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CELERY *(APIUM GRAVEOLENS* L.*)* AND WEED RESPONSE TO
COVER CROPS AND NUTRIENT MANAGEMENT ON MUCK SOIL

presented by

Kevin Charles

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of the requirements for the

Master degree in Horticulture

Major Professor's Signature

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CELERY *(APIUM GRAVEOLENS* L.*)* AND WEED RESPONSE TO COVER CROPS AND NUTRIENT MANAGEMENT ON MUCK SOIL

By

Kevin Charles

A THESIS

Submitted to
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ABSTRACT

CELERY *(APIUM GRAVEOLENS* L.*)* AND WEED RESPONSE TO COVER CROPS AND NUTRIENT MANAGEMENT ON MUCK SOIL

By

Kevin Charles

Michigan ranks second in the nation for celery production. Most of Michigan celery is produced under intensive systems with limited crop rotation. Many celery growers are increasingly interested in sustainable practices, such as the use of cover crops, to reduce external inputs, suppress weeds, enhance soil quality, and improve yield and quality. This study was undertaken to assess the potential to integrate cover crops into intensive celery production systems. Specific goals were to measure celery growth and yield under different cover crops, evaluate the effects of the cover crops on soil fertility, measure the weed suppressiveness of the cover crops, and determine if the cover crops can enable growers to reduce fertilizer inputs. Our results indicated that cover crops could fit into celery cropping systems, especially for early planted crop that is usually harvested between July and August. Oilseed radish and mustard species showed the greatest benefit, both at the research station and at a grower's farm compared with rye or hairy vetch. Celery growth and yield was enhanced by oilseed radish. Hairy vetch (a legume) failed to improve nitrogen concentration in the soil primarily because of low nodulation under muck soil. On the other hand, oilseed radish recycled large amount of potassium and nitrogen. All cover crops studied suppressed weed early in the season with oilseed radish providing the greatest effect. Combining oilseed radish with different fertilizer rates showed that growers can potentially reduce their fertilizer inputs by up to 50% without any yield reduction.

DEDICATION

HTP DE NASUT USIR, INPU

De snu prt khru, ta, henket, Kha tau, kha henktu, kha kau, Kha apedu, kha seshu, kha menkhtu, Kha kht, nbt, nfrt, wabt, Ankh NTR em N Ka n Imaky Tehuti, Imaky Queen Tiye, Imaky Queen Nefertari, Imaky Ahmose I, Imaky Queen Nefertiti, Imaky Akhenaten, Imaky Ramses II, Imaky Thutmose III, Imaky Senusret III, Imaky Amenemhet III, Imaky Aha, Imaky Imhotep, Imaky Tehuti, Imaky MerNeith, Imaky Hatshepsut, Imaky Queen Tetisheri, Imaky Taharqa, Imaky Piankhi, Imaky Charles Harris, Imaky Joshua Harris, Imaky Mable Wallace, Imaky Andrew Charles, Imaky Nelly Charles, Imaky Queen Sheba, Imaky Menilik I, Imaky Menilik II, Imaky Rt. Hon. Prince Emmanuel Charles Edwards the 7th, Imaky Marcus Garvey, Imaky HIM Haile Selassie I, Imaky HIM Menilik II, Imaky Malcolm X, Imaky John Henrik Clarke, Imaky Dr. Cheikh Anta-Diop, Imaky Eida Harris, Imaky Anselm Charles, Imaky Louise Dowling, Imaky Gustavo Dowling, Imaky Clarke Theus Charles, Imaky Kebra-Seyoun Charles

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PREFACE

This thesis is written as a manuscript in the style required for publication in Agriculture, Ecosystem and Environment; Journal of Plant Nutrition and Soil Science; and Weed Science.

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Chapter 1. Literature Review

Introduction

In 2004, the USDA reported 1.95 million acres of fresh vegetables were harvested at an estimated total market value of US$ 9.82 billion (USDA, 2005). In the state of Michigan, 65 thousand acres of fresh vegetables were harvested, adding US$ 18.8 million to the state's economy. Unfortunately, crop specialization, intensive use of farm land, and reliance on external inputs has resulted in environmental stress leading to a decline in agroecosystems productivity. Moreover historically, the mainstream approach of commercial agricultural practices has often caused specific ecological disturbances (Shi, 2004). Some of the documented effects of conventional cropping systems are field resistance (Ngouajio and McGiffen, 2002), poor soil fertility, and increased potential for water pollution (Hallberg, 1989). As a result, over the past several decades there has been activism against conventional farming usage of synthetic inputs and more urging to develop alternate management strategies (Kelly, 1990; Phatak, 1992).

Substantial efforts are currently directed to the restoration of soil health and improvement of agroecosystems efficiency. Globally, there is a collective advocacy on the part of science to develop and promote the use of agricultural sustainable methods (Shi, 2004). Considering the known benefits, rehabilitating soil organic matter (SOM) has become the key to soil fertility and productivity (Allison, 1973). In view of this fact, adoption of sustainability as a means to use renewable inputs (Sainju and Singh, 1997) and researching the optimum amounts of fertilizer for vegetable production has gained favor (Hochmuth, 2003). In this study, we focus on several cover crops to help improve growth and development of celery in Michigan. In addition, the study evaluated the overall cover crop performance in achieving specific management goals i.e., weed control and enhancement of soil mineral composition.

