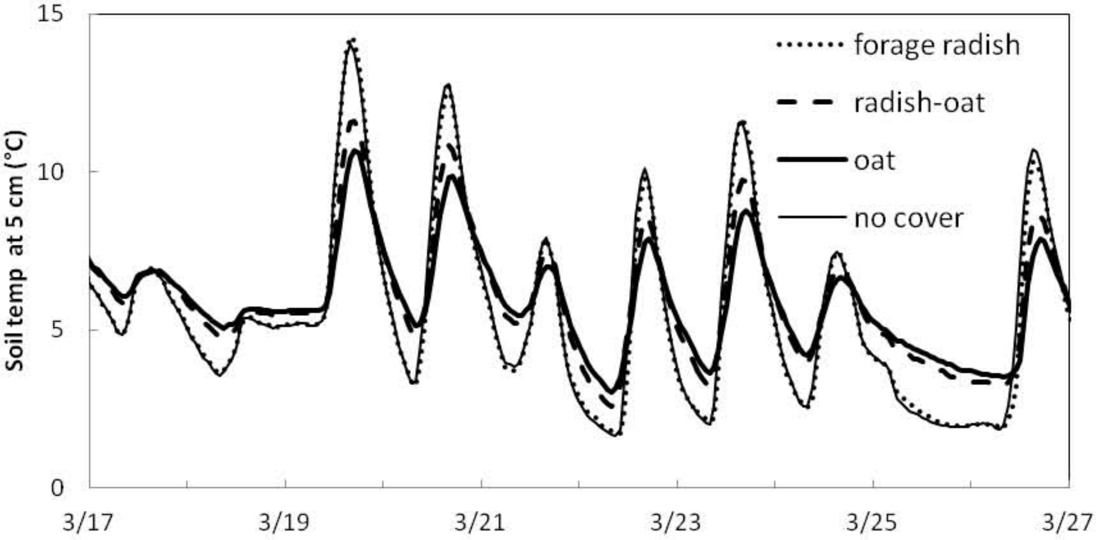


Figure 4.5 Average (n=3) soil temperature after cover crop treatments (no-till) at Wye Research and Education Center during a ten day period in March.

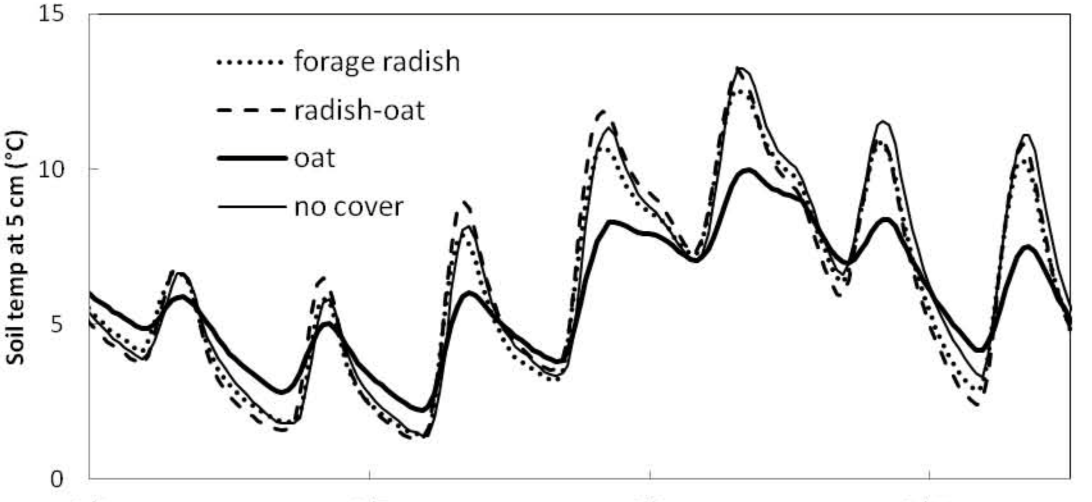


Figure 4.6 Average (n=5) soil temperature after cover crop treatments (no-till) at Central Maryland Research and Education Center, Clarksville, during early March planting window for vegetables in 2013.

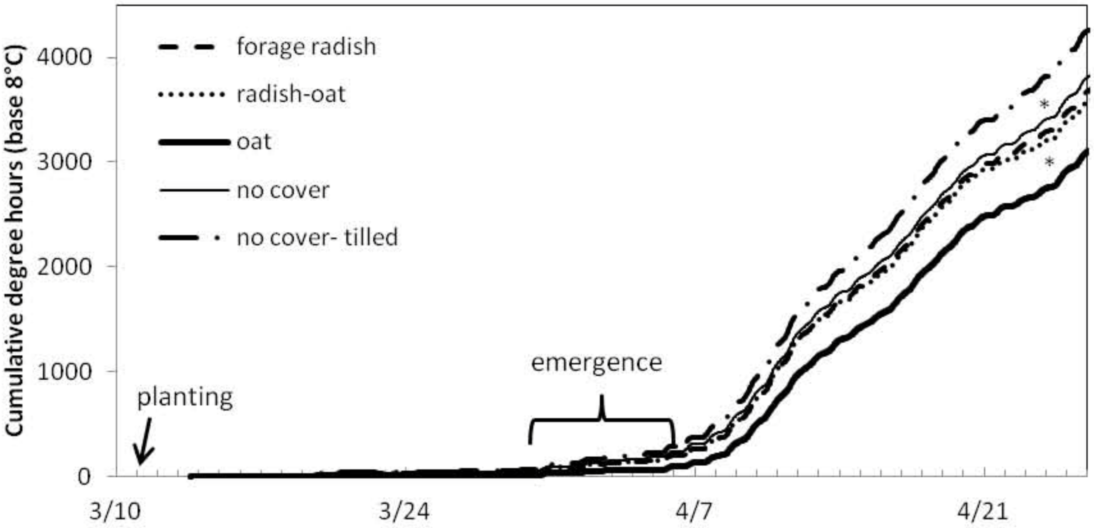


Figure 4.7 Average (n=3) cumulative degree hours in soil (5 cm depth) after planting into cover crop treatments (all no-till except no cover tilled) at Central Maryland Research and Education Center, Clarksville in 2013 .
Astericks between lines represent significantly different means as of April 22 (*F*-protected LSD, $p<0.05$)**).**

Spinach response to cover crops and NT planting

Fresh spinach yields ranged from outright crop failure to 24 Mg ha^{-1} fresh weight (Table 4.4). In New Jersey, the three year average yield of fresh market conventional spinach from 2008-2010 was 15 Mg ha^{-1}(NASS, 2012b) and in North Carolina, successful conventional spinach crops are projected to yield 6.3-13 Mg ha^{-1}(Sanders, 2001). The highest yielding treatments for each site year were within or above these values except WREC 2. In three out of four site years, the FRNT was, or was among, the highest yielding treatments. WREC 2 was the exception as tillage had a pronounced positive effect on yield and FRRT and RORT were the highest yielding treatments.

Table 4.4 Fresh spinach yields as influenced by cover crop and tillage treatments at Central Maryland Research and Education Center, Clarksville (CMREC) and Wye Research and Education Center (WREC) in Maryland, USA.

		CMREC		WREC	
Cover crop[1]	**Spring tillage treatment**	**1(2012)**	**2(2013)[2]**	**1(2012)[3]**	**2(2013)**
		---------------------------*Mg ha^{-1}*--------------------------			
Forage radish (FR)	No-till (NT)	19 ab	12 a	6.0 ab	2.8 b
FR	Rototill (RT)	24 a	9.9 b	10 a	4.7 a
Radish-oat (RO)	NT	5.3 b	10 b	— [4]	1.7 bc
RO	RT	3.7 b	9.1 b	8.2 ab	4.4 a
OAT	NT	4.7 b	6.2 c	—[4]	0.8 (c
OAT	RT	3.3 b	6.4 c	1.6 b	—[6]
No cover (NC)	NT	1.8 b	4.2 d	—[4]	—[4]
NC	RT	10 ab	7.3 c	—[5]	0.8 c

Treatment means are presented (n=4). Letters signify significant differences in treatment means (F-protected LSD $p<0.05$). No fertilizer was applied in spring**.**

[1] Cover crops were planted in August of the year prior to spring spinach planting.

