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COVER CROPS TO ENHANCE SOIL PRODUCTIVITY IN ORGANIC
VEGETABLE CROPPING SYSTEMS

Abstract

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The supply of plant available nitrogen (N) is often limiting in organic vegetable cropping systems. Cereal and legume cover crop mixtures may enhance plant available N to subsequent crops. But cover crops often require adjustments to the timing of field operations. The rate of N release from cover crops is also uncertain due to variations in climate, residue quality, and N content. We conducted two field studies and one laboratory incubation study to optimize cover crop growth and N availability to a subsequent crop.

A field trial was conducted to assess the effect of planting date, harvest date, and rye (Secale cereal)-hairy vetch (Vicia villosa) seeding ratio on cover crop establishment, N accumulation, and residue quality. While late harvest favored larger biomass, there was an increase in C:N ratio and fiber content. Seeding ratio did not have a large effect on cover crop biomass yield or composition. In a related N mineralization laboratory incubation study, hairy vetch and a 75:25 rye-hairy vetch blend released similar amounts of N over 70 d. But the initial rate of N release was nearly 3-fold greater for hairy vetch. The slower rate of N release from the 75:25 rye-hairy vetch blend may result in N release that is better timed with crop N uptake. Nitrogen release was well correlated with residue C:N ratio, and therefore may be used to predict N release from rye-hairy vetch residues.
The effect of a fall planted 50:50 rye-hairy vetch cover crop on organic sweet corn nitrogen use efficiency was determined in a second field trial. Feather meal was applied over top of cover crops at four rates. A trend of increased sweet corn dry matter and ear yield was noticeable in cover crops treatments when no feather meal was applied. But a large contribution from the soil N pool made it difficult to separate the N contributions from cover crops and soil. Early and late planted cover crops had fertilizer replacement values of 57 and 27 kg N ha\(^{-1}\). Our results demonstrate that a 50:50 rye-hairy vetch blend may supply significant amounts of N to a subsequent crop.
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DEDICATION

For my Olivia
CHAPTER 1

Cover crops in organic vegetable cropping systems: a literature review

1. INTRODUCTION

Grass-legume cover crop blends have the potential to supply all or a significant portion of nitrogen to subsequent cash crops (Burket et al., 1997; Griffin et al., 2000; Cline and Silvernail, 2002; Tonitto et al., 2006; Sainju and Singh, 2008). Inclusion of cover crops in crop rotations provides a range of other benefits, including reduced soil erosion and runoff, improved N cycling, weed and pest control, enhanced soil quality, and increased crop yields (Sarrantonio and Gallandt, 2003; Fageria et al., 2005). Despite these benefits, cover crops often require adjustments to the timing of field operations (Teasdale et al., 2004; Snapp et al., 2005). The rate of release of N from cover crops is also uncertain due to variations in climate, residue quality and nutrient content (Rannels and Wagger, 1996; Ruffo and Bollero, 2003a; Ruffo and Bollero, 2003b). Therefore, growers have been slow to adopt cover crops in crop rotations.

There is renewed interest for including cover crops in rotation for the purpose of soil fertility management and enhanced crop production; especially among organic growers who are prohibited from using synthetic fertilizers (USDA, National Organic Program, 2010). The organic sector has experienced rapid growth since inclusion in the Organic Foods Production Act of 1990, with 20-25 % annual increase of organic food product sales (Lotter, 2003). One of the largest challenges to efficient production of organic crops is adequate and timely N supply and efficient use (Berry et al., 2002). Numerous studies have estimated the N fertilizer value of cover crops to subsequent cash crops (Rannels and Wagger, 1996; Burket et al., 1997; Griffin et al., 2000; Sarrantonio and Malloy, 2003; Tonitto et al., 2006; Sainju and Singh, 2008). However, use among organic growers is limited because of lack of research on optimal dates of establishment,
effect of early incorporation, and influence of cereal-legume seeding ratio on stand establishment, N accumulation, and N availability to subsequent crops (Cogger, personal communication).

Greater understanding of N release from cover crop residues, N availability to subsequent crops, and ability to predict plant available N supply might provide a “keystone service” necessary for widespread adoption of cover crop use in crop rotations (Cherr et al., 2006). Research is necessary at a regional scale because rates of N release are affected by variations in climate, residue quality, and nutrient content (Cabrera et al., 2005). Grower uncertainty concerning the effect of planting and harvest date and cereal-legume seeding ratio on cover crop biomass production, N accumulation, and N availability to crops in rotation varies across regions due to climate differences and crop rotation restrictions (Snapp et al., 2005). Therefore, research is needed to optimize planting and harvest dates and cereal-legume seeding ratio, and N availability to crops grown in rotation.

2. OVERVIEW OF ORGANIC VEGETABLE PRODUCTION

The organic farming sector has been one of the most rapidly expanding segments of agriculture for over a decade (Greene, 2006), during which demand has periodically outpaced supply (Dimitri and Oberholtzer, 2009). In response to consumer interest, the number of certified organic crop acres has increased from 638,500 acres in 1995 to 2,655,382 acres in 2008 (USDA, Economic Research Service, 2010). Fresh produce continues to be the top selling organic product (Organic Trade Association, 2010). The number of certified acres in vegetable production more than tripled between 1997 and 2008 to a total of 168,776 acres, nearly 5% of total vegetable farmland in the United States (USDA, Economic Research Service, 2010).

Organic vegetable production in Washington
According to the 2008 Organic Production Survey (USDA, National Agriculture Statistics Service, 2010), Washington was the second leading producer of certified organic vegetables in the country. Harvested organic vegetable acreage in Washington State doubled between 2004 and 2007; however, there was little growth in 2008, with 19,836 acres recorded (Kirby and Granatstein, 2009). The lag in growth may be related to the recent economic recession and higher cost of organic products versus conventional (Dimitri and Oberholtzer, 2009). Washington had 887 certified and exempt organic producers (USDA, Economic Research Service, 2010), of which one-third were located west of the Cascade Mountains (Kirby and Granatstein, 2009). Besides Whatcom and Lewis counties, which had larger farms and 8 percent of the state’s vegetable production acreage, farms in western Washington were characterized as small, diverse, direct market enterprises (Kirby and Granatstein, 2010). In particular, land in King, Pierce, and Thurston Counties tended to be farmed intensively and net a high economic return on a per acre basis. Climate and production systems are distinct from Eastern Washington, a main agriculture region in the state, and therefore research must reflect those differences (Granatstein et al., 2010).

Despite a growing demand for organic food products, many farmers have not been willing to transition to organic management production. High costs, low yields, and lack of understanding of organic management practices have been cited as obstacles to adoption of organic production (USDA, Economic Research Service, 2010). In a statewide survey of organic farmers in Washington, Goldberger (2008) found that production expenses and variable or low yields were the greatest challenges to organic production. Organic farmers in the Puget Sound region of western Washington have similarly expressed concerns over yield reduction due N deficiency (Cogger, personal communication). A number of studies have validated this concern,
demonstrating 20-41% lower yields in organic and transitional cropping systems when compared to conventional systems (Mader et al., 2002; Cavigelli et al., 2008; Dresboll et al., 2008; Herencia et al., 2008).

**Soil fertility management**

Soil fertility management has been listed as one of the largest challenges to growing crops organically (Walz, 2004; Gaskell and Smith, 2007). Organic crop production has prohibited the use of synthetic fertilizers. While soil fertility is not different in organic and conventional cropping systems, there is greater reliance on the soil biology that transforms nutrients into plant available forms because mineral fertilizers cannot be used (Mader et al., 2002; Tu et al., 2006). It is more crucial to manage nutrient pools and the processes and rates that dictate nutrient transformation from one form to another (Stockdale et al., 2002). The quality and quantity of organic inputs and the affect on soil microbiology is of particular concern because of its influence on N mineralization and soil organic matter accumulation (Cabrera et al., 2005). It is widely held that soil organic matter formation and decomposition forms the foundation of N supply to crops grown organically (Magdoff and van Es, 2000; Gaskell and Smith, 2007).

Similar importance on soil fertility has been emphasized in the USDA National Organic Program standards that mandate growers to develop a crop production management plan that builds the inherent fertility of soil by managing organic matter; a crop rotation must include cover crops, green manures, and catch crops that build soil organic matter, effectively limit erosion, and properly manage limiting or excessive plant nutrients (USDA, National Organic Program, 2010).

A variety of products and management practices have been used to supply N to crops in organic production, including animal manures, compost, cover crops, and specialty products (Cogger, 2000; Watson et al., 2002; Gaskell, 2006). But none of these means are without
challenge. Livestock manure is often used as a source of fertility and organic matter, however there are restrictions on timing of application (Riddle and McEvoy, 2005) and high variability in N content and availability between types and sources has been reported (Bary et al., 2000). Using manure as a fertilizer can also result in excessive application of phosphorus and contamination of groundwater (Hao et al., 2004). Well-composted materials decompose slowly, solving P loading issues but supplying smaller amounts of plant available N (Gale et al., 2006). In contrast, some commercial organic fertilizers, such as sea bird guano, fish powder, feather meal, and blood meal, consistently provide relatively rapid and predictable nutrient availability. Farmers often complain that specialty products are expensive and cost-prohibitive while compost and manures are bulky and costly to import and apply (Gaskell and Smith, 2007). Legume cover crops are often worked into rotation as a source of short-term nitrogen fertility. Both summer interseeded and winter legume and cereal-legume cover crop mixtures have been shown to provide significant amounts of nitrogen to subsequent crops (Rannels and Wagger, 1996; Burket et al., 1997; Griffin et al., 2000; Sarrantonio and Malloy, 2003; Teasdale et al., 2008). But it is difficult to predict N availability to subsequent crops (Cabrera et al., 2005) because N mineralization of residues is controlled by many factors, including residue composition (Ranells and Wagger, 1996), soil temperature and water content (Ruffo and Bolero, 2003b), and soil characteristics (Whitmore and Groute, 1997).

The challenge in organic farming is matching inorganic N supply with crop demand on a temporal basis (Pang and Letey, 2000). Berry et al. (2002) found that while Organic farming systems that use cover crops, manures, and composts have the potential to supply large amounts of N, release is often not timed with N uptake in subsequent crops. Because synthetic fertilizers cannot be used in organic systems, delivery of readily soluble nutrients is not possible. There is a
general need for greater understanding and ability to predict N release from various organic products and green manures so fertility recommendations can be accurately made (Granatstein et al., 2010). Recently, work has been done to measure N release from manures, composts, and specialty products in the Pacific Northwest (Gale et al., 2006). But, current research concerning cover crop use for N management is almost entirely based on synthetic inputs of a conventional system, which are inadequate for effective management in organic production (Cherr et al., 2006), and it fails to address N availability issues and parameters for cover crop establishment (Kramberger et al., 2009). Regional information on cover crop growth, N accumulation, and N release patterns is needed in organic cropping systems.

3. EVALUATION OF COVER CROP BENEFITS

Cover crops have been an integral part of crop rotations for many millennia, providing a range of on-farm benefits and ecosystem services (Sarrantonio and Gallandt, 2003; Fageria et al., 2005; Cherr et al., 2006). Earliest uses date to 500 BC, where Chinese records acknowledge understanding of its value as fertilizer (Paine and Harrison, 1993). Clovers and other legumes filled traditional fallow periods in turnip-grain rotations in the eighteenth century in Europe and winter cover crops were common in cropping systems in the early twentieth century in North America (Pieters, 1917). But cover crop use declined in most industrial countries after commercialization of Haber-Bosch process and widespread availability of commercial fertilizers, as fertility systems based on soluble nutrient sources supplanted cover crop practices in most cropping systems (Galloway and Cowling, 2002). There is renewed interest for including cover crops in rotation for the purpose of soil fertility management and enhanced crop production, especially in organic cropping systems where mineral fertilizer use is prohibited (USDA National Organic Program, 2010).
Cover crops are grown between periods of normal production or inter-seeded between rows of cash crops or trees or vines in orchard or vineyard for the purpose of soil and water conservation and enhanced soil productivity (Hartwig and Ammon, 2002; Sarrantonio and Gallandt, 2003). These crops are not grown for purpose of sale or feed, but are often plowed under and incorporated into the soil (as green manures) or desiccated and left on the soil surface. Inclusion of cover crops in crop rotations provides on-farm benefits and environmental services, including reduced soil erosion and runoff, improved N cycling, N fixation and supply to crops, weed and pest control, enhanced soil quality, and increased crop yields (Fageria et al., 2005; Snapp et al., 2005; Cherr et al., 2006). However, benefits of inclusion of cover crops in rotation vary among different soils types, crop rotations, environmental variables, type and species of cover crop, and management schemes (Fageria, 2007).

**Improved N management**

Improved N cycling is an advantage to inclusion of cover crops in crop rotations (Sarrantonio and Gallandt, 2003). Significant amounts of residual soil N can be captured by catch crops and reduce leaching by recycling N for subsequent crop uptake (BrandiDohrn et al., 1997). Legumes biologically fix atmospheric N, which enhances short-term soil N fertility. Cherr et al. (2006) suggest that N supply from cover crop residues to cash crops grown in rotation provides a “keystone” service that makes cover crop use attractive to farmers. But low N utilization efficiency by cash crops and unreliable N supply from cover crop residues represent nutrient management challenges (Pang and Letey, 2000; Teasdale et al., 2008).

Non-leguminous winter cover crops can take up significant amounts residual soil nitrate to reduce leaching to waterways and improve N cycling (Sainju and Singh, 2008; Moller and Reents, 2009; Thorup-Kristensen and Dresboll, 2010). This is important in humid, temperate
climates such as the maritime Pacific Northwest, where mild temperatures can make winter mineralization significant and high rainfall causes extensive leaching and removal of nitrates from the soil profile by spring (Kuo et al., 1997; Hooker et al., 2008). Studies show that variation in N uptake by winter cover crops are dependent upon rainfall patterns and the cover crop species grown. In an 11 year-study of fall-seeded cover crops in the Willamette Valley, Oregon, water quality benefits of reduced N leaching were controlled by the timing and quantity of annual rainfall. Early rainfall following a dry year increased leaching potential regardless of cover crop treatment (Feaga et al., 2010). However, in the case of a dry winter season, N uptake by winter cover crops has reduced N availability to subsequent crops, causing pre-emptive competition (Thorup-Kristensen and Dresboll, 2010). Cereal and brassica cover crops are adapted for high N uptake (Weinert et al., 2002). Although some research demonstrates that legume cover crops are not effective in reducing soil nitrate leaching over winter (Rosecrance et al., 2000), others find cereal-legume mixtures plausible (Moller and Reents, 2009). In a study of the effect of winter grown oats, lupins, and an oats-lupins mixture on soil nitrate leaching, Fowler et al. (2004) found a 50 % reduction in winter nitrate leaching compared to bare soil, but no difference between cereal and cereal-legume cover crop treatments. In general, cereal-legume cover crop blends are more efficient at N uptake from soil than legume monoculture (Rinnofner et al, 2008).

Biological N fixation by legume cover crops can supply significant N to crops grown in rotation and replace off-farm N fertility inputs (Tonitto et al., 2006; Gselman and Kramberger, 2008), making it a sustainable and renewable source of N. The amount of atmospheric N fixed by winter legumes is affected by soil N status at the time of cover crop growth. Moller et al. (2008) found that high soil inorganic N content reduced legume growth and N fixation when
combined in mixture with cereal. Similarly, Kramberger et al. (2009) demonstrated that legumes are better adapted to low N fertility soils than cereal cover crops because of their ability to fix N. Soil temperature has been shown to affect N fixation efficiency of legumes and has impacted what legume species are best suited to a given crop rotation and climate (Power and Zachariassen, 1993). A variety of legume cover crops are adapted for winter growth in temperate climates, including Trifolium spp. (clovers), Vicia spp. (vetches), Medicago spp. (alfalfa, trefoils, and other medics), and Lupinus spp. (lupins) (Rannels and Wagger, 1996; Jeranyama et al., 1998; Griffin et al., 2000; Zemenchik et al., 2001; Ross et al., 2001; Fowler et al., 2004; Kankanen and Eriksson, 2007; Teasdale et al., 2008).

A cereal-legume cover crop blend can serve the “dual purpose” of recycling residual fall soil N, supplying additional N by biological fixation, and increasing N availability compared to pure cereal (Clark et al., 2007). But Cline and Silvernail (2002) found that N availability following cereal-legume mixtures was lower than pure legume cover crops. Manipulating cover crop residue N content and quality by optimizing planting and kill dates and cereal-to-legume biomass ratios can have a significant impact on N availability following cover crop incorporation (Kuo and Sainju, 1997; Wagger et al., 1998). This is a chief concern to growers because the timing of N availability is not always synchronized with crop N uptake demands, decreasing crop N use efficiency (Pang and Letey, 2000).

**Weed control**

Cover crops are an effective management option for weed control and suppression. Competition by cover crops for light, water, and nutrients and microclimate modification is one means for weed control (den Hollander et al., 2007). Isik et al. (2009) cited this mechanism in finding that hairy vetch, ryegrass, oats, and common vetch cover crops grown over winter
reduced total weed biomass by 87-91 % compared to winter fallow. Summer inter-seeded cover crops can effectively reduce weed biomass but competition with crop and yield reduction can be a problem (den Hollander et al., 2007). However, relay planted cover crops planted between main crop rows after crop establishment can provide effective weed suppression without reducing yields (Vanek et al., 2005). Cover crops may also control weed emergence and germination by releasing allelopathic chemicals (Weston, 1996). Malik et al. (2008) suggested that ten identified glucosinolates, or possible allelopathic elements, in wild radish cover crop residue contributed to 35 % reduction in weed biomass in a corn rotation. However, other research demonstrated that N availability can influence weed germination and biomass. Kumar et al. (2008) found that buckwheat (Fagopyrum esculentum) residues suppressed shepherd’s purse (Capsella bursa-pastoris) growth and emergence through N immobilization. Similarly, Sung et al. (2010) reported 65% less weed biomass following rye but an increase in weed biomass in hairy vetch incorporated treatments due to higher N availability. In contrast, hairy vetch mowed at flowering and left on surface prior to planting cash crops reduced weed biomass by 40% (Campiglia et al., 2010). Residue placement can impact N availability and provide physical barrier to weed emergence (Teasdale and Mohler, 1993; Campiglia et al., 2010).

**Improved soil quality**

Soil organic matter content is commonly used as the principal indicator of soil quality and health (Doran, 2002) because of its role in nutrient cycling, soil tilth, biological activity, and water availability (Magdoff and van Es, 2000). Studies have shown that cover crop residues can supply large amounts of C to the soil (Kuo et al., 1997, Sainju et al., 2005; Fortuna et al., 2008), resulting in increases or maintenance of soil organic matter (Nyakatawa et al., 2001). Cereal cover crops increase or maintain soil organic matter levels relative to legume cover crops and no
cover crop management by supplying greater C inputs in the form of plant biomass (Sainju et al., 2000; Ding et al., 2005). Legumes can increase or maintain soil organic matter if the biomass is large enough. In Kentucky, a continuous corn-hairy vetch cropping system increased total soil C and N compared to management without hairy vetch because of greater residue inputs (Fortuna et al., 2008). Another study found that soil organic carbon increased in a cropping system with legume cover crops in comparison to a no legume, fertilizer-based system, which was likely because of greater C input from plant biomass inputs (Bakht et al., 2009).

4. COVER CROP MANAGEMENT

Implementing a cover crop management scheme depends on targeted goals or benefits desired and crop rotational niche (Sustainable Agriculture Network, 2007). Goals and ground availability affect what species are most suitable to a given rotation and environment (Snapp et al., 2005).

Niches in rotations for cover crops

Defining spatial and temporal niches where cover crops can be integrated into crop rotations can be the greatest obstacle to widespread cover crop use (Snapp et al., 2005). Vanek et al. (2005) explain that cover cropping is limited in vegetable production because of frequent tillage, complex rotations, and continuous cropping for harvest. There are a number of considerations for identifying where and when cover cropping is possible, including seeding method, weather restrictions, soil conditions, cover crop growth habit, method of kill and subsequent bed preparation, and effect on economic crop growth and yield (Sustainable Agriculture Network, 2007; Cherr et al., 2006). Sarrantonio (1992) lists non-simultaneous cover cropping, relay planting, and intercropping as living mulch between crop rows as options for position in rotations. Relay planting is a system where cover crops are planted into standing cash
crops, allowing early establishment of cover crops without negatively impacting cash crop growth. Winter cover crops planted after cash crop harvest are most common in temperate climates because full-season or summer cover crops represent income loss from field that is not cropped for an entire growing season (Griffin et al., 2000).