Sustainability

Opinions vary considerably in the definition of sustainable agriculture (Phatak, 2003). Today, management strategies that uses less external inputs (Liebman and Davis, 2000) and relies on a comprehensive cropping systems' approach (USDA, 1980) has gained broad acceptance. Consequently, reliance on conventional cultural practices is declining considerably with scientific advances. This inverse correlation results from present attempts to remedy the consequences of production, albeit harmful, farming practices levied upon agroecosystem. The intensity in which the natural environment has been modified to attain past productive capacity has directly resulted in degradation of the natural resources, notably land and water that sustain these very systems (Oberle, 1994). Today, new advances are being developed as the search for alternative solutions continues to shift toward reuse of the environment and on-farm resources (Sanchez et al., 2001). Greater adoption of low-external-input (LEI) management systems has been proposed ways that can ameliorate environmental problems associated with conventional farming systems (Liebman and Davis, 2000). Current research activities include viable resource management of on farm recyclable sources to facilitate a LEI farming system. Although LEI systems occupy only a small portion of the agricultural landscape in most regions, they are becoming increasingly prominent as regulatory, and biological pressures on conventional farming systems intensify (Liebman and Davis, 2000). The overall awareness caused by the development of LEI systems has revived sustainability efforts.

No longer is "sustainability" a catch term, its meaning is being applied in scientific research as solutions are developed to answer the effects of past farming practices. The term has also become a synonym for sound and acceptable economic, social, and ecological development of society (Francis, 2004; Lewandowski et al., 1999). Today, cropping systems that efficiently recycles on field resource by managing crop residues has become a key component in sustainability efforts (Ruffo and Bollero, 2003). Soil organic matter (SOM) is considered a major component in agriculture systems (Sikora et al., 1996), because SOM influences many of the physical, chemical and biological properties in soil. Some of the properties are soil structure, infiltration water holding capacity, nutrient dynamics, and biological activity. Due to this importance, SOM becomes a precious on farm commodity therefore, sustaining its health and productive quality is crucial. Thus, soil-conserving efforts using sustainability principles and practices can preserve agroecosystems conditions for long-term farm productivity. Sustainability can be accomplished by a variety of approaches using cropping sequences and cash crop diversification practices. Crop rotation requires rotating crops over successive growing seasons (Locke et al., 2002). Studies have shown marked improvement in cropping systems using well-timed crop rotation designs. For instance, Odihiambo and Bomke (2001), demonstrated cover crop planted in late August provides an N source during early spring growth. This fact results from the accumulation of soil available N, which would be leached or washed with erosion during the fallow period. Because of recycling, this N accumulation is essentially used as a nutrient source for plant growth in the following year. By retaining N, farmers can potentially limit the amount of inorganic fertilizer used the subsequent year and prevent the environmental consequences of nitrate leaching. Equally important, crop rotation schemes using cover crop must be viewed as a viable environmental and economical option to farmers (Stute Posner, 1995). Therefore, soil-improving methods using crop rotations can play a role and provide benefits to cropping systems. For instance, crop rotation using alternative crops such as cover crops during the off-season improves soil quality and preserves agroecosystems productivity. In a study conducted to determine soil productivity, Wortmann et al. (2000), reported significant performance by maize and bean crops due to N fixation and green manure biomass production. Moreover, cover crops when planted after harvest produce biomass prior to winter (Teasdale, 1996) and can offer value added to subsequent crop yields. This biomass establishment and function is vital to cropping system sustainability focus of improving soil quality, soil health and sustaining agroecosystems' productivity. To conclude, agroecosystems' management strategies recycling N within its boundaries can potentially reduce inorganic N inputs and is a viable approach to achieving sustainability (Sanchez et al., 2001).

Cover Crop and Soil Fertility

In the last century, the application of N fertilizer to grow crops received tremendous growth. This in part was due to dramatic declines in the cost of nitrogen resulting from great improvements in technology for manufacturing (Aldrich, 1980). Because of the apparent exhaustible supply and relative low cost of nitrogen fertilizer, farmers used less nitrogen capturing crops (Aldrich, 1980). Today, nitrate contamination of surface and groundwater is a major environmental concern (Peng and Tabatabai, 2000), because excess soil NO_3^- N can accumulate from residual fertilizer N during winter fallow period (Jackson et al., 1993). Presently, one of the major sources of contamination is the liberal application of inorganic fertilizers used in intensive crop production systems (Roth and Fox, 1990). Therefore, reducing nitrate leaching can prevent ground water NO_3^- N accumulation (Strebel et al., 1989) and lessen environmental impact. The contamination problems that result from N mineralization can lead to detrimental consequences. Hence, the need for alternative field management practices, i.e., cover cropping has accelerated. Management practices which minimize NO_3^- N concentrations include: modifying cropping systems by integrating cover crops and growing a winter cover crop to assimilate NO_3^- N into organic plant N (Stevenson, 1999). If synchronized with crop demand, using cover crops and supplemental inorganic N applications can reduce the liberal use of fertilizers and lessen the associated environmental consequences (Nyiraneza, 2003).

Cover crops are vegetation that is grown in the off-season for soil benefits and have been long considered a vital practice in sustainable cropping systems. Cover crops have been used for hundreds of years (Bloodworth and Johnson, 1995). Early on Xenophon (434-355 B.C.) the Greek historian, may have noticed herbage benefits having suggested turning up the grass may serve as manure (Thomas and Frye, 1984). Today, the use of cover crops is widely recognized and has been reported for known benefits. For instance, benefits of cover crops include increased soil fertility (Griffen et al., 2000; Ranells and Wagger, 1996), weed suppression, (Kenerley and Bruck, 1983; Pinkerton et al., 2000; Utkhede and Hogue, 1999) and improved management of soil borne diseases (Czarnota et al., 2001; Herrero et al., 2001; Liebman and Davis, 2000; Ohno et al., 2000, Ohno and Doolan, 2001). Because of the countless contributions, cover crops can play a pivotal role in achieving environment sustainability by the reuse of natural resources. Sustainable practices that include both a soil and crop management focus can have a profound influence on agroecosystem efficacy. Mention must be made to the soil improving ability of cover crops. Cover crops have been used for many years because of benefits to soil fertility and structure (Teasdale et al., 1993). Utilization of cover crop is dependant upon determined goals as a way to develop strategies in achieving agricultural aims. Generally, the production objectives are to maintain quality yields in view of environmental factors, i.e. resource regimes.