[2] Two successive harvests of mature leaves; all other site years whole plants were harvested once. The third harvest is not accounted for in these data because it was only one block.

[3] n=3 because a block was inadvertently harvested prior to data collection.

[4] Crop failure because of weeds; no rescue weeding applied. No results were significant WREC 2012.

[5] Crop failure because of seed corn maggots—no seeds survived.

[6] Only one block planted because soil was too wet for tillage; yield data not included.

CMREC 2 was the only site for which successive harvests were made to investigate possible delayed maturity in some of the treatments. The yield data in Table 4 are presented as the total of two harvests, but data from the individual harvests show that while there was no difference in yield between the first and second harvests in the FR, RO, and OAT plots, the NC RT treatment had a lower second harvest than first, and the NC NT treatment had increased yield for the second harvest compared to the first ($p<0.05$) (Figure 4.8).

Because of a lightning storm, only one block of a third harvest was completed, and while it cannot be statistically verified, there appears to be a continuation of the trend that the NC RT yields drop with each successive harvest. This has implications for spinach that is grown for multiple pickings. Whereas sidedressing fertilizer may be necessary for a tilled planting without a cover crop, this need may be reduced or eliminated where cover crops are grown. Although the fertilizer replacement value of cover crops cannot be determined because there was no fertilizer treatment in this experiment, these data show that with a high biomass, high N cover crop/cover crop mix that includes radish, competitive spinach yields can be achieved without spring fertilizer.

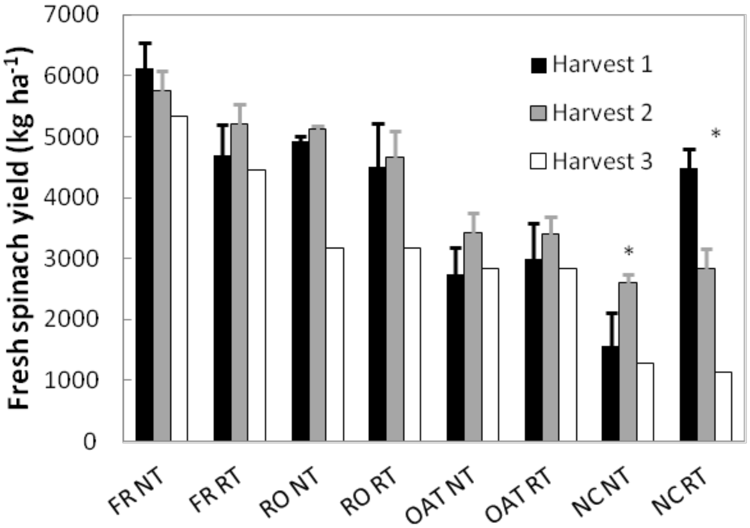


Figure 4.8 Fresh weights for three successive harvests of spinach leaves at Central Maryland Research and Education Center, Clarksville. Error bars are standard error of the mean (n=4 except Harvest 3 n=1).
*Significant difference between first and second harvests ($p<0.05$)
FR= forage radish RO=Radish-oat OAT=oat NC=no cover
NT= no-till RT=rototilled

A large portion of the yield response at WREC 1, WREC 2, and CMREC 1 can be attributed to differences in spinach emergence that resulted in inadequate stand density for some of the treatments in those years (FiguresFigure 4.9-Figure 4.11). The stand densities at CMREC 2 were less variable among treatments (Figure 4.12) The differences in emergence were a function of both cover crop and tillage treatment. The FR NT treatment had the highest or was one of multiple treatments with the highest stand densities in all four site years. There was no site year at which NC RT, the standard practice, had the highest emergence of spinach. There were, however, site years at which NC RT had the lowest emergence of all treatments. At WREC 1, the NC RT treatment was a crop failure because of seed corn maggots (*Delia platura),* whereas the FR NT and RT treatments had 8-10 spinach plants per row m. High stand density at emergence did not always result in similar densities at harvest. In the case of WREC 1, no rescue weeding was applied to the RO, OAT, and NC NT treatments and by harvest, there were no spinach plants remaining in these treatments (the RT treatments were weeded).

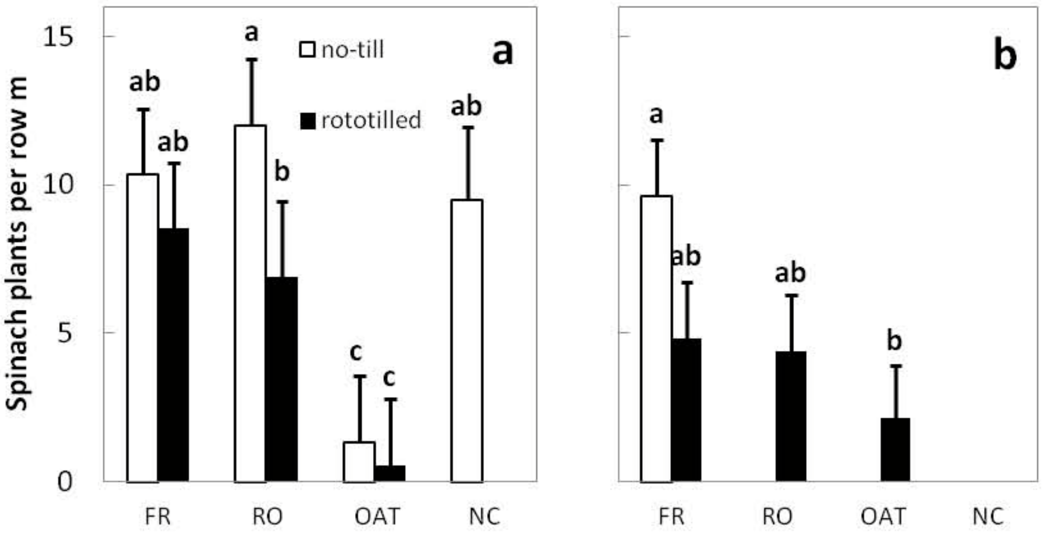


Figure 4.9 Spinach stand density at emergence (a) and at harvest (b) at Wye Research and Education Center in 2012.

No rescue weeding was applied to RO NT, OAT NT or NC NT, and by harvest there were no remaining plants. Seed corn maggots were found in NC RT plots after planting and no seedlings emerged.

FR= forage radish RO= radish-oat OAT=oat NC= no cover

NT= no-till RT=rototilled

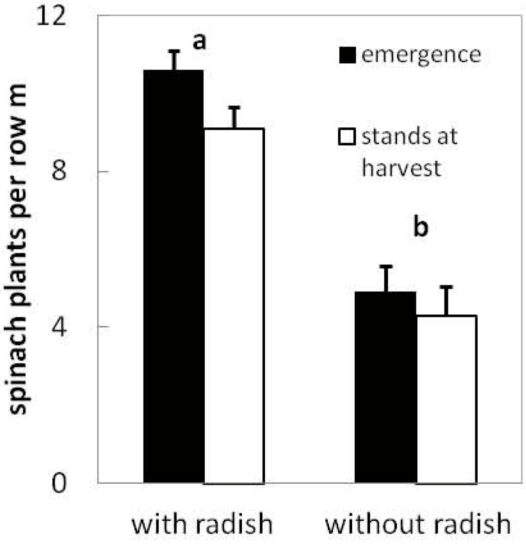


Figure 4.10 Spinach stand densities three weeks after planting (emergence) and at harvest for no-till and rototilled treatments combined at Wye Research and Education Center, 2013.
On each date, the presence of radish in the cover crop mix was significant (*F*-protected LSD, p<0.0001).