Cover crops are usually planted in a fallow period of a rotation when weather is not favorable for production of a cash crop (Cherr et al., 2006). Winter grown cover crops are grown without sacrificing ground for cash crop production. But establishment can be troublesome in temperate climates because of low temperature at time of sowing and significant loss to winterkill (Teasdale et al., 2004; Bransdaeter et al., 2008). Growers in cold climates, such as Maine, often have a narrow window of opportunity for establishing cover crops after harvesting a cash crop in fall, which can result in inadequate biomass or winterkill (Griffin et al., 2000). A number of studies list rapid germination and establishment, extensive rooting systems, good winter-hardiness, and early spring growth as characteristics for successful winter cover crops in cool, temperate climates (Nelson et al., 1991; Creamer et al., 1997; Delate et al., 2008). However, variability in annual weather conditions can result in inconsistent cover crop biomass yield and N accumulation between years despite cover crop vigor and cold-tolerance (Burket et al., 1997; Odhiambo and Bomke, 2000; Rinnofner et al., 2008). The literature demonstrates that promising winter cover crop for temperate climates include monoculture or combinations of barley, rye, ryegrass, wheat, hairy vetch, crimson clover, and red clover (Nelson et al., 1991; Creamer et al., 1997; Teasdale et al., 2004; Bransdaeder et al., 2008).

Cover crops are often inter-seeded with a main crop and maintained as a living ground cover over the cropping season (Hartwig and Ammon, 2002). Relay or simultaneous planting of cover crops with a cash crop is attractive because a soil improving crop can be grown without
taking land out of cash crop production and it can potentially control weeds (Sarrantonio and Gallandt, 2003). Cover crop species and timing of planting in relation to crop establishment has an impact on cash crop yield because of competition for nutrients, water, and light, and modification of growing conditions (Biazzo and Masiunas, 2000; Brainard and Bellinder, 2004). For example, annual medic planted simultaneously with corn reduced early growth and subsequent yield by decreasing N availability to the crop (Smeltekop et al., 2002). However, Negrini et al. (2010) found that intercropping white lupin with lettuce did not affect lettuce performance when planted at the same time. In the same study, black oat or cowpea sown 20, 40, and 60 days prior to lettuce were found to negatively influence lettuce growth and yield via competition for sunlight. Relay planting cover crops can benefit crops by contributing N to intercropped or subsequent cash crops without reducing crop growth and yield (Jeranyama et al., 1998). Additionally, wide row spacing and rapid growth habits of some crops, such as pumpkins, make some crop systems better suited to intercropping systems than others (Vanek et al., 2005). Therefore, intercropping schemes are specific to site and cropping system.

**Cereal-legume cover crop blends**

Mixed cereal-legume cover crop blends are considered to be a better management option than growing either species alone because it can reduce risk of stand failure, enhance biomass productivity, and prevent N immobilization after spring incorporation (Sustainable Agriculture Network, 2007). A number of studies demonstrate that mixtures have increased yield stability compared to monocultures because together species have a wider range of tolerance to adverse environmental conditions than when grown alone (Creamer et al., 1997; Gaskell, 2006). In some cases, the cereal crop can act as a nurse crop for the legume, enhancing winter hardiness by reducing exposure to harsh weather. A cereal can also enhance the performance of a legume
when grown in biculture. For example, the support from rye plants prevented lodging in winter pea in one study (Karpenstein-Machan and Stuelpnagel, 2000). Further, cereal crops, such as rye, can provide structure for sprawling crops like hairy vetch, thereby increasing use of solar energy and biomass (Sustainable Agriculture Network, 2007).

Cover crop blends that include cereal and legume species optimize N cycling and N availability to subsequent crops. This is because cereals are capable of recycling residual soil nitrate after fall harvest to minimize leaching and legumes fix atmospheric N, which increases N concentration in residue (Clark et al., 1997). But in one rye-winter pea mixture, high residual soil N decreased winter pea establishment and vigor because rye exhibited greater competitive advantage in high N conditions (Burket et al., 1997). In some cases, the N concentration of a cereal in mixture with a legume is higher than when it is grown alone (Rannels and Wagger, 1996). Burket et al. (1997) observed that cereal residue had 28% higher N concentration when grown in mixture with red clover than when cropped alone. Mineralization of decomposing legume roots can enhance soil (NH$_4^+$+NO$_3^-$)-N for uptake by a simultaneously grown cereal (Evans et al., 2001)

Cereal and legume cover crops grown mixtures often produce greater biomass and accumulate more N than grown when grown in monoculture (Ranells and Wagger, 1996; Clark et al., 1997; Sainju et al., 2005). For example, Teasdale et al. (2008) found that hairy vetch accumulated 4.67 to 5.75 Mg ha$^{-1}$ of dry matter while a rye-hairy vetch mixture produced 8.95 to 11.17 Mg ha$^{-1}$. In one study, rye-hairy vetch biculture dry matter was no different than pure rye (Cline and Silvernail, 2001). In that same study, the biculture accumulated significantly more N than a pure cereal crop because of higher N concentrations of the residues in the blend. While monocropped cereals, such as rye, can immobilize N following incorporation, cereal-legume
bicultures can supply N to subsequent crops because of increased residue N concentration (Kuo and Sainju, 1998).

**Suitable winter cover crops for the maritime pacific northwest**

In the maritime Pacific Northwest, winter cover crops are typically planted by late September and incorporated in late April to ensure sufficient biomass and N accumulation without interrupting common crop rotations (Kuo and Jellum, 2000). The climate in this region is characterized by cool, wet winters that leach residual soil NO$_3^-$ out of the soil profile (Feaga et al., 2010), and warm, dry summers, which can limit cover crop establishment without irrigation (Burket et al., 1997). Minimum annual temperatures ranged from -13 to -3 °C over the past 15 years in Puyallup, WA (Washington Agriculture Weather Network, 2010), which makes freeze tolerance an important trait. Date of planting can also affect winter survival. Brandsaeter et al. (2002) found a negative correlation between freeze resistance and age in hairy vetch and clover spp. Although delay of spring incorporation can increase cover crop dry matter production, excessive C accumulation in residue can lead to N immobilization (Thorup-Kristensen and Dresboll, 2010). High rainfall during fall establishment can create saturated soil conditions and stand failure in some species.

Cereal rye is a standard winter cover crop in many temperate climates, including the maritime Pacific Northwest, because it is winter-hardy and tolerant of late planting (Managing Sustainable Agriculture Network, 2007). Dry matter production ranged from 1.42 to 4.19 Mg ha$^{-1}$ in a study in Puyallup, WA when planted in early October and killed in late April (Kuo and Jellum, 2000). Winter wheat and annual ryegrass produced similar dry matter in other locations in the Pacific Northwest when sown before October (Sattell et al., 1999; Odhiambo and Bomke, 2000). Rapeseed and canola are other non-leguminous cover crops that have been grown in the
region. Difficulties with establishment and winterkill have been reported on some occasions and some researchers have viewed these species as unsuitable for winter growth in this region (Kuo et al., 1996; Sattell et al., 1999). Hairy vetch has proven to be a cold tolerant winter annual legume (Brandsaeter and Netland, 1999). In a study in south coastal British Columbia, hairy vetch produced more reliable stands than crimson clover, which was susceptible to winter kill during below average winter temperature conditions (Odhiambo and Bomke, 2000). In Puyallup, hairy vetch yielded 0.91 to 3.48 Mg ha\(^{-1}\) of dry matter when planted by late September (Kuo and Jellum, 1997). Crimson clover, red clover, and subterranean clover produced similar biomass and were consistent in growth in a study in the Willamette Valley, OR (Sattell et al., 1999). Austrian winter pea has been listed as a potential winter annual for the maritime Pacific Northwest. However, occasional stand failures have been noted in wet years (Kuo et al., 1996; Sattell et al., 1999).

Past research at the WSU Research and Extension Center in Puyallup, WA demonstrates that rye-hairy vetch cover crop blends are well suited for the climate and cropping systems of this region (Kuo and Sainju, 1997; Kuo and Jellum, 2000; Cogger et al., 2008). Cereal rye establishes rapidly when planted by early October and it can effectively utilize residual soil nitrate because rapid root development puts it in contact with soil N (Kuo and Jellum 2000; Thorup-Kirstensen et al., 2003 Feaga et al., 2010). In contrast, hairy vetch is known to have slow fall growth and low soil cover (Holderbaum et al., 1990), possibly because its optimum temperature for root growth is relatively high (20-25 °C) (Mosjidis and Zhang, 1995). But hairy vetch has high winter survival in northern temperate climates (average minimum temperatures from -2 to -10 °C) (Teasdale et al., 2004; Brandsaeter et al., 2007) and it accumulates biomass rapidly in the spring as soil temperatures increase (Holderbaum et al., 1990; Kuo and Jellum,
Further, hairy vetch consistently accumulates more N than rye, which impacts N availability to subsequent crops (Kuo et al., 1997). A summary of biomass, N content, and C:N ratio of winter cover crops typical in the maritime Pacific Northwest is found in Table 1.

5. NITROGEN AVAILABILITY FROM COVER CROP RESIDUES

Winter cover crops are commonly included in crop rotations to supply N to successive cash crops but N release patterns from residues are uncertain (Griffin et al., 2000; Cabrera et al., 2005; Teasdale et al., 2008). Soil microbial processes, which are affected by residue composition and various environmental factors, are responsible for the decomposition and release of nutrients from organic materials (Wolf and Wagner, 2005). Specifically, microbes transform organic N to ammonium via mineralization and immobilize ammonium through assimilation in microbial biomass (Myrold, 2005). Nitrification, the process by which microbes convert ammonium to nitrate, is considered to be the fate of most ammonium in N-rich agricultural soils (Robertson, 1997). Ammonium and nitrate compose the soluble pool of soil N, which is subject to future immobilization and re-mineralization (Burger and Jackson, 2002), losses via leaching (Moller and Reents, 2009; Thorup-Kristensen and Dresboll, 2010) and denitrification (Rosecrance et al., 2000), and plant uptake. The factors that affect the cycling of N into soil inorganic pools, microbial biomass, and more stable soil forms play a large role in the timing and amount of N available for plant uptake (Myrold and Bottomley, 2008).

Influence of environmental factors

The rate of decomposition of organic residues and release of N is influenced by soil environmental conditions, including temperature, moisture status, and soil texture. Variability in N mineralization and nitrification of soil organic N and amended materials have been studied in the laboratory, via incubation using different soils and under controlled climate (Gonzalez-Prieto
et al., 1996; Sierra, 1997; Griffin et al., 2002), and in the field (Quemada and Cabrera, 1997; Delin and Linden, 2002; Watts et al., 2010).

The biological processes involved in soil N transformations are temperature-dependent (Davidson and Janssens, 2006), generally increasing with temperature until some optimum is reached. In general, temperatures between 20 and 30 °C are considered ideal for N mineralization and nitrification (Robertson et al., 1999; Curtin and Campbell, 2008). The effect of temperature on N mineralization can be standardized using a Q(10) factor, which calculates the increase in mineralization rate for every 10 °C increase. Research has demonstrated that N mineralization is also a function of growing degree days when moisture is adequate (Honeycutt and Potaro, 1990; Griffin and Honeycutt, 2000). The advantage to using growing degree days to account for the effect of temperature on N mineralization is that it allows for comparison between laboratory and field trials (Ruffo and Bollero, 2003b). Some studies have demonstrated that N mineralization rates increase exponentially with temperature up to 35 °C (Sierra, 1997; Cookson et al., 2002; Wang et al., 2006). Others have shown linear correlations for rates of N mineralization (Quemada and Cabrera, 1997) and nitrification (Griffin and Honeycutt, 2000). Soil properties and management practices likely account for differences between these results (Kruse et al., 2004; Wang et al., 2006). For example, in a study in China the Q(10) of net N mineralization increased from 1.70 in grazed grassland to 2.24 in an adjacent, non-grazed site (Wang et al., 2006).

Soil moisture fluctuations can have a large affect on N mineralization and nitrification rates (Paul et al., 2003). It is often reported that soil moisture at field capacity is most favorable for N transformation processes, but it is difficult to compare results from different studies because of the variety of methods used to measure soil water status (i.e. water holding capacity,
water-filled pore space [WFPS], and water potential) (Griffin, 2008). In one study, soil water status was linearly related to N mineralization rate from 35 to 60% WFPS (Sierra, 1997). Drury et al. (2003) reported a similar relationship, also demonstrating that denitrification is likely at high soil water contents (>70% WFPS). The drying and rewetting of soil, which is common in summer irrigated cropping systems, was reported to significantly reduce N mineralization of cotton leaf residue and compost (Kruse et al., 2004). But Griffin et al. (2002) found the effect of water status on N mineralization to be less profound in soil amended with animal manures.

Several studies have shown that the influence of temperature on soil N transformations varies with soil moisture (Sierra, 1997; Knoepp and Swank, 2002; Wang et al., 2006). These interactions are most obvious at relatively high temperatures (15 to 30 °C). Variation in N mineralization rate as affected environmental conditions (Odhiambo and Bomke, 2000; Delin and Linden, 2002) can be accounted for by using degree- and decomposition-day modeling (Ruffo and Bollero, 2003b) or Q10 parameters in soils not limited by moisture (Rey et al., 2005; Pavelka et al., 2007) to correct for seasonal or climatic differences.

Soil properties affect N mineralization and nitrification processes (GonzalezPrieto et al., 1996; Delin and Linden, 2002) primarily via variation in soil texture (Gordilla and Cabrera, 1997; Cabrera et al., 2005). For example, in a laboratory incubation measuring N release from swine slurry, N mineralization was highest in coarse textured soils (Griffin et al., 2002), which is likely because of increased aeration in soils with high sand content (Thomsen et al., 1999). Soil texture variation across landscape positions within a field influenced N mineralization due to changes in relative water holding capacity (Watts et al., 2010). In that study, a bottomland loam soil with high water content mineralized 9 to 10% more N than a loam or sandy loam on sideslope and summit under identical management. Soil properties can affect N mineralization
from organic residues in other ways, including physical protection of organic residue via formation of macroaggregates in clayey soils (Egelkraut et al., 2000) and variability in soil microbial activity and biomass C:N ratio (Hassink, 1994). Additionally, GonzalezPrieto et al. (1996) found that soils with high pH and base saturation are more likely to immobilize N in a study of N transformations of 112 native and agricultural soils. Nitrification reactions are generally more sensitive to pH than N mineralization (Griffin, 2008).

**Impact of residue quality on net N mineralization**

Under constant environmental conditions and management schemes, short-term N mineralization-immobilization processes are primarily a function of available C and N. Amending soil with organic residues stimulates microbial growth via addition of available C (Wang et al., 2003; Tu et al., 2006). But microbial biomass must assimilate a certain amount of N, which is determined by microbial C:N ratio (Kaye and Hart, 1997). If the N concentration available from the residue is greater than what is needed by microbial biomass, there will be net N mineralization (Myrold and Bottomley, 2008). Research has often shown that the C:N ratio and total N concentration of amended substrate explain N mineralization-immobilization dynamics fairly well (Vigil and Kissel, 1991; Ranells and Wagger, 1996; Gilmour et al., 1998; Chaves et al., 2004; Justes et al., 2009). A number of studies report a critical C:N ratio, which is used to describe the tipping point between net mineralization and immobilization, ranging between 24 and 36 for incorporated plant residues (Kuo and Sainju, 1998 Trinsoutrot et al., 2000; Chaves et al., 2004; Jensen et al., 2005). But the C:N break-even point has been reported to be as low as 15 (Gilmour, 1998) and has high as 40 (Whitmore, 1996). Such wide variation in the critical C:N value is likely related to variation of the C:N ratio of the microbial biomass and differences in biochemical quality of the residue (Cabrera et al., 2005).
Some research has demonstrated that C:N ratio is only initially correlated with N mineralization because residue biochemical composition changes as substrate decomposes and releases nutrients (Chaves et al., 2004; Myrold and Bottomley, 2008). Others have demonstrated that it is neither an adequate measure of residue quality (Ruffo and Bollero, 2003a) nor a useful parameter for estimating N mineralization rate (Vigil and Kissel, 1995). Several studies have characterized fiber fractions groups in organic residues and related these measurements to N release patterns (Wagger et al, 1998; Kuo and Sainju, 1998; Chaves et al., 2004; Jensen et al., 2005). But there is no consensus on what residue qualities best correlate with N release.

Lignin:N ratio is often cited as correlating well with net N mineralization (Vigil and Kissel, 1991; Constantinides and Fownes, 1994; Kumar and Goh, 2003). For example, Vigil and Kissel (1991) found that including lignin:N ratio in a regression model of crop residue N mineralization bolstered the rigor of the equation. In another study, lignin:N ratio was well correlated with rate constants of a first-order kinetic model for N mineralization of plant residues of varying quality (Chaves et al., 2004). However, Jensen et al. (2005) found that C:N and lignin:N ratios of plant residues were poor parameters for estimating N release. In that study, net N mineralization of plant residue was initially most closely related to water soluble N content ($r = 0.76$), and neutral detergent soluble N and total plant N were best correlated after three weeks ($r = 0.90$ to 0.94). Other research has reported similar findings (De Neve and Hofman, 1996; Bending et al., 1998; Trinsoutrot et al., 2000). But additional research is necessary to enhance our understanding of the variability in results and better estimate net N mineralization from plant residues (Cabrera et al., 2005).

Management practices influence N release dynamics
Management practices can impact N release dynamics from plant residue by manipulation of residue quality via kill date (Wagger et al., 1998), enhanced mineralization through interaction with fertilizer (Snapp and Borden, 2005), and increased access of residue to microbial community through tillage (Drinkwater et al., 2000) and residue size reduction (Giaconimi et al., 2007). First, delaying cover crop kill date in spring may result in slow release of N because residue quality has become more recalcitrant (Wagger, 1989). In one study, an eight day delay in spring kill of hairy vetch resulted in a decrease in residue N concentration, which could reduce the rate of N mineralization (Cline and Silvernail, 2001), and therefore N release may not be harmonious with crop N uptake (Crandall et al., 2005). Multiple incorporation dates of rye cover crop between early March to late April demonstrated decreased net N mineralization with increased delay, which was likely due to an increase in residue C:N ratio (Thorup-Kristensen and Dresboll, 2010). But Vaughan and Evanylo (1998) demonstrated that spring kill date of hairy vetch had no influence on N availability or subsequent corn N concentrations as long as it was desiccated before early flowering stage. This is probably because the approximately three week delay in desiccation had no influence on hairy vetch residue C:N ratio, like it did with rye and rye-hairy vetch cover crop residue. Influence of climate and desired N fate will influence the ideal kill date.

Combining fertilizer applications with organic substrate can increase apparent N mineralization. For example, ammonium nitrate stimulated N mineralization of compost when applied together in comparison to compost alone (Sikora and Enkiri, 2000). In another study, mixed granulated hen-manure and compost fertilizer amendments enhanced total N mineralization compared to the sum of individual N supplies (Ribeiro et al., 2010). But a combination of clover green manure and either farmyard cattle manure or green compost did not
increase N mineralization rates compared to either component separately (Canali et al., 2010). Combining mineral fertilizer with corn stover in an incubation study had a negative interactive affect on N availability (Gentile et al., 2008). But mineralization of the stover was increased in relation to stover without fertilizer. Retaining residues of crops such as corn or grain, which have low N concentrations and recalcitrant fractions, can temporarily immobilize fertilizer N, and therefore help retain N in the cropping system (McSwiney et al., 2010; Starovoytov et al., 2010).

Residue management can affect N mineralization rate via increased microbial access to substrate. For example, reducing tillage can decrease net N mineralization from plant residues (Schellenberg et al., 2009). Drinkwater et al. (2000) found that N availability was much higher in chisel-disc and moldboard plow treatments than under no-tillage management, which is likely because of increased microbial contact with substrate (Giacomini et al., 2007). Increased soil compaction, which is common in no-tillage systems, decreased N mineralization, probably due to decreased aeration (Pengthamkeerati et al., 2006). However in one case, reduced tillage enhanced N mineralization of crop residue because of improved soil moisture conservation (Soon et al., 2004). In a mixed tillage system, cultivation for weed control increased mineralization of hairy vetch residue during maximum crop N uptake (Drinkwater et al., 2000). Smaller substrate size, which may simulate mowing, increased N mineralization of crop residues (Giacomini et al., 2007). In one study, mowing rye or rye-hairy vetch cover crop residue enhanced harmony of cover crop N release and crop N uptake (Vaughan and Evanylo, 1998). Snapp and Borden (2005) reported enhanced N mineralization of rye and rye-hairy vetch-oriental mustard cover crops when either mowed or sprayed with glyphosate eight days prior to spring incorporation, likely because of increased microbial access. But killing by either mowing or tillage did not impact potential N mineralization of rye or triticale cover crops in a California
vineyard (Steenwerth and Belina, 2008). In that study, moisture limitations during summer season might account for discrepancies.