To achieve agricultural aims, cover crops can play a crucial role in N management schemes (Kowalenko, 1987). Previous studies conducted with the integration of cover crops into vegetable production systems rendered favorable results (Teasdale, 1996). For instance, legume cover crops have demonstrated an N contribution to the growth of principal crops by fixing atmospheric N. Symbiotic biological fixation from the intimately formed relationship between soil microbes and legumes can provide meaningful amounts of N (Dabney et al., 2001). Consequently, cover crops can potentially increase production yields. Abdul-Baki et al. (1996), found significantly higher tomato yields and enhanced early fruiting in plant mulch. In addition, Ngouajio and Mennan (2004) reported high yields in rye and sorghum sudangrass system and concluded cucumber yields may be potentially improved using cover crops. Clearly, using legume cover crops in crop management systems offers the opportunity to enhance yields (Boquet et al., 2004). On the other hand, non-legume cover crops have been associated with reducing N leaching by removing residual available N (Isse et al., 1999) and have been advocated to reduce nutrient loss (Njunie et al., 2004). The ability of cover crops to improve soils by trapping soil residual N left from by previous crops is well documented (Singogo et al., 1996). Logsdon et al. (2002) found significant NO_3^- N reduction in oat and rye cover crops during their field studies. Furthermore, Shipley et al. (1992) study concluded that cover crops reduced the risk of leaching because of uptake of soil NO_3^-N. These cover crop functions of N provisions and reducing nitrate leaching from agricultural soils can replace some intensively applied inorganic N (Burket et al., 1997). Therefore, cover crops can be useful in cycling nutrients as a crop management strategy to preserve nutrient loss and offer N credits as well. It is abundantly clear that establishing cover crops in crop rotations to manage nutrients can enhance both agroecosystems productivity and sustainability.

Cover Crop and Weeds

Due to today's market economy, more and more growers are specializing on one or two major crops, thereby reducing their rotations systems to a strict minimum. The monoculture specialization has contributed to the resurrection of field problems i.e., resistant weeds, and pathogen populations, which have become difficult to control. The continuous cropping method makes weed management challenging (Derksen et al., 2002) and causes considerable financial losses (Swanton et al., 1993). In addition, weed response to other agronomic practices has resulted in community composition shifts (Derksen et al., 2002). Consequently, conventional control measure tendencies were to rely on agrochemicals to ameliorate the problem. As a result, the use of synthetic pesticides has lead to the reduction in biodiversity, creating a less productive agroecosystem (Ngouajio and McGiffen, 2002) and threatens farm profitability (Liebman and Davis, 2000). The environmental risks associated with agrochemical exposure, include shifts in weed dynamics and other pests towards pesticide-resistant species (Benbrook, 1996). Therefore, much attention has been given to strategies that improve weed management and are among the top research priorities (Liebman and Davis, 2000). One approach is to introduce crop rotation systems to disrupt and prevent the regeneration of weed species (Liebman and Davis, 2000). Furthermore, there is significant empirical evidence that two or more crops within a rotation can reduce weeds (Teasdale et al., 2004). Moreover, crop rotations offer different vegetative growth habits and thereby alter weed life cycles (Liebman and Cyck, 1993). Many studies have reported cover crops' influence in weed suppression when incorporated into a crop rotation system (Johnson et al., 1993; Teasdale et al., 1991; Yenish et al., 1996). Crop patterns including non-host crops are effective ways of managing weeds, and diseases while improving soil health. Therefore, cover crops have shown good potential, remedying some of the problems created by short-term or lack of crop rotations (Kenerley and Bruck, 1983; Pinkerton et al., 2000; Utkhede and Hogue, 1999). Weed suppression is another benefit attributed to cover crops. Several studies have reported the positive effect of cover crops on weed suppression. Generally, the relative location of cover crop residue to soil surfaces alters growth conditions of weeds (Teasdale and Mohler, 1993). The principle goal of using cover crops for weed control is replacing an unmanageable weed population with a manageable cover crop (Teasdale, 1996). The presence of winter vegetation provides a protective cover during winter while preventing weed emergence at a critical time. The objective of using a winter annual cover crop for weed management is the production of sufficient residue to create an unfavorable environment for weed germination and establishment (Teasdale, 1996). The correlation between reduced weed density and cover crop biomass is a function of residue levels. This is indirectly due to the substantial biomass production by cover crops changes environmental conditions. Both provide significant soil cover and alter weed seed germination because of the proximity to weed seed bank site. Cover crop residue influences weed populations in no-tillage cropping systems because of the proximity of residue to the site of seed germination at the surface of soils (Teasdale and Mohler, 1993) and modify the growing conditions under which weeds germinate or emerge (Fisk et al., 2002). The presence of ground covers provided by cover crops becomes a physical barrier impeding weed growth because of plant architecture and morphology (Ponce et al., 1996). Seavers and Wright (1999) reported a strong suppressive ability of cover crops on weeds in their study. Weed infestation can be reduced over time by cover crops (Ngouajio et al., 2003). For these reasons, crop rotation is recognized as an important tool for weed management because some crops in the rotations suppress weeds by competing for resources (Liebman and Dyck, 1993). This has the double advantage of reducing herbicide inputs and monoculture practices that have otherwise created insurmountable challenges.