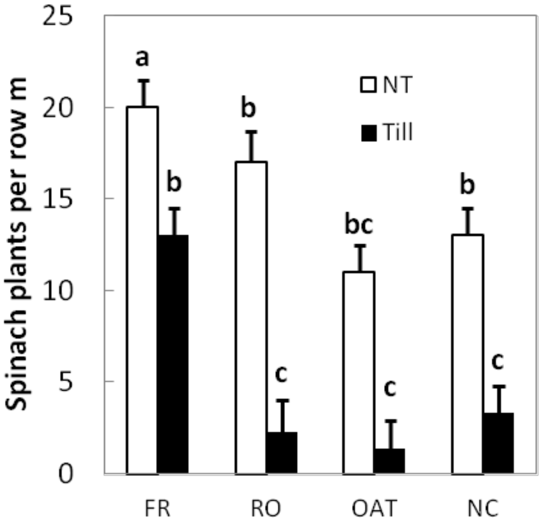


Figure 4.11 Spinach stand densities after emergence at Central Maryland Research and Education Center, Clarksville, 2012 .
No significant stand losses occurred between emergence and harvest.

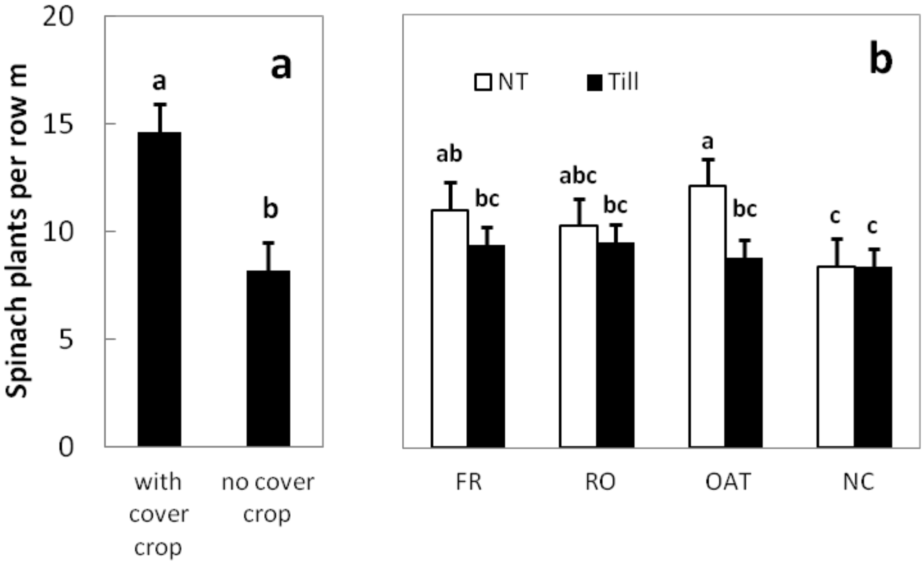


Figure 4.12 Spinach stand density four weeks after planting (a) and at harvest (b) at Central Maryland Research and Education Center, Clarksville, 2013.
Damping off (Pythium spp) symptoms were observed and may have been responsible for stand losses. At emergence, the only significant effect on stand density was the presence of a cover crop (*F*-protected LSD, $p<0.05$). By harvest, some changes in stand densities had occurred and significant differences are indicated by letters ($p<0.05$). Error bars are standard error of the mean.

Radish and NT planting generally appear to have positive effects on emergence of spinach, but it is difficult to understand these phenomena mechanistically because of the multiple physical, chemical, and biological factors that influence seed germination and emergence.

Soil mineral N in spring

Four to six weeks after planting, when spinach growth and nutrient uptake was becoming rapid, both tillage and the presence of radish in the cover crop increased soil NO_3^--N concentrations at both sites (Figure 4.13Figure 4.14). At WREC 1, FR and RO (RT and NT) had among the highest NO_3^--N concentrations, but the interactions between radish, oat and tillage were significant so conclusions about main effect cannot be drawn. Soil NH_4^+-N concentrations were small in comparison to NO_3^--N and there were no differences among treatments four to six weeks after spinach planting. The average NH_4^+-N concentration across all treatments was 2.0 mg kg^{-1} on April 14 at CMREC 1 and 4.5 mg kg^{-1} NH_4^+-N on April 22 at CMREC 2. NH_4^+-N levels averaged 3.3 mg kg^{-1} across all treatments on 8 at WREC 1and 3.0 mg kg^{-1} across all treatments on April 27 at WREC 2

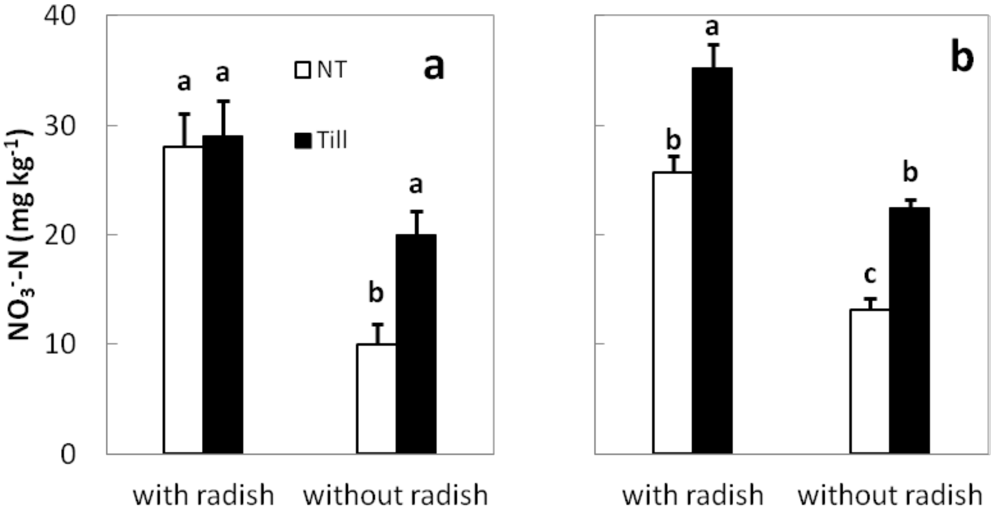


Figure 4.13 Soil NO_3^--N concentrations (0-20 cm) on April 14, 2012 (a), and April 22, 2013 (b) after cover crops at Central Maryland Research and Education Center, Clarksville.
There were no significant interactions between radish, oat and tillage. In both years, tillage and the presence of radish in the cover crop caused significant (*F*-protectected LSD, $p<0.05$) effects. Error bars represent standard error of the mean (n=8).

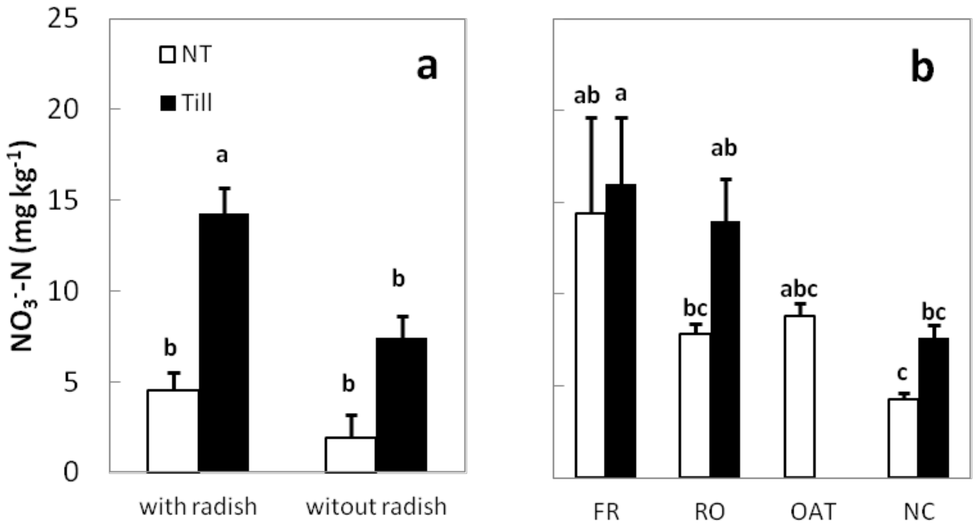


Figure 4.14 Soil NO_3^--N concentrations (0-20 cm) on and April 8, 2012 (a) April 27, 2013 (b) after cover crops at Wye Research and Education Center .
Simple effects are presented for (b) because there were significant interactions. At WREC 1, main effects of radish and tillage on NO_3^--N were significant ((*F*-protectected LSD, $p<0.05$).

