AN ABSTRACT OF THE THESIS OF

Amy Garrett for the degree of Master of Science in Horticulture presented on June 15, 2009.

Title: Improving Nitrogen Management with Cover Crops in Organic Broccoli Production.

Abstract approved:

John M. Luna

Legume cover crops can serve as important sources of nitrogen (N) in sustainable agriculture and can be economically beneficial when fertilizer inputs are reduced without a yield reduction. Synchronizing N mineralization from organic materials with the needs of the subsequent crop is a challenge for organic growers. Predicting plant available nitrogen from cover crop residue enables N fertilizer inputs to be adjusted for optimum economic yield and reduced environmental risk.

An experiment was conducted near Corvallis, OR in 2006 through 2008 to evaluate cover crop and N effects in organic broccoli production in western Oregon. The specific objectives of this experiment were to: 1) evaluate biomass production and N accumulation from selected cover crop treatments; 2) compare the effects of selected cover crops grown as sole crops and as mixtures on broccoli yield, yield components, and net economic benefit; 3) estimate the quantity of feather meal N replaced by cover crops 4) estimate plant available nitrogen from cover crop residue in an organic broccoli production system; 5) evaluate soil NO_3-N and petiole NO_3-N as predictors of broccoli yield; and 6) evaluate models derived from laboratory incubation of cover crop residue to predict apparent nitrogen recovery (ANR) from cover crop residue in the field. The cover crop treatments included common vetch (*Vicia sativa*), phacelia (*Phacelia tanacetifolia*), 'Monida' oats (*Avena sativa* L.), phacelia plus common vetch, and 'Monida' oats plus common vetch. A fallow treatment was used as the control. Prior to incorporation, cover crop samples were collected from each block and frozen for later use in laboratory aerobic incubations. After the cover crops were flail-mowed and incorporated, four N rates (0, 100, 200, and 300 kg N ha^{-1}) were randomized within each cover crop treatment in a split plot design.

All cover crop treatments produced much less biomass and accumulated less N in 2008 than in 2007. Planting vetch with oats or phacelia increased biomass production and N accumulation compared to sole crops in 2007 but not in 2008. Common vetch as a sole crop or in a mixture increased broccoli yield with 0 and 100 kg N ha^{-1} applied compared to fallow. Legume cover crop mixtures with 100 kg N ha^{-1}

produced similar net economic returns for organic compared to fallow treatments with 300 kg N ha^{-1}. Nitrogen fertilizer input can be reduced by at least 100 kg N ha^{-1} if common vetch is in the mixture and produces more than 5000 kg ha^{-1} of biomass (130-180 kg N ha^{-1}). Vetch as a sole crop produced higher levels of soil NO_3-N than the fallow treatments up to 80 days after soil incorporation in 2007. Oats and phacelia as sole crops, however, reduced soil NO_3-N compared to fallow for up to 68 days after incorporation. Vetch mixtures with oats or phacelia produced intermediate levels of soil NO_3-N between vetch as a sole crop and the fallow. Treatment effects were similar in 2008, but differences were less due to reduced cover crop biomass compared to 2007. Broccoli petiole nitrate levels were not affected by cover crop treatment in 2007, and there was no correlation with yield. In 2008, the oat cover crop treatment reduced broccoli petiole nitrate levels compared to the fallow. Petiole nitrate levels were strongly correlated with broccoli yield, with highest yields associated with petiole NO_3-N greater than 10,000 ppm.

In the aerobic incubations with cover crop mixtures, a quadratic model described the relationship of percent N in the mixture to the apparent nitrogen recovery (ANR) at both 4 and 10 weeks. The highest ANR (about 40 percent) was similar for both extraction days. Net mineralization occurred when the percent N of the cover crop mixture was 1.5-1.8 percent. There was a strong correlation in 2007 between the ANR predicted by the incubation-derived model and the ANR in the soil and in the aboveground broccoli biomass. The model over predicted the ANR in the field soil, however the model more accurately predicted ANR in the broccoli biomass. The incubation model correctly predicted negative ANR values for the oat and phacelia cover-crop treatments. In 2008, the laboratory-predicted ANR and the field soil ANR were correlated (r^2=.45), and the laboratory model over predicted the field ANR. The incubation model gave a poor prediction of broccoli biomass ANR.

Improving Nitrogen Management with Cover Crops
in Organic Broccoli Production

by
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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Amy Garrett, Author

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CONTRIBUTION OF AUTHORS

Dr. Lan Xue assisted with statistical analysis. Dr. Dan Sullivan assisted with laboratory procedures of Chapter 2.

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Chapter 1

General Introduction

Organic agriculture has grown during the last decade and continues to grow as consumers become increasingly concerned about the negative impacts of conventional farming practices on human health and the environment. Researchers are concentrating more on defining fertilization methods that result in the greatest crop yield with the least amount of fertilizer, and the least negative impact on the environment (Hochmuth, 2003). Energy efficiency is another concern since nitrogen (N) fertilizer is one of the most energy-costly agrichemicals to produce, distribute, and apply (Magdoff, 2007). Nitrogen management is challenging for organic farmers because of the complexity of organic fertilizer materials and the multiple factors that affect N availability for cash crops.

Organic farming systems use a variety of sources of N, including manures, composts, specialty animal-processing by-products (e.g. fish, feather, and blood meal), and legumes (Berry et al., 2002; Gale et al., 2006). All of these sources differ in cost, nutrient content, mineralization rate, and environmental impact (Gale et al., 2006). In organic systems, N must be mineralized by soil microbes before it is available for plant uptake. The different physical and chemical properties of these organic sources of nitrogen, in addition to environmental conditions and management practices, affect the efficiency and economics of these materials in serving as a fertilizer source

The nutrient content of manure is affected by the type system it came from. For example, the total N concentration of organically produced manures has been demonstrated to be approximately 15% less than conventionally produced manures (Dewes and Hunsche, 1999). Animal manure also has a smaller ratio of N to phosphorus (P) than is required for crop production. Relying solely on manure for a crop N needs leads to P loading of soils which can endanger water quality (Laboski and Lamb, 2004).

Composts, including composted manure, have less odor and better physical properties than do fresh materials, as well as reduced weed seed viability. However, their fertilizer value is reduced compared to fresh materials (Schlegel, 1992). Removal of water from fresh materials such as manure concentrates nutrients, but some studies have shown reduced N use efficiency from composted compared to non-composted manure and N-fertilizer (Castellanos and Pratt, 1981; Brinton, 1985). Schlegel (1992) demonstrated that the apparent N recovery efficiency from compost was about 13% compared with 36% for N fertilizer.

Specialty products are most often by-products of fish-, livestock- and food-processing industries. The nutrient analyses of these products vary considerably, and tend to be quite expensive. Also, the N from specialty organic fertilizer materials, such as fish and feather meal, has been shown to mineralize rapidly with a large fraction of the amendment N becoming plant-available in the first 28 days after application (Gale et al., 2006).

Legume cover crops have long been used as an economical N source for farmers. Crews and Peoples (2004) suggest that the energetic basis of legume N_2 fixation (solar energy) is more sustainable than fertilizer N sources which require significant amounts of non-renewable fossil fuels or other commercial energy sources to produce. Substituting legume-supplied N for manufactured N can potentially save 15,000 $MJ \cdot ha^{-1}$ (Pimentel et al., 1973; Buffington and Zar, 1977), primarily in natural gas used to produce urea. Ess et al. (1994) found that in both conventional and no-till systems, cover-cropped treatments used about half as much energy per hectare as the corresponding winter-fallow N fertilizer treatments.

Cover-crop contributions to organic farming systems

Some of the important roles for which cover crops have long been used include: the enhancement of soil structure, conservation or improvement of environmental quality (Dabney et al., 2001), management of soil-borne diseases (Stone et al., 2004), weeds and insect pests, and improvement of soil fertility (Sullivan et al., 1991).

Legume cover crops such as vetch and clovers are able to fix atmospheric N through a symbiotic relationship with the *Rhizobia* bacteria living in root nodules of the plant. The amount of N legumes are able to fix and contribute to subsequent crops varies considerably, often from 70 to 150 kg N ha^{-1} (Sullivan et al., 1991; Rannells and Wagger, 1996). This variability in N contribution of a legume is due to factors such as: 1) the nitrogen content of the cover crop; 2) plant available nitrogen in the soil; 3) the genetic potential of the legume species; and 4) soil factors such as microbial activity, pH, moisture content and temperature (Fageria et al., 2005).

In contrast, non-legume cover crops supply C to soil through increased biomass production and soil organic matter (Sullivan et al., 1991; Kuo et al., 1997). Non-legume cover crops also reduce nitrate leaching from the soil profile in the winter better than do legumes, due to more rapid growth and root development in the fall (Meisinger et al., 1991; Shipley et al., 1992; Rannells and Wagger, 1997;). McCracken et al.(1994) suggest that rye may have prevented NO_3^- leaching more effectively than did vetch due to more rapid growth development in the fall and resuming growth earlier in the spring.

"Nitrogen fertilizer equivalency" is the difference of fertilizer required to produce equivalent yields between a cover crop and a no-cover crop fallow. One way to estimate N fertilizer equivalency is to compare different cover crop and fertilizer treatments to a no-cover crop/0 fertilizer N control (Mangan et al., 1991). Legume cover crops have been shown to have a N fertilizer equivalency commonly ranging from 70 to 150 kg N ha^{-1} which is generally correlated to higher N contents than are non-legumes and greater mineralization potential as indicated by C:N ratios of 20:1 or less (Doran and Smith, 1991; Sullivan et al., 1991; Rannells and Wagger, 1996). Stute and Posner (1995) demonstrated in a conventional system that mean corn grain yields following legumes were similar to those produced with 179 kg ha^{-1} of fertilizer N. Berry et al. (2002) suggest that within a three-month period the incorporation of leguminous crops can release about 150 kg N ha^{-1} of mineral N.

Non-legumes often have a low or negligible N fertilizer equivalency due to a lower N concentration, higher C:N ratio, and high concentrations cellulose and lignin (Doran and Smith, 1991). Therefore, using a non-legume monoculture may immobilize

N making it unavailable to subsequent crops (Ranells and Wagger, 1996). One management option for reducing the C:N ratio of non-legume cover crops is to mix them with legume cover crops (Sainju et al., 2005).

Advantages of legume-cereal mixtures

Using mixtures of legume and non-legume cover crops, such as cereals, may offer advantages to growing the cover crop species as sole crops. Potential advantages include: increased biomass yields, reduced N leaching compared with legumes, and increased crop productivity compared with non-legumes (Rannells and Wagger, 1996; Sainju et al., 2005). Soil mineralization rates of N from crop residues are determined primarily by the N concentration in the plant material. For example, combining rye with crimson clover or hairy vetch in biculture can increase N concentration of the rye thereby decreasing the C:N ratio. Ranells and Wagger (1996) found that the C:N ratio decreased 46% when rye was grown in biculture with hairy vetch, compared to rye grown as a monoculture. Sullivan et al. (1991) demonstrated that rye from a vetch-rye biculture had a C:N ratio of 47 compared with 59 for the rye monoculture. Decreasing C:N ratio results in less potential for N immobilization from the rye residue (Sullivan et al., 1991; Ranells and Wagger, 1996; Vaughan and Evanylo 1998). A greater C:N ratio (>30:1), leads to less net mineralization (Berry et al., 2002; Chaves et al., 2007).

Estimating plant-available N from cover-crop residue

Estimating the amount of N released from cover-crop residues depends on multiple factors involved in the mineralization process including temperature, moisture, and residue quality. Nitrogen mineralization from organic residues has been modeled in field and laboratory studies (Cabrera et al., 2005). In many of these models, residue N concentration and the C:N ratio have been used to estimate the rate of N mineralization (Vigil and Kissel, 1991). However, some residues with similar C:N ratios may mineralize different amounts of N due to other compositional differences (Cabrera et al., 2005). Other compounds such as proteins, soluble carbohydrates, cellulose, hemi-cellulose and lignin-like compounds also affect N mineralization (Constantinides and Fownes, 1994; Cabrera et al., 2005). A greater amount of lignin, cellulose and hemicellulose in residues has been shown to reduce the rate of mineralization (Honeycutt et al., 1993; Wagger, 1989a).

Using legume cover crops in organic broccoli production

Many studies have reported broccoli yield to increase with increasing N fertilizer application (Dufault and Waters, 1985; Kowalenko and Hall, 1987; Everaarts and de Willigen, 1999a; Feller and Fink, 2005). The N requirement for maximum broccoli yield ranges from 270 kg·ha^{-1} (Everaarts and de Willingen, 1999a), to 465 kg·ha^{-1} (Zebarth et al., 1995). However, there is conflicting literature related to the rate and timing of N fertilizer application required to obtain maximum broccoli yields. Everaarts and de Willigen (1999a) recommend applying 270 kg N ha^{-1}, minus the mineral N in the soil layer 0-60 cm at planting. Karitonas (2003) reported that the dependence of broccoli yield upon the N supply is best expressed by a quadratic parabola equation with the optimal N supply being 240 kg N ha^{-1} (Karitonas, 2001). Vägen (2003) demonstrated that with 240 kg N ha^{-1} applied, N did not appear to be limiting or excessive. Karitonas (2003) reported the optimal N fertilizer rate to be 180 kg N ha^{-1}, whereas, Riley and Vägen (2003) showed there to be no benefit of increasing N supply beyond 150 kg ha^{-1} in broccoli or white cauliflower. The variable results of many of these studies may be due to differences in soil fertility and climatic conditions (Zebarth et al., 1995).

In the research presented by this thesis, selected cover crops commonly grown in the maritime Pacific Northwest were evaluated for their N contribution to organic broccoli production. In addition, a relatively new cover crop in the region, *Phacelia tanacetafolia*, also was evaluated as a potential alternative to commonly used cereal cover crops such as oats and rye. Experiments were conducted near Corvallis, Oregon from 2006 to 2008.

The major objectives of this project were to: 1) evaluate biomass production and N accumulation from selected cover crop treatments; 2) compare the effects of selected cover crops grown as sole crops and as mixtures on broccoli yield, yield components, and net economic benefit; 3) estimate the quantity of feather meal N replaced by cover crops; 4) estimate plant available nitrogen from cover-crop residue in an organic broccoli production system; 5) evaluate soil NO_3-N, and petiole NO_3-N as predictors of broccoli yield; and 6) evaluate models derived from laboratory incubation of cover crop residue to predict apparent N recovered from cover-crop residue in the field.

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Chapter 2

Nitrogen Contribution of Cover Crops in Organic Broccoli Production

Abstract

Legume cover crops can serve as important sources of nitrogen (N) for subsequent crops and can be economically beneficial when fertilizer inputs are reduced without a yield reduction. Phacelia (*phacelia tanacetifolia)* has several qualities that make it a potential substitute for cereal cover crops grown in mixtures with vetch. An experiment was conducted near Corvallis, OR in 2006 through 2008 to evaluate cover crop and N effects in organic broccoli production in western Oregon. The specific objectives of this experiment were to: 1) evaluate biomass production and N accumulation from selected cover crop treatments; 2) compare the effects of selected cover crops grown as sole crops and as mixtures on broccoli yield, yield components, and net economic benefit; and 3) estimate the quantity of feather meal N replaced by cover crops. The cover crop treatments included common vetch (*Vicia sativa*), phacelia (*Phacelia tanacetifolia*), 'Monida' oats (*Avena sativa* L.), phacelia plus common vetch, and 'Monida' oats plus common vetch. A fallow treatment was used as the control. After the cover crops were flail-mowed and incorporated, four N rates (0, 100, 200, and 300 kg N ha^{-1}) were randomized within each cover crop treatment in a split-plot design. All cover crop treatments produced much less biomass and accumulated less N in 2008 than in 2007. Planting vetch with oats or phacelia increased biomass production and N

accumulation compared to sole crops in 2007 but not in 2008. Common vetch as a sole crop or in a mixture increased broccoli yield with 0 and 100 kg N ha^{-1} applied compared to fallow. Legume cover crop mixtures with 100 kg N ha^{-1} produced similar net economic returns for organic compared to fallow treatments with 300 kg N ha^{-1}. Nitrogen fertilizer input can be reduced by at least 100 kg N ha^{-1} if common vetch is in the mixture and produces more than 5000 kg ha^{-1} of biomass (130-180 kg N ha^{-1}).

Introduction

Synthetic N fertilizer is one of the most energetically costly agrichemicals to produce, distribute, and apply (Magdoff, 2007). Organic farming systems use a variety of sources of N, including manures, composts, specialty animal processing by-products (e.g. fish, feather, and blood meal), and legumes (Berry et al., 2002; Gale et al., 2006). All of these sources differ in cost, nutrient content, mineralization rate, and environmental impact (Gale et al., 2006). Crews and Peoples (2004) suggest that the energetic basis of legume N_2 fixation (solar energy) is more sustainable than are fertilizer N sources, which require significant amounts of non-renewable fossil fuels or other commercial energy sources to produce and transport. Substituting legume-supplied N for manufactured N can potentially save 15,000 MJ·ha^{-1} (Pimentel et al., 1973; Buffington and Zar, 1977) primarily in natural gas. Ess et al. (1994) found that in both conventional and no-till systems, cover-cropped treatments used about half as much energy per hectare as the corresponding winter fallow N fertilizer treatments.

Legume cover crops have long been used by farmers as an economical N source to yield multiple benefits in agro-ecosystems (McCracken et al., 1994; Wyland et al., 1996; Dabney et al., 2001). The amount of nitrogen legumes are able to fix and contribute to subsequent crops varies considerably, often from 70 to 150 kg N ha^{-1} (Sullivan et al., 1991; Rannells and Wagger, 1996). This variability is partially due to soil factors such as microbial activity, pH, moisture content and temperature. Other factors that determine the N contribution of a legume cover crop are C:N ratios of the cover crop, plant-available N in the soil, and the genetic potential of the legume species (Fageria et al., 2005).

Non-legume cover crops contribute carbon (C) to soil through increased biomass production and increased soil organic matter. Non-legume cover crops also have been suggested to be a more effective NO_3^- sink than legumes (Meisinger et al., 1991). McCracken et al. (1994) suggest that rye may have prevented NO_3^- leaching more effectively than did vetch, due to more rapid growth development in the fall and resumed growth earlier in the spring.

Residues from non-legume cover crops may have high C:N ratios, as well as high concentrations of cellulose and lignin. Nitrogen mineralization of organic materials decreases when the lignin content is >10% on a dry-matter basis for legumes and >14% on a dry matter basis for non-legumes (Constantinides and Fownes, 1994; Honeycutt et al., 1993). Therefore, using a non-legume monoculture may immobilize N making it unavailable to subsequent crops (Ranells and Wagger, 1996). One management option for reducing the C:N ratio of non-legume cover crops is to mix them with legume cover crops (Kuo and Sainju, 1998, Rannells and Wagger, 1996, Sainju et al., 2005).

Using mixtures of legume and non-legume cover crops, such as cereals may offer advantages to growing the cover crop species as sole crops. Potential advantages include: increased biomass yields, reduced N leaching compared with legumes, and increased crop productivity compared with non-legumes (Ranells and Wagger 1996; Sainju et al. 2005). Soil mineralization rates of N from crop residues are determined primarily by the N concentration in the plant material. For example, combining rye with crimson clover or hairy vetch in biculture can increase N concentration of the rye, thereby decreasing the C:N ratio. Ranells and Wagger (1996) found that the C:N ratio decreased 46% when rye was grown in biculture with hairy vetch, compared to rye grown as a monoculture. Sullivan et al. (1991) demonstrated that rye from a vetch-rye biculture had a C:N ratio of 47 compared with 59 for the rye monoculture. Decreasing the C:N ratio results in less potential for N immobilization from the rye residue (Sullivan et al., 1991; Ranells and Wagger, 1996; Vaughan and Evanylo, 1998). A greater C:N ratio (>30:1) leads to less net mineralization (Berry et al., 2002; Chaves et al., 2007).

In this study, one legume and two non-legume cover-crop cultivars were evaluated as sole crops and as mixtures. They included common vetch (*Vicia sativa*), phacelia (*Phacelia tanacetifolia*), 'Monida' oats (*Avena sativa* L.), phacelia plus common vetch, and 'Monida' oats plus common vetch. A fallow treatment without cover crops was used as the control. These cover crops were selected based upon different characteristics. Common vetch (*Vicia sativa*) is a winter-annual legume used in the Willamette Valley. 'Monida' oats was selected for its ability to establish quickly and is commonly used by vegetable growers in the Oregon Willamette Valley (Luna, 2007). One of the primary reasons for evaluating phacelia as a cover crop was the possibility for substitution of phacelia for cereals in the cover crop mixtures. Phacelia has a very different root structure than cereals and the above-ground plant is much more fragile and succulent than the cereals as it approaches maturity (Luna, 2007). These differences in physical structure of the cover crop may allow growers to delay killing the cover crop and accumulate more biologically-fixed nitrogen in the legume component of the cover crop. Also, more biomass carbon is accumulated adding to soil organic matter.

Cover crops can serve as a nutrient source for subsequent crops, and can be economically beneficial when fertilizer inputs are reduced without a yield reduction. Many organic-vegetable growers are unable to accurately adjust N fertilizer applications based upon uncertainty of the cover crop contribution.

"Nitrogen fertilizer equivalency" is the difference of fertilizer required to produce equivalent yields, between a cover crop and a no-cover crop fallow. One way to estimate N fertilizer equivalency is to compare different cover crop and fertilizer treatments to a no-cover crop/0 fertilizer N control (Mangan et al., 1991). Legume cover crops have been shown to have a N-fertilizer equivalency ranging from 70 to 150 kg N ha^{-1} which is generally correlated to higher N contents than non-legumes and greater mineralization potential as indicated by C:N ratios of 20:1 and less (Doran and

Smith, 1991; Sullivan et al., 1991; Rannells and Wagger, 1996). Berry et al. (2002) suggest that within a three-month period the incorporation of leguminous crops can release about 150 kg N ha^{-1} of mineral N. Non-legumes often have a low or even negative N fertilizer equivalency due to a lower N concentration and a greater C:N ratio, which leads to N immobilization (Doran and Smith, 1991).