The benefits of crop rotations are well understood by most growers. For instance, fall-seeded winter cover crops are the most commonly used practice by celery growers in Michigan. The winter hardy cover crops, which survive the frost, are incorporated into soil prior to the spring growing season. The cover crop is usually killed late in the spring by cultivation or by herbicide application, followed by crop planting (Mutch and Martin, 1998). The idea that with timely management, the spring cultivated cover crop will supply nitrogen and suppress weed growth.

Oilseed Radish, Cereal Rye and Hairy Vetch

Understanding cover crop influences on cropping systems is important. As Michigan farmers seek sustainable agroecosystems innovations, integrating cover crops and crop rotation practices are gaining wide acceptance in the state of Michigan. Primarily, cover crops are used during the fall period to reduce soil erosion (Ranells and Wagger, 1996) and prevent nutrient leaching when the bare ground is vulnerable (Shipely et al., 1992). Because of the amount of time vegetation is present during the winter period, cover crop offer the opportunity to reduce nitrate leaching (Stock et al., 2004). The fallow period of most cropping systems is short (Jackson et al., 1993) therefore limiting nitrate leaching can be achieved with efficient and quickly established cover crops (Meisinger et al., 1991). Notwithstanding, improving cropping systems using cover crops has been a general convention in Michigan (Ngouajio and Mutch, 2004). Specifically, Michigan celery growers are becoming increasingly interested in adopting cover crops into their intensive production designs. Farmer adoption facilitates the need to ensure competitive production yields and maintain a sustainable agroecosystem. To achieve these goals, Michigan celery growers are integrating cover crops into existing field operations to maximize cover crop benefits. Thus, cover crops have become a viable option for sustainable agriculture purposes because farmers realize the contributions to soil fertility, improved crop performance (Smith et al., 1987) and weed suppression (Teasdale and Daughtry, 1993) cover crops provide. The use of cover crops to absorb soil nutrients is also an important component in production yield objectives. Nutrients that would otherwise be loss to the agriculture systems are recycled on site with cover crop. Sainju et al. (1998) reported rye demonstrated recycling efficiency of soil NO_3^-N.. Non-legume cover crops have been associated with reducing N leaching loss (Isse et al., 1999). Two winter hardy cover crops, hairy vetch *(Vicia villosa* Roth*)*, rye grass *(Secale cereale* L.*)* are well adapted to relatively cool environment; along with oilseed radish *(Raphanus sativus* [L.] var *oleiferus*Metzg [Stokes]). They are annual cover crops used in field management practices during the frost fallow season. Due to N fixation, hairy vetch a legume can have an important role in increasing N concentration at spring planting (Odhiambo and Bomke, 2001). On the other hand, cereal rye grass produces fall biomass while sequestering a moderate amount of soil available N (Meisinger et al., 1991). As a biculture, both hairy vetch and rye grass can be used simultaneously in cropping systems for nutrient benefits (Wagger et al., 1998). In consecutives years, Ranells and Wagger (1996), reported significant amounts of N content in hairy vetch and rye grass biculture of 82 and 200 kg ha^{-1}. Also, Jackson et al. (1993) reported reduced soil moisture, indicator of decline in NO_3^- N leaching tendencies. Similarly, oilseed radish was found to sequester residual soil NO_3^- N following wheat harvests (Vyn et al., 2000).

Several researchers found that hairy vetch residue suppressed some weed species (Hoffman et al., 1993; Teasdale, 1993) due to biomass production. Similarly, rye cover crop suppressed certain broad-leaved and grass weeds (Shilling et al., 1986). Ngouajio and Mutch (2004), found that oilseed radish planted in the fall can provide weed suppression.

Monitoring Soil NO_3^- N Pool

Nitrogen is considered the most limiting nutrient in agriculture productivity (Woodmansee et al., 1978). Agricultural crops take up N in two forms, primarily from soil organic matter, inorganic N from fertilizer, manure, and N fixation by legumes (Nyiraneza, 2003). Soil NO_3^-N leaching threatens groundwater quality and is a major issue to agroecosystems function and structure (Strebel et al., 1989). Therefore, a nutrient management strategy monitoring N transformation can provide soil NO_3^-N. One method of monitoring trace metals is by using ion exchange resin (IER). IER are resin within a membrane with a strongly basic anion exchanger or counter ions. IER can be used in ionic form for sorption and exchange of low molecular weight anions i.e., sample ions. Using IER can be a useful tool in measuring the concentration of NO_3^-N found in soil and can be used to quantify N mineralization rates. Dodd et al. (2000) reported a correlation between increased soil water and NO_3^-N leaching using resin bags when assessing N mineralization. In these studies, results suggest the presence of nitrate on IER reflects its ability to absorb ions in the soil. IER can be effective in attracting nutrients transported by mass flow that potentially leaches through the soil (Chen et al., 2003). There are ecological consequences, due to nitrogen enrichment practices of the last century. Thus IER can provide management systems with a tool to monitor soil nitrate dynamics and better manage the rates of inorganic fertilizers.