Because of dramatic treatment differences in stand density at CMREC 1, WREC 1, and WREC 2, it was difficult to determine the possible effects of soil NO_3^--N on spinach yields. Correlation analysis to investigate the relationship between soil NO_3^--N content and yield was prudent only for CMREC 2, where stand densities were comparable among treatments (Figure 4.12). There was a correlation between soil NO_3^--N content (0-20 cm) two to three weeks prior to harvest and total fresh yield for the NT treatments at CMREC 2 (Figure 4.15). However, the correlation between soil NO_3^- content and yield was not significant for the RT treatments (Figure 4.15). This indicates that increased mineralization of N after tillage does not always result in concomitant increases in yield. Data from more site years are needed to test these relationships under a variety of conditions.

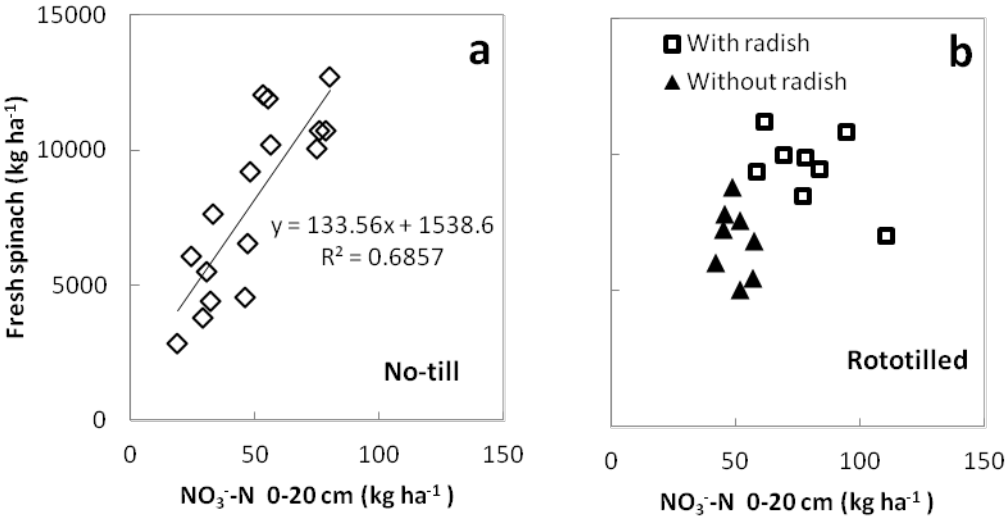


Figure 4.15 Soil NO3- -N content on April 22, 2013 at CMREC vs. fresh spinach yields (first two harvests on May 10 and May 21 combined) for no-till (a) and rototilled (RT) (b) treatments
There was no significant correlation between soil NO_3^- and yield for the RT treatments either combined or divided into with and without radish.

Variable stand counts that were mostly a result of the presence or absence of radish in the cover crop (Figure 4.10) at WREC 2 make the interpretation of a soil NO_3^--N - yield correlation more difficult. The data clearly show conditions under which NO_3^--N is not predictive of yield, and a phenomenon of clustered data is evident (Figure 4.16). The clustering of higher yields in the RT plots even within the same range of soil NO_3^- content indicates that NT yields were hindered by something more than total NO_3^- content of the soil.

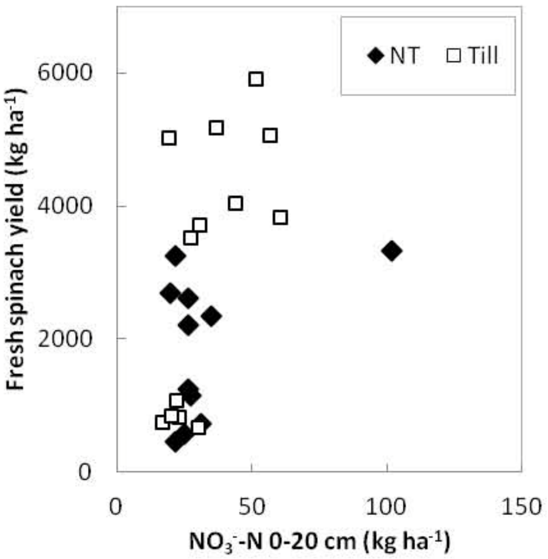


Figure 4.16 Soil NO_3^--N content at Wye Research and Education Center on April 27vs. fresh spinach yields harvested on May 17, 2013.

One plausible explanation for decreased yields in the NT plots is that the lower porosity/higher bulk density in the NT plots limited spinach growth (Figure 4.11). Despite similar surface textures at both sites (SiL), the two soils differ in porosity (probably due to greater aggregation at CMREC). Porosity influences the availability of oxygen for root respiration and microbial activity. Higher bulk density at WREC vs. CMREC and in the NT plots at WREC vs. the RT plots may have restricted spinach root growth. Bulk density may not have been limiting at CMREC in the first place, so the decrease in bulk density and increase in porosity created by tillage may not have affected spinach growth. The soil's inherent drainage class also contributes to the likelihood of saturated or near-saturated conditions that can affect root growth and N dynamics. CMREC is well drained, whereas the WREC soil is only moderately well drained.

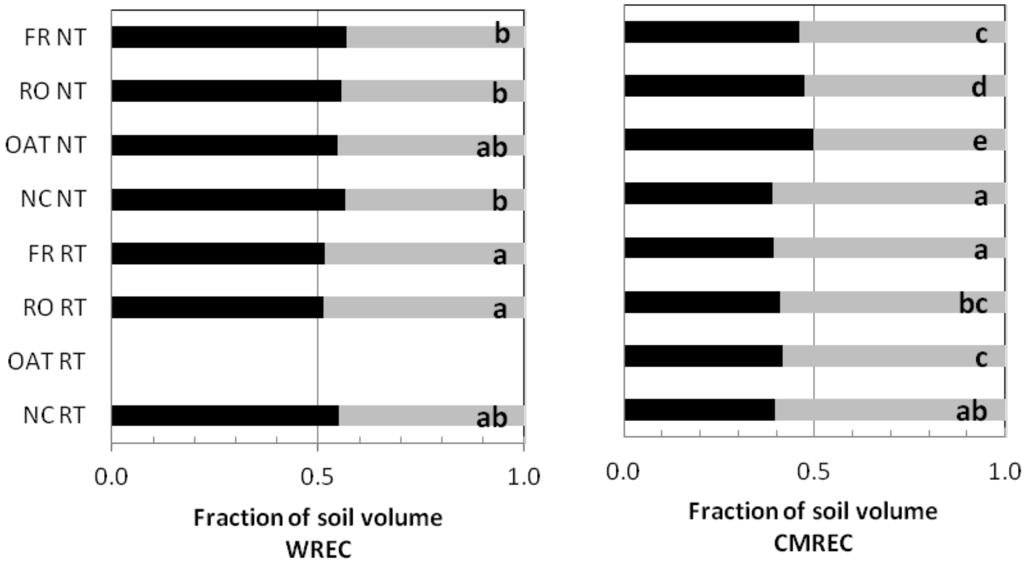


Figure 4.17 Soil porosity at Wye Research and Education Center (WREC) and Central Maryland Research and Education Center, Clarksville (CMREC) three weeks after tillage (on April 27, 2013 and April 2, 2013 respectively) as infleunced by treatments. Black bars= solid particles; white bars = porespace. OAT RT treatment is missing from CMREC 2 because the soil under the OAT plots was too wet to till. Letters represent differences in treatment means (n=4, $p<0.05$).
FR=forage radish RO=radish-oat OAT=oat NC=no cover RT=rototilled NT=no-till

Weed management

FR NT plots had near complete weed suppression at planting time and into mid April at CMREC 1 and 2. RO and OAT plots also provided substantial weed suppression, but the presence of oat residue necessitated hand-weeding. For organic growers, weed competition is a primary limitation to production. Most mechanical weeding equipment has been designed for a tilled and residue-free surface. Investigating weeding methods was beyond the scope of this research, but it should be noted that the difference in soil surface characteristics between both cover crop and tillage treatments was substantial.