The N requirement for maximum yield in broccoli ranges from 270 $kg \cdot ha^{-1}$ (Everaarts and de Willigen, 1999a), to 465 $kg \cdot ha^{-1}$ (Zebarth et al., 1995). Greenwood et al. (1980) obtained maximum broccoli yield in England at N rates of approximately 400 kg N ha^{-1}, but calculated the N rate for maximum economic return to be 248 kg N ha^{-1}. According to Zebarth et al. (1991a), caution should be used in the development of N fertility recommendations for vegetable production based on crop yield response alone, because percent N recovery is low at the high N rates applied to obtain maximum yields. Muramoto et al. (2007) found that the feather meal N replacement value of a mixed legume/cereal cover crop was 71 to 92 kg N ha^{-1}, and that 14-23% of the cover crop N was utilized by the successive broccoli crop.

The following experiment was designed to evaluate cover crop and N effects in organic broccoli production in western Oregon. The specific objectives of this experiment were to: 1) evaluate biomass production and N accumulation from selected cover crop treatments; 2) compare the effects of selected cover crops grown as sole crops and as mixtures on broccoli yield, yield components, and net economic benefit; and 3) estimate the quantity of feather meal N replaced by cover crops.

Materials and Methods

Site Description

Field studies were conducted in 2007 and 2008 at the Oregon State University Lewis Brown Farm (LBF) located near Corvallis. The soil was a Chehalis silt loam. The field used in 2007 was planted in blackberries from 2001 until 2003 and was fallowed for two years before the cover crop trials were planted during the first week of October 2006. In preparation for planting in 2007, the field was disked and rolled with a cultipacker; prilled lime was applied on 23 May at a rate of 2.7 $t \cdot ha^{-1}$ and incorporated with a 2.4 m wide tine-harrow drag.

The 2008 experiment was relocated to an adjacent plot at LBF. The field was planted in grasses 2003 through 2004, assorted vegetables in 2005, summer buckwheat in 2006 and fallowed in 2007 before the cover crop trials were planted in October 2007. In preparation for planting in 2008, the field was disked and rolled with a cultipacker, and prilled lime was applied on 24 September 2007 at a rate of 2.2 $t \cdot ha^{-1}$ and incorporated with a 2.4 m wide tine-harrow drag. No synthetic insecticides or fertilizers had been applied for at least three years prior to the start of these experiments.

Cover Crops

Cover-crop treatments were arranged in a randomized-block design with six treatments and four replications. To evaluate cover crop and N interactions, a split-plot design was established, details of which will be provided in the ‘Broccoli Experimental Design’ section.

2007 Experiment. Experimental treatments consisted of five cover-crop treatments and a no-cover crop control (Table 2-1). Cover-crop plots were 4.6 m x 36.6 m. To ensure accurate and uniform seeding rates, cover-crop plots were subdivided into 4.6 m x 6.1 m subplots, and strings were stretched to define the sub-plot boundaries. Cover-crop seed was weighed separately for each subplot and the seed distributed by hand.

The vetch in all treatments was inoculated with *Rhizobium leguminosarum* at the rate of approximately $4 \cdot g \cdot kg^{-1}$ of seed. A few drops of water were added to the seed before mixing in the *Rhizobium*. Because of the small size of the phacelia seed, a “seed shaker” was made by drilling 0.2 cm diameter holes in the lid of a Mason® fruit jar. After seeding, strings were removed and a 2.4 m wide tine-harrow drag was pulled longitudinally down the length of the plots to cover the seed. After planting, irrigation was applied with overhead sprinklers several times to assure germination and establishment during a very dry October.

2008 Experiment. Experimental treatments consisted of the same five cover-crop treatments and a no-cover crop control, but the phacelia seeding rates were increased slightly (Table 2-1). A randomized complete block design with four replications was used. Cover-crop plots were 4.1 m x 24.4 m. Cover crops were hand seeded as described above for 2006.

The vetch treatments were inadvertently not inoculated with *Rhizobium leguminosarum* as they were the previous year. After seeding, a 2.4 m wide tine-harrow drag was pulled longitudinally down the length of the plots to cover the seed. Irrigation was not needed due to plentiful rains in October.

Cover crop biomass and N content estimation

Cover crop above-ground biomass was sampled in early May in both 2007 and 2008 by clipping cover crops at the soil surface with a sickle bar mower. Two biomass samples were taken in each cover crop treatment by mowing across each replication using a 0.76 m-wide powered sickle bar mower. Cover crops were raked within a 4.6 m-long section and weighed using a hanging scale. A sub-sample was then taken and returned to the laboratory where the cover-crop species and weeds were separated and placed in paper bags. The samples were oven-dried at 65^{o}C for 72 hours and then weighed to determine percent dry matter. Sub-samples were analyzed for percent total C and total N by the OSU Central Analytical Laboratory using a LECO CNS-2000®.

Broccoli Experimental Design

Cover crops were flail mowed and a Tortella® power-spader and Lely Roterra® were used to incorporate the cover-crop biomass and prepare a seed bed in all treatments. A split-plot randomized block design was established, with cover-crop plot split into four sub-plots with four N fertilizer rates (0, 100, 200, and 300 kg N ha^{-1}). Feather meal, an organically approved source of N, was selected for this experiment because it has an N-P-K analysis of 12-0-0. Feather meal was weighed and hand-applied in an approximate 15 cm-wide band over the row.

2007 Experiment. Feather-meal was incorporated to a depth of 5 to 8 cm using a tine harrow on 29 May. 'Arcadia' broccoli seedlings were planted in the greenhouse on 19 April in 200-cell trays using an organically-approved potting mix (Appendix I). These seedlings were transplanted on 30 May through 1 June using a mechanical transplanter and irrigated immediately afterward. Broccoli rows were on 90 cm centers, with plants spaced at 46 cm apart within the rows, for a planting density of 24,200 plants/ha.

Tractor-mounted sweep cultivators and hand hoeing were used for weed control. Insect populations were monitored weekly by visual examination of 40 broccoli plants randomly selected within the block. Pyrethrin (0.06 kg·A.I. ha^{-1}) was applied with a power spray-boom at 400 psi to control cabbage aphid on 21 June and again on 3 July (0.12 kg·A.I. ha^{-1}). To control flea beetles and cabbage aphids, azadirachtin (0.15 kg·A.I. ha^{-1}) was applied using a Solo® backpack sprayer on 20 July. To control cabbage loopers and imported cabbage worm, spinosad (0.10 kg A.I.·ha^{-1}) was applied using a Solo® backpack sprayer on 6 Aug.

2008 Experiment. 'Arcadia' broccoli transplants were grown in the greenhouse as in 2007. Planting density was increased in 2008 from 24,200 plants/ha to 36,300 plants/ha, by reducing in-row plant spacing to 36 cm and between row spacing to 75 cm. This row-spacing configuration was used to more closely mimic the planting density of vegetable growers. A rotary strip-tiller was used to mark the rows in all plots. Feather meal was weighed and hand applied in a 15 cm-wide band over the row and incorporated to a depth of 10 to 15 cm using the strip-tiller. Broccoli seedlings were hand-transplanted on 10 June and irrigated immediately afterward.

Tractor-mounted sweep cultivators and hand hoeing were used for weed control. Insect population densities were estimated each week by visual observation. Flea beetle population was estimated to be 5.6 beetles/plant on 19 June. To control flea beetles, azadirachtin (0.15 kg·A.I. ha^{-1}) was applied using a Solo® backpack sprayer on 23 June.

Flea beetle population density was unaffected, so the rate of azadirachtin was increased to 0.3 kg A.I. ha^{-1} and applied again on 26 June. Flea beetle population was still at an average of 4.6 beetles/plant, so rotenone (0.04 kg·A.I. ha^{-1}) was applied on 28 June. In an effort to mechanically control flea beetle population, a modified Sears® Craftsman leaf blower was used to vacuum beetles off the plants on 9 July and 10 July. In a final effort to protect the nearly defoliated broccoli plants from flea beetles, spinosad (0.3 kg A.I. ha^{-1}) was applied using a Solo® backpack sprayer on 10 July.

To control cabbage aphid, pyrethrin was applied on 7 Aug. (0.15 kg A.I. ha^{-1}) in a tank mix with spinosad (0.15 kg A.I. ha^{-1}) to control cabbage loopers and imported cabbage worm. Pyrethrin was applied to control cabbage aphid once again on 22 Aug. (0.14 kg A.I. ha^{-1}) with a hand gun sprayer at 200 psi.

Broccoli Yield Estimation

2007 Experiment. Fifteen broccoli plants were selected to be harvested from the center two rows within each treatment plot. The broccoli plants selected for harvest had plants on both sides. Selected heads larger than 10 cm in diameter were harvested upon maturity. Broccoli was harvested on 3 to 6 day intervals, from 14 Aug. through 30 Aug., for a total of five cuttings. The weight of the total plot sample, number of heads harvested, and size or width of the individual broccoli heads were recorded.

2008 Experiment. Eighteen broccoli plants were selected from each treatment for harvesting. Broccoli was harvested on 3 to 4 day intervals, from 26 Aug. through 12 Sept., for a total of six cuttings. The weight and size of the broccoli heads were recorded as in 2007.

N-fertilizer equivalency

Pair-wise comparisons were made between the yield from the fallow plots with 300 kg N ha^{-1} to the other treatments in 2007 that yielded 10 t·ha^{-1} or more and received less than 300 kg N ha^{-1}.

Economic Analysis

The cost associated with each cover crop x N fertilizer treatment was estimated using the costs of seed, as well as the variable cash costs for cover cropping from the enterprise budget analysis for organic broccoli production in the Willamette Valley (Julian et al., 2008). The irrigation cost was adjusted to $78.50, because only one inch of water was applied to the cover crop in the fall. Cost of feather meal N was based on purchase price of $0.71/kg for this 12% N meal ($5.93/kg N). The value of organic broccoli was set at $1.67/kg based on actual prices paid during 2007 and 2008 by wholesale organic produce buyers. The net benefit associated with each treatment was then calculated by subtracting the total cost per hectare from the value of the average broccoli yield produced by each treatment.

Statistical Analysis

All data were analyzed using SAS (SAS, 2008) using PROC MIXED to determine treatment class effects and calculate p-values for pair-wise comparisons. The treatment classes were cover crop treatment (6 levels), and N rate (4 levels).

Results

Cover crop biomass and N content estimation

2007 Experiment. The phacelia-vetch mixture produced the highest above-ground, dry matter (10,530 kg ha^{-1}) similar to the oat-vetch mixture (8890 kg ha^{-1}) ($p=.22$) (Table 2-2, Fig. 2-1). Vetch made up more than half of the total biomass of both mixtures. The oats and oat plus vetch mixture produced similar quantities of biomass ($p=.45$). Phacelia as a sole crop produced less biomass than when grown with vetch ($p<.01$). Cover crop treatments including vetch (V, OV, PV) accumulated more than three times the total N than the non-legume cover crops, with a majority of the N being contributed by the vetch component (Table 2-2, Fig. 2-2). The non-legume component of the mixtures produced a higher percent N than the same crop grown as a sole crop (Table 2-2).

2008 Experiment. All cover crop treatments produced much less biomass and accumulated less N in 2008 than in 2007. Average vetch biomass ranged from 5,000 $kg\cdot ha^{-1}$ (2007) to 1,000 $kg\cdot ha^{-1}$ (2008); oats ranged from 7,000 $kg\cdot ha^{-1}$ (2007) to 4,000 $kg\cdot ha^{-1}$ (2008); and phacelia ranged from 4,000 $kg\cdot ha^{-1}$(2007) to 700 $kg\cdot ha^{-1}$ (2008).

The treatments including oats (O, OV) produced the most biomass (Table 2-2, Fig. 2-3), and the oat-vetch mixture produced more nitrogen than all of the other treatments (Fig. 2-4), except for phacelia-vetch ($p=.22$). The non-legume component of the mixtures did not contain a higher percent N than the same crop grown as a sole crop as in 2007, which may have been due to less vetch biomass, hence less N fixation and accumulation (Table 2-2).

2007 Broccoli Yield and Yield Components

There was a statistically significant interaction between cover-crop treatments and N fertilizer rates in relation to marketable head yield ($p<.01$), number of heads ($p<.01$), head size ($p=.04$), and head weight ($p=.08$) (Table 2-3). Therefore the cover-crop treatment effects were examined for each N-rate separately.

Broccoli total yield. At the-zero N rate, both oat and phacelia sole crops suppressed broccoli yield compared to the fallow control (Fig. 2-5A). Also, the yield from the phacelia-vetch treatment exceeded that of the fallow treatment ($p<.01$) whereas, the oat-vetch treatment was similar to the fallow treatment ($p=.29$) (Table 2-4; Fig. 2-5A).

At 100 kg·ha^{-1} of N, oats continued to reduce yield (5.1 t·ha^{-1}) compared to the fallow treatment (8.3 t·ha^{-1}) ($p=.05$), whereas there was no yield loss in the phacelia treatments (9.0 t·ha^{-1}) ($p=.64$) (Table 2-4; Fig. 2-5B). The yield suppressive effect of phacelia was overcome by the addition of vetch or 100 kg N·ha^{-1}, whereas oats required the addition of vetch or 200 kg N ha^{-1} (Fig. 2-5A and B). The apparent nitrogen contribution by the vetch in the cover crop mixtures was obscured at the higher N fertilizer rates of 200 and 300 kg N ha^{-1} (2-5C and D).

Broccoli cumulative yield. Although broccoli was harvested over five dates, a majority of the broccoli from all treatments was harvested by the third harvest date. For example, 89% of the broccoli yield (13.4 t·ha^{-1}) was harvested from the phacelia-vetch treatment with 200 kg N ha^{-1} by the third harvest date (Fig. 2-6C).

Number of heads. Cover-crop treatment effected the number of heads produced with zero ($p<01$) and 100 kg·N ha^{-1}($p<.01$), however that effect was lost at 200 ($p=.50$) and

300 kg·N ha^{-1} (p=.23) (Table 2-3, Fig. 2-7). Oats and phacelia planted as sole crops with zero kg N·ha^{-1} produced fewer heads compared to the other cover crop treatments (Fig. 2-7A). At 100 kg·N ha^{-1}, the oats treatment produced fewer heads than oat-vetch (p<.01), whereas phacelia produced a similar number of heads as phacelia-vetch (p=.35) (Table 2-5, Fig. 2-5B).

Broccoli head size. The non-legume treatments (O, P) produced a smaller average head size than the fallow plots at zero kg·ha^{-1} of N (p<.01), but that effect was lost at 100 kg·ha^{-1} of N (p=.11) (Fig. 2-8). At zero kg·ha^{-1} of N, oats produced smaller heads than oat-vetch (p<.01), and phacelia produced smaller heads than phacelia-vetch (p<.01) (Table 2-6).

Broccoli head weight. Average head weights exhibited similar trends to that of broccoli head size. The non-legume treatments reduced head weight at the zero N-rate (p<.01), but that effect was lost at 100 kg·ha^{-1} of N (p=.17) (Table 2-3). At zero kg N ha^{-1}, the cover crop treatments including legumes (V, OV, PV) produced greater head weights than fallow and the non-legume treatments (O, P) (Table 2-7).

<u>2008 Broccoli Yield and Yield Components</u>

Both cover crops and N rate influenced broccoli yield and yield components (Table 2-3). There was no interaction between cover crop treatments and N fertilizer rates in relation to broccoli yield (p=.60), head size (p=.96), or head weight (p=.60) therefore, data were pooled and analyzed by main effects. There was however a significant interaction between cover crop and N rate for number of heads harvested, therefore the cover crop treatment effects were examined for each N rate separately (Table 2-3).

Broccoli total yield. Across N rates, the non-legume treatments (O, P) reduced yields compared to the fallow control ($p<.01$), whereas the legume treatments (V, OV, PV) produced similar yields to fallow ($p=.46$, .81, .10 respectively) (Table 2-8). As in the previous year, the addition of vetch to oats and phacelia overcame the yield suppressive effects when planted as sole crops (Table 2-8, Fig. 2-9).

Broccoli cumulative yield. Although cover crops affected total broccoli yield, the rate of accumulation across the 5 harvest dates was similar (Fig. 2-10).

Number of heads. Cover crop had an effect on the total number of heads harvested at all of the N fertilizer rates (Fig. 2-11). At 0 kg N ha^{-1} all of treatments produced a similar number heads compared to the fallow, except for oats which produced fewer heads ($p<.01$) (Table 2-9, Fig. 2-11). The addition of vetch to oats and phacelia with 100 kg N ha^{-1} resulted in more broccoli heads than either planted as sole crops (Table 2-9, Fig. 2-11). At 300 kg N ha^{-1}, the addition of vetch to oats and phacelia still produced more heads than either planted as a sole crop, and phacelia-vetch produced more heads than all of the other treatments (Table 2-9, Fig. 2-5).

Broccoli head size. Cover crop had no effect ($p=.51$) on broccoli head size, whereas N rate had a significant effect ($p<.01$) (Table 2-3) (data not shown).

Broccoli head weight. Head weights exhibited similar trends to head size. Cover crop had no effect ($p=.20$) on broccoli head weight, however head weights increased with increasing N rate ($p<.01$) (Table 2-3).

N fertilizer equivalency

In 2007, the largest yield benefit compared to fallow with 300 kg N ha^{-1} came from phacelia-vetch with 200 kg N ha^{-1} (p=0.20) (Fig. 2-12). Oat-vetch with 100 kg N ha^{-1} and vetch with 200 kg N ha^{-1} produced similar yields to fallow with 300 kg N ha^{-1} (p=0.97 and .84 respectively) (Fig. 2-12). These data suggest the vetch based cover crops contributed at least 100 kg ha^{-1} of feather meal N equivalence. These comparisons were not made in 2008, because there was no interaction between cover crop and N rate (p=0.60) (Table 2-3).

Economic analysis

2007 experiment. The greatest net benefit, considering the broccoli value, the variable costs associated with cover cropping, and the cost of feather meal N and seed, was in the phacelia-vetch treatment with 200 kg N ha^{-1}. This was the only treatment with a greater net benefit than no cover crop with 300 kg N ha^{-1}(p=.15) (Table 2-10). However, there were several treatments that had a similar net benefit to fallow with 300 kg N ha^{-1} but with less N applied, including: oat-vetch with 100 and 200 kg N ha^{-1} ,(p=.66 and .67 respectively), phacelia with 200 kg N ha^{-1} (p=.72), and vetch with 100 and 200 kg N ha^{-1} (p=.49 and .70 respectively).

2008 experiment. No-cover crop N fertilizer combinations had a greater net benefit than no-cover crop with 300 kg N ha^{-1} (Table 2-11). However, both the oat and phacelia sole cover crops with 300 kg N produced nearly $4,000 less in net benefit than did the fallow, suggesting the economic cost of nitrogen immobilization by these cover crops.

The oat-vetch and phacelia-vetch mixtures on the other hand produced similar yields to the fallow at 300 kg ($p=0.37, 0.23$), again demonstrating the contribution of the legume in overcoming the yield reductions associated with the sole crops. Only vetch with 200 kg N ha^{-1} had a similar net benefit compared to fallow with 300 kg N ha^{-1} ($p = .41$). Caution must be taken in interpreting this partial budgeting analysis because other economic benefits of cover crops, such as improvements in soil organic matter and structure and erosion reduction were not calculated.

Discussion

A nitrogen deficit following incorporation of oat cover crops in the early stages of broccoli plant development likely reduced broccoli yield in 2007 and 2008 (see Chapter 3). The yield suppressive effect of phacelia was overcome by the addition of vetch or 100 kg N ha^{-1}, whereas oats required the addition of vetch or 200 kg N ha^{-1}. Vetch was in all of the cover crop treatments that had a net economic benefit similar or greater than fallow with 300 kg N ha^{-1}. Legume cover crops produced similar economic yields of organic broccoli with 100 kg N ha^{-1} as fallow with 300 kg N ha^{-1}. However this was dependent on how much vetch biomass is produced. When vetch produced more than 5000 kg ha^{-1} of biomass, fertilizer inputs could be reduced by approximately 100 kg N ha^{-1}.

Planting density was increased in 2008, to more closely mimic vegetable-growers' plant spacing. Population density can be the most important factor influencing broccoli yield (Wien and Wurr, 1997). Despite a reduction of head weight with high plant populations, marketable yields may increase simply due to increased numbers of heads (Dufault and Waters, 1985; Cutcliffe, 1971). Differences between 2007 and 2008 may have been more pronounced if the planting density were kept the same.

Cover crop stand is affected by environmental conditions as seen in the difference between the biomass produced in 2007 and 2008. ‘Monida’ oats established more quickly and produced more biomass under poor weather conditions than phacelia as seen in 2008. Also, the vetch was not inoculated in 2008, which may have contributed to the reduced biomass and N contribution. However, since there was much less biomass produced by phacelia and oats in 2008, the effects were likely due to poor establishment related to the colder and rainier weather conditions compared to 2007. Oats and phacelia planted as sole crops accumulated less N than when planted with vetch in 2007. This effect was not seen in 2008 due to much less vetch biomass and N accumulation.

Timing of incorporation is an important consideration whether using oats or phacelia alone or in a mixture with vetch. Clark et al. (1994) demonstrated with hairy vetch and cereal rye planted in mixtures or as sole crops, that N concentration decreased from early (April) to late (May) kill in Maryland. If oats were terminated earlier, the percent N likely would have been higher, and the yield reduction likely would have been less pronounced, because the N content would have been greater. Maximum biomass production from a cover crop is not always desirable from a fertility management perspective. However, early termination of an oat-vetch mixture early may mean compromising the maximum N-contribution from the vetch. Phacelia, with a lower C:N ratio and more easily incorporated residue may be a valuable substitution for cereals in cover crop mixtures. Estimating N release from cover-crop residue and the synchrony with broccoli N uptake will be evaluated and discussed in Chapter 3.