Total Soluble Solids

Fruit quality is determined by a few sensory attributes i.e., color, size, shape, flavor, and firmness. Visually, the term 'quality' suggests a degree of excellence (Abbott, 1999), but when measured do not account for the hidden and equally important nutritional value (Shewfelt, 1999). Plant sap contains self-nourishing nutrients, which determines overall plant health. These soluble elements found in plants are mobile nutrients used by plants as a source of nutrition. To assess the nutritional qualities, instrumentation is often required (Abbott, 1999) and is currently being used to evaluate internal fruit quality (Valero et al., 2004). Measuring plant tissue can provide valuable information for crop management. For instance, a good sap or Brix level of 12 or higher offers greater disease resistance, higher yields, longer shelf lives, and improved taste (Narendranath and Power, 2005). A low Brix value indicates sub-standard fruit quality. Measuring plant tissue can provide information of how to modify cropping management techniques to ensure greater disease resistance, higher yields and better quality crops.

Michigan celery production

There are approximately 1,550 vegetable farms on 65,964 ha of farmland in Michigan (MDA, 2003). Michigan vegetable growers produced 882,410 tons of fresh and processed vegetables in 2003 (MDA, 2004). Dual purpose vegetable acreages are used for both fresh market and processing. The value of production totaled $227 million. Nationally, Michigan ranked second after California in fresh celery *(Apium graveolens* L.*)* production (6.2 % of total national production). In 2004, *c.* 890 ha of celery was harvested at a value of $18.8 million. Celery comes from a biennial, herbaceous plant of the *Apiaceae* (formerly *Umbelliferae*) family, and is believed to have originated from the Mediterranean basin. The first production of celery in the United States is thought to have occurred mainly in Florida. Today, Celery is being grown in California, Michigan, Florida, Texas, Ohio, New York, and Pennsylvania. Its seed was brought to Kalamazoo, Michigan, in the 1850s from Scotland, and it became a commercial crop there. Currently, the majority of celery production in Michigan is concentrated on the southwest side of the state along Lake Michigan in Newaygo, Oceana, Muskegon, Ottawa, Kent, Allegan, and Van Buren counties. Celery transplants are produced in controlled environments for 12 weeks at 18 to 21 °C. In Michigan, celery is mainly grown on muck soil. Organic muck soils are ideal for celery production due to its water holding capacity. Once transplanted, most common celery varieties require 12 weeks to mature and grow best at a daily optimum temperature of *c.* 18° C. Most Michigan celery growers plant from 80 - 104,000 plants per hectares. Michigan farmers face major problems that threaten field production and can potentially limit annual yields. The continued use of synthetic inputs coupled with limited crop rotations, have reduced sustainability of celery production. In addition, weeds interfere with field operations, competing for useful resources i.e., space, nutrients, moisture, light and space required in celery production (Hausbeck, 2002). Each year, diseases can cause significant losses to crop production (Summer et al., 1986). Fusarium yellows of celery is a detrimental disease that can severely destroy the crop. Bacterial blights are diseases affecting celery in Michigan causing annual leaf and petiole destruction. Early blight is common and destructive (Kucharek and Berger, 2000). Also, leafhoppers (*Macrosteles quadrilineatus*) and nematodes are both pests that negatively affect celery growth and quality in Michigan. Realizing this fact, Michigan celery growers are increasingly seeking sustainable practices that will offer solutions to aforementioned problems and still maintain competitive productivity. The use of cover crops is among the options currently being evaluated for celery production by Michigan farmers.

Objectives

The overall objective of this study is to provide celery production alternatives to Michigan growers interested in sustainable farming practices. Establishing cover crops after harvest of early transplanted celery can provide benefits to the production system. Therefore, winter cover crops will be selected to suitably fit the crucial time interval before and after periods of main crop production. The fall fallow season is critical to the program's sustainability efforts and will receive paramount emphasis. Results will be shared with growers to develop sustainable systems and enhance their existing field operations.

To achieve this objective; we will (i) evaluate the potential to integrate cover crops into celery production system; (ii) measure the effect of cover crops at providing non-chemical weed suppression, and their impacts on weed species composition of weed populations; (iii) determine if cover crops can reduce the use of fertilizer inputs in celery production;(iv) study the effects of cover crop and fertilizer rates on celery quality, growth, and yield; (v) measure the ability of cover crops to reduce nitrate leaching in celery production systems.

Rationales are:

1. Early transplanted celery is harvested in Mid July. This allows a significant window at which to introduce cover crops into field operations prior to the frost and winter season. Assuming celery is grown the next year.

2. Evaluating weed population response to cover crops will provide relative information to field composition trends of resource competitors during growing season.
3. Reducing the use of external inputs while maintaining competitive celery yield production will provide a model system for sustainable farming practices.
4. Determine if the interaction between both factors improves the overall celery production system.
5. Assessing tissue and IER resin extractions will provide information about nutrient (NO_3^-N) mobility in the presence of cover crops.

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Chapter 2: Celery *(Apium graveolens* L.) growth responses to various cover crops and soil fertility levels.

ABTRACT

Our objective was to determine the combined effects of different annual cover crops and fertilizer rates on celery *(Apium graveolens* L.) growth, quality, and yield. Field experiments were conducted from 2002 to 2004 on Houghton muck soil in Laingsburg and Hamilton, MI. Oilseed radish consistently produced higher biomass at both sites during the first year at 719 (Laingsburg) and 585 g m^{-2} (Hamilton) compared to all other treatments. Celery dry matter (DM) accumulation, crop growth rate (CGR), relative growth rate (RGR), and marketable yields were usually low in the bare ground system. The use of cover crops improved celery growth and yield under the low and half rate of fertilizer. Oilseed radish showed the highest benefits. Celery growth and yield was highly affected by heat accumulation (growing degree days), which may also have effected decomposition of cover crops. Faster growth and high yield were observed under warm conditions. These results suggest that growers can use cover crops as a part of crop rotation system to improve celery growth and yield.