At CMREC 2, the use of rototilling did not reduce the time required for weeding; i.e., the NC RT plots were not significantly different from the FR, RO, and

OAT NT plots (Figure 4.18) with respect to the time required for weeding. Cover crops provided some weed suppression compared to NC plots at WREC but there were weeds present in the NT plots at the time of planting both years. The only partial weed suppression can be attributed to the less than ideal cover crop stands achieved in fall at this site. By mid to late April, the weed ground cover was substantial (Figure 4.18). Tillage reduced the weed ground cover in FR, RO, and NC plots (there was no OAT RT treatment at WREC 2 because the OAT treatment was too wet to till), but the weeds quickly grew back in the NC plots such that in under three weeks after planting, the ground cover in the NC RT plots was equal to that in the FR, RO, and OAT NT plots. However, ground cover is not necessarily a good estimation of the time required to remove weeds as the weeds in the NT plots tended to be more firmly rooted than the weeds in the RT plots.

It was observed that weed species varied in the different cover crop treatments but a thorough inventory was not taken. Lawley et al. discuss weed dynamics following FR and other cover crops in more detail (Lawley, 2010). We speculate, given the observation that bare patches of soil were observed in October at WREC, that fall growth of FR was not adequate to allow for complete canopy closure and therefore complete spring weed suppression. This inadequate growth was likely a result of unusual wetness in fall (associated with hurricanes) that limited early plant establishment and growth.

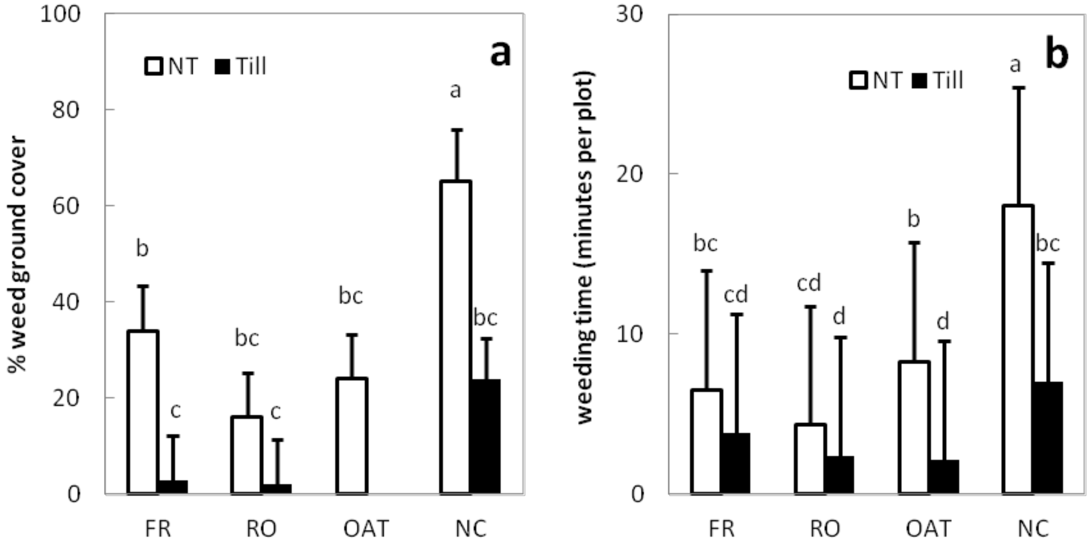


Figure 4.18 Weed groundcover by visual estimation on April 21, 2013 at Wye Research and Educaiton Center (a) and weeding time at Central Maryland Research and Education Center, Clarksville on April 22, 2013 (b).
FR= forage radish RO=radish-oat OAT=oat NC=no cover crop

Spinach water content

At CMREC 2, when spinach leaves were harvested instead of whole spinach plants, there was a difference on both harvest dates between the dry matter content of the NT and the RT plots for all cover crop treatments. The NT planted spinach had greater dry matter as a fraction of fresh yield (7.5% dry matter vs. 7.1% dry matter ($p=0.0015$) on the first harvest, and 7.6% dry matter vs. 7.1% dry matter ($p=0.007$) on the second harvest). This phenomenon did not occur at other site years when the whole plant was harvested. Lower water content may increase post-harvest quality and nutrient content for consumers.

Experiment 2: Vegetable response to no-till planting and forage radish cover crop

Lettuce was harvested at three out of four site years. At WREC 2, emergence for all treatments was so low (two lettuce plants per row m) that the plots were not maintained or harvested. Yields are presented in Table 4.5. The only site year for which there was a treatment effect on lettuce emergence was WREC 1, when FRRT>FRNT>NCRT ($p<0.05$).

Table 4.5 Fresh yields of lettuce at three site years in Maryland, USA.

Cover crop/tillage treatment	Central Maryland Research and Education Center, Clarksville		Wye Research and Education Center
	2012	2013	2012
	---------------------*Mg ha^{-1}*---------------------		
Forage radish (no-till)	21 (4.3) ns	18 (2.5) ab[1]	6.5 (1.5) b
Forage radish (rototilled)	37 (6.7) ns	20 (3.1) a	17 (1.1) a
No cover (rototilled)	29 (3.9) ns	12 (2.0) b	—

Means of three blocks are presented and number in parentheses is standard error of the mean.

[1] letters are presented for differences although the F-test probability =0.07 for treatment effects.

These yield data are from single harvest dates of lettuce. At CMREC 2 and WREC 1, the lettuce was harvested before any had formed full romaine heads because it was beginning to bolt. At CMREC 1, we observed that the RT treatments had formed full heads, but the FR NT treatment had not (Figure 4.19). A few FR NT heads were left in the field to determine if they would mature and they did so approximately two weeks later, but there were not enough remaining to determine meaningful yield data. For nearly all early season cool weather crops, the dramatic increase in temperature that can occur in the mid-Atlantic in May or June can lead to rapid bolting. If a crop has not matured by this point, it will be lost. Slower maturity of crops to NT planting, perhaps because of lower soil temperatures, could therefore have considerable economic consequences. On the other hand, a more slowly maturing crop can allow farmers who have a later target market date to plant crops earlier than they otherwise would, alleviating some of the pressure of planting time later in the spring. A sugar beet (*Beta vulgaris* L.) crop NT planted into wheat (*Triticum aestivum* L.) and rye cover crop residue in France matured more slowly than when planted after tillage, but the authors concluded that this could be counteracted by the ability to plant sooner (Richard et al., 1995).

Figure 4.19 Lettuce harvested on May 23 at CMREC 1 after no-till (left) and rototilled (right) planting (right)

Peas and kohlrabi

At WREC 1, like spinach, peas and kohlrabi in the NC RT treatment exhibited complete crop failures (no emergence) because of seed corn maggots. Among the remaining treatments at WREC 1, The FR NT treatment had higher pea emergence (17 plants per row m) than the FR RT treatment (10 plants per row m) (p=0.10). However, at WREC 2, the FR NT treatment had lower emergence (9.1 pea plants per row m) than the NC RT treatment (15 pea plants per row m) and the FR RT treatment (17 pea plants per row m) (p<0.05). At CMREC 2, the only year peas were planted at

CMREC, there was no difference in emergence among the three treatments, with all treatments >17 pea plants per row m.