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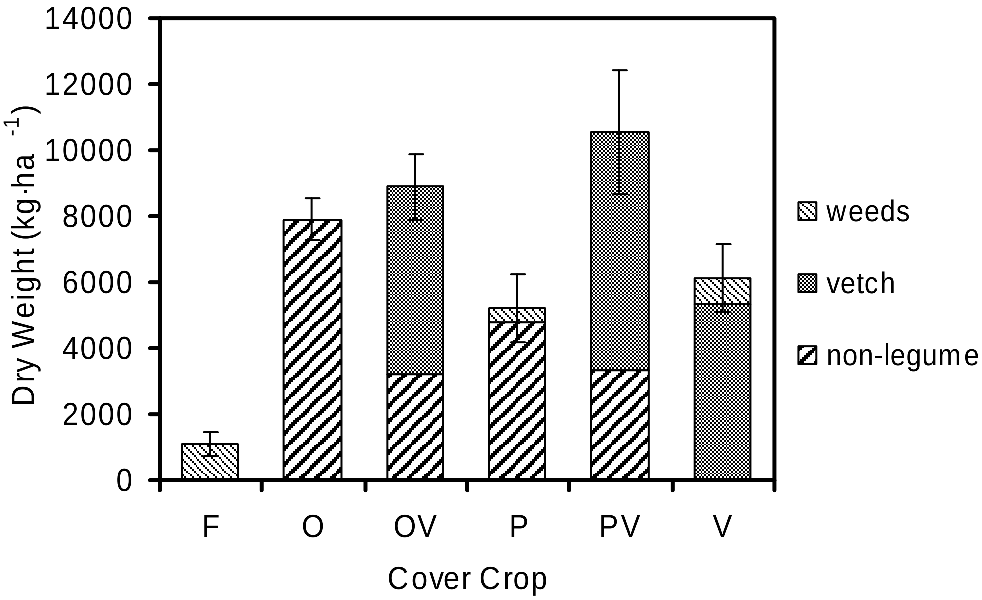
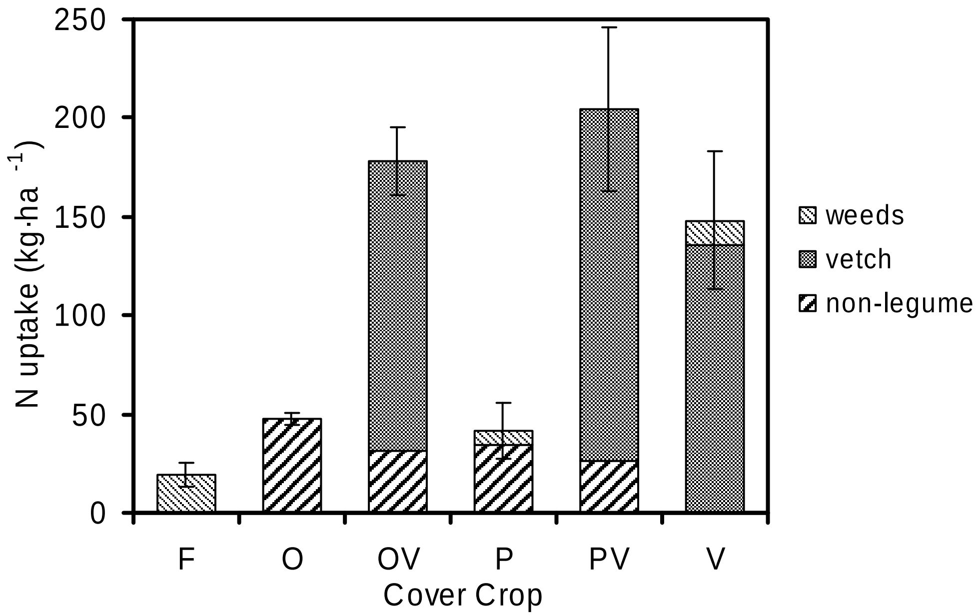


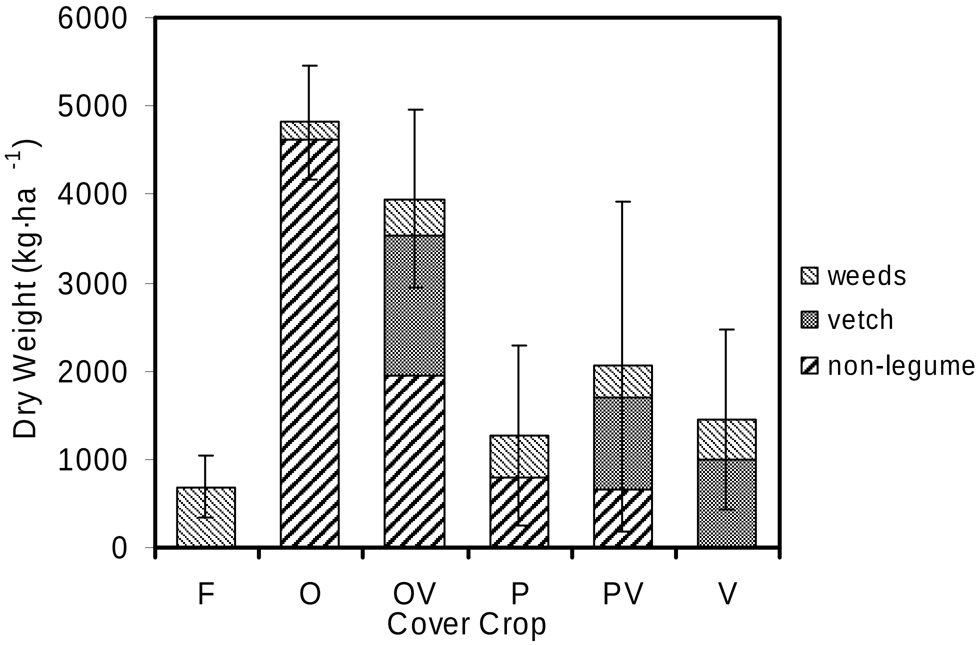
F	O	OV	P	PV	V	
-	<.01	<.01	<.01	<.01	<.01	F
	-	0.45	0.05	0.06	0.19	O
		-	0.01	0.22	0.05	OV
			-	<.01	0.49	P
				-	<.01	PV
					-	V

Fig. 2-1. Average cover-crop biomass and associated p-value comparisons for 2007. Cover crop treatments: F = fallow; O = oats; OV = oat-vetch; P = phacelia; PV = phacelia-vetch; V = vetch. Error bar is the standard error for the whole treatment, including each component (n=8).



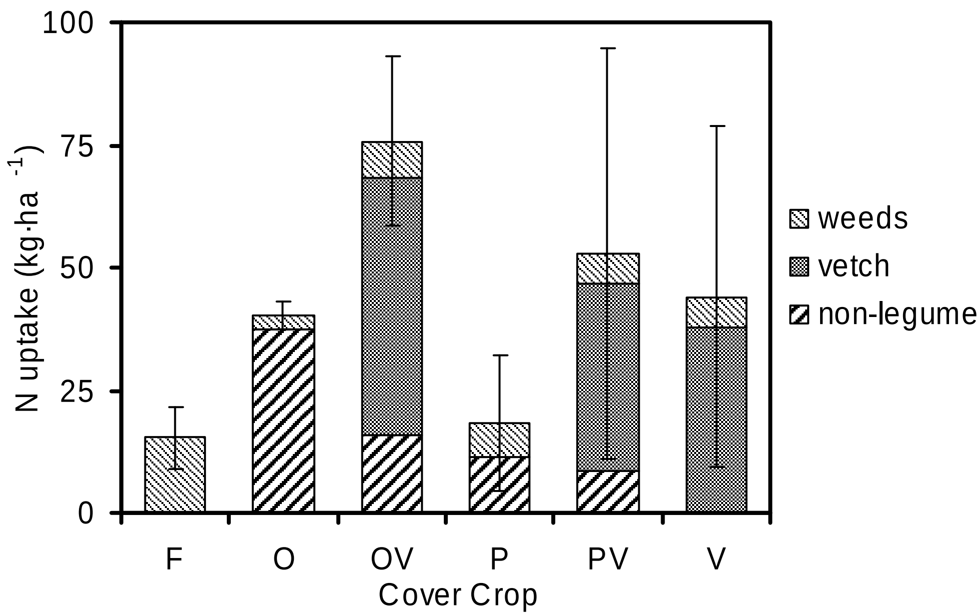
F	O	OV	P	PV	V	
-	0.36	<.01	0.47	<.01	<.01	F
	-	<.01	0.84	<.01	<.01	O
		-	<.01	0.38	0.33	OV
			-	<.01	<.01	P
				-	0.08	PV
					-	V

Fig. 2-2. Average cover-crop N uptake and associated p-value comparisons for 2007. Cover crop treatments: F = fallow; O = oats; OV = oat-vetch; P = phacelia; PV = phacelia-vetch; V = vetch. Error bar is the standard error for the whole treatment, including each component (n=8).



F	O	OV	P	PV	V	
-	<.01	<.01	0.46	0.04	0.30	F
	-	0.14	<.01	<.01	<.01	O
		-	<.01	0.01	<.01	OV
			-	0.15	0.76	P
				-	0.24	PV
					-	V

Fig. 2-3. Average cover-crop biomass and associated p-value comparisons in 2008. Cover crop treatments: F = fallow; O = oats; OV = oat-vetch; P = phacelia; PV = phacelia-vetch; V = vetch. Error bar is the standard error for the whole treatment, including each component (n=8).



F	O	OV	P	PV	V	
-	0.15	<.01	0.94	0.03	0.09	F
	-	0.04	0.18	0.35	0.78	O
		-	<.01	0.22	0.07	OV
			-	0.03	0.11	P
				-	0.51	PV
					-	V

Fig. 2-4. Average cover crop N uptake and associated p-value comparisons in 2008. Cover crop treatments: F = fallow; O = oats; OV = oat-vetch; P = phacelia; PV = phacelia-vetch; V = vetch. Error bar is the standard error for the whole treatment, including each component (n=8).

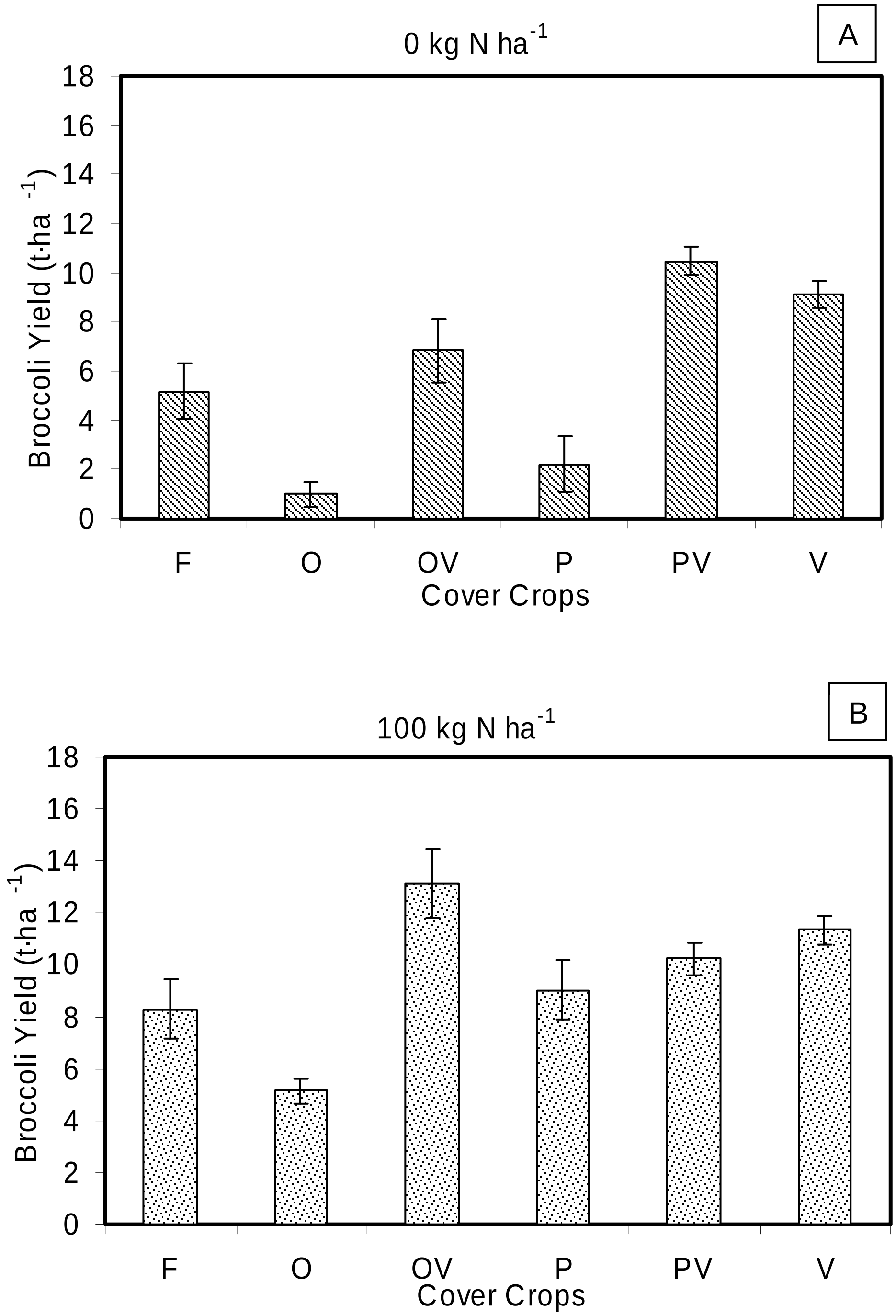


Fig. 2-5. Effect of cover crops on broccoli yield ($t \cdot ha^{-1}$) with 0 (A), 100 (B), 200 (C), and 300 kg N ha^{-1} in 2007. Cover crop treatments: F = fallow; O = oats; OV = oat-vetch; P = phacelia; PV = phacelia-vetch; V = vetch. Error bar represents the SE of the mean (n=4).

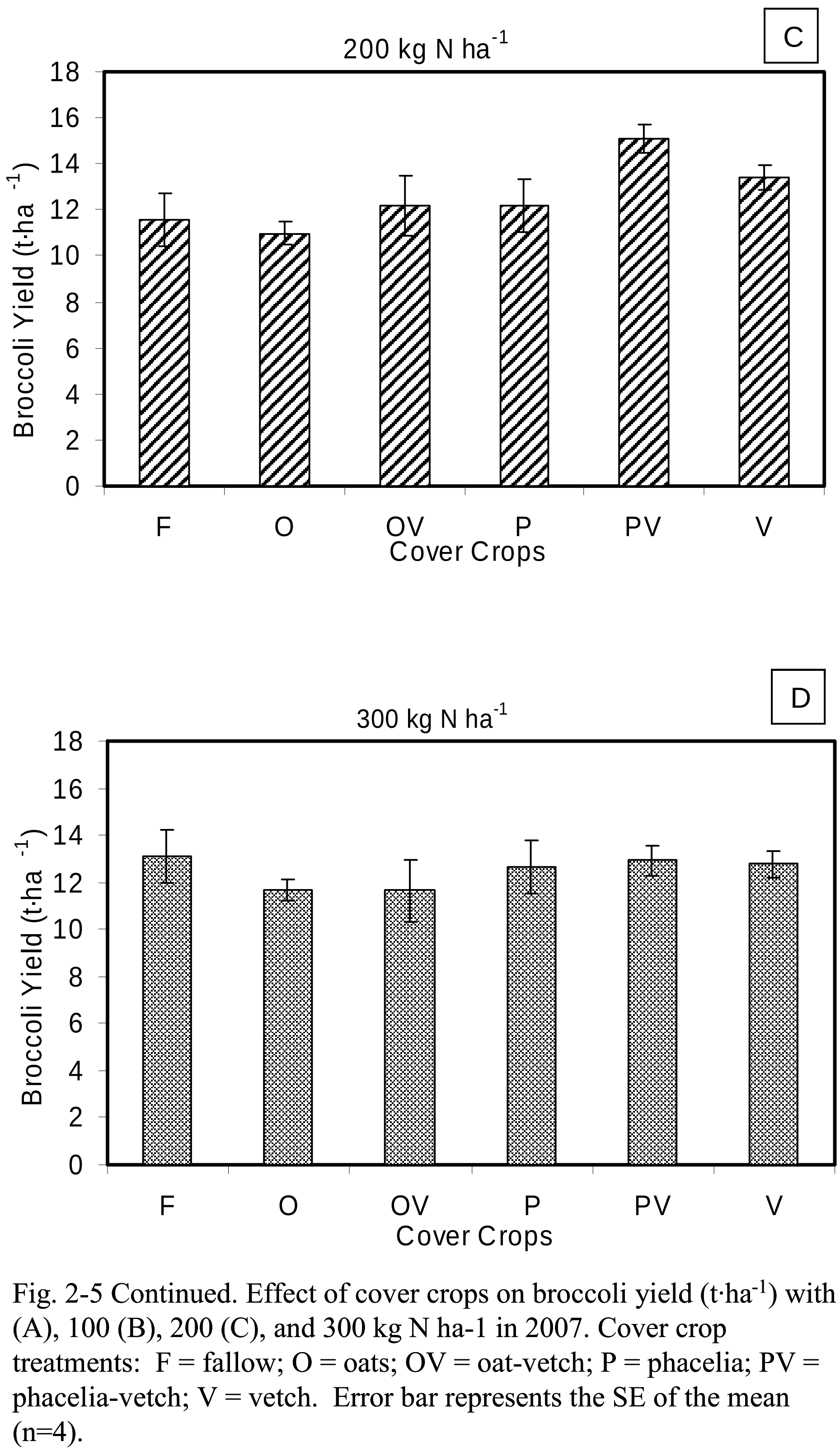
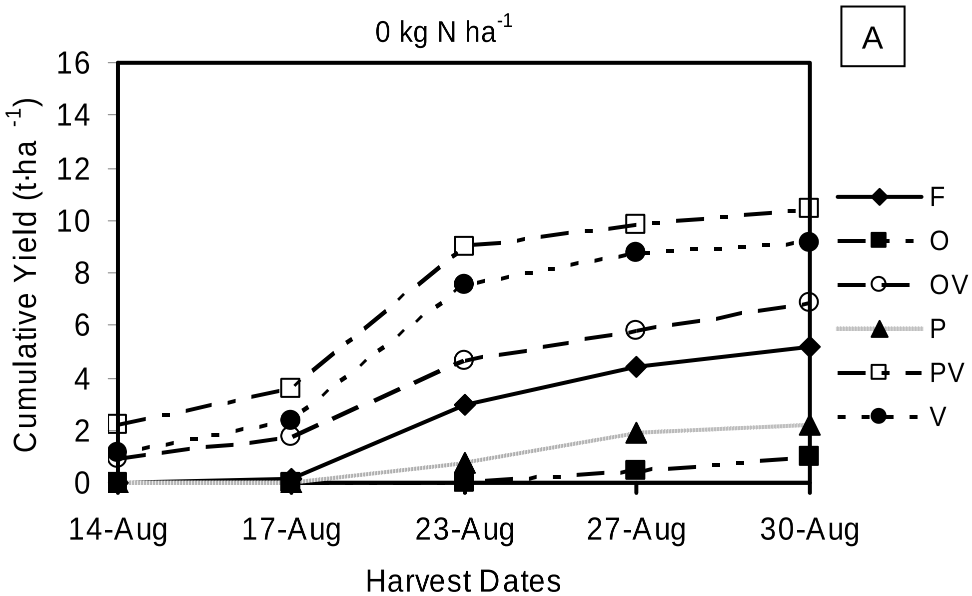


Fig. 2-5 Continued. Effect of cover crops on broccoli yield ($t{\cdot}ha^{-1}$) with 0 (A), 100 (B), 200 (C), and 300 kg N ha-1 in 2007. Cover crop treatments: F = fallow; O = oats; OV = oat-vetch; P = phacelia; PV = phacelia-vetch; V = vetch. Error bar represents the SE of the mean (n=4).



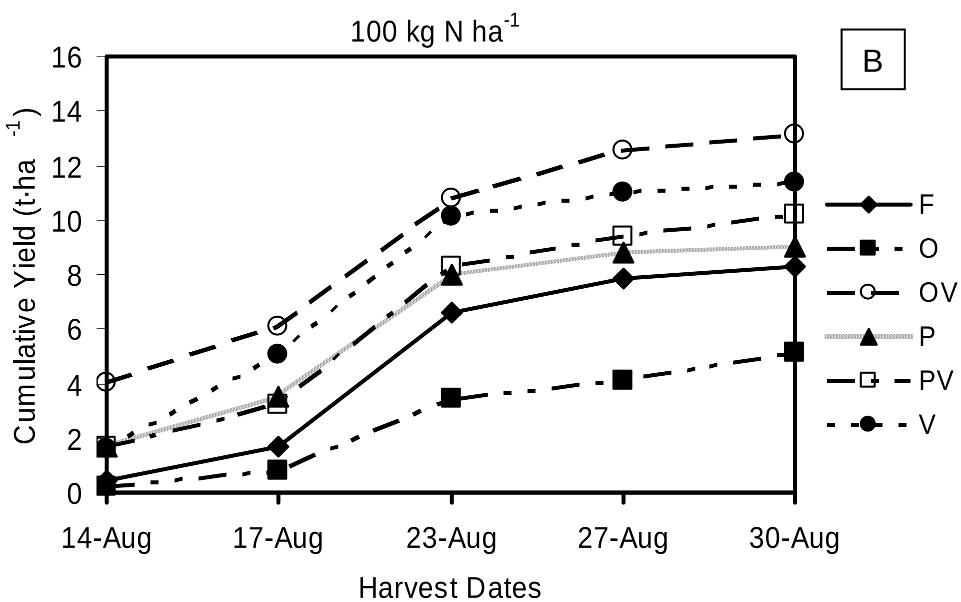
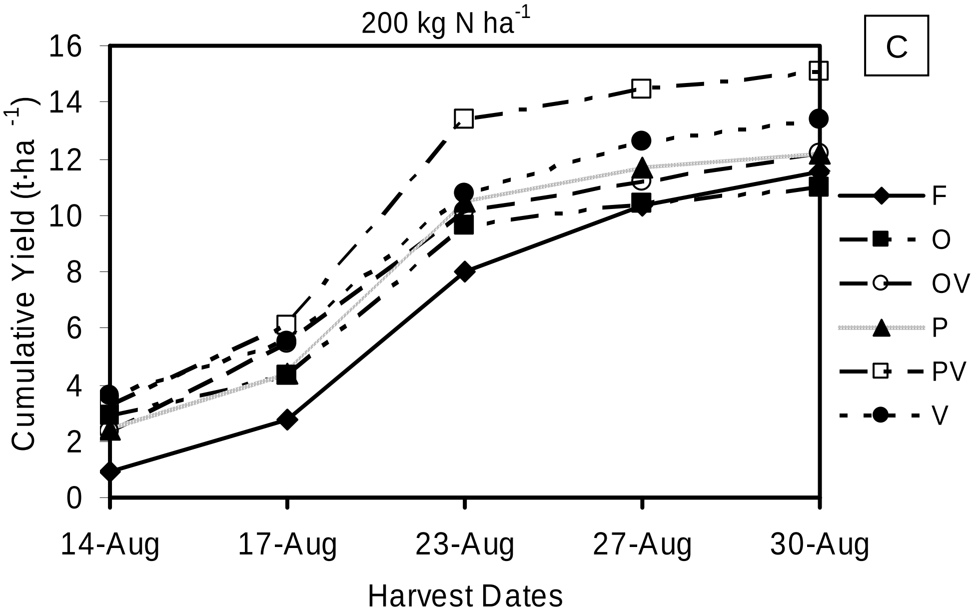


Fig. 2-6. Cumulative broccoli yield over harvest period for cover crop treatments with 0 (A), 100 (B), 200 (C), and 300 (D) kg N ha^{-1} in 2007. Cover crop treatments: F = fallow; O = oats; OV = oat-vetch; P = phacelia; PV = phacelia-vetch; V = vetch.