6. CROP N RESPONSE AND UPTAKE EFFICIENCY

Cover crops influence subsequent crop yield primarily via their affect on N availability (Torbert et al., 1996; Vaughan and Evanylo, 1998; Kuo and Jellum, 2000; Cherr et al., 2006). Crop yields can be maintained by replacing or supplementing N fertilizer application with winter legume or cereal-legume cover crop residues (Sainju et al., 2005; Fortuna et al., 2008). But there must be sufficient cover crop biomass and N accumulation, and timely N mineralization for cover crops to supply sufficient N to crops (Griffin et al., 2000; Teasdale et al., 2008). Reported N fertilizer replacement values for winter grown cover crops to subsequent cash crops vary greatly. Several studies examine sweet corn performance after legume and mixed cereal-legume cover crops because of its marked response to N fertility. Some have shown that it can produce yields as good as N-fertilizer treatments when grown in rotation with hairy vetch (Griffin et al., 2000; Cline and Silvernail, 2002; Carrera et al., 2004). But Cline and Silvernail (2002) demonstrate poor yield response to rye-hairy vetch blends. In Florida, hairy vetch and rye-hairy vetch blends contributed 62 to 75 kg N ha⁻¹, much lower than agronomic rates (Zotarelli et al., 2009). Often crop yield potential may be optimized when cover crops are combined with low supplemental N fertilizer rates. Schellenberg et al. (2009) recommended that legume-based cover crops systems be combined with modest sidedress N fertilizer to maximize organic broccoli yield. But Cherr et al. (2006) demonstrated that sweet corn yields were greater with fertilizer N than a cover crop-fertilizer combination.

Lack of synchrony between N supply from cover crop residue and crop N uptake may influence efficiency of crop N use (Teasdale et al., 2008). But this depends on the timing of field
events and types of crops grown. For instance, a delay in spring cover crop desiccation may result in a late flush of N release, which is better timed with crop N uptake (Cline and Silvernail, 2001). Cover crop residue characteristics or cereal-legume mixture ratio can influence N availability patterns (Kuo and Sainju, 1998). In one study, legume cover crops achieved higher crop N utilization efficiency than cereals because of more rapid mineralization and therefore greater N availability to the subsequent crop (Lenzi et al., 2009). Thorup-Kristensen et al. (2006) demonstrated that deep-rooted crops utilized legume-derived N more efficiently than shallow rooted crops (i.e. carrot and cabbage vs. onion and lettuce), likely because of access to a larger pool of soil (NH$_4^+$+NO$_3^-$)-N.

There are mixed results for crop N utilization efficiency of cover crop derived N. Sarrantonio and Molloy (2003) reported that sweet corn utilized between 19 and 62% of clover N. These data demonstrated that high N utilization efficiency is possible under optimal conditions in a legume-based system. But lower N utilization efficiencies may be expected under poor conditions (e.g. dry conditions that limit the rate of N mineralization). In another study, cabbage shoot biomass only recovered an average of 27% of hairy vetch N, but 43% when hairy vetch shoots were amended in fallow soil (Haas et al., 2007). Low N concentrations and the more recalcitrant quality of hairy vetch roots probably caused difference. Interestingly, Henry et al. (2010) observed a yield response in corn from clover plus 90 kg N ha$^{-1}$ UAN fertilizer but not in clover without fertilizer. This could reveal improved N use efficiency when a cover crop and fertilizer are combined. In contrast, Teasdale et al. (2008) found that N use efficiency by sweet corn was higher for ammonium nitrate than hairy vetch and lowest when these treatments were combined.
In some cases, crop N use efficiency of cover crop-derived N is low but overall efficiency is high because of high N recovery in soil (Seo et al., 2006). For example, broccoli and lettuce grown in succession after a clover cover crop recovered 11 and 4 % of total residue N, respectively, but 81 and 79 % remained in soil after each crop (Holness et al., 2008). Likewise, Collins et al. (2007) found that potatoes utilized 29 % of total cover crop N and 66 % remained in soil after crop harvest. Further, Seo et al. (2006) indicated that legumes were twice as efficient in building soil N as ammonium sulfate fertilizer but only one-half as effectively in supplying N to crops. These studies indicate a high plant-soil N percent recovery. Recovery of cover crop N in soil may be reduced in sandy soils with high leaching potential (Cherr et al., 2006). Pang and Letey (2000) suggest that crops with high maximum uptake rates have low N utilization efficiencies because it is difficult to meet peak N crop demands with relatively slow release materials. In general, there is a need to optimizing timing of N mineralization with N uptake demands of subsequent crop. The research focus needs to shift from maximum N supply to synchronizing N release with the N uptake demands of a subsequent crop.
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**Note:** Some columns have been truncated for display purposes. Full table can be found in the original document.
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CHAPTER 2

Evaluating fall cover crop blends for biomass production, residue quality and weed suppression

1. INTRODUCTION

There is renewed interest for including cover crops in crop rotations for the purpose of nitrogen (N) management and enhanced crop productivity, especially among organic growers who are prohibited from using synthetic fertilizers (USDA, National Organic Program, 2010). In the maritime Pacific Northwest, rye (Secale cereale)-hairy vetch (Vicia villosa) cover crop blends have the potential to produce large biomass yields, enhance plant available N to subsequent crops, and suppress winter weeds when seeded by early October (Kuo and Sainju, 1996; Kuo et al., 2002; Cogger et al., 2008). But organic vegetable growers in the region are often challenged to find a niche for cover crops in rotations because of late season vegetable production for niche markets and land limitations. As a consequence, growers are interested in the effect of delayed planting, early incorporation, and rye-hairy vetch seeding ratio on cover crop biomass yield, supply of plant available N, and winter weed control.

Winter cover crops can recycle residual soil nitrate (NO$_3^-$) that may leach below the rooting zone (BrandiDohrn et al., 1997) and depending on the species may reduce N fertilizer requirements in subsequent crops (Kuo et al., 1997; Cline and Silvernail, 2002). Nitrogen availability from cover crop residues is of primary interest to organic growers in N-limited systems. Mixing cereal and legume cover crops enhances biomass yields and carbon (C) and N contents compared to monoculture cover crops (Sainju et al., 2005). Cereal cover crops increase soil organic matter via increased C production (Sainju et al., 2000) while legumes increase plant available N by atmospheric N fixation (Vaughan et al., 2000). When cereals are combined with
legumes, the resulting mixture typically has higher N concentration and increases plant available N (Rannels and Wagger, 1996). A blend of legume and cereal cover crops is ideal because it can supply sufficient C and N to soils to maintain soil quality and improve crop productivity compared to pure stands (Rannels and Wagger, 1997; Kuo et al., 1997; Sainju et al., 2005).

The timing of fall cover crop planting is affected by harvest of the previous cash crop, reliable establishment, and the number of growing degree days required for sufficient biomass production. Regional research has demonstrated that cereal-hairy vetch blends should be planted by early October to ensure successful establishment and biomass accumulation (Odhiambo and Bomke, 2000; Kuo and Sainju, 2002; Cogger et al., 2008). Recent work at WSU Puyallup suggests the optimal planting date for hairy vetch is early September (Cogger, personal communication). Hairy vetch has been shown to have slow fall growth and low winter soil cover (Holderbaum et al., 1990), possibly because its optimal temperature for root growth is relatively high (20-25 °C) (Mosjidis and Zhang, 1995). But several studies have demonstrated that hairy vetch has a high rate of winter survival in northern climates (Teasdale et al., 2004; Brandsaeter et al., 2008) and rapid growth in spring as soil temperatures warm (Holderbaum et al., 1990; Kuo and Jellum, 2000). Zachariassen and Power (1991) reported that hairy vetch dry matter production was greatest when soil temperatures were 10 °C, when grown at temperatures ranging from 10 to 30 °C. Contrary to hairy vetch, cereal rye has been shown to establish quickly when planted by early October and it can effectively utilize residual soil nitrate (NO₃⁻) because rapid root development puts it in contact with soil N (Kuo and Jellum, 2000). Because the timing of harvest of summer crops can vary and unfavorable weather conditions may delay planting beyond the optimal window, improved understanding of the effect of delayed planting on stand establishment and biomass yields is needed.
Cover crop N accumulation and biomass composition may be affected by spring kill date (Clark et al., 1997; Sainju and Singh, 2001; Thorup-Kristensen and Dresboll, 2010). Several studies show a marked increase in hairy vetch biomass by delaying the kill date 2 wk between late April and early May, ranging from 35 to 61% (Wagger, 1989; Clark et al., 1995). In addition, late kill may be essential when planting late in fall to ensure adequate biomass and N accumulation (Teasdale et al., 2004). But delaying kill date may decrease residue N concentration, increase C:N ratios, and result in higher concentrations of hemicellulose and lignin in residue (Wagger, 1989; Cline and Silvernail, 2001), which has an important effect on N release. For hairy vetch, this effect on residue quality may not be important if desiccated before flowering stage because of relatively high quality until flowering (Vaughn and Evanylo, 1998). For example, a delay in killing hairy vetch resulted in a large increase in inorganic N, likely because of increased N content (Cook et al., 2010). But a delay in rye incorporation from early March to late April decreased net N mineralization and availability to the subsequent crop (Thorup-Kristensen and Dresboll, 2010). This is likely because the delay in desiccation has less influence on hairy vetch residue quality than it does on cereal crops. Influence of climate and N mineralization rate will affect what is an ideal kill date. Sufficient N accumulation and timely N release from cover crop residues is essential to affect N supply to the subsequent crop.

There is little information on how rye-hairy vetch seeding ratio affects biomass composition, residue quality, and winter weed suppression. Rye-hairy vetch cover crop blends generally have higher residue quality than stands of pure rye and therefore higher N availability to subsequent crops (Rannels and Wagger, 1996; Kuo and Jellum, 2002; Sainju et al., 2005). Kuo and Sainju (1998) found that rye-hairy vetch biomass ratio should not exceed 60% to result in an initial net increase in inorganic N. But it is unclear what seeding ratio best achieves that
composition and if plant and kill dates have an interactive effect. In addition winter weed suppression is a primary interest of growers in this region. Due to the mild winter climate, weed germination and growth in winter can increase weed management costs in summer crops. It has been shown that rye is suitable for winter weed suppression because of rapid establishment and competition for light (Kruidhof et al., 2008). However, there is limited research on the effect of rye-hairy vetch blends on winter weed control.

In this study, rye-hairy vetch winter cover crops were evaluated for their ability to provide winter ground cover, accumulate N, suppress winter weeds, and increase plant available N in soil. Our objective was to: (i) evaluate the effect of rye-hairy vetch seeding ratio and planting date on cover crop establishment, weed pressure, dry matter production and N accumulation and (ii) evaluate the effect of harvest date on cover crop dry matter production and residue quality.

2. MATERIALS AND METHODS

Site description

The Fall Cover Crop Blends field plots, located at Washington State University Puyallup Research and Extension Center, were established in September 2004. This ground was placed in organic transition in 2001 and has been certified organic in accordance with the National Organic Program since 2004. The soil is classified as Briscot loam (coarse-loamy, mixed, superactive, nonacid, mesic Fluvaquentic Endoaquepts). The average annual precipitation and temperature is 102.9 cm and 10.9°C, with mild, dry summers and cool, wet winters. Approximately 75% of precipitation occurs between October and March. Figure 1 shows mean monthly precipitation and temperature.

Experimental design
The experiment included five cover crop treatments, two planting dates, and two harvest dates, arranged in a randomized complete block split plot design, with cover crop treatment as the main plot and planting date as the split. Main plots measured 11 x 6.1 m and there were 4 replications for each treatment. Cover crop treatments as a seeding ratio of rye-hairy vetch included 100:0, 75:25, 50:50, 25:75, and 0:100. The 75:25 rye-hairy vetch treatment was added in 2008. The two planting dates were mid-September and early-October and the two harvest dates were late-March and late-April. A summer cover crop of sudangrass was planted in June and harvested in August of each year. Starting in 2006, supplemental organic nitrogen (feather meal) was applied at 89 kg N ha\(^{-1}\) to the 100% rye plots only before planting the sudangrass.

**Management**

Cover crops were planted in the fall using a 3.1 m John Deere grain drill. The rye-hairy vetch blends were seeded at 112 kg ha\(^{-1}\). All hairy vetch seed was inoculated with the appropriate rhizobia bacteria to ensure nitrogen fixation. In the spring, cover crops were chopped and incorporated using a rotary spader and sudangrass (*Sorghum bicolor*) was planted using a 3.1 m John Deere grain drill. Supplemental feather meal nitrogen was hand broadcast on pure rye plots at time of planting. In August, sudangrass was flail mowed and incorporated with a rotary spader, and the plots prepared for fall cover crops. Dates of field activities are listed in Table 1.

**Measurements**

Cover crop stand density was evaluated on three dates during the winter of each year. Two observers each evaluated 3 representative 0.25 m\(^2\) quadrats per plot as a percent of soil covered by cover crop (excluding weeds) per the method of Sarrantonio (1991). In late March and late April, plots were harvested for above ground biomass by harvesting a 6.1 x 0.91 m swath approximately 5 cm above the soil surface with a flail mower. Cover crop heights were
measured along the harvest swath. A subsample of the residues was dried at 55°C and ground to pass through a 2-mm sieve. Total C and N in residue were measured by dry combustion with a TruSpec CN Carbon/Nitrogen Determinator (Leco, St. Joseph, MI). The remaining residue was returned to the plots. Three additional subsamples were randomly collected from representative 0.25 m² quadrats in each plot, and the proportion of rye, vetch, and weeds was determined (Sarrantonio, 1991).

In June, soil samples were collected to a depth of 30 cm. Six samples were taken in each plot with a 2.5 cm diameter tube sampler and composited. Inorganic N (NH₄⁺ and NO₃⁻)-N was extracted from 10 g soil samples with 100 mL of 2M KCl. Samples were shaken on a reciprocal shaker for 1 h and then filtered through No. 42 Whatman filters. Aliquots were run on an automated, continuous flow QuikChem 8000 Injection Flow Analysis System (Hach Instruments, Loveland, CO). Ammonium-N was determined using the salicylate-nitroprusside method (Mulvaney, 1996) and NO₃⁻-N was determined using the cadmium reduction method (Gavlak et al., 1994).

Biochemical fractions of the residues were determined by using the neutral detergent and acid detergent stepwise procedure developed by Van Soest et al. (1991) using an ANKOM automated system with filter bags (ANKOM Technology Corp., Fairport, NY). Neutral detergent fiber includes hemicellulose, cellulose, and lignin as the primary components; acid detergent fiber consists of cellulose and lignin; and acid detergent lignin is the component remaining after cellulose has been removed (Stubbs et al., 2010).

**Statistical analysis**

Analysis of variance was done on cover crop soil cover, biomass yields, crop biomass composition, weed biomass, residue biochemical fractions, and June NO₃⁻ using the SAS
MIXED procedure (SAS 9.2, SAS Institute, Cary, NC, 2008). For a randomized complete block split plot design, cover crop rye-hairy vetch seeding ratio and planting date were fixed effects and replication was a random effect. Harvest date and year were other fixed effects included in the analysis. The 75:25 rye-hairy vetch blend was not included in the analysis because it was not included in all years of the study. The data for 2008 was omitted from the analysis because of poor germination by rye, which may be attributed to bad seed. Pearson correlation coefficients were calculated to test the relationship between cover crop biomass yields and growing degree days elapsed between planting and harvest using the SAS CORR procedure (SAS 9.2, SAS Institute, Cary, NC, 2008). Growing degree days were calculated per the Baskerville-Emin method (Andresen, 2010), using base temperature of 4 °C.
<table>
<thead>
<tr>
<th>Date</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 June</td>
<td>30 June</td>
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<td>19 June</td>
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<td>26 June</td>
<td>26 June</td>
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<tr>
<td>7 May</td>
<td>1 May</td>
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<tr>
<td>5 May</td>
<td>25 April</td>
</tr>
<tr>
<td>27 April</td>
<td>30 April</td>
</tr>
<tr>
<td>31 March</td>
<td>2 April</td>
</tr>
<tr>
<td>3 March</td>
<td>29 PEB</td>
</tr>
<tr>
<td>25 Jan</td>
<td>23 Jan</td>
</tr>
<tr>
<td>19 Nov</td>
<td>2 Nov</td>
</tr>
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<td>2 Nov</td>
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<tr>
<td>14 Sept</td>
<td>18 Sept</td>
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<tr>
<td>20 Sep</td>
<td>20 Sep</td>
</tr>
<tr>
<td>15 Sep</td>
<td>15 Sep</td>
</tr>
</tbody>
</table>

Table 1: Dates of sampling and field activities.
Table 2. Analysis of variance for cover crop biomass, nitrogen (N) concentration, N content, and C:N ratio as affected by experiment year, harvest date, planting date, and cover crop seeding ratio.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Biomass Probability &gt; F</th>
<th>N concentration Probability &gt; F</th>
<th>N Content Probability &gt; F</th>
<th>C:N Ratio Probability &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year (Y)</td>
<td>&lt;.0001</td>
<td>&lt;.0001</td>
<td>&lt;.0001</td>
<td>&lt;.0001</td>
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<td>&lt;.0001</td>
<td>&lt;.0001</td>
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<tr>
<td>Y x H</td>
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<td>&lt;.0001</td>
<td>&lt;.0001</td>
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<tr>
<td>Y x P</td>
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<td>0.0001</td>
<td>&lt;.0001</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>H x P</td>
<td>0.0156</td>
<td>0.8059</td>
<td>&lt;.0001</td>
<td>0.0492</td>
</tr>
<tr>
<td>Y x H x P</td>
<td>0.1962</td>
<td>0.7641</td>
<td>0.099</td>
<td>0.1874</td>
</tr>
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<td>Cover crop (C)</td>
<td>&lt;.0001</td>
<td>&lt;.0001</td>
<td>0.0346</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Y x C</td>
<td>&lt;.0001</td>
<td>&lt;.0001</td>
<td>&lt;.0001</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>H x C</td>
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<td>&lt;.0001</td>
<td>0.1391</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Y x H x C</td>
<td>0.0982</td>
<td>0.6234</td>
<td>0.8734</td>
<td>0.0012</td>
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<tr>
<td>P x C</td>
<td>&lt;.0001</td>
<td>0.0037</td>
<td>&lt;.0001</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Y x P x C</td>
<td>0.0074</td>
<td>0.0437</td>
<td>0.261</td>
<td>0.0001</td>
</tr>
<tr>
<td>H x P x C</td>
<td>0.0297</td>
<td>0.3084</td>
<td>0.246</td>
<td>0.2987</td>
</tr>
<tr>
<td>Y x H x P x C</td>
<td>0.884</td>
<td>0.5695</td>
<td>0.1602</td>
<td>0.301</td>
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</table>
Table 3. Cover crop biomass as a function of growing degree days

<table>
<thead>
<tr>
<th>Cover crop</th>
<th>Slope</th>
<th>Y-intercept</th>
<th>R²</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rye</td>
<td>11.22</td>
<td>-5377 b</td>
<td>0.712</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>R50V50</td>
<td>8.50 b</td>
<td>-3640 b</td>
<td>0.616</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>R25V75</td>
<td>7.38 b</td>
<td>-3026 b</td>
<td>0.604</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>Vetch</td>
<td>2.79 c</td>
<td>-567 a</td>
<td>0.220</td>
<td>&lt; 0.05</td>
</tr>
</tbody>
</table>

1Values followed by same letter are not significantly different (P < 0.05)

Table 4. Cover crop biomass yield and total C and N content as affected by planting and harvest date and rye-hairy vetch seeding ratio (% rye)

<table>
<thead>
<tr>
<th>Plant</th>
<th>Harvest</th>
<th>Rye-hairy vetch seeding ratio</th>
<th>Biomass yield kg ha⁻¹</th>
<th>N conc. g kg⁻¹</th>
<th>N content kg ha⁻¹</th>
<th>C:N ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sept</td>
<td>Early</td>
<td>0:100</td>
<td>1354 h¹</td>
<td>44 a</td>
<td>55 e</td>
<td>10 i</td>
</tr>
<tr>
<td>Sept</td>
<td>Early</td>
<td>25:75</td>
<td>2224 f</td>
<td>35 c</td>
<td>77 c</td>
<td>13 g</td>
</tr>
<tr>
<td>Sept</td>
<td>Early</td>
<td>50:50</td>
<td>2384 f</td>
<td>32 d</td>
<td>73 cd</td>
<td>14 f</td>
</tr>
<tr>
<td>Sept</td>
<td>Early</td>
<td>100:0</td>
<td>2820 e</td>
<td>29 e</td>
<td>77 c</td>
<td>15 e</td>
</tr>
<tr>
<td>Sept</td>
<td>Late</td>
<td>0:100</td>
<td>2271 f</td>
<td>39 b</td>
<td>86 b</td>
<td>11 h</td>
</tr>
<tr>
<td>Sept</td>
<td>Late</td>
<td>25:75</td>
<td>4183 c</td>
<td>25 g</td>
<td>99 a</td>
<td>19 c</td>
</tr>
<tr>
<td>Sept</td>
<td>Late</td>
<td>50:50</td>
<td>4758 b</td>
<td>23 h</td>
<td>105 a</td>
<td>20 b</td>
</tr>
<tr>
<td>Sept</td>
<td>Late</td>
<td>100:0</td>
<td>5518 a</td>
<td>18 i</td>
<td>98 a</td>
<td>25 a</td>
</tr>
<tr>
<td>Oct</td>
<td>Early</td>
<td>0:100</td>
<td>714 j</td>
<td>44 a</td>
<td>29 f</td>
<td>10 i</td>
</tr>
<tr>
<td>Oct</td>
<td>Early</td>
<td>25:75</td>
<td>923 ij</td>
<td>35 c</td>
<td>32 f</td>
<td>13 g</td>
</tr>
<tr>
<td>Oct</td>
<td>Early</td>
<td>50:50</td>
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<td>34 cd</td>
<td>36 f</td>
<td>13 g</td>
</tr>
<tr>
<td>Oct</td>
<td>Early</td>
<td>100:0</td>
<td>1036 i</td>
<td>30 e</td>
<td>29 f</td>
<td>15 e</td>
</tr>
<tr>
<td>Oct</td>
<td>Late</td>
<td>0:100</td>
<td>1853 g</td>
<td>38 b</td>
<td>69 d</td>
<td>12 gh</td>
</tr>
<tr>
<td>Oct</td>
<td>Late</td>
<td>25:75</td>
<td>2960 e</td>
<td>26 f</td>
<td>77 c</td>
<td>17 de</td>
</tr>
<tr>
<td>Oct</td>
<td>Late</td>
<td>50:50</td>
<td>3039 e</td>
<td>25 fg</td>
<td>75 cd</td>
<td>18 d</td>
</tr>
<tr>
<td>Oct</td>
<td>Late</td>
<td>100:0</td>
<td>3311 d</td>
<td>19 i</td>
<td>62 de</td>
<td>24 a</td>
</tr>
</tbody>
</table>