Kohlrabi emergence at CMREC 2 was higher in the FR NT treatment (4.5 kohlrabi plants per row m) than the FR RT and NC RT treatments (2.0 kohlrabi plants per row m) ($p<0.05$), but there was no difference between the FR NT and FR RT treatments at WREC 1 and no difference between any treatments at WREC 2. Experiment 2 pea and kohlrabi plots were not maintained after emergence and yield data were not collected. Overall, NT planting was effective in terms of emergence, even for species such as kohlrabi. Crop performance past emergence was not monitored enough to draw further conclusions.

Conclusion

This research shows that radish which can provide weed suppression in spring without leaving large amounts of residue can fill a cover-cropping niche for early spring vegetables that traditional high-residue cover crops do not adequately fill. In addition to providing nitrogen capture and other environmental benefits of a winter cover crop, radish can eliminate the need for spring tillage and reduce fertilizer requirements for early vegetables. This is a novel concept and several questions still remain regarding implementation on farms of a system utilizing radish and/or potentially other low-residue winterkilled cover crops that function similarly.

Our two sites exemplify situations in which NT planting after FR does and does not work well. CMREC, with a well-drained Piedmont soil with high organic matter and fertility, produced cover crops with high biomass, and near 100% weed suppression in spring after FR. The early and rapid availability of N after FR, with both NT and RT planting, produced high-yielding spinach crops. WREC, with a moderately well drained Coastal Plain soil formed on loess deposits, did not produce any cover crop that provided adequate weed suppression for NT planting. In addition, at WREC, physical conditions of the NT soil appear to have limited spinach growth. Despite the poor performance of NT planting at WREC, FR did provide some weed suppression and allowed for more rapid soil drying in spring than did OAT.

For adequate weed suppression to plant NT without herbicides in spring, complete FR canopy closure four to six weeks after FR cover crop planting in late August in Maryland is necessary, which requires adequate fertility and growing conditions. To avoid the problem of insufficient fertility in fall, we suggest that an effort should be made to develop a predictive test for FR cover crops similar to the pre-sidedress nitrate test, which has been shown to be effective for fall planted vegetable crops like cabbage (Heckman et al., 2002) as well as for spring planted corn. Inadequate FR cover crop growth is a risk, but the lack of complete canopy closure is a visible benchmark that farmers can observe in fall and plan accordingly. If there is visible bare soil in fall or weeds are present at planting time in spring, the usual practice of RT can be performed and will not be hindered by heavy residue. In the case that FR does not winterkill, as was the case at WREC a single pass with a mower will effectively terminate the FR cover crop.

Regardless of cover crop, weeds do begin to appear in mid-April, even with 100% weed suppression at planting time after FR. In our experiments, hand weeding with a hoe was applied, but this is only reasonable for small operations. The surface of FR NT soil can have dried radish roots remaining that may interfere with mechanical weeding equipment that was designed for a tilled seedbed. Further research is needed to identify weed control strategies that work at a variety of farm equipment scales.

Like weeding equipment, most vegetable planting equipment was designed for a tilled surface. Small-scale (< 5 ha) growers are an economically important in vegetable production, especially in the organic sector. In 2011, 4,671 organic farms reported less than $100,000 in sales whereas only 1,520 reported sales greater than $100,000 (NASS, 2012a). Most vegetable planting equipment specifically designed for NT, such as the planter used in our experiment, are not affordable for small-scale farmers. One of the barriers to adoption of NT practices in agriculture has been the high price for specialized equipment (Lu et al., 2000). Because FR does not leave high amounts of residue requiring heavy equipment to cut through it for planting, it may be possible that small human-powered equipment can plant into an untilled seedbed after FR. Small-scale equipment in other countries has proven to be effective even in high-residue NT cover crop systems (Derpsch et al., 2010).

Our data provides strong evidence for a positive response from spinach to NT planting and to FR, but our experiments were inconclusive regarding other early vegetable crops. We also recognize that there is a possibility that Brassica cover crops, such as radish, may harbor Brassica pests and diseases that concern vegetable growers who have Brassicas in their cash crop rotations. This needs to be investigated further. Although this experiment focused on FR cover crop followed by spinach, future research should extend the concept of low-residue winterkilled cover crops for NT vegetable planting to other cover crops not in the Brassica family and spring crops in addition to spinach. Future research should also include fertilizer treatments to enable a sound assessment of the fertilizer replacement value of different cover crops as farmers may be understandably reluctant to reduce fertilizer inputs (Jackson et al., 2004). Reduced fertilizer inputs and lower fuel use from eliminating tillage will alter the economics of the production system. In some cases, lower yields return greater profits because of reduced input costs (Jackson et al., 2004). However, the time period in fall devoted to growing a cover crop could also be used to grow an additional short-season cash crop. An economic analysis of this alternative production system would include these variables as well as the long-term impacts on soil quality and productivity. Such an analysis would greatly increase our ability to continue to develop systems that are environmentally and economically sound.

Chapter 5 Conclusions and General Recommendations

I think there are a few major hurdles to widespread adoption of no-till vegetable production. The first is general soil quality on farms. Long-term intensively tilled soils may *need* tillage to create adequate growing conditions for crops. Tillage breeds more tillage, and the cycle is hard to break. A continued effort to develop soil-building management techniques that farmers can practice without taking their fields entirely out of production for long periods is still needed.

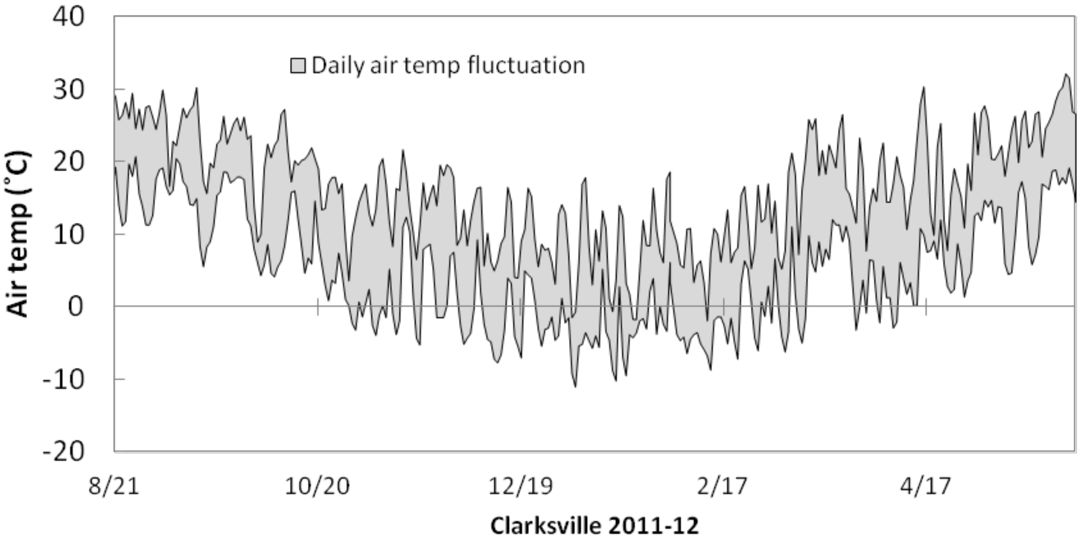
There is also some cultural resistance to no-till among some vegetable farmers, just as I imagine there was among grain farmers. This can be overcome.