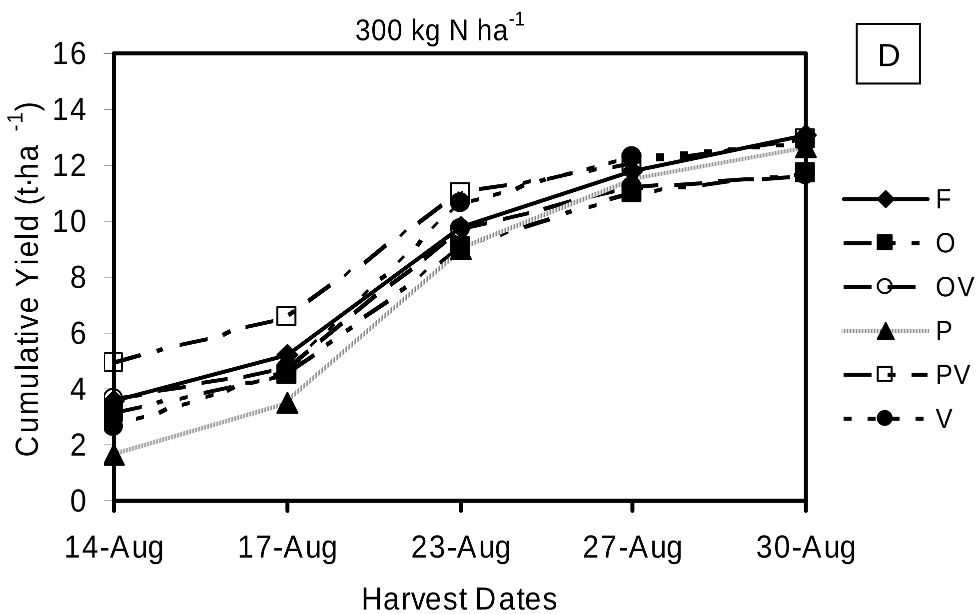


Fig. 2-6 Continued. Cumulative broccoli yield over harvest period for cover crop treatments with 0 (A), 100 (B), 200 (C), and 300 (D) kg N ha^{-1} in 2007. Cover crop treatments: F = fallow; O = oats; OV = oat-vetch; P = phacelia; PV = phacelia-vetch; V = vetch.

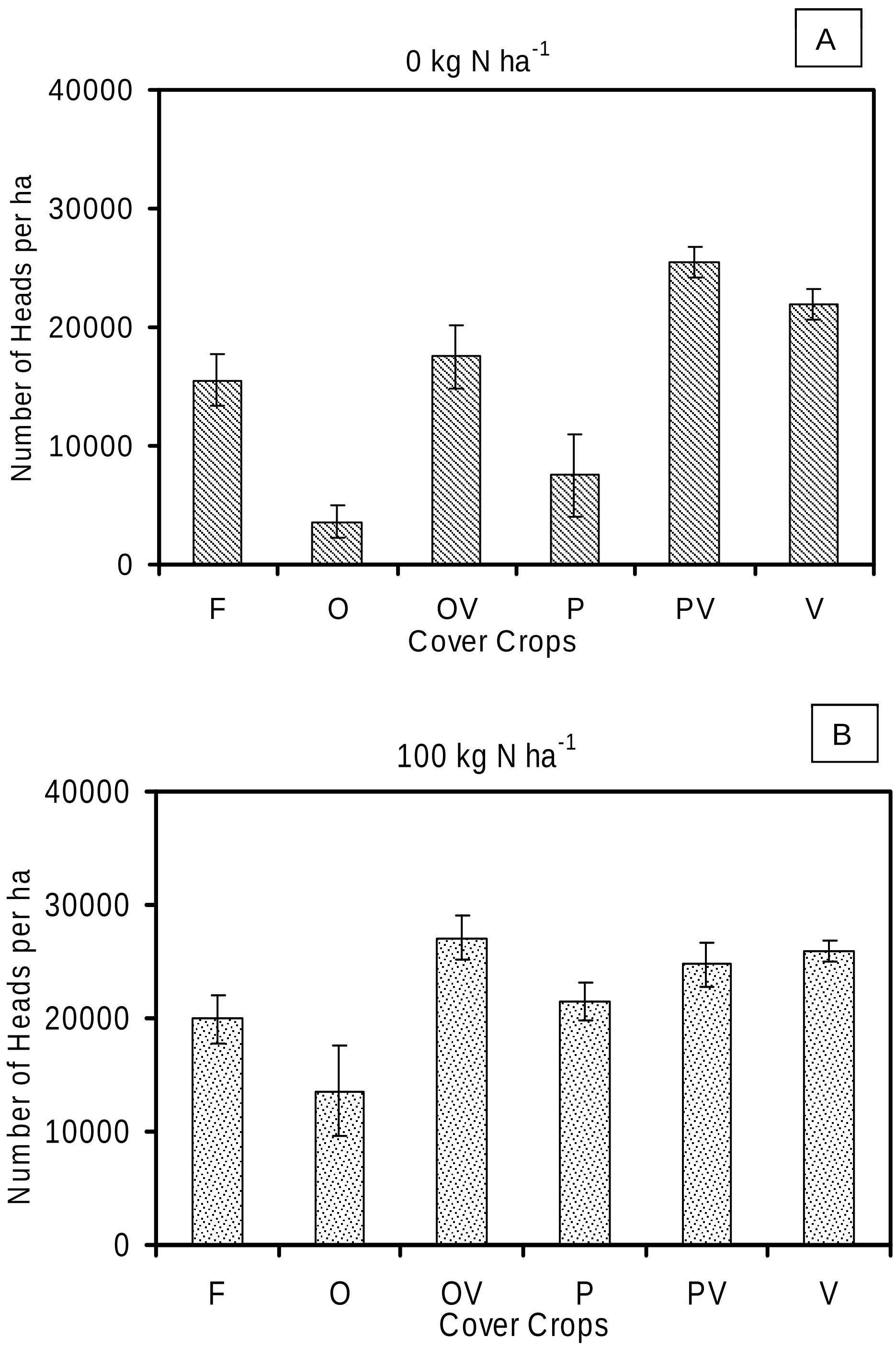


Fig. 2-7. Average number of broccoli heads harvested per hectare in zero (A) and 100 kg N ha^{-1} (B) treatments in 2007. Cover crop treatments: F = fallow; O = oats; OV = oat-vetch; P = phacelia; PV = phacelia-vetch; V = vetch. Error bar represents the SE of the mean (n=4).

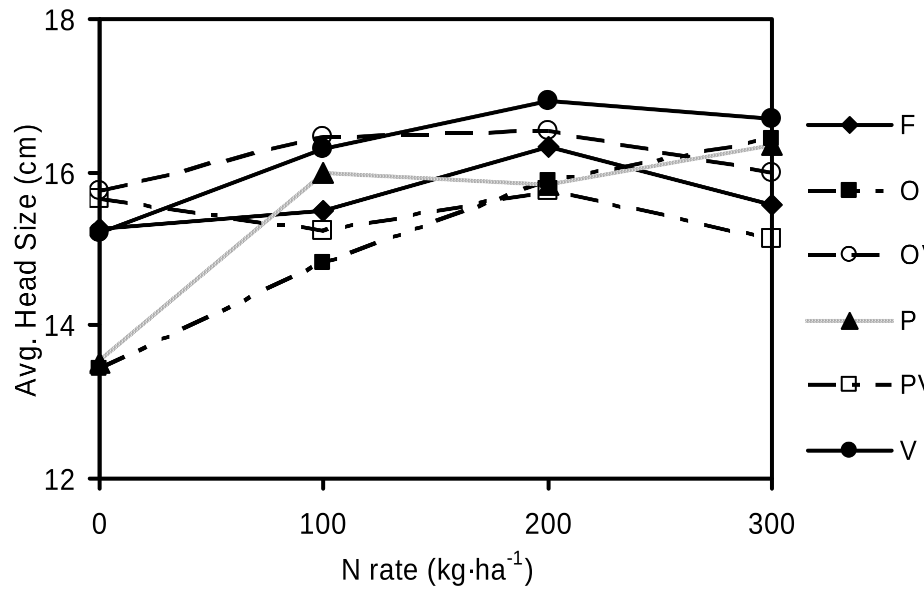


Fig. 2-8. Effect of N fertilizer rate on average head size in 2007. Cover crop treatments: F = fallow; O = oats; OV = oat-vetch; P = phacelia; PV = phacelia-vetch; V = vetch.

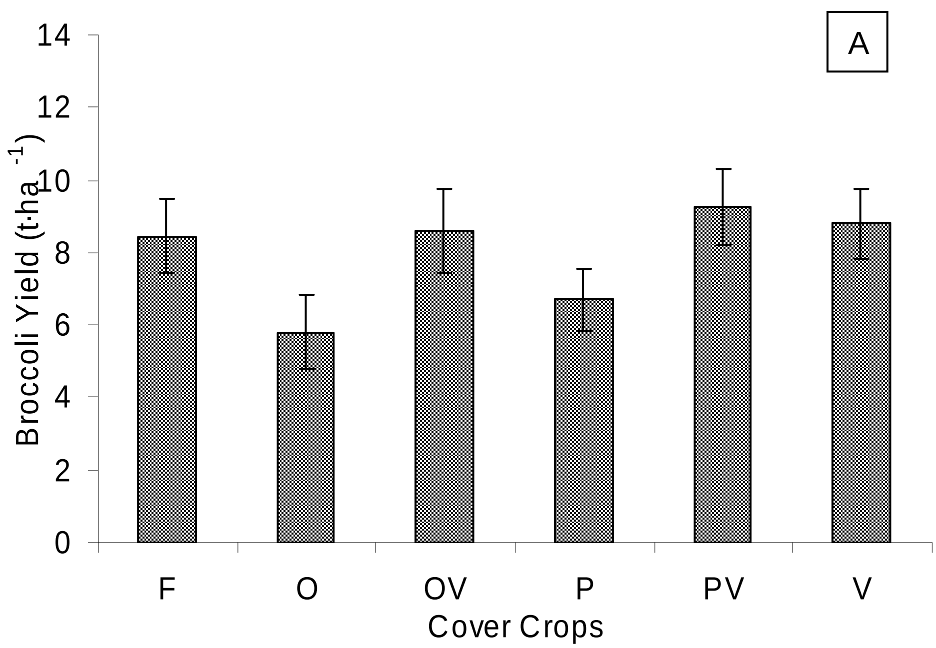


Fig. 2-9. 2008 broccoli yield pooled across N rate (A) and cover crop (B). Cover crop treatments: F = fallow; O = oats; OV = oat-vetch; P = phacelia; PV = phacelia-vetch; V = vetch. Error bar represents the SE of the mean (n=16).

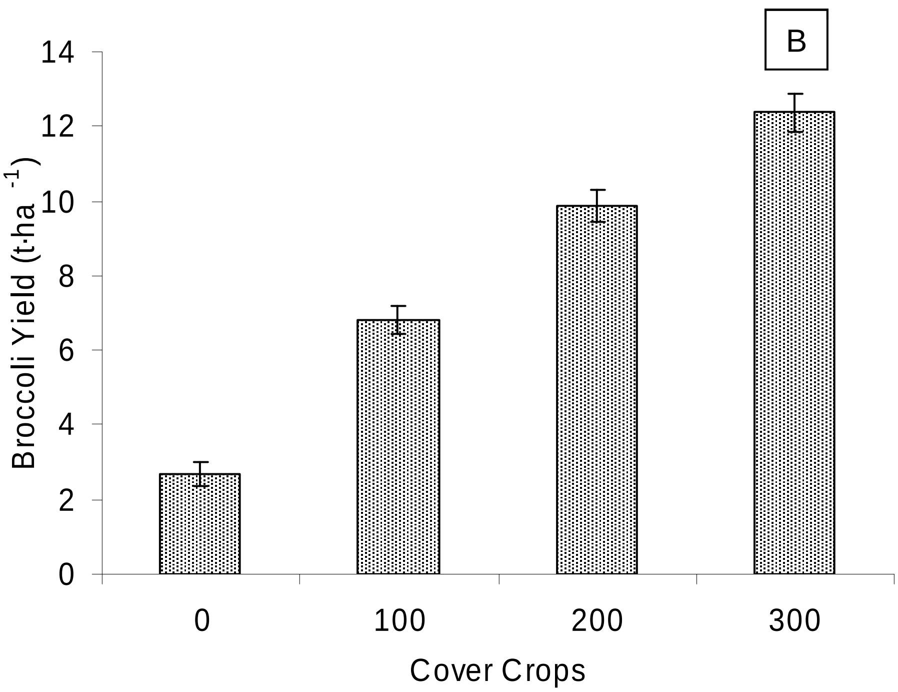


Fig. 2-9 Continued. 2008 broccoli yield pooled across N rate (A) and cover crop (B). Cover crop treatments: F = fallow; O = oats; OV = oat-vetch; P = phacelia; PV = phacelia-vetch; V = vetch. Error bar represents the SE of the mean (n=24).

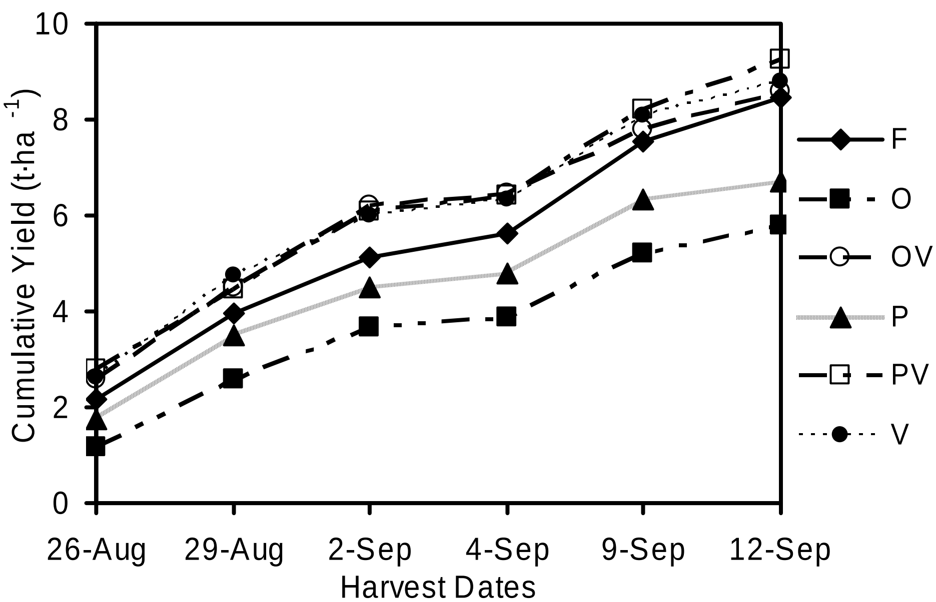


Fig. 2-10. Cumulative broccoli yield over harvest period pooled across N rates in 2008. Cover crop treatments: F = fallow; O = oats; OV = oat-vetch; P = phacelia; PV = phacelia-vetch; V = vetch.

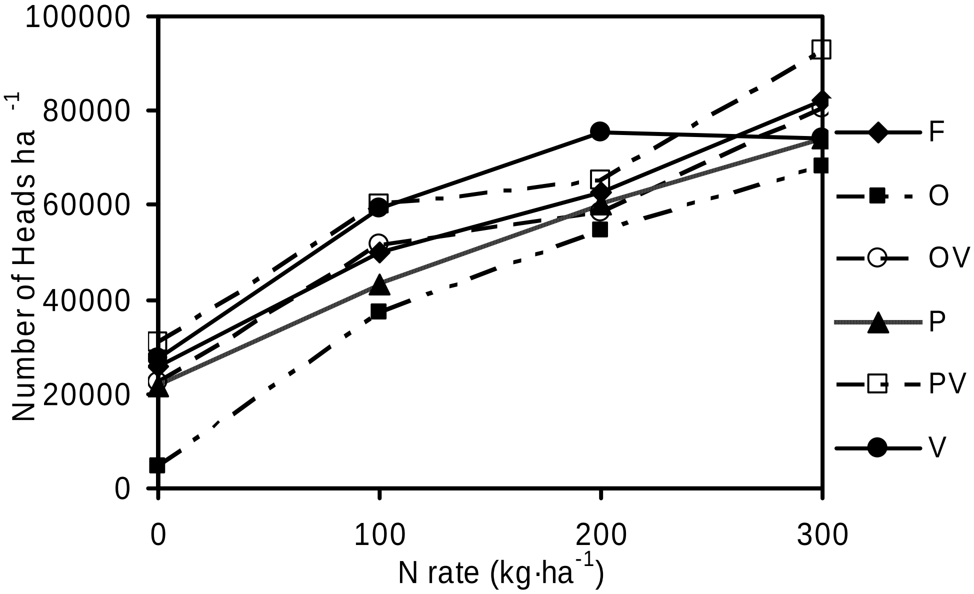
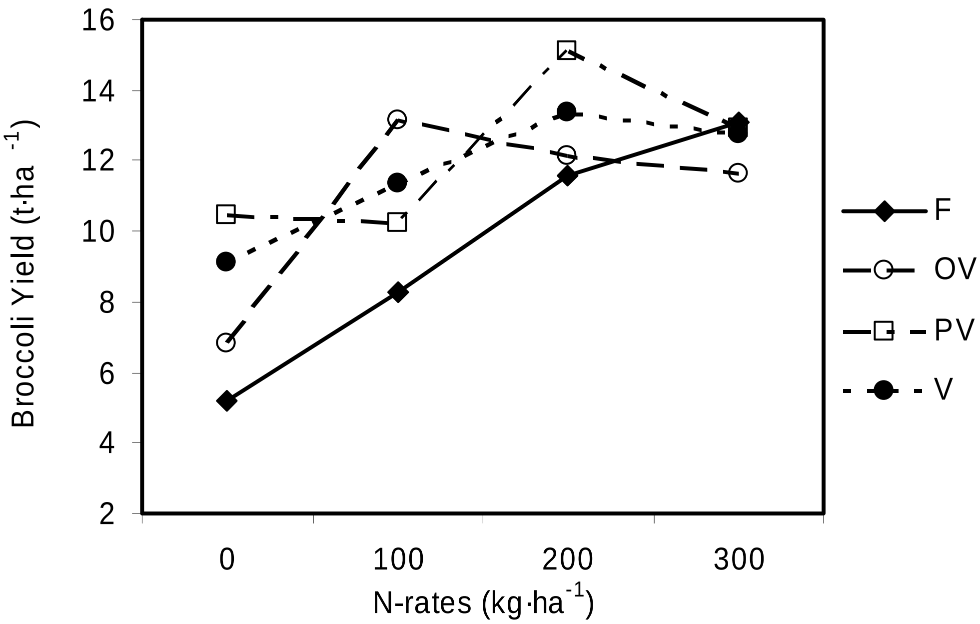


Fig. 2-11. Effect on N fertilizer rate applied at transplanting on number of heads harvested per hectare in 2008. Cover crop treatments: F = fallow; O = oats; OV = oat-vetch; P = phacelia; PV = phacelia-vetch; V = vetch.



	F 200	OV 200	PV 200	V 200	OV 100	PV 100	V 100
F 300	0.25	0.55	0.20	0.84	0.97	0.07	0.27

Fig. 2-12. Effect of N fertilizer rate on broccoli yield in 2007 and p-value comparisons between fallow at 300 kg N ha^{-1} with selected cover crop and N rate combinations. Cover crop treatments: F = fallow; OV = oat-vetch; PV = phacelia-vetch; V = vetch.

Table 2-1. 2007 and 2008 cover crop treatments, species and seeding rates.

Cover crop mixtures	Code	Cover crop species	2007 Seeding rate ($kg{\cdot}ha^{-1}$)	2008 Seeding rate ($kg{\cdot}ha^{-1}$)
'Monida' oats	O	*Avena sativa L.*	90	90
Common vetch	V	*Vicia sativa*	45	45
Phacelia	P	*Phacelia tanacetifolia*	3.4	4.7
'Monida' oats / Common vetch	OV	*Avena sativa L. / V. sativa*	22 / 45	22 / 45
Phacelia / Common vetch	PV	*P. tanacetifolia / V. sativa*	2.2 / 45	3.5 / 45
No cover crop (fallow)	F	-	-	-

Table 2-2. Average cover crop biomass, carbon and nitrogen content for 2007 and 2008 experiment. Cover crop treatments: F = fallow; O = oats; OV = oat-vetch; P = phacelia; PV = phacelia-vetch; V = vetch. The weed component of each treatment is represented by 'W'.