1Values followed by same letter within a column are not significantly different (P < 0.05)
Table 5. Analysis of variance for fiber fractions as affected by cover crop, planting date, harvest date, and year

<table>
<thead>
<tr>
<th>Effect</th>
<th>NDF$^{1}$</th>
<th>ADF</th>
<th>ADL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cover crop (C)</td>
<td>&lt;.0001</td>
<td>&lt;.0001</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Plant (P)</td>
<td>&lt;.0001</td>
<td>&lt;.0001</td>
<td>0.321</td>
</tr>
<tr>
<td>C x P</td>
<td>0.0062</td>
<td>0.0635</td>
<td>0.1874</td>
</tr>
<tr>
<td>Harvest (H)</td>
<td>&lt;.0001</td>
<td>&lt;.0001</td>
<td>0.8354</td>
</tr>
<tr>
<td>C x H</td>
<td>0.007</td>
<td>0.0133</td>
<td>0.0503</td>
</tr>
<tr>
<td>P x H</td>
<td>0.0514</td>
<td>0.0020</td>
<td>0.6645</td>
</tr>
<tr>
<td>C x P x H</td>
<td>0.0443</td>
<td>0.2954</td>
<td>0.9958</td>
</tr>
<tr>
<td>Year (Y)</td>
<td>&lt;.0001</td>
<td>&lt;.0001</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>C x Y</td>
<td>0.0588</td>
<td>&lt;.0001</td>
<td>0.066</td>
</tr>
<tr>
<td>P x Y</td>
<td>0.0008</td>
<td>&lt;.0001</td>
<td>0.0116</td>
</tr>
<tr>
<td>C x P x Y</td>
<td>0.4973</td>
<td>0.0235</td>
<td>0.0034</td>
</tr>
<tr>
<td>H x Y</td>
<td>0.0726</td>
<td>&lt;.0001</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>C x H x Y</td>
<td>0.0059</td>
<td>&lt;.0001</td>
<td>0.1495</td>
</tr>
<tr>
<td>P x H x Y</td>
<td>0.4719</td>
<td>0.0083</td>
<td>0.4559</td>
</tr>
<tr>
<td>C x P x H x Y</td>
<td>0.8506</td>
<td>0.003</td>
<td>0.3935</td>
</tr>
</tbody>
</table>

$^{1}$Neutral detergent fiber, NDF; acid detergent fiber, ADF; acid detergent lignin, ADL

Table 6. Neutral detergent fiber (NDF), acid detergent fiber (ADF), and acid detergent lignin (ADL) by harvest date, and rye-hairy vetch seeding ratio

<table>
<thead>
<tr>
<th>Harvest date</th>
<th>Rye-hairy vetch seeding ratio</th>
<th>NDF</th>
<th>ADF</th>
<th>ADL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early</td>
<td>0:100</td>
<td>374 e$^{1}$</td>
<td>237 c</td>
<td>66.4 b</td>
</tr>
<tr>
<td>Early</td>
<td>25:75</td>
<td>401 de</td>
<td>230 d</td>
<td>57.6 c</td>
</tr>
<tr>
<td>Early</td>
<td>50:50</td>
<td>408 d</td>
<td>226 d</td>
<td>56.3 c</td>
</tr>
<tr>
<td>Early</td>
<td>100:0</td>
<td>420 cd</td>
<td>224 d</td>
<td>56.6 c</td>
</tr>
<tr>
<td>Late</td>
<td>0:100</td>
<td>426 c</td>
<td>325 a</td>
<td>74.5 a</td>
</tr>
<tr>
<td>Late</td>
<td>25:75</td>
<td>500 b</td>
<td>330 a</td>
<td>57.2 c</td>
</tr>
<tr>
<td>Late</td>
<td>50:50</td>
<td>508 b</td>
<td>324 a</td>
<td>59.7 c</td>
</tr>
<tr>
<td>Late</td>
<td>100:0</td>
<td>525 a</td>
<td>305 b</td>
<td>47.2 d</td>
</tr>
</tbody>
</table>

$^{1}$Values followed by same letter within a column are not significantly different (P < 0.05)
3. RESULTS AND DISCUSSION

Cover crop establishment

Cover crop establishment was monitored over each winter as a percent ground cover excluding weed species. As shown in Figure 2, planting date had a significant effect on cover crop establishment. At the October planting, there were considerable reductions in percent ground cover across all treatments in comparison to the September planting. The differences between treatments at the October planting were not large. In contrast, there were significant differences between treatments at the September planting date. Rye treatments had the highest ground cover at the November rating date, whereas the rye-hairy vetch blends provided the most ground cover at the later two rating dates. These differences are not surprising, given the growth habits of rye and hairy vetch. Cereal rye is a standard winter cover crop in many regions because it establishes quickly and thrives in cool conditions (Sustainable Agriculture Network, 2007). Hairy vetch has been shown to be a hardy winter legume, but it prefers warm soil temperatures and therefore establishes more slowly in cool conditions (Mosjidis and Zhang, 1995). Increased ground cover at the last two rating dates in the rye-hairy vetch blend treatments suggest that the rye may act as a nurse crop to the hairy vetch, as has been observed in other experiments (Bjorkman and Shail, 2008; Grubinger, 2010). There is evidence that cover crops grown in biculture have a wider range of tolerance to adverse environmental conditions than grown in monoculture (Creamer et al., 1997; Gaskell, 2006).

Cover crop biomass yield

Cover crop biomass yield was significantly affected by planting date, harvest date, rye-hairy vetch seeding ratio, and experiment year (Table 2). The benefit of increased biomass yield of hairy vetch when combined with rye was evident in our study (Figure 3). On average, the
50:50 rye-hairy vetch blends yielded 66 to 81% (1.02 to 1.26 Mg ha\(^{-1}\)) higher biomass than pure hairy vetch. Other studies have reported similar findings, but also demonstrate that rye-hairy vetch blends may produce equal or more biomass than pure rye stands (Clark et al., 1994; Teasdale and Abdul-Baki, 1998; Sainju et al., 2005). In contrast, the rye-hairy vetch blends in our study yielded up to 19% (0.59 Mg ha\(^{-1}\)) less biomass than pure rye, depending on planting and harvest date. There is little published data on rye-hairy vetch biomass yields in the maritime Pacific Northwest that include seeding ratios similar to ours. The studies cited were conducted in Maryland and Georgia, states with warmer fall and spring conditions that favor the growth of hairy vetch. Given the cool climate in the maritime Pacific Northwest, it is not surprising that lowering the seeding ratio of rye in favor of hairy vetch may decrease biomass yields. Cool fall and spring temperatures are likely to support rye growth more than hairy vetch. Results from a long-term study in Puyallup, WA support this hypothesis, demonstrating that on average, hairy vetch biomass was 32% (0.85 Mg ha\(^{-1}\)) lower than rye (Kuo and Jellum, 2000).

The interaction between planting and harvest date on cover crop biomass yield demonstrates that on average, early harvest reduced biomass yields more (1.92 Mg ha\(^{-1}\)) than late planting (1.33 Mg ha\(^{-1}\)) when compared cover crops planted early and harvested late. But when analyzed according to rye-hairy vetch seeding ratio, planting and harvest dates affected biomass yields differently. For late planted treatments, biomass was reduced 0.53 and 2.00 Mg ha\(^{-1}\) for hairy vetch and rye, respectively, compared to 1.03 and 2.49 Mg ha\(^{-1}\) at early harvest. These figures demonstrate that although hairy vetch growth is slow in fall, it experiences a period of rapid growth in spring as the temperature increases.

The effect of planting date, harvest date, and experiment year on cover crop biomass yields can be explained by variation in growing degree days accumulated between planting and
harvest. Teasdale et al. (2004) have demonstrated that hairy vetch cover crop biomass yield is linearly related to growing degree days accumulated between planting and harvest dates. In our experiment, differences in growing degree days between planting and harvest across all rye-hairy vetch seeding ratios could explain variation in biomass yields (Table 3). The relationship was much stronger for pure rye and rye-hairy vetch bicultures than pure hairy vetch, and therefore growing degree days is not a good indicator of hairy vetch biomass. It is possible that winter injury from cold temperatures could affect hairy vetch growth and biomass yield. Absolute minimum temperatures reached -12°C on three occasions in 2009-10 and -8 to -10°C in 2008-09. Teasdale et al. (2004) have observed winter injury to hairy vetch foliage when absolute winter temperatures reached -11 to -13°C. In that study, winter injury was highest on late planted hairy vetch.

Cover crop dry matter composition and weed biomass

The contribution of rye and hairy vetch to total dry matter varied by planting date and rye-hairy vetch seeding ratio (Figure 4). Rye dominated dry matter composition regardless of seeding ratio and planting date. For early planted cover crops, a 50:50 rye-hairy vetch seeding ratio had 67% rye in dry matter, while a 25:75 rye-hairy vetch blend had 59%. Rye established quickly in the cool conditions typical in this region in the fall, and therefore it may have a competitive advantage over hairy vetch when planted early. At late planting, the percent rye in total dry matter is lower than for early planted cover crops (52 and 40% for 50:50 and 75:25 rye-hairy vetch seeding ratios, respectively). Although weeds make up a slightly larger fraction of the total dry matter (13% compared to 20 to 21% for early and late planting, respectively), the hairy vetch component is larger at the late planting date. Hairy vetch seems to be more competitive with rye when planted late because most growth and biomass production occurs in
spring when warm temperatures favor more rapid growth of hairy vetch. Hairy vetch is slow to establish regardless of planting date. Rye has a competitive advantage when planted early because of its ability to establish quickly. The dry matter composition of cereal-legume cover crop mixtures has important implications on N availability because of its affect on biomass yield, N concentration, and residue quality.

The weed component of the total dry matter was significantly lower when rye and hairy vetch were combined than for either species alone (Figure 4). Winter cover crops may affect winter weed germination and growth by competition for light (Kruidhof et al., 2008). As reported above, rye-hairy vetch bicultures had higher ground cover than either species alone when planted early. It is likely that increased competition for light from the rye-hairy vetch blend treatments reduced weed pressure compared to monocultures. Planting date significantly affected the percentage of weeds in total dry matter, regardless of rye-hairy vetch seeding ratio. This suggests that cover crops are less effective at suppressing weed growth when planting date is delayed.

Total weed biomass was lower for rye-hairy vetch blends than for stands of pure rye (Figure 5). This is consistent with our discussion above concerning ground cover and light interception. Only the 25:75 rye-hairy vetch seeding ratio at early planting lowered weed biomass compared to pure hairy vetch. Given the higher biomass and greater ground cover of rye compared to hairy vetch, it is surprising that weed biomass was greater under rye than hairy vetch. Because of its marked growth response to warm spring temperatures and sprawling nature, it is possible that hairy vetch better competed with weeds late in the season.

**Cover crop N concentration and N content**
Residue N concentration was largely affected by rye-hairy vetch seeding ratio and harvest date (Table 2). The effect of planting time was significant but differences were not large. Nitrogen concentration decreased from early to late harvest for all rye-hairy vetch treatments, with the change being most drastic for pure rye (Table 4). While rye had the lowest N concentration, hairy vetch had the highest, and both blends were intermediate. The N concentration of the rye-hairy vetch bicultures was not significantly different, which was likely because rye-hairy vetch biomass composition was similar for both seeding ratios. There were significant differences in N concentrations between pure rye and hairy vetch treatments and rye-hairy vetch bicultures. On average the N concentration of the rye-hairy vetch bicultures was 11.5 g kg\(^{-1}\) less than hairy vetch but 5.5 g kg\(^{-1}\) greater than rye. Other studies report that the N concentration of rye-hairy vetch mixtures range between the N concentration of pure hairy vetch and pure rye, and the ratio of the components has a large effect (Clark et al., 1994).

The interaction between cover crop treatment and harvest date was significant across all years (Figure 6). The N concentration decreased from early to late harvest by an average of 5 g kg\(^{-1}\) for pure hairy vetch, compared to 10 and 11 g kg\(^{-1}\) for rye-hairy vetch bicultures and pure rye, respectively. Hairy vetch was in a vegetative stage at both harvests, and therefore a smaller decrease is expected (Teasdale et al., 2004). Planting date had a small but significant effect on residue N concentration (Table 4). On average, late planting increased N concentration 1 g kg\(^{-1}\) for rye-hairy vetch biculture and pure rye treatments.

The total N content (kg N ha\(^{-1}\)) of rye-hairy vetch bicultures was equal to or greater than the N contents of either cover crop grown in monoculture. Surprisingly, mean N content of pure rye was greater than pure hairy vetch (Table 4). Research shows that rye N uptake is increased by residual soil N (McCracken et al., 1994). In our study, a summer crop of sudangrass was
incorporated 3 to 6 weeks prior to cover crop planting, which may have provided a slow-release N supply for N uptake during fall and spring. In an intensively cropped system where post-harvest residual soil N is low, hairy vetch and rye-hairy vetch blends may have higher N content than pure rye because hairy vetch fixes N (Rannels and Wagger, 1996; Teasdale and Abdul-Baki, 1998; Sainju et al., 2005).

For cover crops planted late and harvested early there was no difference in total N content (29 to 36 kg N ha\(^{-1}\)) (Table 4). Such a small amount of cover crop N is not significant enough to impact N dynamics in a subsequent cash crop. Nitrogen content was highest when cover crops were planted early and harvested late (86 to 105 kg N ha\(^{-1}\)), which was likely because the highest number of growing degree days were accumulated between these dates. On average there was a 32 kg ha\(^{-1}\) decrease in N content when planting date was late and a 33 kg ha\(^{-1}\) increase in N content when harvest was late. The interaction between cover crop and planting and harvest dates demonstrated that rye and hairy vetch N content was affected by planting and harvest dates differently. Nitrogen uptake in hairy vetch was higher for late planting/late harvest than early planting/early harvest. This is not surprising because hairy vetch goes through a period of rapid growth in N fixation in spring as temperatures increase. In contrast, rye accumulated more N for early planting/early harvest than late planting/late harvest. Unlike hairy vetch, rye established quickly in fall and is well-adapted to take up residual fall soil N. Soil inorganic N is low in spring after winter precipitation and therefore may limit N uptake in rye at that time.

**Residue quality**

The release of N from cover crop residues to a subsequent cash crop is largely dependent on residue quality (Myrold and Bottomley, 2008). Cover crop C:N ratio, which is a simple measure of residue quality, has been negatively correlated to N release (Vigil and Kissel, 1991;
Quemada and Cabrera, 1995; Chaves et al., 2004). Our data demonstrated that rye combined with hairy vetch had a lower C:N ratio than pure rye treatments (Table 4), which is consistent with what others have reported (Rannels and Wagger, 1996; Kuo and Jellum, 2002; Sainju et al., 2005). But rye-hairy vetch seeding ratio of the biculture treatments did not have a large impact on C:N ratio, as we had hypothesized. Similarity in the portions of rye and hairy vetch in the total biomass for the two bicultures offers a likely explanation. Harvest date had a large impact on C:N ratio while planting date did not. The interaction between cover crop treatment and harvest date demonstrated that the C:N ratio of rye was more affected by harvest date than hairy vetch. On average, delaying harvest increased C:N ratio by 1.1, 1.4, and 1.7 times for hairy vetch, rye-hairy vetch bicultures, and rye, respectively. This is likely because rye went from a vegetative to heading stage while hairy vetch remained in a vegetative stage. The growth stage of plant residues at kill date has been shown to affect residue quality (Handayanto et al., 1997). Vaughan and Evanylo (1998) reported a similar trend, demonstrating that a three week delay in spring kill date increased C:N ratio of rye but not hairy vetch. All cover crop C:N ratios were below 25, which is often considered the breakeven point between net mineralization and immobilization (Myrold and Bottomley, 2008).

The fiber content of plant residues has been shown to influence residue decomposition and N release (Ruffo and Bollero, 2003; Jensen et al., 2005; Stubbs et al., 2009). Therefore, it is important to understand how management and cereal-legume mixture affects fiber content. We found that planting date, harvest date, and rye-hairy vetch seeding ratio significantly affected residue fiber (Table 5). On average, hairy vetch had the lowest NDF (386 g kg\(^{-1}\)) and rye the lowest ADF (257 g kg\(^{-1}\)) and ADL (51.5 g kg\(^{-1}\)). There were large differences in NDF between hairy vetch and rye (386 to 462 g kg\(^{-1}\)) but only small differences in ADF (257 to 265 g ka\(^{-1}\)).
This is consistent with the literature, which has shown that hemicellulose content may vary widely between rye and hairy vetch residues while cellulose portions were typically similar (Rannels and Wagge, 1996; Magid et al., 2004). These findings are in agreement with our results because NDF includes hemicellulose, cellulose, and lignin and ADF contains cellulose and lignin but not hemicellulose. In addition, our results demonstrated that ADL was relatively low for all cover crop residues (51.9 to 70.5 g kg\(^{-1}\)). Other studies with rye and hairy vetch cover crop residues reported similar lignin contents, ranging from 27 to 92 g kg\(^{-1}\) (Rannels and Wagge, 1996; Kuo and Sainju, 1998). Research has shown that even small amounts of lignin can significantly affect residue decomposition and N release (Vigil and Kissel, 1991; Quemada and Cabrera, 1995; Hadas et al., 2004).

Rye-hairy vetch biculture treatments were not significantly different in NDF (441 g kg\(^{-1}\)), ADF (265 g kg\(^{-1}\)), or ADL (52.3 g kg\(^{-1}\)) content in our study. This was likely due to the similarity in the portions of rye and hairy vetch in total biomass of the biculture treatments. In general, fiber in rye-hairy vetch bicultures resembled the rye treatments more closely than hairy vetch. This is likely because of the high portion of rye in the total biomass yield for both treatments.

Cover crop planting and harvest date significantly affected fiber across all cover crop treatments (Table 5). But planting date had a much smaller affect on residue fiber than harvest date. Overall, late planting date decreased NDF, ADF, and ADL by an average of 17, 14, and 7.6 g kg\(^{-1}\) (data not shown). There was only a minor effect of planting date on residue fiber likely because planting date had a small effect in plant development of rye and hairy vetch. Alternatively, fiber content, NDF, ADF, ADL was significantly affected by harvest date and cover crops (Table 5). Delaying harvest date had a small but significant affect on the NDF and ADF contents of hairy vetch (68 and 77 g kg\(^{-1}\) increase) relative to rye and rye-hairy vetch.
blends (100 to 121 and 96 to 107 g kg\(^{-1}\) increase, respectively) (Figure 7). As previously described, this may be because rye went from a vegetative to heading stage between early to late harvest dates while hairy vetch remained in a vegetative stage. Other research has shown that NDF, ADF, and ADL have been found to increase with crop maturity (Cherney et al., 1993; Elizade et al., 1999). Therefore, the benefits of increased N content at the late harvest date must be weighed against the increase in fiber content when considering N release dynamics.

**Mid-June soil nitrates**

The N availability from the incorporated cover crop residues was monitored via mid-June soil NO\(_3^–\)-N analysis. We compared the effects of planting date and rye-hairy vetch seeding ratio on the soil N response (early harvested cover crops were not incorporated until time of late harvest). Soil NO\(_3^–\)-N data from 2010 is not included in this analysis. On average, NO\(_3^–\)-N was approximately double in pure hairy vetch treatments relative to pure rye. This trend is not surprising given the high N concentration of hairy vetch compared to rye. There was a significant increase in NO\(_3^–\)-N in the rye-hairy vetch blends compared to pure rye. We hypothesize that a slower release of NO\(_3^–\)-N from rye-hairy vetch blends may be better timed for crop N uptake in comparison to pure hairy vetch.