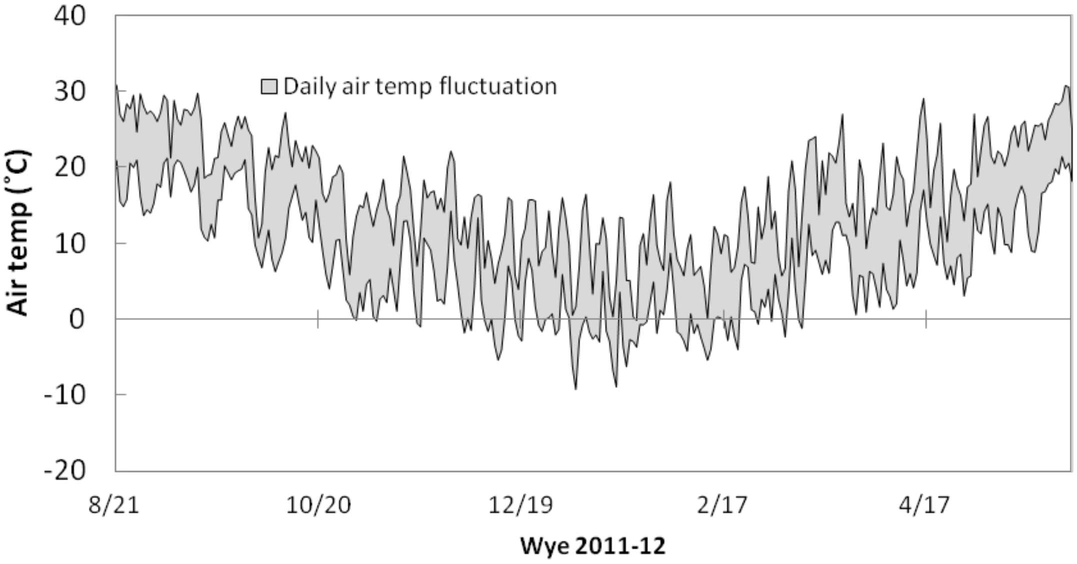
Weeds are a huge problem to adopting no-till practices for organic farmers. In addition to continuing to investigate mechanical techniques, I think we need to think about non-toxic, or minimally toxic herbicides.

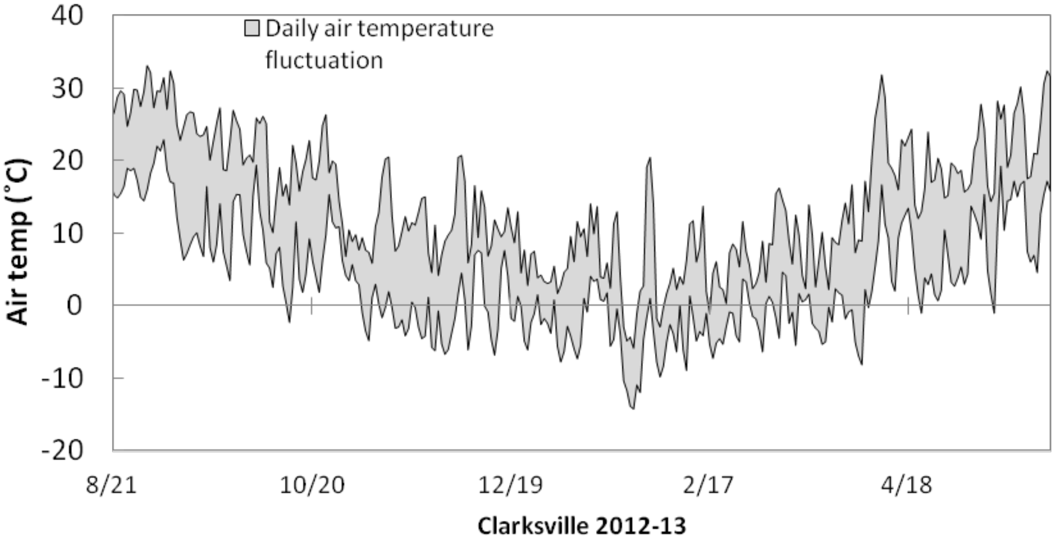
Finally, although this research did not address cover crop mixtures beyond radish and oat, and did not include legumes at all, I think any truly efficient and low-input system has to include legumes, either by themselves or in mixtures with other cover crops. The legume-brassica relationship is worth investigating.

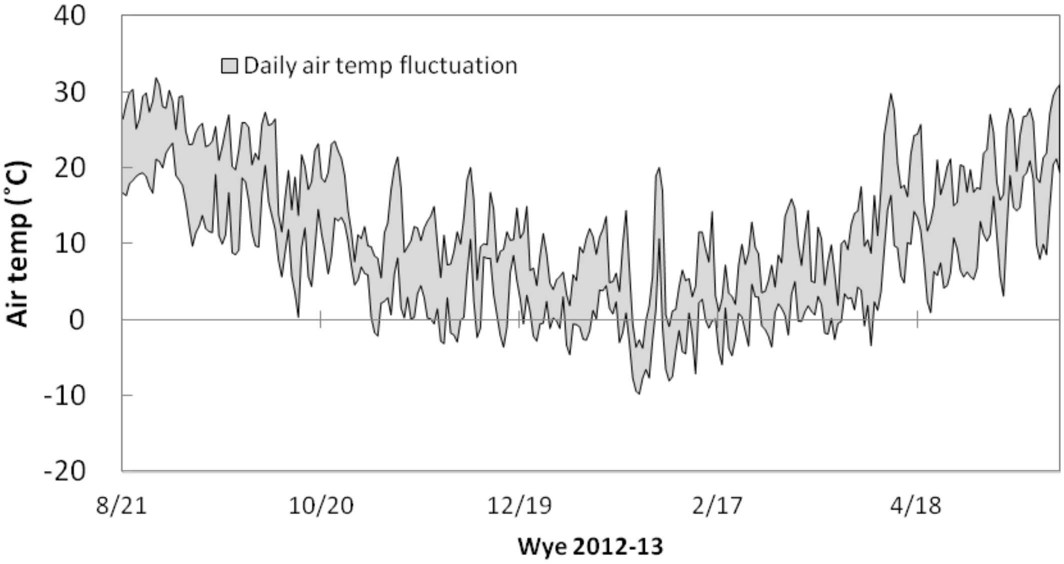
Appendices

Appendix 1: Daily air temperature fluctuations for cover crop and spinach growing seasons for four site years.

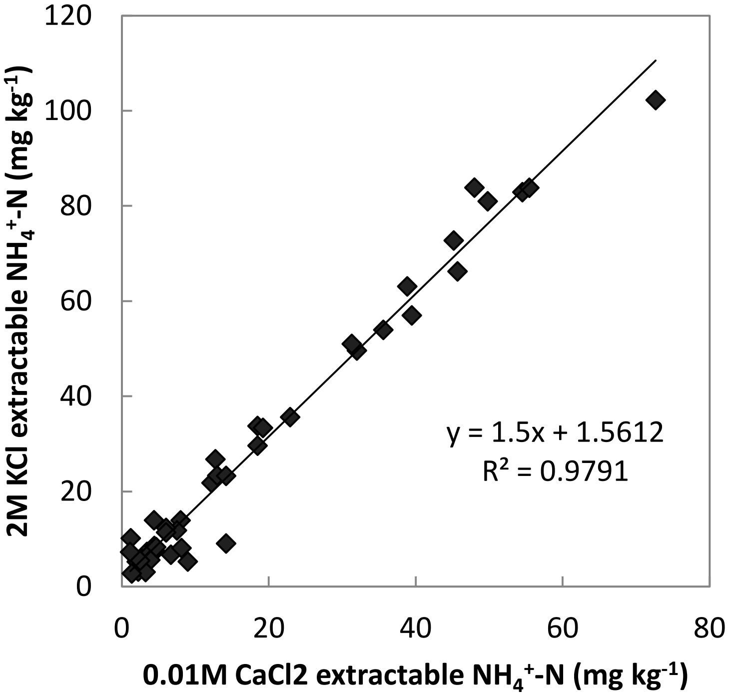





40
30
20
10
0
-10
-20
Air temp (°C)
▨ Daily air temperature fluctuation
8/21
10/20
12/19
2/17
4/18
Clarksville 2012-13


40
30
20
10
0
-10
-20
Air temp (°C)
▨ Daily air temp fluctuation
8/21
10/20
12/19
2/17
4/18
Wye 2012-13

Appendix 2: Correlation between NH_4^+-N extraction methods using soil samples from CMREC January 28, 2013 and WREC February 7, 2013



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Appendix 3: Cover crop nutrients from four site years.