		2007				2008			
Cover crop	Component	C	N	biomass	Total N	C	N	biomass	Total N
		%		($kg{\cdot}ha^{-1}$)		%		($kg{\cdot}ha^{-1}$)	
F	W	42.2	1.8	1086	19	42.8	2.2	689	15
O	O	41.4	0.6	7903	48	42.2	0.8	4627	37
	W	-	-	-	-	40.9	1.5	192	3
OV	O	42.0	1.0	3186	32	42.4	0.8	1951	16
	V	42.7	2.6	5702	146	43.2	3.3	1572	52
	W	-	-	-	-	41.9	1.8	418	8
P	P	40.5	0.7	4768	34	39.9	1.4	793	11
	W	42.4	1.7	458	8	41.7	1.4	471	7
PV	P	40.4	0.8	3317	27	40.3	1.3	649	8
	V	42.6	2.5	7212	178	42.8	3.7	1051	38
	W	-	-	-	-	41.3	1.7	358	6
V	V	42.7	2.5	5333	135	43.1	3.8	998	38
	W	43.1	1.6	800	13	41.7	1.4	446	6

Table 2-3. Summary of analyses of variance showing the sources of effects on broccoli yield and yield components for 2007 and 2008.

Year	Sources of variation	Number of heads	Yield	Head weight	Head size
			$kg \cdot ha^{-1}$	kg	cm
			Pr>F		
2007	cover crop	<.01	<.01	0.01	0.03
	N rate	<.01	<.01	<.01	<.01
	cover crop x N rate	<.01	<.01	0.08	0.04
	cover crop @ 0 N	<.01	<.01	<.01	<.01
	cover crop @ 100 N	<.01	<.01	0.17	0.11
	cover crop @ 200 N	0.50	0.13	0.59	0.40
	cover crop @ 300 N	0.23	0.89	0.13	0.19
2008	cover crop	<.01	<.01	0.20	0.51
	Nrate	<.01	<.01	<.01	<.01
	cover crop x N rate	0.04	0.60	0.61	0.96

Table 2-4. P-value comparisons of broccoli yield between cover crop treatments for 0 and 100 kg $N \cdot ha^{-1}$ in 2007. Cover crop treatments: F = fallow; O = oats; OV = oat-vetch; P = phacelia; PV = phacelia-vetch; V = vetch.

0 N

F	O	OV	P	PV	V	
-	0.01	0.29	0.06	<.01	0.01	F
	-	<.01	0.42	<.01	<.01	O
		-	<.01	0.02	0.15	OV
			-	<.01	<.01	P
				-	0.38	PV
					-	V

100 N

F	O	OV	P	PV	V	
-	0.05	<.01	0.64	0.22	0.05	F
	-	<.01	0.02	<.01	<.01	O
		-	0.01	0.07	0.25	OV
			-	0.44	0.14	P
				-	0.47	PV
					-	V

Table 2-5. P-value comparisons of number of heads harvested between cover crop treatments with 0 and 100 kg N·ha^{-1} in 2007. Cover crop treatments: F = fallow; O = oats; OV = oat-vetch; P = phacelia; PV = phacelia-vetch; V = vetch.

0 N

F	O	OV	P	PV	V	
-	<.01	0.56	0.02	<.01	0.06	F
	-	<.01	0.24	<.01	<.01	O
		-	<.01	0.02	0.20	OV
			-	<.01	<.01	P
				-	0.29	PV
					-	V

100 N

F	O	OV	P	PV	V	
-	0.06	0.04	0.64	0.16	0.08	F
	-	<.01	0.02	<.01	<.01	O
		-	0.10	0.48	0.72	OV
			-	0.35	0.20	P
				-	0.72	PV
					-	V

Table 2-6. P-value comparisons of average head size for 0 kg N ha^{-1} treatments in 2007. Cover crop treatments: F = fallow; O = oats; OV = oat-vetch; P = phacelia; PV = phacelia-vetch; V = vetch.

0 N

F	O	OV	P	PV	V	
-	0.01	0.46	0.01	0.55	0.95	F
	-	<.01	0.87	<.01	0.01	O
		-	<.01	0.89	0.43	OV
			-	<.01	0.01	P
				-	0.51	PV
					-	V

Table 2-7. P-value comparisons of average weight for 0 kg N ha^{-1} treatments in 2007. Cover crop treatments: F = fallow; O = oats; OV = oat-vetch; P = phacelia; PV = phacelia-vetch; V = vetch.

0 N

F	O	OV	P	PV	V	
-	0.07	0.03	0.16	0.07	0.10	F
	-	<.01	0.61	<.01	<.01	O
		-	<.01	0.72	0.60	OV
			-	<.01	<.01	P
				-	0.86	PV
					-	V

Table 2-8. P-value comparisons for 2008 broccoli yield pooled across across N rates (0, 100, 200, 300 kg N ha^{-1}), and cover crop treatments. Cover crop treatments: F = fallow; O = oats; OV = oat-vetch; P = phacelia; PV = phacelia-vetch; V = vetch.

N Rate

0	100	200	300	
-	<.01	<.01	<.01	0
	-	<.01	<.01	100
		-	<.01	200
			-	300

Cover Crop

F	O	OV	P	PV	V	
-	<.01	0.81	<.01	0.10	0.46	F
	-	<.01	0.06	<.01	<.01	O
		-	<.01	0.16	0.62	OV
			-	<.01	<.01	P
				-	0.36	PV
					-	V

Table 2-9. P-value comparisons for number of heads harvested at all N rates for each cover crop treatment in 2008. Cover crop treatments: F = fallow; O = oats; OV = oat-vetch; P = phacelia; PV = phacelia-vetch; V = vetch.

0 N

F	O	OV	P	PV	V	
-	<.01	0.57	0.46	0.41	0.81	F
	-	<.01	0.01	<.01	<.01	O
		-	0.87	0.17	0.41	OV
			-	0.12	0.33	P
				-	0.57	PV
					-	V

100 N

F	O	OV	P	PV	V	
-	0.04	0.74	0.29	0.09	0.12	F
	-	0.02	0.33	<.01	<.01	O
		-	0.17	0.17	0.22	OV
			-	0.01	0.01	P
				-	0.87	PV
					-	V

200 N

F	O	OV	P	PV	V	
-	0.19	0.46	0.68	0.68	0.04	F
	-	0.57	0.37	0.09	<.01	O
		-	0.74	0.25	0.01	OV
			-	0.41	0.02	P
				-	0.10	PV
					-	V

300 N

F	O	OV	P	PV	V	
-	0.02	0.81	0.19	0.09	0.19	F
	-	0.04	0.33	<.01	0.33	O
		-	0.29	0.05	0.29	OV
			-	<.01	1.00	P
				-	<.01	PV
					-	V

Table 2-10. The net economic benefit in 2007 associated with cover crop-feather meal treatments based upon the organic broccoli yield value and the variable input costs ($315/ha) (Julian et al., 2008). Cover crop treatments: F = fallow; O = oats; OV = oat-vetch; P = phacelia; PV = phacelia-vetch; V = vetch.

Cover crop	Feather meal N rate	Cover crop seed cost	Feather meal N cost	Broccoli Yield	Broccoli Yield value [1]	Net Benefit [2]	Net Benefit compared to F 300
	$kg \cdot ha^{-1}$	$/ha	$/ha	$t \cdot ha^{-1}$	$/ha	$/ha	p-value
F	0	0	0	5.2	8,640	8,330	<.01
	100	0	590	8.3	13,850	12,940	<.01
	200	0	1190	11.5	19,290	17,790	0.37
	300	0	1780	13.1	21,830	19,740	1.00
O	0	170	0	1.0	1,630	1,140	<.01
	100	170	590	5.1	8,580	7,500	<.01
	200	170	1190	11.0	18,340	16,670	0.24
	300	170	1780	11.7	19,520	17,260	0.34
OV	0	167	0	6.8	11,400	10,920	<.01
	100	167	590	13.1	21,950	20,870	0.66
	200	167	1190	12.1	20,280	18,620	0.67
	300	167	1780	11.6	19,460	17,200	0.33
P	0	42	0	2.2	3,710	3,350	<.01
	100	42	590	9.0	15,080	14,130	0.03
	200	42	1190	12.2	20,340	18,800	0.72
	300	42	1780	12.6	21,110	18,970	0.77
PV	0	152	0	10.5	17,490	17,030	0.30
	100	152	590	10.2	17,070	16,010	0.16
	200	152	1190	15.1	25,190	23,530	0.15
	300	152	1780	12.9	21,570	19,330	0.87
V	0	125	0	9.1	15,210	14,770	0.06
	100	125	590	11.3	18,950	17,920	0.49
	200	125	1190	13.4	22,350	20,720	0.70
	300	125	1780	12.8	21,330	19,110	0.81

1 Broccoli yield value = Broccoli yield x wholesale organic broccoli value ($1.67/kg).

2 Net benefit = Broccoli value - variable costs for managing cover crop ($315/ha), feather meal, and seed.

[3] P-values were generated with pair-wise comparisons with F 300.

Table 2-11. The net economic benefit in 2007 associated with cover crop-feather meal treatments based upon the organic broccoli yield value and the variable input costs ($315/ha) (Julian et al., 2008). Cover crop treatments: F = fallow; O = oats; OV = oat-vetch; P = phacelia; PV = phacelia-vetch; V = vetch.

Cover crop	Feather meal N rate	Cover crop seed cost	Feather meal N cost	Broccoli Yield	Broccoli Yield value [1]	Net Benefit [2]	Net Benefit compared to F 300
	$kg{\cdot}ha^{-1}$	$/ha	$/ha	$t{\cdot}ha^{-1}$	$/ha	$/ha	p-value
F	0	0	0	3.2	5,280	4,970	<.01
	100	0	590	7.6	12,600	11,690	<.01
	200	0	1190	10.4	17,300	15,800	0.04
	300	0	1780	12.9	21,290	19,200	1.00
O	0	170	0	0.4	710	220	<.01
	100	170	590	4.3	7,200	6,120	<.01
	200	170	1190	7.9	13,080	11,410	<.01
	300	170	1780	10.7	17,670	15,410	0.05
OV	0	167	0	2.5	4,170	3,690	<.01
	100	167	590	7.3	12,130	11,050	<.01
	200	167	1190	10.7	17,800	16,130	0.11
	300	167	1780	14.0	23,180	20,920	0.37
P	0	58	0	2.5	4,070	3,700	<.01
	100	58	590	5.9	9,710	8,750	<.01
	200	58	1190	8.1	13,420	11,870	<.01
	300	58	1780	10.6	17,590	15,440	0.05
PV	0	169	0	3.9	6,470	5,990	<.01
	100	169	590	8.2	13,510	12,430	<.01
	200	169	1190	10.9	18,070	16,400	0.15
	300	169	1780	14.4	23,800	21,540	0.23
V	0	125	0	3.7	6,180	5,740	<.01
	100	125	590	7.9	13,050	12,020	<.01
	200	125	1190	11.6	19,230	17,610	0.41
	300	125	1780	12.3	20,400	18,180	0.60

1 Broccoli yield value = Broccoli yield x wholesale organic broccoli value ($1.67/kg).

2 Net benefit = Broccoli value - variable costs for managing cover crop ($315/ha), feather meal, and seed.

[3] P-values were generated with pair-wise comparisons with F 300.

Chapter 3

Estimating Plant-Available Nitrogen from Cover Crop Residue

Abstract

Synchronizing N mineralization from organic materials with the needs of the subsequent crop is a challenge for organic growers. Predicting plant available nitrogen from cover crop residue enables N fertilizer inputs to be adjusted for optimum economic yield and reduced environmental risk. Field experiments were conducted in 2007 and 2008 at the Lewis Brown Farm (LBF) near Corvallis, OR. The objectives of this experiment were to: 1) estimate plant available nitrogen from cover crop residue in an organic broccoli production system; 2) evaluate soil NO_3-N and petiole NO_3-N as predictors of broccoli yield; and 3) evaluate models derived from laboratory incubation of cover crop residue to predict apparent nitrogen recovery (ANR) from cover crop residue in the field. Six cover crop treatments included common vetch (*Vicia sativa*), phacelia (*Phacelia tanacetifolia*), 'Monida' oats (*Avena sativa* L.), phacelia plus common vetch, and 'Monida' oats plus common vetch, with a fallow treatment used as the control. Cover crops were arranged in a randomized block design with six treatments and four replications. Prior to incorporation, cover crop samples were collected from each block and frozen for later use in laboratory aerobic incubations. After the cover crops were flail-mowed and incorporated, four N rates (0, 100, 200, and 300 kg N ha^{-1}) were randomized within each cover crop treatment. Laboratory and field

Vetch as a sole crop produced higher levels of soil NO_3-N than the fallow treatments up to 80 days after soil incorporation in 2007. Oats and phacelia as sole crops reduced soil NO_3-N compared to fallow for up to 68 days after incorporation. Vetch mixtures with oats or phacelia produced intermediate levels of soil NO_3-N between vetch as a sole crop and the fallow. Treatment effects were similar in 2008, but differences were less due to reduced cover crop biomass compared to 2007. Broccoli petiole nitrate levels were not affected by cover crop treatment in 2007, and there was no correlation with yield. In 2008, the oat cover crop treatment reduced broccoli petiole nitrate levels compared to the fallow. Petiole nitrate levels were strongly correlated with broccoli yield, with highest yields associated with petiole NO_3-N greater than 10,000 ppm.

In the aerobic incubations with cover crop mixtures, a quadratic model described the relationship of percent N in the mixture to the apparent nitrogen recovery (ANR) at both 4 and 10 weeks. The highest ANR (about 40%) was similar for both extraction days. Net mineralization occurred when the percent N of the cover crop mixture was 1.5-1.8 percent. There was a strong correlation in 2007 between the ANR predicted by the incubation-derived model and the ANR in the soil and in the aboveground broccoli biomass. The model over predicted the ANR in the field soil, however the model more accurately predicted ANR in the broccoli biomass. The incubation model correctly predicted negative ANR values for the oat and phacelia cover-crop treatments. In 2008, the laboratory-predicted ANR and the field soil ANR were correlated (r^2=.45), and the laboratory model over predicted the field ANR. The incubation model gave a poor prediction of broccoli biomass ANR.

Introduction

Predicting plant available nitrogen from cover crop residue enables N fertilizer inputs to be adjusted for optimum economic yield and reduced environmental risk. Methods used to estimate N availability from organic amendments and crop residues include fertilizer equivalence (Doran and Smith, 1991), apparent N recovery (ANR) (Gale, 2005) and ^{15}N labeling (Muñoz, 2004). Muñoz (2004) suggests that some of the drawbacks of ^{15}N labeling and ANR, can be accounted for by comparing crop and soil responses from organic amendment treatments with synthetic fertilizer in the N-fertilizer equivalency method. When using ^{15}N labeling in cover crop research, N availability can be underestimated (Seo, J, 2006). Soil organic N recovers a majority of legume residue ^{15}N because a portion of the residues are resistant to decomposition or associated with soil microbial biomass or other organic compounds produced during residue decomposition (Azam et al., 1985; Harris et al., 1994; Varco et al., 1993). Muñoz et al. (2004) argued that ANR estimates N mineralized from organic amendments actually taken up by plants, while N-fertilizer equivalency compares crop yield or N uptake in organic amendment plots with those obtained from N fertilizer. In cover crop based production systems, assessments of N cycling have often been based upon methods that evaluate plant and soil N pools (Sullivan et al., 1991), N release from cover crop residue (Rannells and Wagger, 1992), and N uptake by a subsequent cash crop (Clark et al., 1994).

N mineralization from organic residues has been modeled in field and laboratory studies (Cabrera et al., 2005). In many of these models, residue N concentration and the C:N ratio have been used to estimate the rate of N mineralization (Vigil and Kissel, 1991). However, some residues with similar C:N ratios may mineralize different amounts of N due to other compositional differences (Cabrera et al., 2005).

If N is available before the crop's needs, it is susceptible to leaching or de-nitrification. If N is released too late, it is again susceptible to leaching, which poses a threat to groundwater quality, and will not benefit the crop (Stute and Posner, 1995). The capacity of cover crops to serve as an effective nutrient source for subsequent crops is affected by seeding rate, desiccation (killing) time, tillage, residue management practices, soil type, climate, as well as the growth stage, quality and C:N ratio of the cover crop species (Clark et al., 1994; Doran and Smith, 1991; Vaughan and Evanylo, 1998). These factors affect the biomass, N concentration and decomposition of cover crop residue and consequently the rate at which N is mineralized and made available to the subsequent crop. According to Kuo and Sainju (1998), the proportion of rye or annual ryegrass when mixed with residues of hairy vetch should not exceed 60% if residues are to increase N availability.

The high demand for N and short growth period for broccoli make the timing and method of application critical. Plant uptake of nitrogen per unit of root mass is highest shortly after planting, which band placement could improve (Everaarts and de

Willigen, 1999a). Everaarts and de Willigen (1999a) showed that band placement of N fertilizer produced higher yields (Everaarts and de Willigen, 1999a). Band placement of fertilizer N has positive effect on broccoli, but not consistently with cauliflower or white cabbage. This may be because broccoli, as compared to the other two crops, has a shorter growth period and a comparatively high uptake of nitrogen (Everaarts, 1993a), which is especially high in the period shortly before harvest (Shelp and Liu, 1992).

About half of the uptake of nitrogen by broccoli occurs in the final third of the season, when plants are switching from vegetative to reproductive growth (Doerge et al., 1991). Studies have shown that the rapid N uptake in broccoli starts about the same time as the small heads just become visible to the eye, usually 50 to 90 days after seeding (Sullivan et al., 1999), which could be a practical indicator for timing of an additional fertilizer application (Vägen, 2003). Rate of N uptake during this stage ranges from 7 to 9 kg N ha^{-1} (Magnifico et al., 1979). Riley and Vägen (2003) demonstrated that split application was beneficial to broccoli, white cauliflower, and green cauliflower, relative to giving all at planting, whereas Everaarts and de Willigen (1999a) found split application of N to have no or a negative effect on yield and was not recommended. Soil and plant samples are commonly taken to monitor N availability, and determine if N side dressing is necessary. Root depth and N uptake affect the interpretation of soil sampling results.

ANR and N use efficiency (NUE) decrease with increasing N application (Vägen, 2003). Caution must be used in the development of N fertility recommendations for broccoli based solely upon crop yield response (Zebarth et al., 1991a), because percent N recovery is low for maximum yields obtained from high N rates (Zebarth et al., 1995). Concentrations of nitrogen in both heads and above-ground residues have been shown to increase with increasing N supply (Riley and Vägen, 2003). At the optimum rates of band-placed nitrogen, the amount of nitrogen in broccoli crop residues range from 100 to 225 kg ha^{-1} (Everaarts and de Willigen, 1999b; Riley and Vägen, 2003; Stivers, 1993). The harvest of broccoli heads generally removes from 40 to 100 kg·ha^{-1} of nitrogen (Stivers, 1993). Muramoto et al. (2007) found that the feather meal N replacement value of a mixed legume/cereal cover crop was 71 to 92 kg N ha^{-1}, and that 14-23% of the cover crop N was utilized by the successive broccoli crop. Zebarth et al. (1995) suggest that the low apparent recovery of fertilizer N in the harvested portion of the crop, particularly at high N rates, indicates that the environmental risk associated with residual N in the soil and in the remaining plant material can be high.

Leaf midrib, petiole, and soil NO_3-N concentration have been evaluated throughout the growing season as N management tools for broccoli production (Gardner and Roth, 1989; Karitonas, 2003; Zebarth et al., 1995). Leaf midribs include the petiole and the thick center vein, which is separated from the leaf blade. A study in Arizona showed that NO_3-N concentration of broccoli midribs was highly correlated to yield (r^2=0.75). For the management and climatic conditions found in the desert regions of Arizona, the following midrib NO_3-N concentrations were recommended: 4 to 6 leaves, 10,000 mg kg^{-1}; 10 to 12 leaves, 9,000 mg kg^{-1}; first bud, 6,000 mg kg^{-1}; head development, 3500 mg kg^{-1}; pre harvest, 2000 mg kg^{-1} (Gardner and Roth, 1989).

Karitonas (2003) found that as the season progresses, petiole NO_3-N correlates more with soil NO_3-N. Zebarth et al. (1995) suggest that soil NO_3-N determined at the time of transplanting (75 cm depth) provides a good estimate of the N available for the crop during the growing season. At harvest, the petiole NO_3-N concentration was best correlated (r^2=0.89) with NO_3-N in soil (0-60 cm).

The objectives of this experiment were to: 1) estimate plant available nitrogen from cover crop residue in an organic broccoli production system; 2) evaluate soil NO_3-N, and petiole NO_3-N as predictors of broccoli yield; and 3) evaluate models derived from laboratory incubation of cover crop residue to predict plant apparent nitrogen recovery (ANR) from cover crop residue in the field.

Materials and Methods

Cover crops and broccoli were grown as described in Chapter 1. Field samples were collected in 2007 (Table 2-1) and 2008 (Table 2-2) as described in the sections below.

Soil Nitrate. Soil samples (30 cm) were taken 4-5 times in bi-weekly intervals throughout the season to evaluate mineralization from the residue in each cover crop treatment. Five soil cores were taken randomly from the zero N treatments on each sampling date. Soil cores were taken outside of the broccoli root zone, in the center of the rows and submitted to Central Analytical Lab (CAL) for nitrate analysis. In 2007, soil samples were taken 51, 68, 80, and 101 days after incorporation (DAI). In 2008, soil samples were taken 29, 47, 63, 88, and 98 DAI.

Petiole Nitrate. Petiole samples (approximately 2.5 cm long) were taken from the newest fully expanded leaf on ten randomly selected broccoli plants within each treatment sampled and analyzed for NO_3-N using cadmium reduction by CAL. In 2007, petiole samples were taken from the 100 kg N ha^{-1} subplots of each cover crop treatment three times (13 July, 27 July, 8 August) (62, 76, and 88 DAI respectively). In 2008, petiole samples were taken from fallow, oats, and vetch treatments with 0 and 100 kg N ha^{-1} on one sample date, 25 July.