As shown in Figure 8, the interaction between rye-hairy vetch seeding ratio and experiment year was significant. In general, the soil NO\(_3^–\)-N response was similar between years. But lower biomass yields in 2007 resulted in reduction of NO\(_3^–\)-N in hairy vetch and rye-hairy vetch blends than other years. Growers relying on cover crop stands as a source of N for subsequent grown crops may be faced with poor stand establishment and N accumulation every few years and therefore insufficient supply of plant available N. In those circumstances, it may be appropriate to supplement N fertility needs with a commercial organic N fertilizer. In this
study, rye-hairy vetch cover crops accumulated sufficient biomass to significantly increase soil NO$_3^-$-N relative to pure rye in three out of four years. Therefore, winter-grown rye-hairy vetch cover crop blends appear to be a reliable means of increasing soil NO$_3^-$-N.
Figure 1. Mean monthly precipitation and mean monthly maximum (max.), minimum (min.) and daily temperatures from 1995-2010
Figure 2. Cover crop establishment measured as a percent ground cover excluding weeds for early (a) and late (b) planted cover crops. Cover crop treatments are hairy vetch (Vetch), 25:75 rye-hairy vetch blend (R25V75), 50:50 rye-hairy vetch blend (R50V50), and pure rye (Rye) (P < 0.0001)
Figure 3. Cover crop biomass yields as affected by planting date, harvest date, and rye-hairy vetch seeding ratio (P < 0.05)
Figure 4. Percentage of above ground biomass from rye, hairy vetch, and weeds at four rye-hairy vetch seeding ratios (Rye, %) at early (a) and late (b) planting dates (P < 0.05)
Figure 5. Weed biomass yield as affected by planting date and rye-hairy vetch seeding ratio (P < 0.05)

Figure 6. Cover crop residue N concentration as affected by harvest date and rye-hairy vetch seeding blend (P < 0.0001)
Figure 7. Neutral detergent fiber (NDF), acid detergent fiber (ADF), and acid detergent lignin (ADL) by rye-hairy vetch seeding ratio and harvest date. Values within the same group for each seeding ratio treatment followed by the same letter are not significantly different (P < 0.05).
Figure 8. Mid-June soil NO$_3^-$-N as affected by rye-hairy vetch seeding ratio and experiment year (P < 0.001)
4. CONCLUSIONS

If planted by early-October, the latest planting date in our study, rye-hairy vetch cover crop blends can accumulate sufficient biomass and N to provide inorganic N to support a subsequent cash crop. Both planting and harvest date impact cover crop biomass yields, total N content, and residue quality. While late harvest favors larger biomass production, we report an increase in greater NDF, ADF, and ADL. It is unclear whether the increase in N content is enough to offset the effect of more recalcitrant C on N release dynamics. Our data suggests that insufficient biomass and N is accumulated when cover crops are planted late and harvested early to impact N supply to subsequent cash crop.

Rye-hairy vetch seeding ratio of mixed species treatments did not have a large affect on cover crop biomass yield or composition. We noticed an advantage in winter weed suppression under rye-hairy vetch bicultures relative to monoculture rye. But this benefit was not consistently different for hairy vetch. Rye established more quickly than hairy vetch in cool fall conditions, which makes it a favorable winter cover crop in the maritime Pacific Northwest. Although hairy vetch is slow to establish, it goes through a period of rapid growth in the spring and has a higher potential to supply large amounts of N to subsequent crops. The soil inorganic N response to incorporated cover crops demonstrates that rye-hairy vetch blends can increase N availability to subsequent cash crops compared to pure rye. We hypothesize that slower N release from rye-hairy vetch blends may be better timed for crop N uptake than pure hairy vetch. Given the similarities between the two rye-hairy vetch seeding blends, we recommend using a 50:50 rye-hairy vetch seeding ratio to optimize biomass yields, N accumulation, winter weed suppression, and N supply to crops in rotation.
5. LITERATURE CITED


CHAPTER 3

Nitrogen release from rye-hairy vetch cover crop residues with and without a semi-fast release organic fertilizer in a laboratory incubation

1. INTRODUCTION

One of the challenges in organic crop production is synchronizing plant available nitrogen (N) with crop uptake (Pang and Letey, 2000). Because synthetic fertilizers cannot be used in organic systems (USDA, National Organic Program, 2010), immediate release of inorganic (NH$_3^+$+NO$_4^-$)-N is not possible. Systems that utilize cover crops have the potential to accumulate large amounts of plant available N, but release of inorganic N must be carefully timed with subsequent crop uptake (Cherr et al., 2006). In general, legumes have been considered superior cover crops compared to nonleguminous crops because of their ability to fix atmospheric N (Fageria, 2007). But mixing cereal cover crops with legumes can enhance N cycling because cereal crops can take up residual soil nitrate (NO$_3^-$) after fall harvest (BrandiDohrn et al., 1997). When cereal and legume species are grown as a biculture, the combined cover crops typically have larger total N content, lower C:N ratios, and increase plant available N relative to cereals in monoculture (Rannels and Wagger, 1996; Kuo and Sainju, 1998; Sainju et al., 2005). But it is unclear how the portions of cereal and legume residues in total dry matter of the blend affect N release. There is a need to better understand and predict N release so that fertility recommendations can be accurately made (Granatstein et al., 2010).

Due to variations in cover crop N content between years (Lawson, 2010), addition of organic N fertilizers in combination with cover crops may be necessary to provide supplemental N. A range of approved organic fertilizers are commercially available, most of which are composed of by-products of fish, livestock, and food processing industries (Gaskell and Smith,
A few common examples include sea bird guano, fish powder, feather meal, and blood meal, which have N concentrations ranging from 9 to 12% (Gaskell et al., 2006). Although these fertilizers can be expensive, the value of these products is high in situations where cover crop N supply is insufficient for an upcoming cash crop. These organic fertilizers have been shown to have rapid N availability, ranging from 48 to 67% of total N released over 4 weeks at 25 °C (Gaskell et al., 2006; Hartz and Johnstone, 2006). Some research has shown that the application of a semi-rapid release organic N fertilizer in combination with organic residues can increase apparent N mineralization (Sikora and Enkiri, 2000). In one study, granulated poultry manure applied in combination with compost enhanced the net N mineralization compared to the sum of each component separately (Ribeiro et al., 2010). But application of N fertilizers in combination with residues with low N concentration can temporarily immobilize N and have an overall negative impact on net N mineralization (McSwiney and Snapp, 2010). It is unclear how N mineralization of cover crop residues is affected by the application of a semi-rapid release organic N fertilizer, such as feather meal.

Under constant environmental conditions, N release from plant residues is primarily a function of the relative availability of carbon (C) and N in residues (Myrold and Bottomley, 2008). A measure of residue quality can be used to describe the availability of C and N from plant residues and has been correlated to residue decomposition and release of plant available N (Palm and Rowland, 1997). Several studies have demonstrated correlation of plant decomposition and N release with residue quality fractions such as polyphenols, lignin, and N concentration (Constantinides and Fownes, 1994; Rannels and Wagger, 1996; Nakhone and Tabatabai, 2008). Others have found that C:N and lignin:N ratios are useful indices of N release (Vigil and Kissel, 1991; Gilmour et al., 1998; Chaves et al., 2004). But there is no clear
consensus of which quality variables are best correlated with N release from cover crop residues. For example, the C:N ratio of organic residues has been well related to N mineralization in many studies. But some have found that it is only initially correlated with N release because residue quality changes as decomposition and nutrient release progress (Chaves et al., 2004). Others have demonstrated that it is neither an adequate measure of residue quality (Ruffo and Bolloro, 2003) nor a useful parameter for estimating N mineralization (Vigil and Kissel, 1995). Mckenney et al. (1995) hypothesize that C:N ratio is not a good predicator of plant residue N mineralization because it does not adequately describe the nutrient availability for microbial growth.

Mineralization of organic residues transforms organic N to ammonium ($\text{NH}_4^+$). In N-rich agricultural soils, the consequence of most $\text{NH}_4^+$ is thought to be nitrification (Robertson, 1997). Nitrification potentials are a measure of the ability of nitrifying bacteria to transform $\text{NH}_4^+$ to $\text{NO}_3^-$. Cropping systems that result in high $\text{NH}_4^+$ levels often increase rates of nitrification (Chantigny et al., 1996; Fortuna et al., 2003). Likewise, seasonal immobilization events, such as incorporation of wheat straw, lower soil inorganic N pool and decrease nitrification rates (Recous et al., 1999). Nitrification potentials are often used in assessments of soil quality because it may be a useful indicator of the effect of management to improve N use efficiency and soil quality (Stamatiadis et al., 1999; Fortuna et al., 2003).

It is difficult to predict N release and availability from field studies due to variability in climate and soils (Cabrera et al., 2005). Laboratory incubations that are conducted at ideal moisture and temperature conditions provide a method for comparing N availability across treatments and systems, which is not possible in the field (Robertson et al., 1999). A laboratory incubation study was set up to measure N availability from cover crop blends applied with and
without a relatively fast release organic fertilizer. The objective was to (i) determine the timing of N release from rye-hairy vetch cover crop blends both with and without organic feather meal fertilizer in a Puyallup fine sandy loam soil, (ii) relate rye-hairy vetch biochemical characteristics to N availability as measured in the incubation, and (iii) and assess changes in nitrification potentials for cover crops and cover crop-fertilizer combinations in the incubation to be used as a soil quality indicator.

2. MATERIALS AND METHODS

Field plots

The Fall Cover Crop Blends study is located at Washington State University Puyallup Research and Extension Center, Puyallup, WA. This ground was placed in organic transition in 2001 and has been certified organic in accordance with the National Organic Program since 2004. The study was established in September 2004 to determine the effect that planting and harvest date and rye-hairy vetch seeding ratio has on cover crop biomass yield and N content. Cover crop samples were harvested from field plots that were planted in mid-September and harvested in late-April. Residues for pure rye and pure vetch were taken from respective field plots while residues for the rye-hairy vetch blends were taken from field plots that had been seeded at a 50:50 seeding ratio. After harvest of above ground cover crop biomass, residues were dried at room temperature.

Because there was no control plot in Cover Crop Blends, soil was collect from the 0 to 30 cm depth from the control plots of an adjacent study Cover Crops-2, also located at the Puyallup station. This ground has been under organic management practices since 2004. The entire field received compost at approximately 34 Mg ha\(^{-1}\) dry matter in July 2008, but control plots had no subsequent amendments or cover crops. The soil is classified as Puyallup fine sandy loam
Soil and cover crop residues were collected on April 27, 2009.

**Laboratory incubation**

The release of inorganic ($\text{NH}_4^+ + \text{NO}_3^-$)-N from cover crop residues was estimated via a laboratory incubation. The experiment included four rye-hairy vetch cover crop blends. As a percent rye biomass, these were 0 (pure hairy vetch), 50 (r50v50), 75 (r75v25), and 100% (pure rye). A no cover crop soil control was included. Application rates for cover crop treatments were equivalent to 2.75, 4.50 and 4.75 Mg biomass ha$^{-1}$ for pure vetch, pure rye, and both rye-vetch blends, respectively, based on yields observed in the *Cover Crop Blends* study. Certified organic feather meal fertilizer was amended to half of the vessels at a rate equivalent to 120 kg N ha$^{-1}$. It contains 12% N and approximately 75% is available in a growing season, which is equivalent to 90 kg N ha$^{-1}$. In total there were 10 treatments (5 cover crops x 2 fertilizer levels), each with three replicates, and 9 sample dates, a total of 270 incubation vessels. Table 1 lists the cover crop-feather meal treatments and the application rates.

Cover crops and feather meal were analyzed for total C and N concentration and cover crops for fiber contents. A subsample of the residues was dried at 55°C and ground to pass through a 2-mm sieve. Total C and N in residue were measured by dry combustion with a TruSpec CN Carbon/Nitrogen Determinator (Leco, St. Joseph, MI). Biochemical fractions of the residues were determined by using neutral detergent and acid detergent stepwise procedure developed by Van Soest et al. (1991) using an ANKOM automated system with filter bags (ANKOM Technology Corp., Fairport, NY). Neutral detergent fiber includes hemicellulose, cellulose, and lignin as the primary components; acid detergent fiber consists of cellulose and
lignin; and acid detergent lignin is the component remaining after cellulose has been removed (Stubbs et al., 2010).

The method for set up of the laboratory incubation was similar to that reported by Fortuna et al. (2003). Prior to construction of the vessels, soil was passed through a 2 mm sieve and pre-incubated at room temperature for 7 days. Each incubation vessel contained the equivalent of 50 g of oven dry soil, which was packed to a bulk density of 1.2 g cm\(^{-3}\), based on field measurements. Soils were weighed into specimen vials and packed prior to addition of distilled water (dH\(_2\)O), residue (where applicable), and simulation of rotary spading. Residues had been cut into 5 to 7 cm lengths and were mixed into the soil such that less than 10% was visible from the surface.

Incubations were maintained at 40% water filled pore space (WFPS). To calculate the percent gravimetric water content of microcosms and the amount of dH\(_2\)O to add per specimen vial, the following equation (1) was used:

\[
\text{[1]} \quad 40\% \text{ WFPS} \times \frac{1 - \left(\frac{1.2 \text{ g/cm}^3}{2.65 \text{ g/cm}^3}\right)}{1.2 \text{ g/cm}^3} = 18\% \text{ gravimetric water content}
\]

where 40% is WFPS, 2.65 g/cm\(^3\) is the bulk density of the soil mineral constituent, and 1.2 g/cm\(^3\) is the bulk density of the soil (Elliot et al., 1999). The field moist soil had a gravimetric water content of 15.4%. Therefore, 57.7 g field moist soil and 1.3 g of dH\(_2\)O was weighed into each vial to achieve 40% WFPS. Distilled water was added to the incubation vessels weekly to maintain 40% WFPS. The caps were not tightly sealed, which allowed gas exchange and prevented microcosms from drying. Temperature was maintained at 25 °C.
Specimen vials were removed and sampled 0, 7, 15, 28, 50, 70, 106, and 157 days after set up. Inorganic N (NH$_4^+$ and NO$_3^-$)-N was extracted from 10 g soil samples with 100 mL of 2 M KCl at each time point. Samples were shaken on a reciprocal shaker for 1 h and then filtered through No. 42 Whatman filters. Aliquots were run on an automated, continuous flow QuikChem 8000 Injection Flow Analysis System (Hach Instruments, Loveland, CO). Ammonium-N was determined using a salicylate-nitroprusside method (Mulvaney, 1996) and nitrate-N using the cadmium reduction method (Gavlak et al., 1994). At the same time, nitrification potentials were measured by the shaken slurry method described by Hart et al. (1994). A 15 g sample of soil was taken from each microcosm and placed in a 250 mL Erlenmeyer flask, which contained a 100 mL mixture of 1.5 mM NH$_4^+$ and 1 mM PO$_4^{2-}$. Substrate concentration was not limiting because excess NH$_4^+$ was available. Samples were shaken on an orbital shaker at 180 rpm for a 24 hours incubation period at 22°C. Each flask was sampled four times during that period at 2, 4, 22, and 24 hours. Nitrate was measured on an automated, continuous flow QuikChem 8000 Injection Flow Analysis System (Hach Company, Loveland, CO), as described above.

**Data analysis**

Net N release from cover crop and cover crop-feather meal residues in the laboratory incubation was calculated by subtracting inorganic N content of control soil from total inorganic N content of each cover crop-feather meal treatment. The percent N release was calculated by dividing net N released from cover crop residue by total N content of residue applied. Net N mineralization data was fitted to a simple exponential model [Eq. 2] (Curtin and Campbell, 2008), which assumes a single pool of potentially mineralizable N, mineralized at a rate proportional to its concentration:

\[ N_m = N_o [1 - \exp(kt)] \]
where $N_m$ is mineralized N at time $t$, $t$ is incubation time, $N_o$ is the potentially mineralizable N pool, and $k$ is the mineralization rate constant. Curve fitting of N mineralized was approximated by least-squares iteration with the SAS NLIN procedure (SAS 9.2, SAS Institute, Cary, NC 2008). Analysis of variance was done with a mixed model procedure to determine the effect of rye-vetch biomass ratio and feather meal amendment on N mineralization and nitrification potential using SAS statistical software (SAS 9.2, SAS Institute, Cary, NC 2008). Correlations between net N mineralization and residue quality were conducted using Pearson correlation coefficients using the SAS CORR procedure (SAS 9.2, SAS Institute, Cary, NC, 2008).
Table 1. Cover crop-feather meal treatments used in (nitrogen) N mineralization incubation study, including the equivalent rates of cover crop biomass application and total applied N.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Cover crop</th>
<th>FM</th>
<th>Total N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mg biomass ha(^{-1})</td>
<td>kg N ha(^{-1})</td>
<td>kg N ha(^{-1})</td>
</tr>
<tr>
<td>Control</td>
<td>None</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Vetch</td>
<td>Hairy vetch</td>
<td>2.75</td>
<td>99</td>
</tr>
<tr>
<td>Rye</td>
<td>Rye</td>
<td>4.50</td>
<td>73</td>
</tr>
<tr>
<td>R50V50(^2)</td>
<td>50:50 R-HV</td>
<td>4.60</td>
<td>137</td>
</tr>
<tr>
<td>R75V25(^3)</td>
<td>75:25 R-HV</td>
<td>4.75</td>
<td>113</td>
</tr>
<tr>
<td>FM</td>
<td>None</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>FM &amp; Vetch</td>
<td>Hairy vetch</td>
<td>2.75</td>
<td>99</td>
</tr>
<tr>
<td>FM &amp; Rye</td>
<td>Rye</td>
<td>4.50</td>
<td>73</td>
</tr>
<tr>
<td>FM &amp; R50V50</td>
<td>50:50 R-HV</td>
<td>4.60</td>
<td>137</td>
</tr>
<tr>
<td>FM &amp; R75V25</td>
<td>75:25 R-HV</td>
<td>4.75</td>
<td>113</td>
</tr>
</tbody>
</table>

\(^{1}\)Feather meal, FM; \(^{2}\)50:50 rye-hairy vetch blend, R50V50; \(^{3}\)75:25 rye-hairy vetch blend, R75V25
Table 2. Total carbon (C) and nitrogen (N) concentration of residue and soil, and residue quality

<table>
<thead>
<tr>
<th>Residue</th>
<th>N (g kg(^{-1}))</th>
<th>C (g kg(^{-1}))</th>
<th>C:N</th>
<th>NDF(^1) (g kg(^{-1}))</th>
<th>ADF (g kg(^{-1}))</th>
<th>ADL (g kg(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rye</td>
<td>17 e(^2)</td>
<td>442 c</td>
<td>26 f</td>
<td>457 a</td>
<td>253 c</td>
<td>21 c</td>
</tr>
<tr>
<td>R75V25(^3)</td>
<td>24 d</td>
<td>446 bc</td>
<td>21 e</td>
<td>444 ab</td>
<td>263 bc</td>
<td>42 b</td>
</tr>
<tr>
<td>R50V50</td>
<td>30 c</td>
<td>447 b</td>
<td>18 d</td>
<td>426 b</td>
<td>271 b</td>
<td>49 ab</td>
</tr>
<tr>
<td>Hairy vetch</td>
<td>36 b</td>
<td>451 b</td>
<td>13 c</td>
<td>392 c</td>
<td>302 a</td>
<td>63 a</td>
</tr>
<tr>
<td>Feather meal</td>
<td>118 a</td>
<td>493 a</td>
<td>4.2 a</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil</td>
<td>1.5 f</td>
<td>17 d</td>
<td>12 b</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^1\)NDF, neutral detergent fiber; ADF, acid detergent fiber; ADL, acid detergent lignin
\(^2\)Numbers followed by same letter within row not different (P < 0.01)
\(^3\)R75V25, 75:25 rye-hairy vetch blend; R50V50, 50:50 rye-hairy vetch blend

Table 3. Parameters of first-order model fitted to net N mineralization from cover crop residues.