Table A1: Average cover crop nutrients from Central Maryland Research and Education Center, Clarksville (n=4). Cover crop monocultures only. Standard deviation in parentheses.

	Forage radish root		Forage radish shoot		Oat shoot		Weed shoot	
	2011	2012	2011	2012	2011	2012	2011	2012
S (%)	0.68 (0.057)	0.78 (0.034)	0.81 (0.077)	0.76 (0.068)	0.19 (0.024)	0.23 (0.010)	0.25 (0.055)	0.31 (0.055)
P (%)	0.47 (0.057)	0.59 (0.031)	0.52 (0.112)	0.64 (0.083)	0.44 (0.028)	0.38 (0.022)	0.54 (0.083)	0.44 (0.056)
K (%)	4.4 (0.69)	5.66 (0.173)	5.0 (0.48)	6.2 (0.45)	3.9 (0.45)	4.6 (0.19)	4.4 (0.92)	4.6 (0.65)
Mg(%)	0.15 (0.029)	0.26 (0.026)	0.19 (0.040)	0.32 (0.062)	0.13 (0.015)	0.20 (0.015)	0.26 (0.022)	0.33 (0.083)
Ca (%)	0.45 (0.064)	0.69 (0.087)	1.8 (0.099)	2.0 (0.80)	0.26 (0.022)	0.38 (0.025)	1.0 (0.21)	1.0 (0.18)
Na (%)	0.018 (0.0050)	0.07 (0.010)	0.043 (0.021)	0.15 (0.047)	0.010 (0.00)	0.10 (0.037)	0.010 (0.00)	0.04 (0.0050)
B mg kg^{-1}	23 (2.6)	25 (1.7)	39 (2.1)	37 (7.5)	4.8 (0.50)	4.2 (0.50)	21 (3.1)	17 (5.7)
Zn mg kg^{-1}	26 (4.2)	37 (2.1)	26 (4.1)	35 (3.4)	22 (1.8)	30 (3.8)	31 (1.3)	27 (5.5)
Mn mg kg^{-1}	28 (8.8)	19 (1.8)	36 (7.5)	63 (30)	66 (15)	99 (19)	84 (34)	142 (101)
Fe mg kg^{-1}	145 (13)	139 (17)	126 (12)	188 (84)	76 (16)	385 (260)	608 (639)	896 (1029)
Cu mg kg^{-1}	7.5 (0.58)	8.7 (1.0)	7.0 (0.82)	10 (1.1)	8.0 (0)	10 (0.82)	13 (0.96)	13 (1.3)
Al mg kg^{-1}	61 (17)	45 (7.6)	43 (11)	78 (42)	18 (6.9)	150 (151)	306 (249)	472 (573)
C (%)	35 (0.49)	37 (0.72)	35 (1.1)	35 (1.1)	40 (0.38)	40 (0.60)	39 (0.73)	38 (2.1)
H (%)	5.3 (0.16)	5.5 (0.042)	5.0 (0.19)	5.2 (0.19)	5.4 (0.046)	5.7 (0.14)	5.3 (0.14)	5.4 (0.36)
N (%)	2.7 (0.16)	3.2 (0.080)	4.1 (0.27)	4.1 (0.61)	2.4 (0.33)	3.1 (0.045)	2.9 (0.35)	3.8 (0.45)

Table A2: Average cover crop nutrients from Wye Research and Education Center (n=4). Cover crop monocultures only. Standard deviation in parentheses.

	Forage radish root		**Forage radish shoot**		**Oat shoot**		**Weed shoot**
	2011	2012	2011	2012	2011	2012	2012
S (%)	0.69 (0.04)	0.80 (0.033)	0.78 (0.096)	0.81 (0.071)	0.18 (0.017)	0.23 (0.045)	0.71 (0.065)
P (%)	0.41 (0.02)	0.38 (0.050)	0.44 (0.073)	0.37 (0.029)	0.25 (0.026)	0.21 (0.017)	0.33 (0.019)
K (%)	2.7 (0.59)	3.9 (0.77)	2.4 (0.64)	3.6 (0.74)	1.6 (0.91)	2.0 (0.28)	3.0 (0.20)
Mg(%)	0.22 (0.04)	0.30 (0.055)	0.29 (0.010)	0.37 (0.041)	0.15 (0.021)	0.16 (0.029)	0.34 (0.050)
Ca (%)	0.55 (0.12)	0.64 (0.056)	2.1 (0.24)	2.5 (0.17)	0.24 (0.026)	0.31 (0.033)	1.7 (0.23)
Na (%)	0.49 (0.24)	0.56 (0.20)	0.86 (0.37)	0.91 (0.37)	0.84 (0.17)	0.72 (0.22)	0.06 (0.017)
B mg kg^{-1}	25 (3.3)	26 (2.4)	49 (9.3)	43 (3.2)	5 (0.82)	3.8 (0.96)	18 (1.7)
Zn mg kg^{-1}	22 (4.0)	29 (4.5)	26.5 (5.1)	34 (3.7)	18 (1.4)	21 (4.3)	93 (23)
Mn mg kg^{-1}	15 (8.5)	10 (2.4)	35.5 (9)	53(10)	62 (12)	83 (16)	63 (16)
Fe mg kg^{-1}	156 (96)	90 (28)	114 (40)	170 (45)	62 (7.4)	367 (206)	278 (160)
Cu mg kg^{-1}	6.8 (0.50)	6.8 (1.3)	6.75(0.96)	7.5 (0.58)	7.5 (0.58)	9.0 (1.4)	10 (1.2)
Al mg kg^{-1}	79 (65)	20 (17)	44 (23)	53(26)	12 (3.9)	143 (96)	185 (60)
C (%)	39 (0.66)	38 (0.32)	39 (0.46)	38 (0)	42 (0.61)	42 (1.1)	40 (1.2)
H (%)	5.6 (0.07)	5.6 (0.13)	5.4 (0.17)	5.2 (0.10)	6.0 (0.058)	5.7 (0.20)	5.5 (0.15)
N (%)	1.8 (0.25)	1.4 (0.11)	3.1 (0.44)	2.3 (0.26)	2.0 (0.35)	1.6 (0.35)	3.5 (0.64)

Appendix 4: Sample SAS codes

Sample SAS code used to analyze soil nutrients in spring (RCBD split plot)

```
title 'CV 5.10.13 NO3 0-20cm';
proc mixed data=cv10may;
class radish oat sprtrt blk;
model NO3=radish|oat|sprtrt/DDFM=sat;
random blk*radish*oat blk;
LSMEANS radish*oat*sprtrt radish*sprtrt/pdiff;
ods output diffs=ppp lsmeans=mmm;
ods listing exclude diffs lsmeans;run;
%include 'C:\Users\Natalie\pdmix800.sas';
%pdmix800(ppp,mmm,alpha=0.05,sort=yes);
```

Sample SAS code used to analyzed repeated measures (depth)

```
title 'NO3 with depth 5.2.12 2012 cv NT only';
proc mixed data=cv2maydepth COVTEST;
class radish oat blk depth;
model NO3=radish|oat|depth/DDFM=kr;
random blk blk*radish*oat;
repeated depth/subject=NO3 (blk radish oat)  TYPE=UN RCORR;
LSMEANS radish*oat*depth radish*depth/pdiff;
ods output diffs=ppp
lsmeans=means;
ods listing exclude diffs lsmeans;
run;
%include 'C:\Users\Natalie\pdmix800.sas';
%pdmix800(ppp,means,alpha=0.05,sort=yes);
```

Sample SAS code used for regression analysis

```
title ‘Regression spinach soil N';
proc reg data=cv13spin2;
model NO3spin=NO3soil;
output out=assumps R=resid P=pred u95m=u95m l95m=l95m;
run;
```

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