Broccoli N Uptake. Plants were selected in each treatment outside of the area flagged for broccoli yield data, clipped at ground level, chopped into 2-3 cm pieces, and dried to determine plant-biomass. After samples were weighed and recorded they were submitted to CAL, where they were ground and analyzed for total N. In 2007, four plants were selected in each 0 kg N ha^{-1} treatment on 10 August, four days before the first broccoli harvest. In 2008, three plants were selected from fallow treatments with 100, 200, and 300 kg N ha^{-1}, as well as all of the 0 kg N ha^{-1} cover crop treatments on 21 August, five days before the first broccoli harvest.

Laboratory aerobic incubations. Cover crop samples were collected from each treatment prior to incorporation, and frozen for aerobic incubations following the methodology described by Gale et al. (2006). Thawed cover-crop samples were chopped into 1 to 2 cm pieces and incorporated into 500 g of soil in 0.9 L freezer bags. The zippered tops of the bags were left partially open by inserting a straw during incubation to facilitate air exchange and reduce the potential for denitrification. Incubation bags were placed in plastic tubs with moistened foam pads to increase humidity. Gravimetric soil moisture in the bags was measured every 14 d and replenished if it fell below 200 g H_2O kg $^{-1}$. Soil moisture data were used to convert inorganic N concentrations in moist soil to a dry weight basis. Inorganic N accumulation was measured for samples of moist soil thoroughly mixed with the cover crop residue. Nitrate was extracted from sub-samples by adding 50 mL 2M KCl, shaking for 1 hour, filtering out soil, and refrigerating at $4^{o}C$ until analysis. Inorganic N in the sub-samples was determined by automated colorimetric methods at CAL.

2007 experiment. Cover-crop samples were collected on 12 May. Treatments included: oats, vetch, phacelia, phacelia-vetch, oat-vetch, fallow (weeds), feather meal, and a soil only control. There were four replications of each treatment. Application rate was determined by the percent of nitrogen in each cover crop, contained approximately the same amount of N to start with (40 mg N·kg^{-1}). However, due to a miscalculation, the phacelia treatments only had 20 mg N kg^{-1} to start with. Sub-samples for inorganic N analysis were collected from the bags on Day 0, 13, 26, 40 and 60 of the incubation.

2008 experiment. Oat, vetch, and phacelia cover-crop samples were collected on 15 May. Vetch was mixed with either phacelia or oats in dry-weight ratios of 100:0, 87:12, 75:25, 62:37, 50:50, 37:62, 25:75, and 12:87. Treatments were replicated three times for the control and each sole crop, and two times for each mixture. Sub-samples for NO_3-N analysis were collected from the bags on Day 0, 28, and 70 of the incubation. The observed amount of NO_3-N was used in the calculation of ANR (Eq. 1 and 2).

$$ANR = Nt – Nc \qquad \text{Eq. 1}$$

Where:

ANR = concentration of nitrate-N (NO_3-N) in the soil (mg N·kg^{-1}).

Nt = nitrate-N (NO_3-N) from cover crop treatment (mg N·kg^{-1})

Nc = nitrate-N (NO_3-N) from soil-only control (mg N·kg^{-1})

$$\text{ANR (\%)} = \text{ANR} / N_{total} \times 100 \qquad \text{Eq. 2}$$

Where:

N_{total} = total cover crop N applied (mg N·kg^{-1})

A field soil bulk density of 1.3 g·cm^3 was assumed for conversion of laboratory NO_3-N in mg·kg^{-1} to kg·ha^{-1}.

Statistical Analysis. All data were analyzed using SAS with PROC MIXED (SAS, 2008) to determine treatment class effects. Linear and quadratic regression analyses were used to determine correlation between broccoli N uptake and yield, and soil NO_3-N concentrations, as well as broccoli yield and petiole NO_3-N concentration.

Results

Cover Crop Effect on Soil Nitrate

There was a significant interaction between cover crop and date both years of this study in relation to soil NO_3-N concentration (30 cm depth) ($p<.01$), therefore the cover crop treatment effects were examined on each date separately.

2007. Vetch produced higher levels of soil NO_3-N than the fallow treatments for the first three sampling dates ($p\leq.03$) (Table 3-3; Fig. 3-1). Oats reduced soil NO_3-N compared to fallow 51 ($p=.14$), whereas phacelia did not ($p=.41$) (Table 3-3, Fig. 3-1).

Soil nitrate values for the oat-vetch and phacelia-vetch treatments were statistically similar (Table 3-3) and intermediate between vetch and fallow. There were no differences in soil NO_3-N among the cover crop treatments 101 DAI. Soil NO_3-N concentration was similar among fallow, oats and phacelia treatments on each sampling date (Table 3-3).

2008. Overall soil nitrate values were considerably lower in 2008 than in 2007 (Fig. 3-1 and 3-2), likely due to much lower quantities of legume N produced in the cover crops. As in 2007, oats as a sole crop suppressed soil nitrate compared to the fallow control (Table 3-4; Fig. 3-2). Both oat-vetch and phacelia-vetch mixtures produced higher levels on NO_3-N than oats or phacelia as sole crops at DAI 29, 47, and 63 ($p<.05$). Soil NO_3-N in oat-vetch plots was similar to fallow at DAI 29 ($p=.60$), 47 ($p=.86$), and 63 ($p=.33$), however phacelia-vetch NO_3-N levels were higher than in the fallow at these sampling dates ($p=.03$, $<.01$, and $.08$ respectively) (Table 3-4). There were no statistical differences in soil NO_3-N in any of the cover crop treatments at DAI 88 or 98 (Table 3-4; Fig. 3-2).

Cover Crop Effects on Petiole Nitrate

2007. Date had a significant effect ($p<.01$) on broccoli petiole NO_3-N concentration in all cover crop treatments with 100 kg ha^{-1} of N applied (Fig. 3-3), reducing from more than 15,000 ppm on DAI 62 to less than 6000 ppm on DAI 88. However, there was no difference in broccoli petiole NO_3-N concentrations among the cover crop treatments at any of the sampling dates ($p=.63$) (data not shown).

2008. There was no significant interaction between cover crop (fallow, oat, and vetch) and N rate (0 and 100 kg N ha^{-1}) ($p=.91$) on the one sampling date in 2008 (71 DAI), so data were pooled and analyzed by main effects. Nitrogen fertilizer rate increased petiole NO_3-N ($p<.01$) (Fig. 3-4A). Broccoli petiole NO_3-N concentration from the oats treatment was less than both the fallow ($p=.02$) and vetch ($p<.01$) treatments, whereas petiole NO_3-N concentration in the vetch plots was similar to the fallow ($p=.31$).

Laboratory Incubation

2007. In the aerobic incubations, vetch increased soil NO_3-N on each extraction day of the 60 day incubation (Fig. 3-5). The oat cover crop completely immobilized soil NO_3-N for the first 26 days (Fig. 3-5). Phacelia also immobilized nitrogen, but intermediate between the oat and no cover crop, soil-only treatment. On day 40 of the incubation, NO_3-N in phacelia was similar to soil-only (20-30 ppm) and NO_3-N in oats was still less than 10 ppm. The aerobic incubation with feather meal showed that nearly all of nitrogen mineralized around day 26 (Fig. 3-6), which is similar to the results of Gale et al. (2005). These data confirm the rather quick release of NO_3-N from feather meal compared to the slower release following microbial mineralization from the legume cover crops.

2008. In the aerobic incubations with a gradient of percent N in cover crop mixtures, relatively similar quadratic models described the relationship of percent N in the mixture to the ANR at both 4 weeks ($r^2=.95$) (Fig. 3-7A) and 10 weeks ($r^2=.91$) (Fig. 3-7B). The highest ANR (about 40 percent) was similar for both extraction days.

Positive net mineralization occurred when the percent N of the cover crop mixture was about 1.5-1.8 percent (Fig. 3-7).

Soil Nitrate and Broccoli N Uptake and Yield

2007. Broccoli N uptake and yield generally increased with increasing soil NO_3-N concentration (68 DAI) up to about 20 ppm in the 0 kg N ha^{-1} plots sampled (Fig. 3-8 and 3-9). There were three data points (2 oat-vetch and 1 vetch), that had high soil NO_3-N concentrations above 20 ppm, but with no additional N uptake by the broccoli and no yield benefit. Reduced broccoli N uptake and yield in the non-legume treatments (oats and phacelia) generally had less than 10 ppm soil nitrate (Fig. 3-8 and 3-9). The broccoli N uptake in the non-legume treatments did not exceed 100 kg N ha^{-1}, compared to 140 kg N ha^{-1} and 7 t·ha^{-1} respectively in the fallow treatments.

2008. Soil NO_3-N did not exceed 20 ppm in any of cover crop treatments 63 DAI. However, broccoli N uptake exceeded 210 kg ha^{-1} in several of the phacelia-vetch and fallow plots (Fig. 3-10 and 3-11). Even though soil NO_3-N concentrations (63 DAI) were similar to 2007 (5-20 ppm), the broccoli N uptake and yield response to soil nitrate was more variable. This was likely due to the highly variable cover crop stand, and the patches of legume weeds, such as clover and black medic in the “fallow” plots.

Petiole Nitrate and Broccoli Yield

2007. There was no correlation between broccoli yield and petiole NO_3-N on each date sampled (62, 76, 88 DAI) (r^2=<.01, .01, and .05 respectively) (data not shown).

2008. Broccoli yield was highly correlated with petiole NO_3-N concentration sampled in the oat, vetch and fallow treatments with 0 and 100 kg N ha^{-1} (r^2=.58) (Fig. 3-12).

The highest yields came from the fallow and vetch treatments with 100 kg N ha^{-1}, with petiole NO_3-N greater than 10,000 ppm.

<u>Laboratory predicted ANR and actual field ANR</u>

2007. There was a strong correlation between the ANR predicted by the incubation-derived model and the ANR recovered in the field soil and in the broccoli biomass (r^2=.45 and .74 respectively) (Fig. 3-13 and 3-14). The model under predicted the ANR in the field soil (comparing model fit to 1:1 correlation line), however the model gave a nearly 1:1 fit with an R^2 of .72. The incubation model correctly predicted negative ANR values for the oat and phacelia cover-crop treatments.

2008. The laboratory predicted ANR and the ANR in the field soil were correlated (r^2=.45), however the laboratory model over predicted the field ANR. The incubation model gave a poor prediction of broccoli biomass ANR (r^2=.36) (Fig. 3-15, 3-16).

Discussion

Cover crop stand in 2008 was affected by weather conditions during the fall of 2007 and winter of 2008. Because of early fall rains in October of 2007, the existing vegetation was not killed prior to cover crop planting. Also, there were large areas of annual ryegrass and legume weeds (e.g. clover and black medic) in the fallow plots. Soil and broccoli biomass samples were not taken in the exact same area as the cover crop biomass samples in the field. In addition, soil NO_3-N samples were taken between the rows, outside of the broccoli rooting zone. If soil NO_3-N concentrations were lower within the broccoli rooting zone, then the quantity of soil NO_3-N present in the entire plot may have been overestimated. In 2007, with a soil NO_3-N concentration of 20 ppm, broccoli N uptake was approximately 180 kg ha^{-1} and broccoli yield was approximately 11 t ha^{-1}. However, in 2008, with a soil NO_3-N concentration of 20 ppm, broccoli N uptake was approximately 140 kg ha^{-1} and broccoli yield was approximately 5 t·ha^{-1}.

The correlation between laboratory and field results, suggest that laboratory incubations may be able to predict ANR in the field when there is a uniform cover crop stand as in 2007. However, when cover crop stands are patchy, as in 2008, sampling error can lead to poor model prediction. The laboratory incubations with the oat-vetch and phacelia-vetch mixtures showed that there was net mineralization when the N content of the cover crop mixture was more than 1.5 percent. Kuo and Sainju (1998) found that the proportion of rye or annual ryegrass when mixed with residues of hairy vetch should not exceed 60 percent if the residues are to increase N availability, which is similar to what we found in mixtures of oats and common vetch.

Although petiole NO_3-N levels were similar for all cover crop treatments with 100 kg N ha^{-1} on the dates sampled in 2007, some of the legume-based cover crop treatments produced higher soil NO_3-N levels and yields. In 2008, when overall soil NO_3-N was lower, petiole NO_3-N levels taken 71 DAI were more closely correlated with broccoli yield (r^2=.58). The treatments with 0 kg N ha^{-1} in 2008 were N deficient (<9000 ppm NO_3-N) 45 days after transplanting (10 to 12 leaves stage), which agrees with the midrib NO_3-N concentrations recommended by Gardner and Roth (1989) for optimum broccoli yield.

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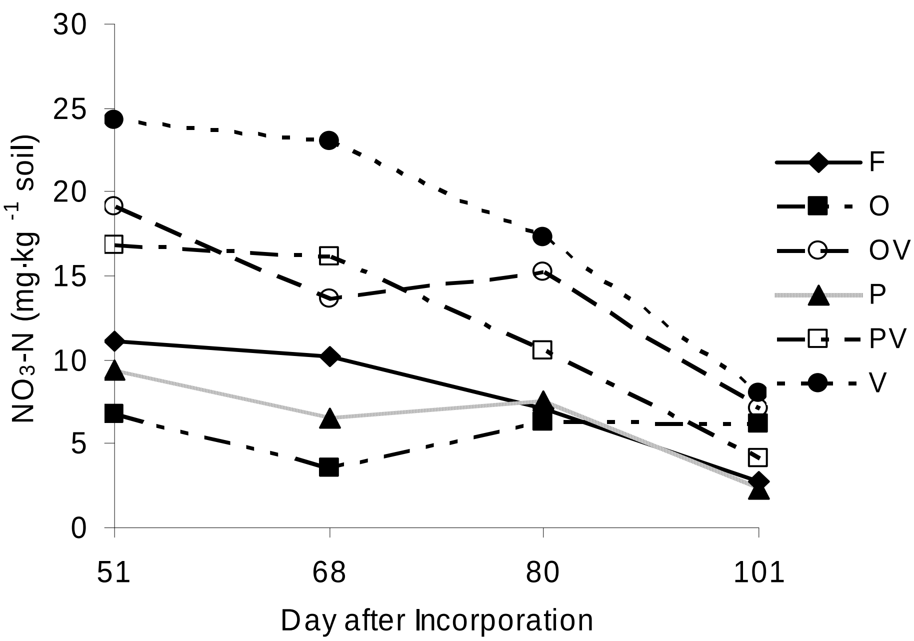

Fig. 3-1. Soil nitrate-N concentration in 0 kg N ha^{-1} treatments between broccoli rows after cover crops incorporation 51, 68, 80, and 101 days after incorporating the cover crop in 2007. Cover crop treatments: F = fallow; O = oats; OV = oat-vetch; P = phacelia; PV = phacelia-vetch; V = vetch.

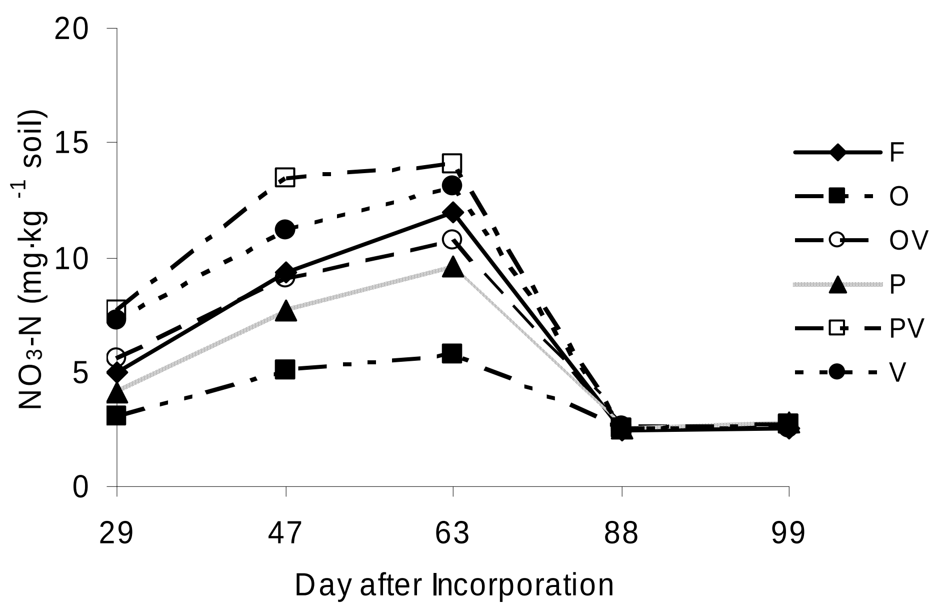

Fig. 3-2. Soil nitrate-N concentration from 0 kg N ha^{-1} treatments between broccoli rows after cover crop incorporation 29, 47, 63, 88, and 99 days after cover crop incorporation in 2008. Cover crop treatments: F = fallow; O = oats; OV = oat-vetch; P = phacelia; PV = phacelia-vetch; V = vetch.

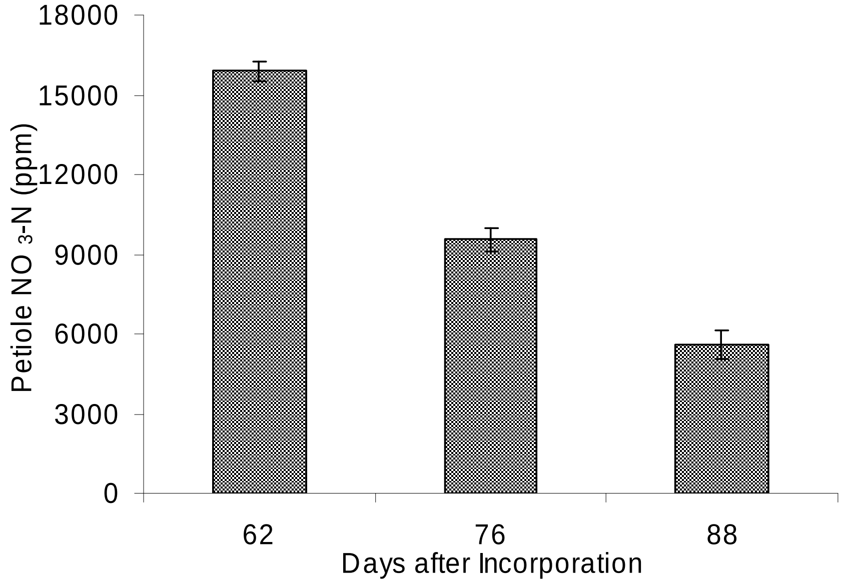

Fig. 3-3. 2007 petiole nitrate-N concentration in the treatments receiving 100 kg of feather meal N ha^{-1}, pooled across cover crops for each sampling date (62, 76 and 88 days after incorporating the cover crops). Error bar represents the SE of the mean (n=24).

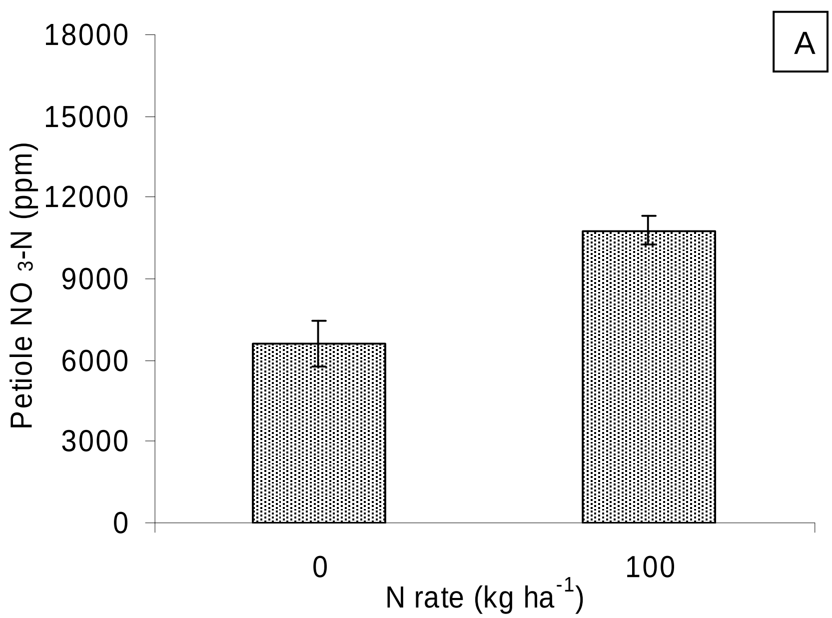

Fig. 3-4. 2008 petiole nitrate-N concentrations pooled across (A) cover crop (fallow, oats, and phacelia) and (B) N-rate (0 and 100 kg N ha^{-1}). Cover crop treatments: F = fallow; O = oats; V = vetch. Error bar represents the SE of the mean (n=24).

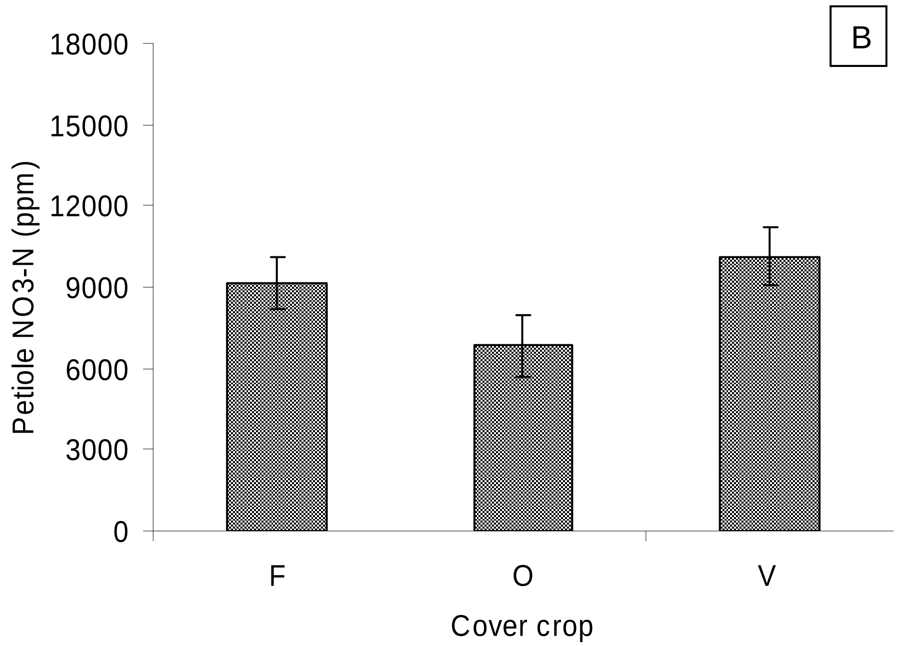

Fig. 3-4 Continued. 2008 petiole nitrate-N data pooled across (A) cover crop (fallow, oats, and phacelia) and (B) N-rate (0 and 100 kg N ha^{-1}). Cover crop treatments: F = fallow; O = oats; V = vetch. Error bar represents the SE of the mean (n=8).