<table>
<thead>
<tr>
<th>Residue</th>
<th>(N_0)(^1) kg ha(^{-1})</th>
<th>k day(^{-1})</th>
<th>(N_0k) kg ha(^{-1}) day(^{-1})</th>
<th>(R^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R100</td>
<td>36.4 d(^2)</td>
<td>0.027 c</td>
<td>1.0 e 1.0</td>
<td>0.931</td>
</tr>
<tr>
<td>R75V25(^3)</td>
<td>63.5 c</td>
<td>0.038 c</td>
<td>2.4 c 2.4</td>
<td>0.949</td>
</tr>
<tr>
<td>R50V50</td>
<td>78.9 b</td>
<td>0.088 b</td>
<td>7.0 b 7.0</td>
<td>0.957</td>
</tr>
<tr>
<td>V100</td>
<td>62.5 c</td>
<td>0.130 a</td>
<td>8.1 a 8.1</td>
<td>0.970</td>
</tr>
<tr>
<td>SOIL</td>
<td>124.2 a</td>
<td>0.014 d</td>
<td>1.7 d 1.7</td>
<td>0.979</td>
</tr>
</tbody>
</table>

\(^1\)To calculate the net pool of potentially mineralizable N from residue only, soil \((\text{NH}_3^++\text{NO}_3^-)\)-N has been subtracted from treatments with residues
\(^2\)Numbers followed by same letter within column not significantly different (P < 0.001)
\(^3\)75:25 rye-hairy vetch blend (R75V25), 50:50 rye-hairy vetch blend (R50V50)
<table>
<thead>
<tr>
<th>Number in parentheses is p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADL</td>
</tr>
<tr>
<td>ADF</td>
</tr>
<tr>
<td>NDF2</td>
</tr>
<tr>
<td>C:N ratio</td>
</tr>
<tr>
<td>N core</td>
</tr>
<tr>
<td>Quality</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Table 4 Pearson correlation coefficients between net nitrogen (N) immobilization and residue</td>
</tr>
</tbody>
</table>
3. RESULTS AND DISCUSSION

Residue quality

As shown in Table 2, hairy vetch had the highest N concentration, approximately double that of rye. Some research has shown that residues of cover crops grown in biculture may have higher N concentration than when grown alone (Rannels and Wagger, 1996; Elgersma and Schlepers, 2000; Ndakidemi, 2006). We found that the rye component of the rye-hairy vetch blends had only slightly greater N concentration than pure rye (+1.8 g kg$^{-1}$), while hairy vetch from mixture was much greater in N concentration than from pure hairy vetch (+5.2 g kg$^{-1}$). Increased competition for residual N by the cereal may enhance N fixation by legumes and increase residue N concentrations (Hardarson and Atkins, 2003). Alternatively, mineralization of decomposing legume roots can enhance soil (NH$_4^+$ + NO$_3^-$)-N pool for uptake by cereal grown simultaneously (Evans et al., 2001).

Cover crop C:N ratios ranged from 13 (hairy vetch) to 26 (rye) (Table 2). The C:N ratios for hairy vetch and the rye-hairy vetch bicultures were below 25, which has typically been considered the break-even point between N mineralization and immobilization (Myrold and Bottomley, 2008). The fiber data for cover crop residues demonstrated that hairy vetch had the lowest NDF (392 g kg$^{-1}$), while rye had the lowest ADF (253 g kg$^{-1}$) and ADL (21 g kg$^{-1}$). The fiber data for the cover crop residues in this study were similar to what has been reported in the Fall cover crop blends study at Puyallup, WA (Lawson, 2010).

Nitrogen release from cover crop residues

As shown in Figure 1, (NH$_4^+$+NO$_3^-$)-N was higher for cover crop treatments at all sample dates relative to the soil control. The net release of N from cover crop residues was calculated by subtracting (NH$_4^+$+NO$_3^-$)-N accumulated in control soil from the cover crop treatments. Nitrogen
mineralization from soil fit a linear relationship for the duration of the incubation ($R^2 = 0.973$, $P < 0.05$). But the rate of net N release for cover crop treatments decreased with time, shown in Figure 2. The curves demonstrate that there was a rapid phase of N mineralization followed by a plateau for all cover crop treatments. Our data for N release from legume and cereal-legume residues are comparative to other studies with cover crop residues (Quemada and Cabrera, 1995; Kuo and Sainju, 1998; Odhiambo and Bomke, 2000). We did not observe net N immobilization at any time during the incubation for pure rye, as has been reported. In our study, the N concentration for pure rye was higher than the critical value for net N mineralization as observed by Odhiambo and Bomke (2000) (14.1 g kg$^{-1}$), but lower than that reported by Kuo et al. (1997) (17.6 g kg$^{-1}$). The literature demonstrates wide variation in the critical N concentration necessary for net N mineralization, ranging as low as 11.0 g kg$^{-1}$ (Nourbakhsh and Dick, 2005). Variation in microbial biomass N and residue quality may account for differences. For example, Deng et al. (2000) demonstrate a significant relationship between potential N mineralization and microbial biomass N, which may account for variation in N mineralization dynamics of cover crop residues. When plant residues are added to soil, microbial growth is stimulated because of available C (Wang et al., 2003; Tu et al., 2006). But the microbial biomass must assimilate a certain amount of N, which is determined by microbial C:N ratio (Kaye and Hart, 1997). If the N concentration available from the residue is greater than what is needed by microbial biomass, there will be net N mineralization (Myrold and Bottomley, 2008). Other studies have demonstrated that cellulose, hemicellulose, and lignin fractions can affect residue decomposition and N release (Vigil and Kissel, 1991; Hadas et al., 2004; Jensen et al., 2005). Therefore, the critical N concentration value may not be an indicator of N release from plant residues.
The rye-hairy vetch blend ratio had a significant impact on net N mineralization from the residues. As the proportion of rye increased from 50 to 100% there was a trend of less (NH$_4^+$ + NO$_3^-$)-N release. The pure hairy vetch treatment released less N than r50v50 after day 50, which is likely because of the lower amendment rate of hairy vetch residue. However, pure vetch and r50v50 released a similar percent of residue N from day 70 to 158 (Figure 2). After 70 days pure vetch, r50v50, r75v25, and pure rye had released 64.9, 56.8, 50.0, and 39.9% of total residue N, respectively. This timeframe is representative of a typical growing season (May-September) in the maritime Pacific Northwest when calculated on a growing degree basis. The release of N as a percent of total residue N was not different for pure hairy vetch and r50v50 treatments. Our data demonstrate that even a small amount of hairy vetch residue (25% of blend total) in combination with rye will significantly increase N release in comparison to pure rye, which is consistent with other findings (Kuo and Sainju, 1998).

Net N release from feather meal-cover crop combinations

The cumulative N release curves for feather meal-cover crop treatments demonstrate that there was a rapid phase of N mineralization over the first 21 days followed by slow linear phase after day 50 (Figure 3). Net N release from feather-meal cover crop treatments were calculated by subtracting (NH$_4^+$+NO$_3^-$)-N accumulated in control soil from these treatments (Figure 4). Feather meal-cover crop combinations released more N than cover crop residues alone, which was likely because of higher total N content of the combined materials. The N release curves for feather meal-cover crop treatments reflected the pattern observed for feather meal without cover crops. In total, 65% of feather meal N was released over the first 21 days of the incubation. Other studies have reported slower N release from feather meal over two weeks after incorporation (48 to 55% of applied N) (Hadas and Kautsky, 1994; Hartz and Johnstone, 2006). In our study,
feather meal pellets were cut into pieces to scale down for microcosms. Fragmenting the feather meal pellets could increase microbial access and therefore enhance N mineralization. Several studies have demonstrated that decreasing particle size facilitated microbial activity and decomposition of organic residues (Ambus and Jensen, 1997; Angers and Recous, 1997), which may enhance N mineralization.

A much more rapid increase in inorganic N was observed in the first 21 days in feather meal-cover crop treatments than cover crops alone. The higher initial N release rate from feather meal and greater total N content of combined materials offers a likely explanation. Nitrogen release for feather meal combinations with r50v50, r75v25, and pure hairy vetch was not different after 14 d. These treatments were applied at approximately the same N rate. The pure rye-feather meal treatment released more N than feather meal only after day 50, which is expected because of lower N content of feather meal-rye treatment and slow release pattern of pure rye. Cumulative (NH$_4^+$ + NO$_3^-$)-N feather meal-cover crop treatments did not change significantly after day 21.

The feather meal-cover crop treatments accumulated less (NH$_4^+$ + NO$_3^-$)-N than the sum of the individual component residues. Several studies have shown that low quality residue (low N concentration, high cellulose and hemicellulose concentrations) applied in combination with other N amendments can immobilize fertilizer-derived N (Gentile et al., 2008; McSwiney and Snapp, 2010; Starovoytov et al., 2010). But the cover crop residues in this study were of relatively high quality (C:N ratio < 26.2). The N mineralization curves for cover crop residues without feather meal demonstrate that there was not N immobilization for any of the residues at any time in the incubation. Because NO$_3^-$-N leaching was not possible, N immobilization in microbial biomass or gaseous N loss must account for the decrease in (NH$_4^+$ + NO$_3^-$)-N in the
feather meal treatment. Immobilization of N in microbial biomass is not likely given the high C:N ratio of the feather meal. We did not observe remineralization of immobilized N later during the incubation, which would be likely given the length of our microcosm study (Zagal and Persson, 1994). Gaseous N loss in the form of nitrous oxide (N₂O) or ammonia (NH₃) may account for decrease in the (NH₄⁺ + NO₃⁻)-N. But conditions were not favorable for high rates of denitrification in this study (Coyne, 2008). Senbayram et al. (2009) reported that N₂O emissions from biogas waste and mineral ammonium sulfate fertilizer were insignificant for soil at 65% water-filled pore space, but that emissions increased approximately 5-fold for soil at 85% water-filled pore space. In this study, soil moisture was maintained at 40% water-filled pore space, and although some denitrification is possible, N₂O loss is not likely to account for the magnitude of N loss we observed. Although ammonia volatilization is minimal when N source is incorporated into soil, a 5 to 10 cm depth is reported as necessary to minimize NH₃ loss (Hargrove, 1988). One study measured 16% of applied urea N was lost to NH₃ volatilization when incorporated to a depth of 0-5 cm (Rochette et al., 2009). In our study, feather meal was incorporated to a depth of approximately 2 cm. No research has been done to look at NH₃ loss from feather meal fertilizer, but the literature suggests that significant N loss from NH₃ volatilization is possible from urea fertilizer under moisture and pH conditions (Bayraklı and Gezgin, 1996; Fox et al., 1996; Ping et al, 2000). Further research is necessary to quantify NH₃ volatilization potential from shallow incorporated feather meal fertilizer.

**Fitting net N mineralization data to kinetics model**

Net N mineralization from cover crop residues fit a single first-order kinetics model well (R² = 0.931 to 0.970). Parameters of the model are given in (Table 3). The size of the mineralizable N pool N₀ for r50v50 was more than double pure rye. The other treatments, r75v25
and pure hairy vetch, had similar $N_0$ values, which were slightly smaller than r50v50. In general, $N_0$ reflects the total N content of the cover crop residues applied. The rate constant $k$ was highest for pure hairy vetch and decreased as the rye component in the blends increased. Although $N_0$ was not different for pure hairy vetch and r75v25, the rate constant $k$ was significantly smaller for r75v25. This suggests that although similar N release is expected for these treatments over 157 d, the timing of release is much more rapid for the pure hairy vetch. The slower N release from r75v25 residues may be better timed with the critical period of crop N uptake and therefore enhance N use efficiency. The initial potential mineralization rate $N_k$ of pure hairy vetch and r75v25 support this hypothesis. Net N mineralization from cover crops applied in combination with feather meal did not fit a single first-order kinetics model. A large portion of the N contained in the feather meal was immediately available. Therefore, fitting a single first-order kinetics model was not appropriate for that data.

**Correlation of cover crop properties and net N mineralization**

Total C and N concentrations and fiber data for the cover crop residues (Table 2) were correlated to net N release from the residues at each time interval of the incubation. Our results demonstrated that residue N concentration and C:N ratio were well correlated to net N release from rye-hairy vetch cover crops for the first 70 days of the incubation (Table 4). Many studies have confirmed that the timing and rate of N release from plant residues incorporated into soil are primarily related to the initial N concentration and C:N ratio of the residues (Vigil and Kissel; 1991; Constantinides and Fownes, 1994; Trinsoutrot et al., 2000; Justes et al., 2009). But some have demonstrated that C:N ratio is only correlated with N mineralization over certain stages of decomposition because residue biochemical composition changes as residues decompose and release nutrients (Heal et al., 1997). Others have demonstrated that it is neither
an adequate measure of residue quality (Ruffo and Bollero, 2003), nor a useful parameter for measuring N mineralization dynamics (Vigil and Kissel, 1995).

The relationship between N mineralization and residue fiber content has been used to improve models that predict N release from residues (Vigil and Kissel, 1991; Kumar and Goh, 2003). In particular, the amount of lignin and other recalcitrant C in plant residues may slow N release from plant materials (Vigil and Kissel, 1991; Quemada and Cabrera, 1995; Hadas et al., 2004). But the research has demonstrated that no single residue quality criterion has been correlated to N release across a range of plant types (Handayanto et al., 1997). Special emphasis has been placed on linking N mineralization to cellulose, hemicellulose, and lignin contents, which are insoluble compounds of the cell wall (Wagger et al., 1998). These components have slower rates of decomposition than soluble compounds (Kumar and Goh, 2000), which may have a negative effect on N mineralization (Muller et al., 1988).

In this study, residue fiber content was reported as NDF, ADF, and ADL, which is the standard way of reporting fiber that was determined using the Van Soest et al. (1991) procedure. We found that NDF was well negatively correlated with net N mineralization through the first 70 days of the incubation and ADF between days 21 and 50 (Table 4). These results are in agreement with the literature, which has shown that NDF and ADF contents are negatively correlated to residue decomposition (Stubbs et al., 2009) and N availability (Ruffo and Bollero, 2003). In one study, the inclusion of hemicellulose content (a component of NDF) bolstered the Pearson correlation coefficient for a model of net N mineralization from plant residues (Johnson et al., 2007). However, Ruffo and Bollero (2003) suggested that NDF and ADF fractions be considered in combination with neutral and acid detergent soluble N as a measure N availability.
which was shown to be a more critical factoring in N release than total N concentration or C:N ratio.

Residue lignin content has been negatively correlated with net N mineralization in a range of studies (Vigil and Kissel, 1991; Constantinides and Fownes, 1994; Kumar and Goh, 2003). But ADL was positively correlated to N release through the first 106 days of this study. We found a strong correlation between ADL and total N concentration of cover crop residues ($R^2 = 0.90, P < 0.0001$), which suggests that this relationship was likely incidental. Although ADL was higher in hairy vetch ($63 \text{ g kg}^{-1}$) than rye ($21 \text{ g kg}^{-1}$), the structural linkages in lignin have been shown to differ between legumes and cereals, with the lignin in cereal residues being more resistant to decomposition than legumes (Gordon et al., 1983). Additionally, lignin typically affects residue mineralization in the late stages of decomposition (McClaugherty and Berg, 1987), which is in contrast with our results. Therefore, the relationship between ADL and net N mineralization in this study is not a meaningful one.

**Nitrification potentials**

Nitrification potentials were significantly higher for treatments receiving cover crop residue than control soil (Figure 5). Treatments with feather meal fertilizer in combination with cover crop residues had greater nitrification potentials than cover crop treatments without feather meal. For treatments without feather meal, r50v50 had the highest nitrification potential and pure rye the lowest (5.78 vs. 4.99 μg N g$^{-1}$ soil per day). Nitrification potentials for pure vetch and r75v25 without feather meal were not significantly different. Regardless of cover crop treatment, nitrification potentials were consistently greater when feather meal was applied than without (5.93 vs. 5.24 μg N g$^{-1}$ soil per day). Mean nitrification potentials for cover crop treatments over the 70 day laboratory mineralization study were well correlated with total ($\text{NH}_4^+ + \text{NO}_3^-$)-N
accumulated from residues and soil over that time ($R^2 = 0.975$, $P = 0.05$). But mean nitrification potentials for feather meal-cover crop treatments over that time were not significantly correlated with total inorganic N accumulation. Similarity in nitrification potentials across cover crop treatments indicates that substrate availability is driver in nitrifier response to cover crop incorporation.

Change in nitrification potential over time is shown in Figure 6. Nitrification potential for all treatments increased with time until a maximum rate was reached. For treatments not receiving feather meal, the maximum rate was achieved on day 28 (6.94 μg N g$^{-1}$ soil per day). Treatments containing feather meal achieved highest nitrification potential on day 50 (8.81 μg N g$^{-1}$ soil per day). By day 70, nitrification potentials had decreased to rates similar to or below those measured on day 7. Therefore, nitrification potentials were not measured after that date. The increase in nitrification potential over the first 28 d after cover crop incorporation is likely due to N release from cover crop residues. The return of nitrification potentials to rates below those measured on day 7 indicate that the temporary increase in nitrification potential is not likely to contribute to potential nitrate leaching because highest rates are achieved at the time of high crop N uptake.
Figure 1. Cumulative N release from cover crops residues and soil over 157 d incubation (P < 0.05)

Figure 2. Cumulative net N release from cover crop residues (soil (NH$_4^+$+NO$_3^-$)-N has been subtracted) over 157 d incubation (P < 0.05)
Figure 3. Cumulative N release from cover crops and feather meal residues and soil over 157 d incubation (P < 0.05)

Figure 4. Cumulative net N release from feather meal (FM) and cover crop residues (soil (NH₄⁺+NO₃⁻)-N has been subtracted) over 157 d incubation (P < 0.05)
Figure 5. The effect of cover crop residue and feather meal (FM) on mean nitrification potentials over 70 day laboratory study (P < 0.05)

Rye-Vetch (RV)

Figure 6. The effect of time and feather meal (FM) on nitrification potentials (rates averaged across all cover crop treatments) (P < 0.05).
4. CONCLUSIONS

Rye-hairy vetch cover crop residues of relatively high quality can release significant amounts of N if sufficient biomass yield is accomplished. Our results indicate that a biculture of cereal and legume cover crops can enhance the N concentration of the mixture compared to either component alone, which has implications for N release dynamics. A 50:50 rye-hairy vetch blend released a similar percent of residue N compared to pure hairy vetch over the course of a 70 day incubation. The 50:50 rye-hairy vetch blend may supply greater amounts of (NH$_4^+$+NO$_3^-$)-N to subsequent cash crops than hairy vetch due to higher biomass and N content. A 75:25 rye-hairy vetch blend released a significantly lower portion of the total residue N compared to hairy vetch but comparable total (NH$_4^+$+NO$_3^-$)-N because of higher biomass yield. Although hairy vetch and the 75:25 rye-hairy vetch blend released similar amounts of N over 70 incubation days, the initial rate of N release was nearly 3-fold greater for the hairy vetch treatment. The slower rate of N release from the 75:25 rye-hairy vetch blend may result in N release that is better timed with crop N uptake and therefore increase crop N use efficiency. When cover crops were combined with organic feather meal fertilizer, the combined net N release was less than the sum of the individual components. The cause of the negative interaction was not well understood and therefore deserves further research.

Residue quality was relatively well correlated to N release from cover crop residues, and therefore may be used to predict N release from rye-hairy vetch cover crop blends. In particular, residue N concentration and C:N ratio were well correlated to net N mineralization over the first 70 incubation days. Neutral detergent fiber and ADF were negatively correlated to net N mineralization during the first 70 days and between days 21 and 50, respectively. Therefore, inclusion of these fractions in a model to predict N release could increase the accuracy of the
model. The recent development of the near-infrared spectroscopy method to determine the fiber content of plant residues offers farmers an inexpensive alternative to the time-consuming, wet chemistry methods currently used, which makes the practical application of these findings relevant.

Nitrification potentials for cover crop treatments were significantly higher than bare soil over the first 70 incubation days. Rates averaged across cover crop treatments increased until day 28 and returned to rates below those measured on day 7 by day 70. Our results indicate that the increase in nitrification potentials over the first 28 days is likely due to increased (NH$_4^+$+NO$_3^-$)-N and that nitrification potentials were not largely different between cover crop treatments. The decrease in nitrification potentials to rates below those measured on day 7 by day 70 demonstrates that higher nitrification potentials are not likely to contribute to nitrate leaching because the highest rates are timed with crop N uptake.
5. LITERATURE CITED


CHAPTER 4

Response of organic sweet corn to a fall planted 50:50 rye-hairy vetch cover crop blend

1. INTRODUCTION

Organic cropping systems are often limited by the timely supply of plant available N (Pang and Letey, 2000; Berry et al., 2002). In the Puget Sound region of Western Washington, organic farmers have expressed concerns over yield reduction due to N deficiency (Cogger, personal communication). Because organic production prohibits the use of mineral fertilizers, a variety of organic materials are used to supply N to crops, including animal manure, compost, cover crops, and specialty products (Cogger, 2000; Watson et al., 2002; Gaskell, 2006). Specialty organic products are expensive while compost and manures are bulky and costly to import and apply (Gaskell and Smith, 2007). Legumes and cereal-legume cover crop blends are often used in rotation as a source of short-term N fertility (Rannels and Wagger, 1996; Burket et al., 1997; Griffin et al., 2000; Sarrantonio and Malloy, 2003; Tonitto et al., 2006; Sainju and Singh, 2008; Teasdale et al., 2008). But it is difficult to predict N availability to subsequent crops because N mineralization is controlled by many factors, including residue composition (Vigil and Kissel, 1991; Rannels and Wagger, 1996; Kuo and Sainju, 1998; Jensen et al., 2005) and environmental parameters such as temperature and soil moisture (Quemada and Cabrera, 1997; Ruffo and Bolero, 2003). Regional information on cover crop N supply to subsequent cash crops is needed in organic cropping systems.