INTRODUCTION

Vegetable production is an important part of the agricultural industries in most of the United States (Hochmuth, 2003). In 2004, *c.* 0.79 million hectares of fresh market vegetables were harvested with an estimated value of $9.82 billion (USDA 2005). Celery is one of the major vegetables produced for fresh market or processing. In 2004 *c.* 11,048 hectares were harvested with a corresponding value of $283.9 million. Nationally, Michigan ranks second after California in celery [*Apium graveolens* L. var. *rapaceum* (Mill.) Gaud.-Beaup] production (6.6 % of total national production in 2004) with *c.* 890 hectares of celery harvested, and a value of $18.8 million to Michigan's economy (USDA 2005).

The development of specialized farming operations has resulted in dependence on synthetic fertilizer for vegetable production (Singogo et al., 1996). Until recently, the use of high-input synthetic systems was a widely used method to maximize yield and product quality (Abdul-Baki et al., 1996). Recently, many farmers and scientists have recognized a need to develop alternative production systems that can preserve productivity and maintain profitability (Wells et al., 2000). Consequently, there has been a resurging emphasis on sustainability (Petersen et al., 2005).

The renewed interest in sustainability includes the use of cover crops in vegetable production as a viable option to rebuild soil organic matter content (Shennan, 1992). Soil organic matter is important to maintaining soil fertility levels (Allison, 1973). The agricultural practice of cover cropping has been used in this context to improve soil organic matter accumulation (Wagger et al., 1998) that in turn, can maintain and increase soil nitrogen (N) content. Ditsch and Alley, (1991) demonstrated in their study that N can be conserved in agriculture systems by cover cropping. Additionally, Kuo et al. (1997a) observed large amounts of available N in the systems using leguminous cover crops. During spring, N from the decomposing plant material is released over a longer time span than most inorganic N sources (Burket et al., 1997) and can reduce the amount of inorganic fertilizer used in intensive vegetable cropping systems. Short and long term release of available nitrogen varies with cover crop species and may affect crop growth at different stages (Kuo et al. 1997a). Studies documenting the additional N provided by cover crops resulted in differential vegetable crop yields (Stivers and Shennan, 1991; Stirzaker and White, 1995). Kuo et al. (1996, 1997a, 1997b) Showed that the type of cover crop (leguminous versus non-leguminous species) and total biomass were the major divers for changes in soil N levels (and availability), soil organic matter levels, and crop yield. Loecke et al. (2004) showed that soil organic amendment affect crop growth and yield. In their study corn treated with composted swine manure produced 10% more grain and 12 to 15% more dry matter than corn treated with fresh manure. The differences in the two systems were detected with growth analysis during the season, with for example greater values of crop growth rate (CGR) found in the composted manure system (Loecke et al. 2004). Thus, soil organic amendments including the use of cover crops can potentially enhance sustainable growth and development of vegetable crops.

Celery requires about 12 weeks to reach maturity under Michigan growing conditions. Harvest of early-planted celery is usually completed by late July. Therefore, allowing for the establishment of cover crops between July and October prior to first frost. Yield increases have been documented in systems using cover crops. Growth analysis is a useful tool for illustrating the relationship between plant growth and environmental flux (Hunt, 1982). Growth analysis could provide a better understanding of changes during the growing season that are responsible for the differential yields (Hunt 1982). To our knowledge, no study has focused on the effect of cover crops and fertilizer regimes on vegetable growth and development on muck soils in general, and on celery in particular. Because of the high organic matter content of muck soil and the high soil fertility requirements of celery, integration of cover crops and fertilization regimes may have significant effects on celery growth, development, and yield. Investigation of such analysis would lead to a better understanding of how cover crop and fertilization improve celery production in Michigan. For this reason, the main objectives of this study were (1) to compare and evaluate winter annual cover crops in an intensive celery production system; (2) study the effects of cover crops and different fertilizer rates on celery growth, yield, and stalk quality.

2. MATERIALS AND METHODS

2.1. Experimental site

Studies were conducted from 2002 to 2004 at the Michigan State University Muck Soils Research Farm in Laingsburg, MI and at a commercial celery farm in Hamilton, MI. The soil at both sites was a Houghton muck with 80 % organic matter and pH of 6.2-6.9. Heat accumulation (degree days) was very different between growing seasons (Fig. 1)

2.2. Laingsburg Experiment

The site was fallow in the year preceding the start of the study. The experimental design was a randomized complete block design with four replications. The treatments consisted of a combination of different cover crops and fertilizer rates. Cover crop treatments were oilseed radish (cv. diakon) (*Raphanus sativus* (L.) var. *oleiferus* Metzg (Stokes), cereal rye (cv. VNS) (*Secale cereale* L.), hairy vetch (cv. common) (*Vicia villosa* Roth), and a bare ground. The fertilizer rates were: full rate (180, 90, and 450 kg ha^{-1} N, P_2O_5, K_2O), half rate (90, 45, and 225 kg ha^{-1} N, P_2O_5, K_2O), and low rate (90 kg ha^{-1} N). The full rate was the recommended rate for commercial celery production. Cover crop treatments were applied to large plots (10.7 m long by 12.9 m wide). Using large plots for the cover crops allowed minimal residue movement among experimental units during land preparation. Each cover crop plot was further divided into smaller plots (10.7 m long by 4.1 m wide) to accommodate the different fertilizer rates. A total of 9 treatments (combination of cover crop and fertilizer rate) were used. This included: the bare ground control plus each of the 3 fertilizer rates, and the three cover crop species (cereal rye, hairy vetch, and oilseed radish) plus the Half and Low fertilizer rates. Combining cover crops and high fertilizer rate treatments was not practically economical and was therefore excluded from this study. Therefore, the experiment was not a factorial. All of the P, K and 25% of N was applied as top dressing; with equal amounts of remaining N applied in 3 side dressings at 23, 43, and 64 days after transplanting (DAT) in 2003 and 2004. Individual experimental units contained four rows of celery at 0.15 m in-row spacing and 0.79 m between row spacing, corresponding to 83,000 plants ha^{-1}.