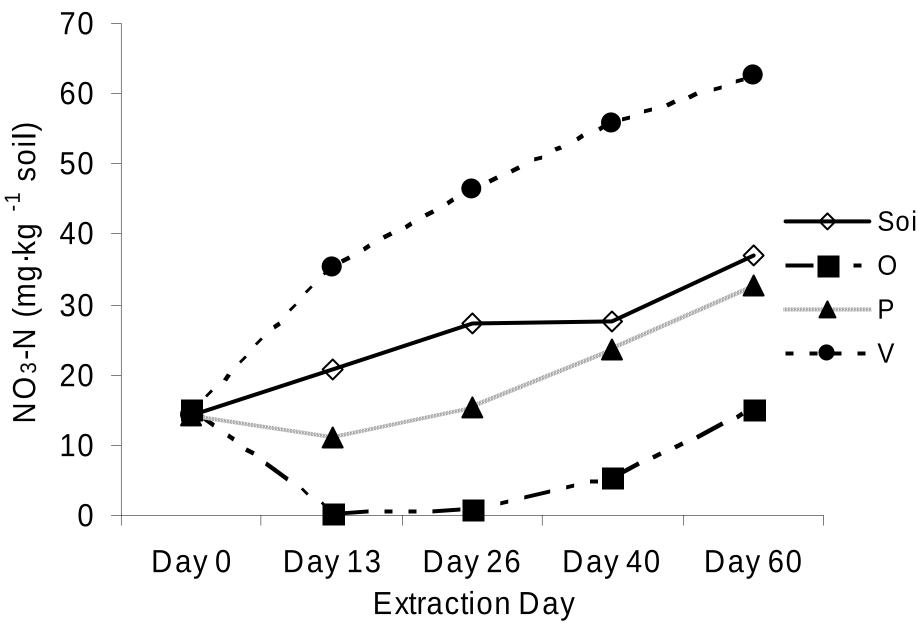

Fig. 3-5. Nitrate-N availability during a 60 day aerobic incubation with sole crops and soil only control. Cover crop treatments: O = oats; P = phacelia; V = vetch.

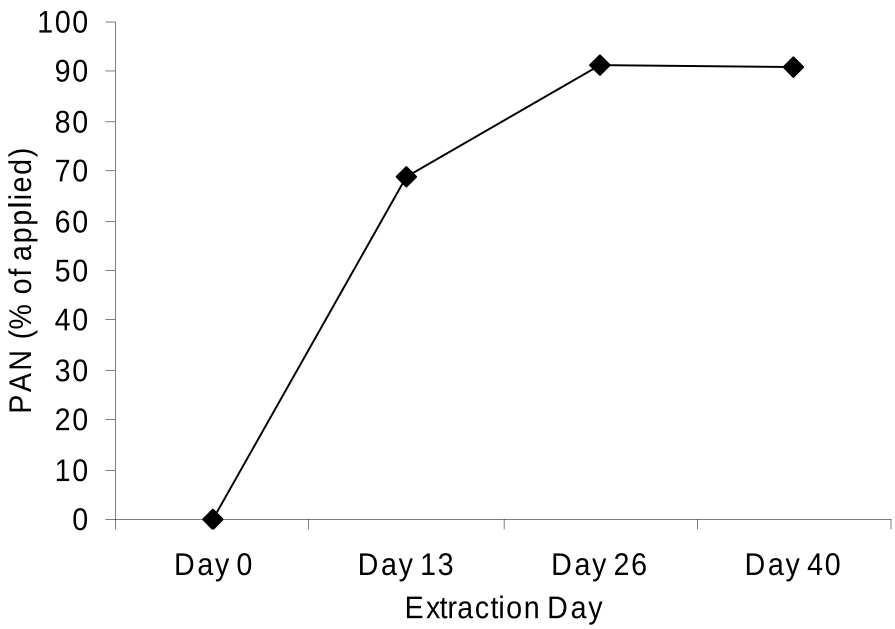

Fig. 3-6. Plant available nitrogen from feather meal based upon the percent applied during a 40 day laboratory incubation. Each point represents the average from 4 replications.

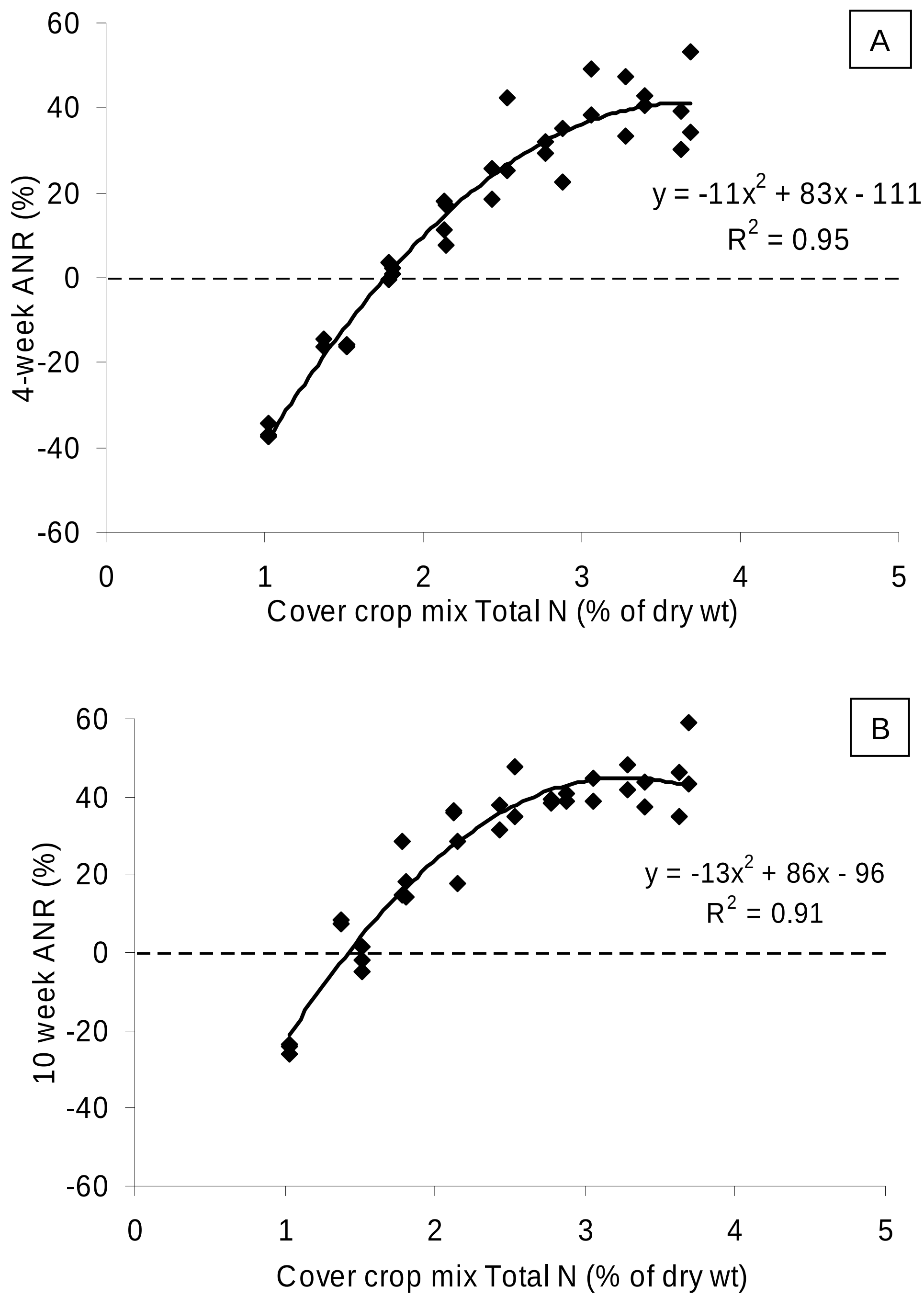

Fig. 3-7. Relationship between apparent nitrogen recovery (ANR) from oat-vetch and phacelia-vetch mixtures at 4 weeks (A) and 10 weeks (B) after the incubation start, and the % nitrogen of the cover crop mix. The points above the dotted line indicate a positive ANR.

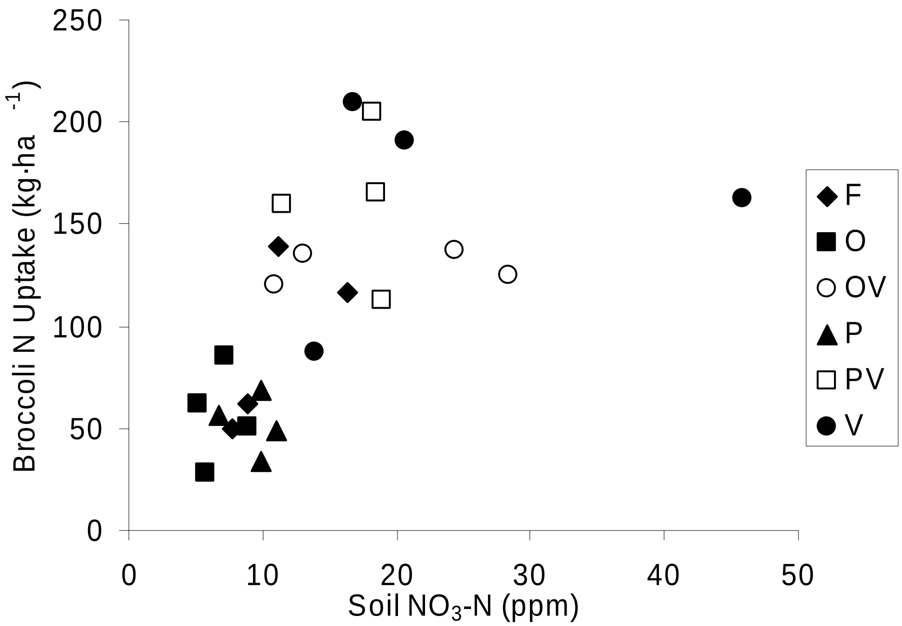

Fig. 3-8. Relationship between pre-harvest broccoli N uptake and soil nitrate-N mid-season (68 DAI) in 2007. Outliers (V,OV) were not included in the regression. Cover crop treatments: F = fallow; O = oats; OV = oat-vetch; P = phacelia; PV = phacelia-vetch; V = vetch.

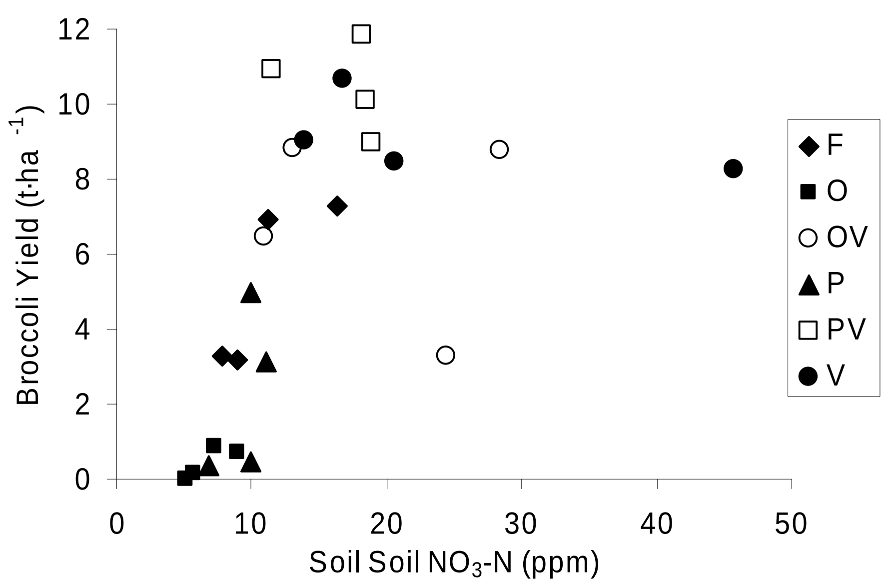

Fig. 3-9. Relationship between total broccoli yield and soil nitrate-N mid-season (68 DAI) in 2007. Outliers (V,OV) were not included in the regression. Cover crop treatments: F = fallow; O = oats; OV = oat-vetch; P = phacelia; PV = phacelia-vetch; V = vetch.

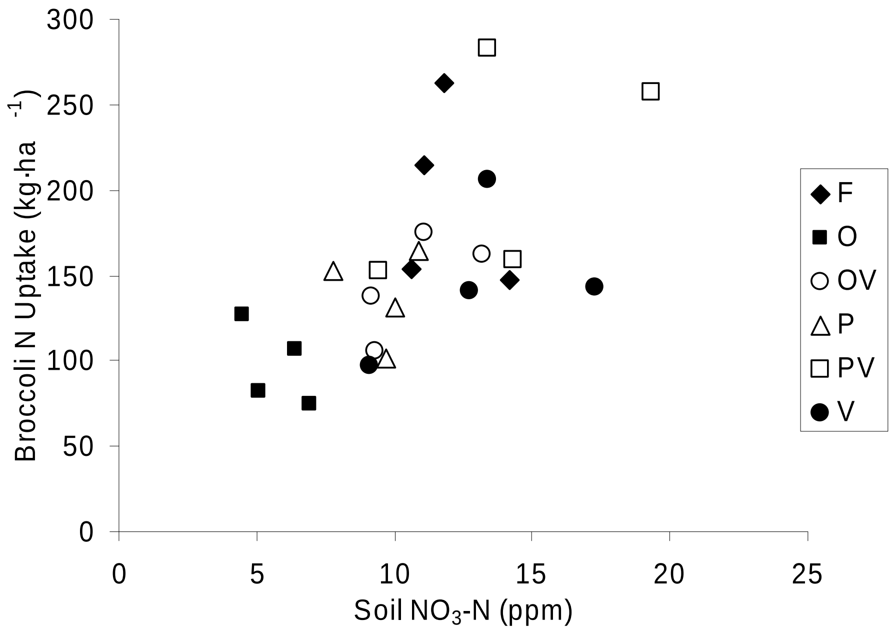

Fig. 3-10. Relationship between pre-harvest broccoli N uptake and soil nitrate-N mid-season 63 days after incorporating the cover crop in 2008. Cover crop treatments: F = fallow; O = oats; OV = oat-vetch; P = phacelia; PV = phacelia-vetch; V = vetch.

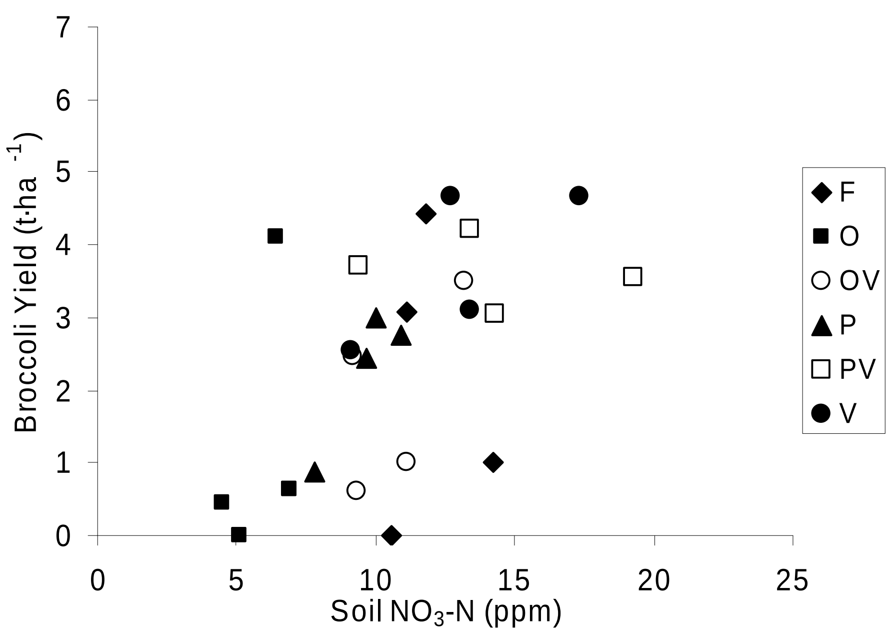

Fig. .3-11. Relationship between broccoli yield and soil nitrate-N mid-season 63 days after incorporating the cover crop in 2008. Cover crop treatments: F = fallow; O = oats; OV = oat-vetch; P = phacelia; PV = phacelia-vetch; V = vetch.

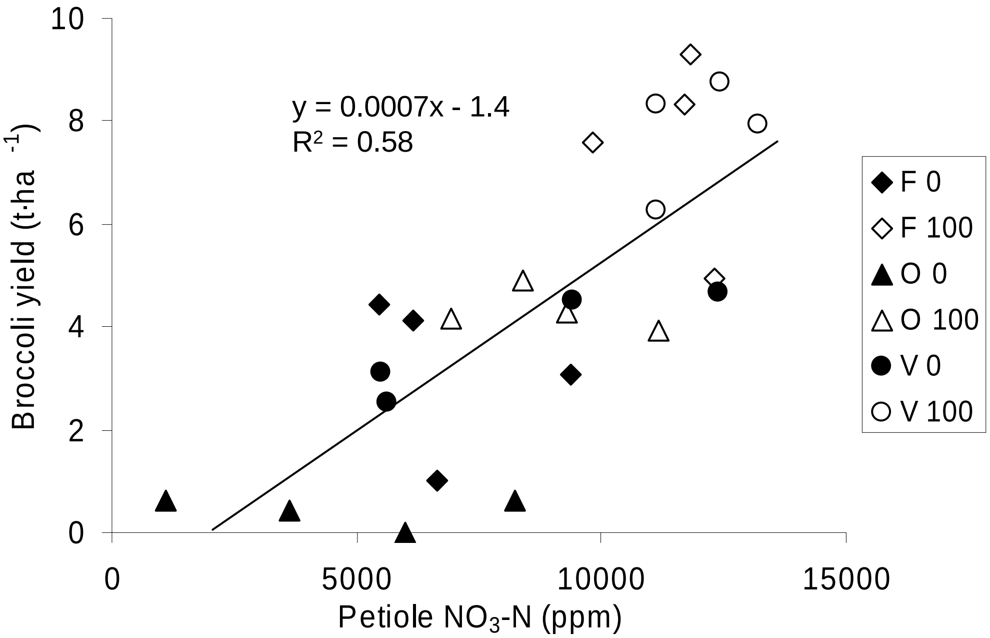

Fig. 3-12. Relationship between broccoli yield and petiole nitrate-N concentration in 0 and 100 kg N ha^{-1} cover crop treatments 71 DAI in 2008. Cover crop treatments: F = fallow; O = oats; V = vetch

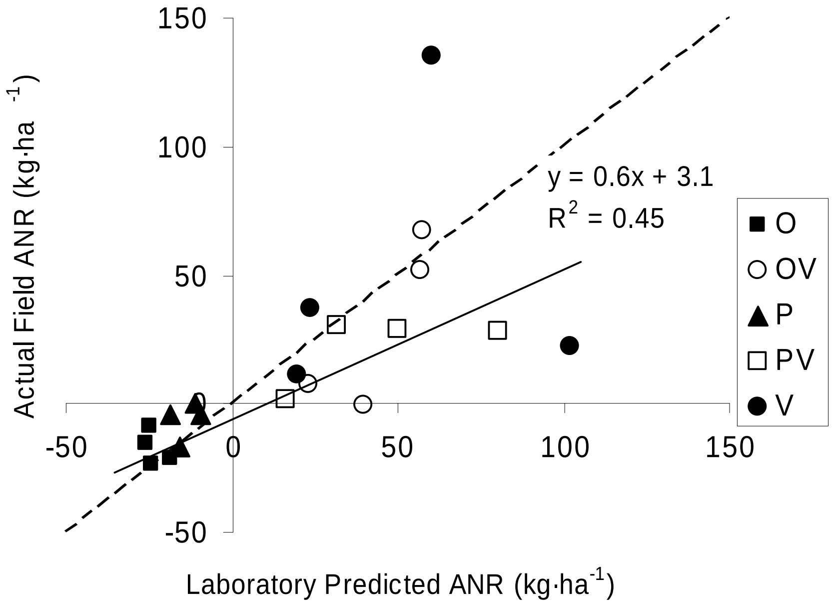

Fig. 3-13. Relationship between actual apparent nitrogen recovered (ANR) from the soil (30 cm) 68 days after cover crop incorporation in 2007, and laboratory predicted ANR. Cover crop treatments: F = fallow; O = oats; OV = oat-vetch; P = phacelia; PV = phacelia-vetch; V = vetch. Points below the dotted line indicate that ANR was over predicted by the laboratory model, and the solid line is the regression.