Mixed cereal-legume cover crop blends are considered to be a better management option than growing cover crops in monoculture because it can reduce the risk of stand failure (Creamer et al., 1997; Gaskell, 2006), enhance biomass productivity (Sainju et al., 2005), and prevent N immobilization after spring incorporation (Rannels and Wagger, 1996; Kuo and Sainju, 1998).
Cover crop blends that include both cereal and legume species synchronize plant available N with subsequent cash crop needs. Cereals are capable of taking up residual soil NO$_3^-$ after fall harvest to minimize leaching (BrandiDohrn et al., 1997; Moller and Reents, 2009, Thorup-Kristensen and Dresboll, 2010). In contrast, legumes fix atmospheric N, which increases residue N concentration, and therefore represents an N input into the system (Clark et al., 1997). In some cases, the N concentration of cereal in mixture with legume is higher than when it is grown alone (Rannels and Wagger, 1996; Burket et al., 1997). While monocropped cereals such as rye can immobilize N following incorporation, cereal-legume bicultures can supply N to subsequent crops because of increased residue N concentration (Kuo and Sainju, 1998).

Past research at the WSU Research and Extension Center in Puyallup, WA demonstrates that rye-hairy vetch cover crops blends are well suited for the climate and cropping systems of the maritime Pacific Northwest (Kuo et al., 1997; Kuo and Jellum, 2000; Cogger et al., 2008). Cereal rye establishes rapidly when planted by early October, and it is an effective N scavenger (Kuo and Jellum 2000; Thorup-Kirstensen et al., 2003; Feaga et al., 2010). Although hairy vetch is characterized by slow fall growth and low soil cover (Holderbaum et al., 1990), it has been found to have high winter survival in northern temperate climates (Teasdale et al., 2004; Brandsaeter et al., 2007) and accumulates biomass and fixes N rapidly in the spring as soil temperatures increase (Holderbaum et al., 1990; Kuo and Jellum, 2000). Research has demonstrated that a 50:50 (seeding ratio) rye-hairy vetch cover crop blend planted by early October and killed in late April optimized N accumulation and residue quality in this region (Lawson, 2010a).

Cover crops influence subsequent crop yield primarily via their affect on N availability (Torbert et al., 1996; Vaughan and Evanylo, 1998; Kuo and Jellum, 2000; Cherr et al., 2006).
Crop yields can be maintained by replacing or supplementing N fertilizer application with winter legume or cereal-legume cover crop residues (Sainju et al., 2005; Fortuna et al., 2008). But there must be sufficient biomass and N accumulation, and timely N mineralization for cover crops to supply sufficient N to crops (Griffin et al., 2000; Teasdale et al., 2008). Several studies have examined sweet corn performance after legume and mixed cereal-legume cover crops because of its marked response to N fertility. Some have shown that it can produce yields as good as N-fertilizer treatments when grown in rotation with hairy vetch (Griffin et al., 2000; Cline and Silvernail, 2002; Carrera et al., 2004). But often crop yield potential may be optimized when cover crops are combined with low supplemental N fertilizer rates. Schellenberg et al. (2009) recommended that legume-based cover crops systems be combined with modest sidedress N fertilizer to maximize organic broccoli yield.

Lack of synchrony between N supply from cover crop residue and crop N uptake may influence efficiency of crop N use (Teasdale et al., 2008). But this depends on timing of field events and types of crops grown. For instance, a delay in spring cover crop desiccation may result in a late flush of N release, which is better timed with crop N uptake (Cline and Silvernail, 2001). There are mixed results for crop N use efficiency of cover crop-derived N (Sarranotonio and Malloy, 2003; Haas et al., 2007; Teasdale et al., 2008). In some cases crop N use efficiency of cover crop-derived N is low but overall efficiency is high because of high N recovery in soil (Seo et al., 2006). Pang and Letey (2000) suggest that crops with high maximum uptake rates have low utilization efficiencies because it is difficult to meet peak N crop demand with relatively slow release materials. The research focus needs to shift from maximum N supply to more timely N release.
A laboratory incubation study was previously conducted to measure N release from rye-hairy vetch cover crop blends under controlled environmental conditions (Lawson, 2010b). This field study was designed to determine N release under field conditions from one rye-hairy vetch cover crop blend treatment, which was included in the incubation study. Because the rate of N release from organic residues is influenced by soil moisture and temperature, it is necessary to test the legitimacy of the N release patterns observed in the incubation under field conditions. A fertility trial was devised with cover crops and organic fertilizer, and sweet corn yield and N uptake were measured. The objective was to: (i) evaluate the response of organically grown sweet corn to a 50:50 rye-hairy vetch cover crop blend and an organic feather meal fertility regime, (ii) assess sweet corn N use efficiency from a 50:50 rye-hairy vetch cover crop blend planted over two fall dates and in combination with feather meal fertilizer, and (iii) use sweet corn yield and N recovery data to validate results from a related N mineralization laboratory incubation study.

2. MATERIALS AND METHODS

Site description

The Cover Crops-2 field plots, located at Washington State University Puyallup Research and Extension Center, Puyallup, WA, were established in September 2007. This ground has not been certified organic, but has been under organic management practices since 2004. The soil is classified as Puyallup fine sandy loam (coarse-loamy over sandy or sandy-skeletal, isotic over mixed, mesic Vitrandic Haploxerolls). The average annual precipitation and temperature is 102.9 cm and 10.9°C, respectively, with mild, dry summers and cool, wet winters. Approximately 75% of precipitation occurs between October and March.

Experimental design
This study was two years in duration starting in September 2008. The experiment was designed to evaluate the N contribution of a 50:50 rye-hairy vetch blend to organically grown sweet corn. Additionally, results from this study were used to validate a related N incubation study. Treatments include two fall planting dates, a no-cover crop control, and four N fertilizer rates, including one zero-N check. The study was arranged in a randomized complete block split plot design with cover crop planting date (early, late, or no cover) as the main plots and N-fertilizer rate as the split. Main plots measure 24.4 x 6.1 m, split plots measure 6.1 x 6.1 m, and there are four replications. Early and late planting dates were mid-September and early-October each year and the 50:50 rye-hairy vetch treatments were a blend by seed weight ratio. The N source is feather meal, a relatively fast release commercially available organic material. It has 12% N and approximately 75% is available over a growing season, according to the manufacturer (California Organic Fertilizers, Inc., Fresno, CA). A summer crop of organically grown sweet corn was planted in June and harvested at maturity. After harvest, sweet corn stover was flail mowed and incorporated with a rotary spader, and the plots were prepared for cover crops. Dates of sampling and field activities are listed in Table 1.

Management

Cover crops were planted in the fall using a 3.1 m John Deere grain drill and chopped and incorporated in the spring using a rotary spader. Seeding rate for the rye-hairy vetch blend was 112 kg ha\(^{-1}\); all vetch seed was inoculated with the appropriate rhizobia bacteria to ensure nitrogen fixation. Field plots were fertilized by hand broadcasting feather meal at four rates prior to planting: 0, 56, 112, and 168 kg N ha\(^{-1}\). ‘Golden jubilee’ sweet corn was seeded with a Cole Planter on 1.5 m beds with 0.76 m between-row and 0.1-0.15 m in-row spacing at rate of 86,100 seeds ha\(^{-1}\). Each plot is 8 rows wide. Weeds were controlled as necessary via cultivation (basket-
weeder, tine-weeder, and sweeps) and hilling. Irrigation was supplied as needed beginning in early July via sprinklers on 2.4 m risers. Approximately 1 inch of water was applied every 10 days through harvest.

**Field measurements**

In late April, plots were harvested for above ground biomass by harvesting a 6.1 x 0.91 m swath approximately 5 cm above soil surface with a flail mower and fresh weights recorded. A subsample of cover crop residue from each plot was collected for total C and N and moisture content determined. The remaining residue was returned to the plots. Three additional subsamples were collected from representative 0.25 m² quadrats in each plot, and proportions of rye, vetch, and weeds were determined (Sarrantonio, 1991).

Soils were sampled for total NO$_3$-N analysis on three occasions: after cover crop incorporation, at the time of pre-sidedress soil nitrate testing (sweet corn approximately 0.15 m tall), and post-harvest (prior to stover incorporation). Soil samples were collected to a depth of 30 cm; 10 samples were taken in each plot with a 2.5 cm diameter tube sampler and composited. Soil was immediately dried at 30°C to stop microbial activity and soil moisture was determined. Dried soil was passed through a 2-mm diameter screen opening. Nitrate-N was extracted from 10 g soil samples with 100 mL of 2M KCl. Samples were shaken on a reciprocal shaker for 1 h and then filtered through No. 42 Whatman filters. Aliquots were run on an automated, continuous flow QuikChem 8000 Injection Flow Analysis System (Hach Instruments, Loveland, CO). Nitrate-N was determined using the cadmium reduction method (Gavlak et al., 1994).

In-season N status of the sweet corn crop was measured at silking on ear leaves. We measured chlorophyll content using a chroma meter (CR-400, Konica Minolta Holding, Inc.). Leaf chlorophyll concentration has been correlated to leaf N concentration (Schepers et al.,
Therefore, a non-destructive measure of leaf chlorophyll concentration, or leaf greenness, can be used as a measure of crop N status (Varvel et al., 1997). Research has demonstrated that a chroma meter can accurately measure chlorophyll content of plant leaves (Madeira et al., 2003; Leon et al., 2007). Amarante et al. (2008) found that the h°/(LxC) ratio was best correlated to chlorophyll content. Readings were taken at silking using the ear leaf from a subsample of 10 leaves per plot. At the same time, ear leaves were pulled for total C and N analysis. Ear leaves from 10 plants from the middle four rows of each plot were removed, dried at 55°C, ground to pass through 2-mm screen opening, and moisture content determined.

Sweet corn population was assessed at harvest by counting the number of plants in a 6.1 m length of an inner row. One ear of sweet corn per plant was harvested within a 6.1 m section of a middle row in each plot and fresh weight recorded. Total aboveground biomass of sweet corn plants in a 6.1 m section of middle row was removed and fresh weight recorded. A subsample of ten plants was chopped, dried at 55°C, and ground to pass through a 2-mm screen opening for total C and N analysis. Water content of total biomass was determined and used to calculate dry weight. All plant residues (cover crop, sweet corn ear leaves, and sweet corn silage) were analyzed for total C and N by dry combustion with a TruSpec CN Carbon/Nitrogen Determinator (Leco, St. Joseph, MI).

Data analysis

Analysis of variance was conducted on cover crop biomass, portion of rye and hairy vetch in total biomass, and N accumulation using the SAS Mixed procedure (SAS 9.2, SAS Institute, Cary, NC, 2008). For a randomized complete block design, planting date and feather meal were fixed effects and replication was a random effect. Sweet corn in-season N status, ear and biomass yield, and N uptake were analyzed in the same procedure. Cover crop planting date,
feather meal, and sample date were fixed effects and replication a random effect in the analysis of variance of soil NO$_3$-N levels, done using a mixed model procedure. Sweet corn N uptake was fitted to a linear regression using the SAS GLM procedure (SAS 9.2, SAS Institute, Cary, NC, 2008). The significance of cover crop treatment effect from the above procedure was the primary consideration for development of linear regression equations.

Apparent N recovery of cover crop derived N in sweet corn was calculated according to the method used by Sullivan et al., (2002). Equation [1] estimates the increase in sweet corn N uptake that is attributed to cover crops:

\[ \text{Apparent N recovery (ANR, kg ha}^{-1}\text{)} = A - B \]

where A is the y-intercept for cover crop treatment and B is the y-intercept for the no cover crop control treatment. We estimated the reduction in the requirement of feather meal fertilizer N attributed to cover crops using equation [2]:

\[ \text{Reduction in fertilizer N requirement} = \frac{\text{ANR}}{e_f} \]

where ANR is apparent N recovery from equation [1] and $e_f$ is fertilizer N uptake efficiency, estimated from the slope of the line for sweet corn N uptake vs. feather meal available N. Nitrogen use efficiency was calculated by dividing sweet corn dry matter by total N supply. We estimated the N contribution from soil as total N uptake in sweet corn in the zero-feather meal control plot.
Table 1. Dates of sampling and field activities

<table>
<thead>
<tr>
<th>Activity</th>
<th>2008-09</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early Planting</td>
<td>17 Sep</td>
</tr>
<tr>
<td>Late Planting</td>
<td>2 Oct</td>
</tr>
<tr>
<td>Harvest</td>
<td>27 Apr</td>
</tr>
<tr>
<td>Field chopped</td>
<td>5 May</td>
</tr>
<tr>
<td>Residue incorporated</td>
<td>7 May</td>
</tr>
<tr>
<td>Soil sampled for NO$_3$-N</td>
<td>2 Jun</td>
</tr>
<tr>
<td>Fertilized</td>
<td>2 Jun</td>
</tr>
<tr>
<td>Corn planted</td>
<td>4 Jun</td>
</tr>
<tr>
<td>Soil sampled for NO$_3$-N</td>
<td>26 Jun</td>
</tr>
<tr>
<td>Ear leaf sampled</td>
<td>4 Aug</td>
</tr>
<tr>
<td>Corn Harvest</td>
<td>27 Aug</td>
</tr>
<tr>
<td>Soil sampled for NO$_3$-N</td>
<td>9 Sep</td>
</tr>
<tr>
<td>Residue incorporated</td>
<td>10 Sep</td>
</tr>
</tbody>
</table>

Table 2. Cover crop dry matter production, nitrogen (N) concentration, total N content and dry matter composition in 2009

<table>
<thead>
<tr>
<th>Planting Date</th>
<th>Dry matter kg ha$^{-1}$</th>
<th>N conc. mg kg$^{-1}$</th>
<th>Total N kg ha$^{-1}$</th>
<th>C:N Ratio</th>
<th>Dry matter composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early</td>
<td>3121 a$^1$</td>
<td>22 c</td>
<td>70 a</td>
<td>19 a</td>
<td>76 b 21 a</td>
</tr>
<tr>
<td>Late</td>
<td>1718 b</td>
<td>23 b</td>
<td>39 b</td>
<td>18 a</td>
<td>84 a 13 b</td>
</tr>
<tr>
<td>None</td>
<td>30 c</td>
<td>29 a</td>
<td>1 c</td>
<td>15 b</td>
<td></td>
</tr>
</tbody>
</table>

$^1$Values followed by same letter within column are not significantly different (P < 0.05)
Table 3. The effect of cover crop and sample date on soil nitrate (NO$_3^-$)-N concentration. Total nitrogen (N) content of early and late cover crops was 70 and 39 kg N ha$^{-1}$

<table>
<thead>
<tr>
<th>Planting Date</th>
<th>Date</th>
<th>Soil (NO$_3^-$)-N kg ha$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early</td>
<td>June 2</td>
<td>29 c$^1$</td>
</tr>
<tr>
<td>Early</td>
<td>June 26</td>
<td>67 a</td>
</tr>
<tr>
<td>Early</td>
<td>Sept 9</td>
<td>10 d</td>
</tr>
<tr>
<td>Late</td>
<td>June 2</td>
<td>27 c</td>
</tr>
<tr>
<td>Late</td>
<td>June 26</td>
<td>59 b</td>
</tr>
<tr>
<td>Late</td>
<td>Sept 9</td>
<td>7 d</td>
</tr>
<tr>
<td>None</td>
<td>June 2</td>
<td>25 c</td>
</tr>
<tr>
<td>None</td>
<td>June 26</td>
<td>52 b</td>
</tr>
<tr>
<td>None</td>
<td>Sept 9</td>
<td>9 d</td>
</tr>
</tbody>
</table>

$^1$Values followed by same letter not different (P < 0.01)

Table 4. Degree day elapsed between cover crop incorporation and soil sampling

<table>
<thead>
<tr>
<th>Sample date</th>
<th>Field Trial Days</th>
<th>Degree Days$^1$</th>
<th>Laboratory Incubation Days</th>
<th>Degree Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-Jun-09</td>
<td>26</td>
<td>249</td>
<td>14</td>
<td>288</td>
</tr>
<tr>
<td>26-Jun-09</td>
<td>50</td>
<td>546</td>
<td>28</td>
<td>576</td>
</tr>
<tr>
<td>9-Sep-09</td>
<td>124</td>
<td>1579</td>
<td>70</td>
<td>1439</td>
</tr>
</tbody>
</table>

$^1$Degree days based on base temperature of 4.4°C
Table 5. The effect of cover crop and feather meal on post-harvest soil (NO$_3^-$)-N

<table>
<thead>
<tr>
<th>Planting Date</th>
<th>Feather meal available N kg ha$^{-1}$</th>
<th>Soil (NO$_3^-$)-N kg ha$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early</td>
<td>0</td>
<td>10 c$^1$</td>
</tr>
<tr>
<td>Early</td>
<td>56</td>
<td>18 c</td>
</tr>
<tr>
<td>Early</td>
<td>112</td>
<td>28 bc</td>
</tr>
<tr>
<td>Early</td>
<td>168</td>
<td>59 a</td>
</tr>
<tr>
<td>Late</td>
<td>0</td>
<td>7 c</td>
</tr>
<tr>
<td>Late</td>
<td>56</td>
<td>9 c</td>
</tr>
<tr>
<td>Late</td>
<td>112</td>
<td>27 bc</td>
</tr>
<tr>
<td>Late</td>
<td>168</td>
<td>29 bc</td>
</tr>
<tr>
<td>None</td>
<td>0</td>
<td>9 c</td>
</tr>
<tr>
<td>None</td>
<td>56</td>
<td>9 c</td>
</tr>
<tr>
<td>None</td>
<td>112</td>
<td>14 c</td>
</tr>
<tr>
<td>None</td>
<td>168</td>
<td>36 b</td>
</tr>
</tbody>
</table>

$^1$Values followed by same letter not significantly different (P < 0.05)

Table 6. Sweet corn fresh ear yield and dry matter as affected by feather meal

<table>
<thead>
<tr>
<th>Feather meal available N kg ha$^{-1}$</th>
<th>Ears fresh weight Mg ha$^{-1}$</th>
<th>Plant dry matter Mg ha$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>8.66 c</td>
<td>7.79 b</td>
</tr>
<tr>
<td>56</td>
<td>9.53 b</td>
<td>8.28 b</td>
</tr>
<tr>
<td>112</td>
<td>10.51 a</td>
<td>8.54 ab</td>
</tr>
<tr>
<td>168</td>
<td>11.02 a</td>
<td>9.04 a</td>
</tr>
</tbody>
</table>

$^1$Values followed by same letter not significantly different (P < 0.05)
### Table 7. Effect of cover crop and available feather meal nitrogen (N) on ear leaf N status at silking and total plant N uptake. The interaction between cover crop and feather meal was not significant at P = 0.05

<table>
<thead>
<tr>
<th>Main plot or split treatment</th>
<th>Ear leaf color</th>
<th>Ear leaf N concentration</th>
<th>Plant N uptake</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>h°/(LxC)</td>
<td>g kg⁻¹</td>
<td>kg ha⁻¹</td>
</tr>
<tr>
<td>Cover crop</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Early</td>
<td>0.222 a⁴</td>
<td>28.7 a</td>
<td>159 b</td>
</tr>
<tr>
<td>Late</td>
<td>0.218 a</td>
<td>27.4 b</td>
<td>148 c</td>
</tr>
<tr>
<td>None</td>
<td>0.212 b</td>
<td>26.0 bc</td>
<td>141 c</td>
</tr>
<tr>
<td>Feather meal N, kg ha⁻¹</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0.197 d</td>
<td>25.0 c</td>
<td>112 d</td>
</tr>
<tr>
<td>56</td>
<td>0.214 c</td>
<td>27.3 b</td>
<td>142 c</td>
</tr>
<tr>
<td>112</td>
<td>0.222 b</td>
<td>28.5 ab</td>
<td>161 b</td>
</tr>
<tr>
<td>168</td>
<td>0.235 a</td>
<td>29.4 a</td>
<td>183 a</td>
</tr>
</tbody>
</table>

¹Values followed by same letter are not significantly different (P < 0.05)

### Table 8. Linear regression equations for sweet corn nitrogen (N) uptake as a function of feather meal available N. Effect of cover crop on apparent N recovery and calculated reduction in feather meal N requirement.

<table>
<thead>
<tr>
<th>Cover crop treatment</th>
<th>Y-intercept Value</th>
<th>Std Error</th>
<th>Slope Value</th>
<th>Std Error</th>
<th>Apparent N recovery kg ha⁻¹</th>
<th>Reduction in feather meal N requirement kg ha⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early CC¹</td>
<td>131</td>
<td>9</td>
<td>0.38</td>
<td>0.07</td>
<td>33</td>
<td>57</td>
</tr>
<tr>
<td>Late CC</td>
<td>114</td>
<td>8</td>
<td>0.47</td>
<td>0.09</td>
<td>16</td>
<td>27</td>
</tr>
<tr>
<td>No CC</td>
<td>98</td>
<td>8</td>
<td>0.57</td>
<td>0.09</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

¹EarlyCC = early cover crops, LateCC = late cover crops, NoCC = no cover crops
3. RESULTS AND DISCUSSION

Cover crops

This chapter cover data collected in the first year of a two year study. In 2009, early planted cover crops yielded almost twice as much dry matter as late planted cover crops (Table 2), while weed biomass was insignificant in no cover crop treatments. Yields across both planting dates were significantly lower than dry matter yields measured in the fall cover crop blends study at WSU Puyallup conducted the same year. In the other study, a similar 50:50 rye-hairy vetch cover crop blend planted in mid-September and harvested in late-April yielded 4240 kg ha\(^{-1}\) dry matter, which was slightly lower than the six year mean in that study (4760 kg ha\(^{-1}\)) (Lawson, 2010a). There is evidence that some crop residues may release allelopathic chemicals, which can negatively impact germination of subsequent crops and weed seeds (Singh et al., 2003). In the continuous corn rotations of the Midwest, allelopathic chemicals released from corn stover have been linked to decreased corn germination in a laboratory incubation study (Elmore and Abendroth, 2007). In our study, corn stover was tilled into the soil just prior to seeding cover crops, which may have created an allelopathic effect, decreasing cover crop germination and early season vigor, accounting for low relative cover crop dry matter yields in comparison to the other study that did not include corn stover.