The cover crops were established in late summer of the year preceding each growing season (26 August 2002 and 25 August 2003). The seed was broadcast and incorporated by discing. Seeding rates were 28 kg ha^{-1} for oilseed radish, 112 kg ha^{-1} for cereal rye, and 39 kg ha^{-1} for hairy vetch.

Top dressed fertilizers were broadcast on 20 May 2003 and 28 June 2004 and incorporated by discing. Celery was transplanted on 23 May 2003 and 28 June 2004. Subsequent N side dressings occurred on 13 June, 3 July, 25 July 2003 and 21 July, 10 August, and 31 August 2004. Cover crop total biomass was determined by harvesting plants in a 50- by 50-cm quadrat placed randomly in each plot. Because oilseed radish winter kills, its biomass was sampled prior to the October frost in 2002 and 2003. Cereal rye and hairy vetch over-wintered, and continued growth through spring, and were then killed with glyphosate [*N* – (phosphonomethyl)- glycine)] prior to celery transplanting. Hairy vetch and rye biomass samples were sampled on 8 May 2003 and 6 May 2004. Dry biomass of cover crop was determined after oven drying at 60 °C until constant weight.

2.3. Hamilton Experiment

The experiment was arranged in a complete block design with three replications. Plots were12.2 m by 18.3 m and consisted of 18 double row beds (total of 36 rows). The cover crop treatments and seeding rates were identical to the Laingsburg site described above, with the additional cover crops: yellow mustard (cv. tilney) (*Sinapis alba* L. *Syn Brassica hirta Moenah*) 22 kg ha^{-1} and oriental mustard (cv. forge) [*Brassica juncea* (L.) *Cosson*] 13 kg ha^{-1} seeding rates in the 2004 season. Planting dates of cover crops were 9 August 2002 and 30 August 2003. Celery was transplanted on raised double row beds system on the 13 May 2003 and 10 May 2004. In row spacing was 0.15 m, spacing between the two rows on the same bed was 0.31 m, and spacing between consecutive beds (center to center) was 1.01 m. Final plant density was 130,000 plants ha^{1}.

2.4. Data Collection

At Laingsburg, celery plants were sampled at 23, 43, and 64 DAT in both 2003 and 2004. At Hamilton, celery plants were sampled at 32, 44, and 64 DAT in 2003 and on 31, 52, and 72 DAT in 2004. During plant sampling, 5 whole celery plants were randomly collected from each plot. During all dates, fresh and dry weights and stalk lengths were measured. Celery dry weight was determined after oven drying at 60 °C until constant weight. At Laingsburg, one of the two middle rows of each plot was used for destructive sampling and the other for final crop yield estimation. During Laingsburg harvest, 20 plants were collected on 12 August 2003 and 20 September 2004. During Hamilton harvest, 10 plants were collected on 29 September 2003 and 20 plants on 6 August 2004. At harvest, plants were separated into marketable and non-marketable stalks, according to market standards. Generally, marketable plants are qualified as well developed, well-formed plants with stalk lengths of *c.* 0.36 m (USDA, 1959). Stalk weight was measured before and after trimming for each yield category. At both sites during harvest, a random sample of 5 petiole segments was collected from each plot for total soluble solids measurement. Total soluble solids content was measured using a digital refractometer (Palette PR-32, ATAGO CO., LTD.32-10 Honcho, Itabashi-ku, Tokyo). Growth analysis was performed using above and below ground plant materials.

2.5. Statistical Analysis

Analysis of variance (ANOVA) was conducted on all data using the PROC GLM of SAS (SAS institute, Inc., 1999). The least significance differences were defined at α = 0.05 level ($LSD_{0.05}$) for all data sets. Means of crop growth rate (CGR) and relative growth rate (RGR) of celery were calculated using the following equations (Ngouajio et al., 2001).

$$\text{Mean CGR} = (W_2 - W_1) / (\Delta T G_A) \quad [1]$$

$$\text{Mean RGR} = (\ln W_2 - \ln W_1) / \Delta T \quad [2]$$

G_A is ground area, W_1 is dry weight at a given sampling date, W_2 is dry weight at the next consecutive sampling date, ΔT is the number of days between the two consecutive samplings, and ln is the natural logarithm. Celery data on dry matter (DM) per plant, CGR, RGR, and stalk length were fitted to nonlinear regression model using Sigmaplot (2005).

The observed DM per plant, CGR, and stalk length data were fitted to the following 3-parameter logistic equation.

$$y = \frac{a}{1 + \left(\frac{x}{x_0}\right)^b}$$

where y represents biomass accumulation (or CGR, or stalk length), x_0 is the degree day (base 10 °C) at maximal value, x is degree day at each sampling date, a is the maximal value of y, and b describes any deviation from logistic growth.

The RGR data were fitted to the following polynomial quadratic equation.

$$y = y_0 + ax + bx^2 \quad [3]$$

All growth analysis regressions were conducted using growing degree days instead of days after celery transplanting (Russelle et al. 1984).