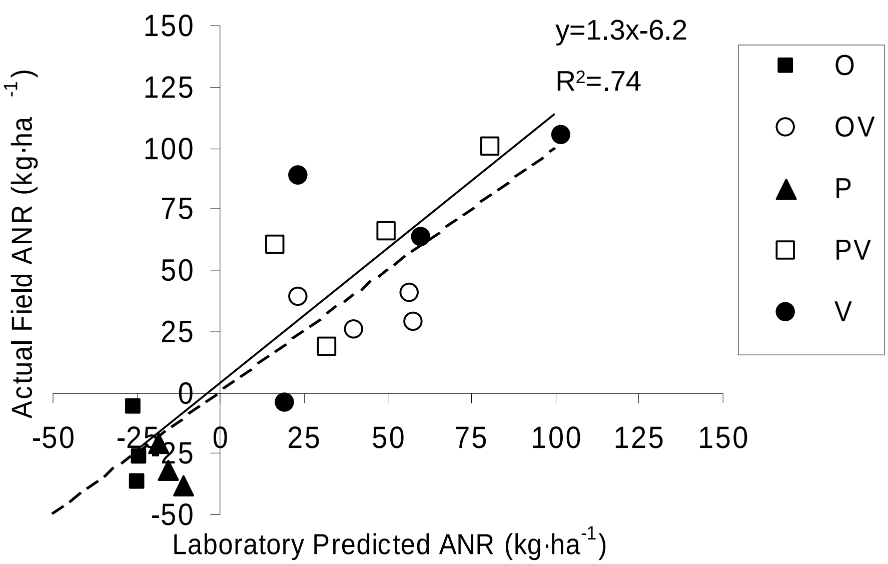

Fig. 3-14. Relationship between the actual broccoli biomass field ANR for 2007, and the laboratory predicted ANR. Cover crop treatments: F = fallow; O = oats; OV = oat-vetch; P = phacelia; PV = phacelia-vetch; V = vetch. For points below the dotted line ANR was over predicted by the laboratory model, and the solid line is the regression.

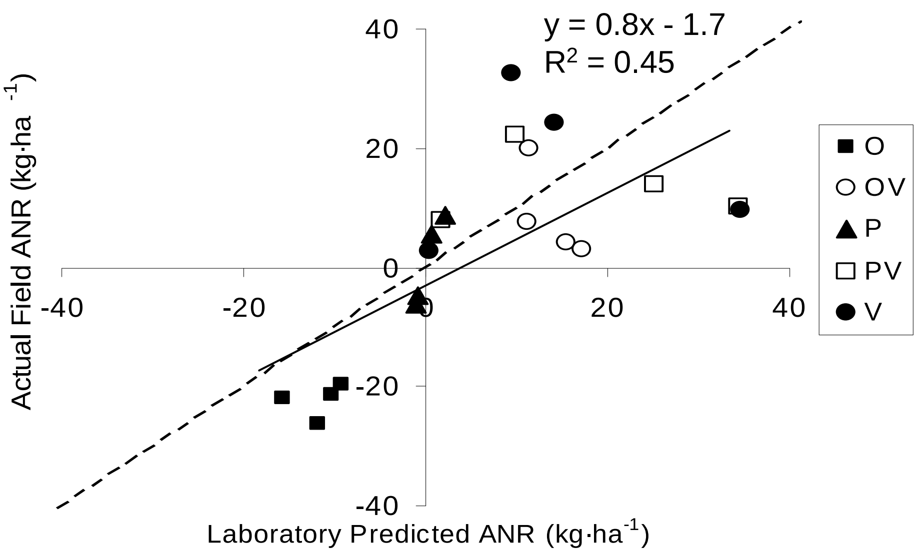

Fig. 3-15. Relationship between actual apparent nitrogen recovered (ANR) from the soil (30 cm) 63 days after cover crop incorporation for 2008, and the laboratory predicted ANR. Cover crop treatments: F = fallow; O = oats; OV = oat-vetch; P = phacelia; PV = phacelia-vetch; V = vetch. Points below the dotted line indicate that ANR was over predicted by the laboratory model, and the solid line is the regression.

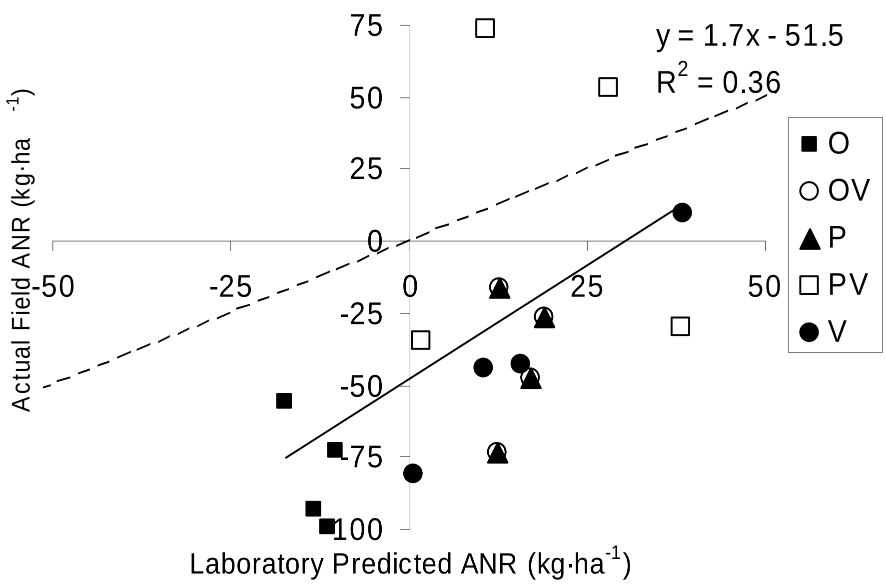

Fig. 3-16. Relationship between the actual broccoli biomass field ANR for 2008, and the laboratory predicted ANR. Cover crop treatments: F = fallow; O = oats; OV = oat-vetch; P = phacelia; PV = phacelia-vetch; V = vetch. All points above the dotted line indicate that ANR in the field was under predicted by the laboratory model, and the solid line is the regression.

Table 3-1. Timeline for 2007 field season

2007 Broccoli Experiment			
Date	DAI[1]	DAT[2]	Event
10/3/2006			Cover crop treatments planted at Lewis-Brown farm
4/19/2007			Planted 'Arcadia' broccoli seeds in greenhouse
5/12/2007	0		Sampled cover crop biomass, dried and submitted sub-samples for total N analysis; flail mow and spade cover
5/23/2007	11		Lime applied (2.7 t·ha^{-1})
5/29/2007	17		Feather meal application
5/30-6/1/2007	18	0	Transplanted broccoli in the field
7/2/2007	51	33	Collected soil samples from 0 kg N ha^{-1} treatments
7/13/2007	62	44	Collected petiole samples from 100 kg N ha^{-1} treatments
7/19/2007	68	50	Collected soil samples from 0 kg N ha^{-1} treatments
7/27/2007	76	58	Collected petiole samples from 100 kg N ha^{-1} treatments
7/31/2007	80	62	Collected soil samples from 0 kg N ha^{-1} treatments
8/8/2007	88	70	Collected petiole samples from 100 kg N ha^{-1} treatments
8/10/2007	90	72	Sampled broccoli whole plant biomass in 0 kg N ha^{-1} treatments
8/14/2007	94	76	Broccoli harvest
8/17/2007	97	79	Broccoli harvest
8/21/2007	101	83	Collected soil samples from 0 kg N ha^{-1} treatments
8/23/2007	103	85	Broccoli harvest
8/27/2007	107	89	Broccoli harvest
8/30/2007	110	92	Broccoli harvest

[1] DAI = days after incorporating the cover crop

[2] DAT = days after transplanting the broccoli in the field

Table 3-2. Timeline for 2008 field season.

2008 Broccoli Experiment			
Date	DAI[1]	DAT[2]	Event
9/24/2007			Lime applied (2.2 $t \cdot ha^{-1}$)
10/8/2007			Cover crop treatments planted at Lewis-Brown farm
5/8/2008			Planted 'Arcadia' broccoli seeds in greenhouse
5/14/2008			Sampled cover crop biomass and submitted sub-samples for total N analysis
5/15/2008	0		Flail mow and spade cover crops
6/9/2008	25		Feather meal application
6/10/2008	26	0	Transplanted broccoli in the field
6/13/2008	29	3	Collected soil samples from 0 kg N ha^{-1} treatments
7/1/2008	47	21	Collected soil samples from 0 kg N ha^{-1} treatments
7/17/2008	63	37	Collected soil samples from 0 kg N ha^{-1} treatments
7/25/2008	71	45	Collected petiole samples from fallow, oat and vetch treatments with 0 and 100 kg N ha^{-1}
8/11/2008	88	62	Collected soil samples from 0 kg N ha^{-1} treatments
8/21/2008	98	72	Sampled broccoli whole plant biomass in 0 kg N ha^{-1} and fallow 100, 200, 300 kg N ha^{-1} treatments
8/22/2008	99	73	Collected soil samples from 0 kg N ha^{-1} treatments
8/26/2008	103	77	Broccoli harvest
8/29/2008	106	80	Broccoli harvest
9/2/2008	110	84	Broccoli harvest
9/4/2008	112	86	Broccoli harvest
9/9/2008	117	91	Broccoli harvest
9/12/2008	120	94	Broccoli harvest

[1] DAI = days after incorporating the cover crop

[2] DAT = days after transplanting the broccoli in the field

Table 3-3. P-value comparisons for soil nitrate-N 51, 68, 80, and 101 days after incorporating the cover crops in 2007. Cover crop treatments: F = fallow; O = oats; OV = oat-vetch; P = phacelia; PV = phacelia-vetch; V = vetch.

51 DAI

F	O	OV	P	PV	V	
-	0.14	0.45	0.41	0.19	0.01	F
	-	0.29	0.52	0.01	<.01	O
		-	0.12	0.58	0.04	OV
			-	0.04	<.01	P
				-	0.13	PV
					-	V

68 DAI

F	O	OV	P	PV	V	
-	0.34	0.08	0.72	0.21	0.01	F
	-	0.01	0.55	0.03	<.01	O
		-	0.04	0.60	0.27	OV
			-	0.11	<.01	P
				-	0.10	PV
					-	V

80 DAI

F	O	OV	P	PV	V	
-	0.84	0.08	0.93	0.46	0.03	F
	-	0.05	0.77	0.35	0.02	O
		-	0.10	0.30	0.65	OV
			-	0.51	0.04	P
				-	0.14	PV
					-	V

101 DAI

F	O	OV	P	PV	V	
-	0.46	0.34	0.92	0.77	0.25	F
	-	0.83	0.40	0.66	0.68	O
		-	0.29	0.51	0.84	OV
			-	0.69	0.21	P
				-	0.39	PV
					-	V

Table 3-4. P-value comparisons for soil nitrate-N 29, 47, and 63 days after incorporating the cover crops in 2008. Cover crop treatments: F = fallow; O = oats; OV = oat-vetch; P = phacelia; PV = phacelia-vetch; V = vetch.

29 DAI

F	O	OV	P	PV	V	
-	0.13	0.60	0.50	0.03	0.06	F
	-	0.04	0.40	<.01	<.01	O
		-	0.23	0.09	0.18	OV
			-	<.01	0.01	P
				-	0.73	PV
					-	V

47 DAI

F	O	OV	P	PV	V	
-	<.01	0.86	0.19	<.01	0.15	F
	-	<.01	0.04	<.01	<.01	O
		-	0.26	<.01	0.11	OV
			-	<.01	0.01	P
				-	0.06	PV
					-	V

63 DAI

F	O	OV	P	PV	V	
-	<.01	0.33	0.06	0.08	0.34	F
	-	<.01	<.01	<.01	<.01	O
		-	0.38	0.01	0.05	OV
			-	<.01	<.01	P
				-	0.43	PV
					-	V

Chapter 4

General Conclusions

Cover crop mixtures containing common vetch provided the fertilizer equivalent of at least 100 $kg \cdot ha^{-1}$ and increased broccoli yields under low fertility conditions. The rate of NO_3-N release into the soil depended on the percent N of the residue, with up to 40 percent of the total N content being released within 4 weeks following incorporation. Although there was more N available as soil nitrate than the broccoli crop could take up during the early stages of growth, increased availability during the early growth stages was correlated to final broccoli yield. Oats and phacelia, grown as sole crops, immobilized soil N for up to 68 days after soil incorporation, with up to 200 $kg \cdot N \cdot ha^{-1}$ of fertilizer required to overcome the immobilization. The addition of vetch in a mixture, however, overcame this immobilization. Phacelia, which had a higher N content than oats (sampled at the same time), produced a less severe N immobilization effect. Phacelia residue was also much easier to work into the soil than oat residue during seedbed preparation, with much less residue remaining on the soil surface.

Petiole nitrate levels were strongly correlated with broccoli yield in 2008, and the highest yields were associated with petiole NO_3-N concentrations greater than 10,000 ppm. In the aerobic incubations with cover crop mixtures, a quadratic model described the relationship of percent N in the mixture to the apparent nitrogen recovery (ANR). Net mineralization occurred when the percent N of the cover crop mixture was 1.5 to 1.8 percent. There was a strong correlation in 2007 between the ANR predicted by the incubation-derived model and the ANR in the soil and in the aboveground broccoli biomass. The model over predicted the ANR in the field soil, however the model more accurately predicted ANR in the broccoli biomass. The incubation model correctly predicted negative ANR values for the oat and phacelia cover-crop treatments. In 2008, the laboratory-predicted ANR and the field soil ANR were correlated (r^2=.45), and the laboratory model over predicted the field ANR. The incubation model gave a poor prediction of broccoli biomass ANR.

Cover crop biomass and total N content depends on the ability to achieve a good stand after the fall planting. Adverse weather conditions can reduce the ability to prepare an adequate seedbed, allowing winter annual weeds to survive and compete with the cover crop. All cover crop treatments produced much less biomass and accumulated less N in 2008 than in 2007. Average vetch biomass ranged from 5,000 $kg \cdot ha^{-1}$ (2007) to 1,000 $kg \cdot ha^{-1}$ (2008); oats ranged from 7,000 $kg \cdot ha^{-1}$ (2007) to 4,000 $kg \cdot ha^{-1}$ (2008); and phacelia ranged from 4,000 $kg \cdot ha^{-1}$ (2007) to 700 $kg \cdot ha^{-1}$ (2008). Phacelia can offer advantages over oats as component of vetch cover crop mixtures, however under cold, wet establishment conditions; oats can establish quicker and produce more biomass the following spring than phacelia.

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APPENDICES

Appendix 1. Potting mix recipe from Springhill Farm used for growing broccoli seedlings in the greenhouse.

Springhill Potting Mix Recipe

Low Fertiliy Mix (for lettuce, greens)
7 bags peat moss (3.8 ft^3)
3 bags medium vermiculite (6 ft^3)
3 small size vermiculite (4 ft^3)

Fertilizer

Feather meal 4.5 lbs
Fish meal 5.5 lbs
Fish bone 25 lbs
Kelp meal 23 lbs
Diatomacious earth 15 lbs
Sulfate of Potassium 3 lbs

Appendix 2. Above-ground broccoli biomass in 0 N cover crop treatments dried and weighed for biomass estimation and analyzed for percent C and N. Total N = biomass x %N/100. Cover crop treatments: F = fallow; O = oats; OV = oat-vetch; P = phacelia; PV = phacelia-vetch; V = vetch.

Cover crop	% C	%N	C:N	biomass (kg·ha^{-1})	Total N (kg·ha^{-1})
F	39.9	2.5	16	3611	92
O	39.5	2.3	17	2432	57
OV	39.6	3.1	13	4357	129
P	39.5	2.3	17	2208	52
PV	39.5	2.8	14	5715	161
V	40.0	3.4	12	4730	163

Appendix 3. Above-ground broccoli biomass in 0 N cover crop treatments, and fallow with 100, 200, and 300 kg N ha^{-1}, were dried and weighed for biomass estimation and analyzed for percent C and N. Total N = biomass x %N/100. Cover crop treatments: F = fallow; O = oats; OV = oat-vetch; P = phacelia; PV = phacelia-vetch; V = vetch.

Cover crop	N rate (kg·ha^{-1})	% C	%N	C:N	biomass (kg·ha^{-1})	Total N (kg·ha^{-1})
F	0	37.3	3.2	12	5013	162
	100	37.5	3.4	11	6774	230
	200	38.1	3.9	10	6117	236
	300	36.9	4.2	9	8057	339
O	0	37.8	3.0	13	2745	82
OV	0	38.7	2.8	14	4237	121
P	0	37.8	2.8	13	4058	114
PV	0	37.8	3.2	12	5521	178
V	0	38.4	2.8	14	4357	122

Appendix 4. Extended literature review.

Manure as an Organic N Source

Different types of manure have different nutrient analyses, which affect the cost of application. For example, Araj et al. (2001) demonstrated that manure application costs range from a low of 37 percent of the cost of commercial fertilizer for chicken manure applied to one type of soil, to 136 percent of the cost of commercial fertilizer for cow manure applied to another type of soil.

Fresh manure is usually more than 80% water, with a relatively low concentration of nutrients. The initial N concentration of the material may also be lost through volatilization, reducing the N concentration by between 25 and 44% (Dewes, 1995). The low value to mass ratio of manure results in higher application and transportation expense than for the equivalent nutrient application from a commercial fertilizer source (Keplinger and Hauck, 2006; Schlegel, 1992). Transportation expense for broiler and dairy manure ranges from $0.10 to $0.13/ton per mile hauled (Ribaudo et al., 2003; Bosch and Napit, 1992).

Cover crop Benefits and Management

Cover crops also yield multiple other benefits in agro-ecosystems that are of real value but are more difficult to quantify (Dabney et al., 2001; Ess et al., 1994; McCracken et al., 1994; Sullivan et al., 1991; Wyland et al., 1996). For example, adding organic materials such as crop residues or composts to cultivated soil builds soil organic matter and improves the ability of the soil to supply nutrients over time (Gaskell et al., 2007).

Before selecting and integrating cover crops into a farming system, objectives as well as spatial or temporal niches must be defined (Snapp et al. 2005). Cover crop characteristics to consider before integrating them into a farming system include: rapid establishment under unfavorable conditions, adequate dry matter production or soil cover, deep root system establishment to assist in nutrient uptake from the lower depths of the soil, organic matter production with low-residue carbon to nitrogen ratio (C:N), production of allelochemicals that may have negative effects on subsequent crops, and the capacity to fix biological N (Fageria et al. 2005).

Assessing N Availability in Organic Systems

In order to improve nitrogen management in organic systems, it is important to understand N cycling and all of the factors controlling net N mineralization. After a cover crop is incorporated into a soil there are several possibilities of what will happen to the N content in the residue. Corbeels et al. (1999) reported that:

1. Net mineralization (NO_3-N) will occur if N present in residue is greater than that required by the microbial biomass, there will be net N mineralization with release of NO_3-N.
2. No net mineralization will occur if N in residue is equal to the amount required by the microbial biomass.
3. Immobilization of N will occur when the amount of N in residue is less than that required by the microbial biomass to complete the decomposition process.

In cover crop based production systems, assessments of N cycling have often been based upon methods that evaluate plant and soil N pools (Sullivan et al., 1991), N release from cover crop residue (Rannells and Wagger, 1992), and N uptake by a subsequent cash crop (Clark et al., 1994). N mineralization of organic materials decreases when the lignin content is >10% on a dry-matter basis for legumes and >14% on a dry matter basis for non-legumes (Constantinides and Fownes, 1994). Understanding the critical role these compounds play in N mineralization may be used as a management tool for growers in synchronizing N availability with the subsequent crops' needs.

The single and double exponential models have been used in the field to estimate net N mineralized from soil organic matter (Cabrera and Kissel, 1988) and N released from organic residues (Gilmour et al., 2003), with the rate constants modified based upon soil moisture and temperature. Complex simulation models have been used that take into consideration N immobilization that occurs with some organic residues (e.g. cereal crop residues) however, the predictions for PAN have been shown to be inaccurate (Quemada and Cabrera, 1997a).

Factors Influencing Broccoli Yield

According to Wien and Wurr (1997), the population density is the most important factor influencing broccoli yield. For production of quality, single head broccoli with high yields of marketable florets, Jett et al. (1995) recommend a population density of 36,000 plant/ha. In another study, as plant populations increased from 24,000 to 72,000 plants/ha with N rates held constant (112 to 224 $kg{\cdot}ha^{-1}$), head weight decreased linearly (Dufault and Waters, 1985). Despite a reduction of head weight with high plant populations, marketable yields may increase simply due to increased numbers of heads (Dufault and Waters, 1985; Cutcliffe, 1971). Dufault and Waters (1985) reported that it is probable that N rates higher than 224 kg·ha^{-1} may increase head weight and yield, because as N rate increased from 56 to kg·ha^{-1} at all plant populations, marketable yields increased linearly.

Timing and method of N application

It is important for growers to obtain optimum broccoli yield and quality, with a minimal negative impact on the environment. The high demand for N and short growth period for broccoli make the timing and method of N application critical. Feller and Fink (2005) found that the N content of transplants had little effect on growth and yield, and there was no significant interaction between the N content in the transplant and fertilizer timing. Plant uptake of nitrogen per unit of root mass is highest shortly after planting, which band placement could possibly improve (Everaarts and de Willigen, 1999a). Everaarts and de Willigen (1999a) showed that band placement of N fertilizer resulted in higher yields, however, no linear relationship was found between optimum nitrogen application rates in each experiment and the amount of mineral nitrogen at planting (Everaarts and de Willigen, 1999a). Band placement of fertilizer N has positive effect on broccoli, and not consistently with cauliflower or white cabbage. This may be related to the fact that broccoli, as compared to the other two crops, has a shorter growth period and a comparatively high uptake of nitrogen (Everaarts, 1993a), which is especially high in the period shortly before harvest (Shelp and Liu, 1992).

Broccoli physiology and nitrogen uptake

Thorup-Kristensen (1993) showed that broccoli is able to root deeper than 1 m and that rooting depth is influenced by the distribution of mineral nitrogen in the soil. Snyder et al. (1989) noted that the roots of mature broccoli plants grown in deep, permeable, well-drained soil under average conditions use available water to a depth of 60 cm. If soil samples are taken between the rows, outside of the root zone, and soil NO_3-N concentrations are lower near the crop plants, then the quantity of soil NO_3-N present in the entire plot might be overestimated. Zebarth et al. (1995) suggest that this may partially explain high apparent N recovery (ANR) by the broccoli plants.

Impact of excess N application

Excess N application not only poses an environmental risk, but also affects the management and quality of the broccoli. Several studies have reported that nitrogen increases broccoli yield and weight of the individual heads (Dufault and Waters, 1985; Kowalenko and Hall, 1987; Vägen, 2003). Greenwood et al. (1980) suggest that low or excessive amounts of N can result in a higher incidence of immature heads. Hollow stem has also been associated with high rates of N application (Stivers, 1993). Increasing N application has also been reported to delay maturity (Cutcliffe et al., 1968). However, Dufault (1988) found that increasing N application, decreased the number of days to heading and to harvest.