The N concentration of cover crop residues was not largely affected by planting date. This is consistent with data collected at WSU Puyallup in the fall cover crop blends study, which has shown that a 50:50 rye-hairy vetch cover crop blend harvested in late-April has a mean N concentration of 23.8 mg kg\(^{-1}\), regardless of planting date (Lawson, 2010a). In the same study, total N content was significantly higher (93 and 74 kg ha\(^{-1}\)) than what we observed for early and late planting dates, respectively (70 and 39 kg ha\(^{-1}\)). Lower cover crop biomass production in this
study is likely to account for the difference. The biomass composition for the early planted cover crops was approximately 75:25 rye-hairy vetch, which is consistent with the previously cited study. The hairy vetch component of the late planted cover crops was slightly lower than what was observed in that study (22% vetch) (Lawson, 2010a). In fact, delaying planting date has been shown to increase hairy vetch biomass composition in that study. It is unclear what caused the decrease in hairy vetch biomass in the late planting.

Parameters of cover crop N concentration, C:N ratio, and dry matter composition were similar to one of the treatments in a related N mineralization laboratory incubation study, which is tested in this study (Lawson, 2010b). Although total N content is lower than what was applied in the incubation study, net N release as a percent of total residue N should be not affected by N content. Residue N concentration and quality are the drivers of N mineralization for a given climate (Wagger, 1989; Rannels and Wagger, 1996; Kuo and Sainju, 1998; Magid et al., 2001).

**Soil nitrates**

Soil was sampled for NO$_3^-$ over three dates as a gauge of N release from cover crop residues in the field (Table 3). Field NO$_3^-$ was highest on June 26, approximately 8 weeks after cover crop incorporation and lowest on September 9, 2 weeks after sweet corn harvest. On June 26, soil NO$_3^-$ was highest for early planted cover crops. Nitrates in the late planted cover crop treatment were not different from the control. We expected a higher soil NO$_3^-$ response from cover crop residues in the field, based on data from a related laboratory incubation study (Lawson, 2010b). Sample times in the incubation were correlated to field dates based on growing degree days elapsed between cover crop residue incorporation and soil sampling (Table 4), which allowed for comparison between the studies. Moisture was not limiting in the field because over-head irrigation was provided in July and August. Based on the incubation data,
cover crop residue should have released 27 and 15 kg N ha\(^{-1}\) by June 26 in the field. But the soil response in the field was approximate half of what was expected. Sweet corn had been planted almost 4 weeks prior to sampling. Therefore crop N uptake may account for the discrepancy. In addition, we did not measure NH\(_4^+\) in the soil samples. Sarrantonio and Malloy (2003) noted slow conversion of NH\(_4^+\) to NO\(_3^-\) in a cool, wet year in a similar cover crop study. Cool, wet conditions are typical of the region in May and June, which suggests that N in the NH\(_4^+\) form may account for lower than expected NO\(_3^-\) on June 26.

Post-harvest soil NO\(_3^-\) was low across treatments receiving 0 and 56 kg ha\(^{-1}\) feather meal N (Table 5), which indicated that N was limiting. At the 112 kg ha\(^{-1}\) feather meal N rate, early and late planted cover crop treatments had significantly higher NO\(_3^-\) than the no cover crop treatment, demonstrating that N was limiting when cover crops were not included. At the highest feather meal N rate, soil NO\(_3^-\) was high across all cover crop treatments. But soil NO\(_3^-\) was nearly double in the early cover crop treatments than in late or no cover crop treatments at that rate, which indicates a large surplus of N.

**Sweet corn in-season N status, fresh ear yield, and dry matter production**

The effect of cover crops on sweet corn fresh ear yield and plant dry matter production was not statistically significant. We noticed a trend of increased fresh ear yield (7.76 to 9.77 Mg ha\(^{-1}\)) and dry matter production (7.53 to 8.13 Mg ha\(^{-1}\)) in the early cover crop treatment compared to the control when no feather meal was applied. But this effect was not significant, likely because of high variability in fresh ear yield data and plant dry matter production. Based on the related N incubation study, only 56% of total residue N is available in a growing season from a similar rye-hairy vetch cover crop blend (Lawson, 2010b), which is equivalent to approximately 38 kg N ha\(^{-1}\) in this study. It is possible that the cover crop N contribution did not
significantly increase sweet corn yield because the N supply was dominated by a relatively large N contribution from the soil (approximately 100 kg N ha\(^{-1}\)) and feather meal. Feather meal available N had a strong affect on fresh ear yield and dry matter production, demonstrating an increase with feather meal from 8.66 to 11.02 Mg ha\(^{-1}\) and from 7.79 to 9.04 Mg ha\(^{-1}\), respectively (Table 6).

Other studies have demonstrated a significant sweet corn ear yield and plant dry matter response to hairy vetch and rye-hairy vetch cover crop residues (Cline and Silvernail, 2002; Sarrantonio and Malloy, 2003; Zotarelli et al., 2009). In those studies, sweet corn planted after cover crops had double the biomass as winter fallow treatments without fertilizer. We had a much larger N contribution from soil than either of those studies, which could have reduced the relative impact of cover crops on available N. Teasdale et al. (2008) reported large N contribution from soil (78 kg ha\(^{-1}\)), demonstrating a smaller but significant response in sweet corn biomass from rye-hairy vetch cover crops. In that study, cover crop N contents were much higher than in our study (197 to 259 kg N ha\(^{-1}\)), which may explain why a response was observed in that study and not ours.

Despite non-significant sweet corn yield response to cover crops, in-season plant N status indicated that cover crops benefited sweet corn via N contribution (Table 7). As the crop begins its reproductive cycle, N is allocated for grain production, and therefore the ear leaf is a good indicator of in-season plant N status (Plenet and Lemaire, 1999). We found that early cover crops had higher ear leaf N concentrations at silking than no cover crop treatments (28.6 and 26.0 g kg\(^{-1}\), respectively). An extension publication from Oregon State has reported that sweet corn is N deficient when ear leaf N concentrations are below 28 g kg\(^{-1}\) (Anonymous, 2004). According to this standard, sweet corn in early planted cover crop treatments was N sufficient at silking, while
the no cover crop treatments were not. Our data indicated that early planted cover crops may have provided N benefits during growth stages leading up to silking. There was a response in ear leaf N concentration to feather meal available N (Table 7), demonstrating that sweet corn was N deficient when feather meal available N was below 112 kg N ha\(^{-1}\). The interaction between cover crop and feather meal was not significant, which was likely due to the relatively small contribution of N from cover crop residues compared to the soil N pool.

Chroma meter measurements of ear leaf chlorophyll content at silking demonstrate that cover crops had a small N benefit to sweet corn. The \(h^9/(LxC)\) ratio, which has been best correlated to leaf chlorophyll content for chroma meter measurements (Amarante et al., 2008), was slightly higher for early planted cover crops than no cover crop treatments. But the effect of feather meal N rate on the \(h^9/(LxC)\) ratio was much greater. Together, in-season N status at silking and sweet corn yield data demonstrated that feather meal N rate had a significant effect on sweet corn. In-season N status at silking suggests that sweet corn had taken up some N at silking from cover crops. But the N contribution from cover crops may have been small enough in comparison to soil and feather meal N that it did not significantly affect sweet corn yield.

**Sweet corn total N uptake and efficiency of N use**

Sweet corn total N uptake in above ground biomass was significantly affected by cover crops and feather meal (Table 7). Total N uptake increased as feather meal N rate increased, ranging from 112 to 183 kg N ha\(^{-1}\). For cover crops, N uptake was highest in early planted cover crops and lowest in the no cover crop treatments. The interaction between cover crops and feather meal was not significant. Regional guidelines suggest that sweet corn yield is maximized when 196 to 224 kg N ha\(^{-1}\) is available (Anonymous, 2004). We estimated the size of the available soil N pool from the total N uptake in the zero-feather meal control plots
(approximately 100 kg N ha⁻¹). When feather meal was applied at the highest two rates (112 and 168 kg available N ha⁻¹), available N was adequate or in excess of what was required by the sweet corn crop if inorganic N from soil was accounted for. Post-harvest soil NO₃⁻ levels at the highest two feather meal N rates (Table 5) also demonstrated that available N was in excess of what was used by the crop. Therefore, it is not surprising that the interaction between cover crops and feather meal was not significant because the available N pool was sufficient or in excess of the crop requirement at the highest two feather meal N rates and cover crops supplied only a small portion of the total available N to sweet corn.

We estimated ANR from the y-intercepts in the regression models for N uptake (Figure 1, Table 8). Apparent N recovery for early and late planted cover crops was 31 and 14 kg N ha⁻¹, respectively (Table 8). The slope of the line for N uptake in the regression models provided an estimate of feather meal N uptake efficiency, which were 38, 47, and 49% for early, late and no cover crop treatments, respectively (Table 8). Based on the standard deviation of these values in each regression model, there were not significant differences in N uptake efficiency between cover crop treatments. Cover crop N uptake efficiency in our study was similar to what has been reported by others in cover crop-vegetable rotations (Sarranotonio and Malloy, 2003; Haas et al., 2007; Collins et al., 2008). In those studies, N uptake efficiency ranged from 29 to 62% of total cover crop N content. These values were comparable to estimates of mineral fertilizer N uptake by corn, which averaged approximately 50% in one study (Karlen et al., 1998). Some research has shown high N recovery of cover crop derived N in soil organic fractions and soil microbial biomass when compared to mineral fertilizers (Harris et al., 1994; Seo et al., 2006; Collins et al., 2007, Holness et al., 2008). Therefore, it is possible that some cover crop derived N will persist in soil and become available to future crops.
We calculated N use efficiency as kg sweet corn dry matter per kg N input (Huggins and Pan, 1993). This calculation was formulated in terms of dry matter production instead of ear yield because our objective was to evaluate total N contribution from cover crops to subsequent cash crops. At the lowest two feather meal N rates, N use efficiency was highest without cover crops (Figure 2). This is likely because only a portion of the total N contained in cover crop residue was available over a single growing season. In a related incubation study, 56% of total residue N was released from a rye-hairy vetch cover crop blend similar to the one in this study. We observed a significant decline in N use efficiency as the feather meal N rate increased. Teasdale et al. (2008) reported similar findings, demonstrating higher N use efficiency for hairy vetch and rye-hairy vetch cover crops without a mineral fertilizer application. In that study, cover crops accumulated much higher N content (197 to 259 kg N ha\(^{-1}\)) than in this study. Therefore, N supply was likely in large excess of what sweet corn requirement when cover crops were combined with fertilizer. A couple studies have reported increased corn root density and length under N deficient conditions, which could increase corn N uptake efficiency (Bonifas et al., 2005; Bonifas and Lindquist, 2009). Therefore, lower dry matter production per N input efficiency as feather meal N rate increased was likely related to the size of the available N pool.

**Cover crop fertilizer N replacement values and validation of N release in a related N mineralization study**

The increase in sweet corn N uptake with cover crops was used in combination with sweet corn N uptake efficiency to estimate of the amount of plant available N supplied by cover crops. We calculated fertilizer N replacement values of 57 and 27 kg N ha\(^{-1}\) for early and late cover crops, respectively (Table 8). The N provided by cover crop, expressed as a portion of the total N content, was 81 and 69% for early and late planted cover crops. These values are higher
than what was observed in a related N mineralization laboratory incubation study with a similar 50:50 rye-hairy vetch cover crop blend (56% of total N content was released). But other field studies have reported high percent N release from similar cover crop residues (Kuo et al., 1996; Rannels and Wagger, 1996; Griffin et al., 2000; Sainju et al., 2006; Teasdale et al. 2008).

Nitrogen release from cereal-hairy vetch cover crops as a percent of cover crop N content ranged from 66 to 112% in a range of similar field studies (Rannels and Wagger, 1996; Griffin et al., 2000; Odihambo and Bomke, 2000; Teasdale et al., 2008). But it is unclear how the ratio of rye and hairy vetch biomass and residue quality in those studies compared to ours.

Very few studies have directly compared N release from cover crop residues in laboratory incubation to N release under field conditions. One study has found that N mineralization of hairy vetch in a laboratory incubation study was consistent with results from related field trail (Honeycutt, 1999). De Neve and Hoffman (1996) were also able to confirm N mineralization results collected in the lab with field trials. We found that N release from cover crop residues in the laboratory incubation were lower than what was observed in the field. But our laboratory incubation did not include root biomass from cover crop residues. Shipley et al. (1992) estimated root biomass of rye and hairy vetch as 25 and 10% of total above ground biomass, respectively. Similarly, Kuo et al., (1997) measured root biomass of rye and hairy vetch cover crops as 32 and 8% of above ground biomass, respectively. In our study, roots could have contributed as much as 15 kg N ha⁻¹, based on those estimates. The contribution of N from root biomass may account for some of the discrepancy.
Figure 1. Sweet corn total nitrogen (N) uptake as a linear function of available feather meal N. Unique regression models plotted for each cover crop treatment because cover crop treatments were significantly different at $P = 0.05$.

EarlyCC, early cover crops; LateCC, late cover crops; NoCC, no cover crops

Figure 2. Nitrogen (N) use efficiency of sweet corn dry matter production per unit N supply, which includes soil N ($P < 0.01$)

EarlyCC, early cover crops; LateCC, late cover crops; NoCC, no cover crops
4. CONCLUSIONS

The results indicate that a 50:50 rye-hairy vetch blend may benefit a subsequent cash crop via increased plant available N, based on one year of data. In-season N status of sweet corn demonstrated that cover crops had provided N for crop uptake at the time of maximum N requirement for corn. A trend of increased ear yield and biomass was noticeable for sweet corn fertilized with early planted cover crops compared to no cover crop treatments when no feather meal was applied. But there were not significant differences in sweet corn ear yield and dry matter production between cover crop treatments, likely due to large variation in sweet corn yield and dry matter production between treatments. There was a large N contribution from the soil N pool, which made it difficult to separate sweet corn N and yield responses from cover crop residue additions relative to soil N.

Sweet corn N uptake was significantly different between cover crop and feather meal treatments. Nitrogen uptake fit a linear regression over feather meal N rates. Apparent N recovery and N uptake efficiency, estimated from the N uptake regression models, were used to calculate an indirect N fertilizer replacement value. We estimated the N fertilizer replacement value to be approximately 57 and 27 kg N ha⁻¹ for early and late planted cover crops. When expressed as a portion of the total N content of cover crops, these were 81 and 69%, much greater than the related N mineralization incubation study. The incubation study did not include N contribution from cover crop root biomass, which may account for some of the discrepancy. It is not possible to make broad conclusions about the validity of the N mineralization incubation study based on just one year of field data.
5. LITERATURE CITED


CHAPTER 5

General conclusions and recommendations

有机蔬菜种植者可能使用黑麦-毛三叶草混播覆盖作物来提高后续经济作物的可利用氮 (N)。我们的研究旨在解决种植者对覆盖作物如何影响作物轮作以及如何优化覆盖作物残余物中氮的可用性。我们设计了两个田间试验和一个实验室腐熟试验来评估种植日期、收获日期和播种比对覆盖作物生长、残余物质量和N可用性的影响。1. SUMMARY OF FINDINGS

如果在10月早些时候种植，黑麦-毛三叶草混播覆盖作物可能会积累足够的生物量和N来影响后续经济作物的N动态。我们发现种植日期和收获日期显著影响了覆盖作物的建立、生物量生产、总N含量和残余物质量。黑麦-毛三叶草混播的二播处理的播种比并不像我们所假设的那样对覆盖作物生物量产生显著影响。黑麦在凉爽的秋季条件下比毛三叶草更快地建立，这使它成为该地区有利的冬季覆盖作物物种。尽管毛三叶草在建立初期较慢，但它在春季通过一个快速生长的时期，并且有更高的潜在能力向后续作物供应大量N。覆盖作物生物量和N含量在覆盖作物早播和晚收时得到优化。虽然晚收有利于更大的生物量生产，但我们测量到显著的C:N比率增加和中性洗涤纤维 (NDF)、酸洗涤纤维 (ADF)、酸洗涤木素 (ADL) 的增加。似乎N含量在晚收时的增加足以抵消更难降解的碳 (C) 对N释放动态的影响。

土壤N对覆盖作物残余物的反应证明了黑麦-
hairy vetch blends can increase N availability to subsequent cash crops compared to pure rye. Our data suggests that insufficient biomass and N is accumulated to impact N supply to subsequent cash crops when cover crops are planted late and harvested early.

Cover crop residue quality was well correlated to N release patterns for rye-hairy vetch residues. Nitrogen concentration and C:N ratio of the cover crop blends was well correlated with net N mineralization over the first 70 days. Neutral detergent fiber and ADF were negatively correlated with net N mineralization over the first 70 days and between days 21 and 50. The inclusion of these fractions in a model to predict N release from cover crop residues may improve the accuracy of the model.

A 50:50 rye-hairy vetch blend released a similar percentage of total residue N over 70 d compared to pure hairy vetch. This blend may supply larger amounts of plant available N to subsequent cash crops because of higher biomass production. A 75:25 rye-hairy vetch blend released a significantly lower percentage of total residue N than pure hairy vetch. But the total inorganic N release was similar between the two treatments because of higher N content of the 75:25 rye-hairy vetch treatment. Although hairy vetch and the 75:25 rye-hairy vetch blend released similar amounts of N over 70 d, the initial rate of N release was nearly 3-fold greater for the hairy vetch treatment. The slower rate of N release from the 75:25 rye-hairy vetch blend may result in N release that is better timed with crop N uptake and therefore increase crop N uptake efficiency. When cover crops were combined with feather meal, the combined net N release was less than the sum of the individual components. The cause of the negative interaction was not well understood and therefore deserves further research. Growers are not likely to apply feather meal at the time of cover crop incorporation. Further research should explore the effect of organic fertilizer application many weeks after cover crop incorporation.
A measure of in-season N status in sweet corn demonstrated that cover crops had provided N benefits to sweet corn by the time of silking. We observed a trend of increased ear yield and biomass for early planted cover crops compared to no cover crop treatments when no feather meal was applied. But these differences were not statistically different. There was a large contribution from the soil N pool (100 kg N ha$^{-1}$) in comparison to cover crops (20 to 35 kg N ha$^{-1}$), which made it difficult to separate the N contributions from cover crops and soil according to the sweet corn yield response. Sweet corn N uptake was significantly increased by early planted cover crops. Nitrogen uptake in sweet corn fit a linear regression over feather meal N rates. Apparent N recovery and N uptake efficiency, estimated from the N uptake regression models, were used to calculate an indirect N fertilizer replacement value. We estimated the N fertilizer replacement value to be approximately 64 and 28 kg N ha$^{-1}$ for early and late planted cover crops. When expressed as a portion of the total N content of cover crops, these were 91 and 72%, much greater than the related N mineralization incubation study. The incubation study did not include N contribution from cover crop root biomass, which may account for some of the discrepancy. It is not possible to make broad conclusions about the validity of the N mineralization incubation study based on just one year of field data.

2. RECOMMENDATIONS

Given the similarities between the two rye-hairy vetch biculture seeding ratios, we recommend using a 50:50 rye-hairy vetch seeding ratio to optimize biomass yield, N accumulation and N supply to subsequent cash crops. There was not significant enough an increase in hairy vetch biomass for the hairy vetch dominated rye-hairy vetch seeding ratio to offset the high cost of hairy vetch seed. Our data indicated that harvest date has a larger impact on cover crop biomass than planting date. If cover crops are planted by early October, we
recommend incorporation at the end of April to optimize biomass and N accumulation. At that
time, cover crops are still in a vegetative stage and residue quality will not significantly affect the
quantity of inorganic N mineralized.

Growers may estimate N release from cover crop stands by measuring biomass,
estimating total N content, and calculating the percent of total residue N that will become
available. Biomass can be accurately measured by harvesting the above ground biomass in
representative quadrats. Cover crop residues can be sent away for analysis of total C and N and
results may be used to calculate total N content. Our results indicate that residue C:N ratio can be
used to estimate the portion of total residue N that will become available over a single growing
season. A measurement of total C and N concentrations in plant residue is a routine analysis that
can be conducted between the time of incorporation of cover crops in spring and planting of a
subsequent cash crop. An estimation of N supply from cover crop stands would allow growers to
better manage fertilizer application needs and promote more efficient use of N.