3. RESULTS

3.1. Cover crop biomass production

There were significant differences in cover crop biomass (total) production during each year at both sites (Table 2.1). In Laingsburg, oilseed radish consistently produced the greatest biomass in both years with 719 and 480 g m^{-2} for 2003 and 2004, respectively. Biomass of cereal rye was 284 g m^{-2} in 2003 and 270 g m^{-2} in 2004. Hairy vetch produced the lowest biomass with 181 g m^{-2} in 2003 and 114 g m^{-2} in 2004. In Hamilton, the highest DM biomass yield was significantly greater in oilseed radish in 2003 and in cereal rye treatment in 2004. Cereal rye stand was excellent in 2004, resulting in the greatest biomass (1599 g m^{-2}). Biomass in the oilseed radish, yellow mustard and oriental mustard was similar and ranged from 691 to 822 g m^{-2}.

Generally, cereal rye biomass was lower than expected in Laingsburg and Hamilton in 2003 due to poor germination in the fall and destruction by herbivores during winter. Observations suggest difficulties for rye establishment under high organic matter soil conditions. Irrigation after sowing may help improve seed germination and seedling establishment.

3.2. Celery biomass production

At Laingsburg, the DM accumulation of all treatments was consistently smaller in 2003 than in 2004 (Table 2.2, Fig. 2.2). The high biomass production in 2004 was probably due to the late transplanting of celery when warmer air temperatures were conducive for rapid growth (Fig. 2.1).

In 2003, all treatments containing oilseed radish enhanced early celery growth. At 23 DAT, biomass (1.0 g plant $^{-1}$) in the oilseed radish-half fertilizer rate was similar to that in the control-full rate (0.8 g plant $^{-1}$). All treatments with cover crops improved celery growth compare to the bare-ground system (Fig. 2.2).

In 2004, no treatment effect was observed (Table 2.2). This may be attributed to two factors: (1) The long delays between land preparation (cover crop kill) and celery transplanting, and (2) nutrient loss resulting from unusually high rainfall. In 2004, the experimental site in Laingsburg received 233.7 mm of rainfall during May in comparison to 97.5 mm in 2003. This delayed celery transplanting at the Laingsburg site to June 28 in 2004 while transplanting was conducted on May 10, 2004 in Hamilton.

At Hamilton, hairy vetch, oilseed radish, and cereal rye did not improve celery growth over the bare soil system (control) in 2003 (Table 2.2, Fig. 2.3). However, in 2004 celery growth in plots previously occupied by cereal rye showed significant growth reduction, especially in early stages. At 31 DAT, celery biomass was only 1.7 g plant $^{-1}$ in the cereal rye plot and varied from 2.7 to 4.3 g plant $^{-1}$ in other treatments. This corresponds to the season when cereal rye produced the greatest biomass, suggesting potential nutrient immobilization or allelopathic interference.

Non-linear regression analysis between celery biomass and growing degree days (GDD) showed excellent fit for all locations and years (Table 2.3, Fig. 2.2 and 2.3). Regression coefficients of determination (r^2) were 0.99 for all treatments (Table 2.3). The maximum value of celery biomass (a) was extremely high, especially for the Laingsburg site, indicating that sampling ceased while celery was still at the exponential growth stage. Allowing more time for growth and additional samplings would have resulted in quality and yield loss.

3.2. Crop Growth Rate (CGR) and Relative Growth Rate (RGR)

Crop growth rate (CGR) over the entire sampling period is presented in Table 2.4 and Fig. 2.4 for Laingsburg. In 2003 and 2004, mean CGR consistently increased during each growth period. In 2004, the mean CGR were higher than 2003 at each sampling date. In all years, there were no statistical differences in plant dry weight gain among the treatments during the final time period. In 2003, the mean CGR varied considerably throughout the growing season but were significant only for the first evaluation conducted at 23 DAT. The weight gain was the highest in the oilseed radish treatment that received half fertilizer rate (0.2 g m^{-2} d^{-1}) and was statistically greater than the control treatment with either low or half fertilizer rate. Throughout the season, celery growth in control plots with low fertilizer rate had the slowest CGR (Fig. 2.4). In 2004, similar mean CGR trends persisted early on, but weight gain at all growth stages was not statistically different. As previously mentioned, CGR were higher at each growth stage in 2004 than 2003.At the final sampling date, celery previously grown in the cereal rye plus half fertilizer plots offered the highest plant weight gain in both years (Fig. 2.4).

In 2003, at Hamilton, there were no significant differences in celery weight gain throughout the season (Table 2.4). However, the CGR was generally greater with hairy vetch treatments at early growth stages. In 2004, the weight gain during the first and second CGR, were less than those observed in 2003 because of the warmer temperatures following celery transplanting in 2003 (Fig. 2.1). Unlike 2003, the weight gain in 2004 increased consistently with time in all treatments. This was likely due to low temperature at later growth stages of celery growth in 2003 (Fig. 2.1).

In 2003, at Laingsburg, mean RGR of plants consistently increased during the second sampling interval (21 July – 10 August), but generally decreased in the final sampling interval (31 August – 20 September) (Table 2.6; Fig. 2.5). Moreover, in 2003, there were generally no RGR differences among the cover crop and fertilizer treatments at the final sampling interval (31 August – 20 September). In 2004, the mean RGR of plants in all treatments were higher than those in 2003during the first sampling (0-21 July) interval. At either low or half rate of fertilizer, RGR for plants from the oilseed radish cover crop were significantly greater than values for plant from the bare ground with similar fertilizer rate for evaluation conducted at 23 DAT. RGR values of all treatments were comparable during the remainder of the season. In 2004, RGR trends were similar to 2003.

In Hamilton during 2003, there were no significant differences in mean RGR of plants among treatments during all sampling intervals (Table 2.6 and Fig. 2.6). The mean RGR declined as time progressed. The mean RGR values of celery in 2004 were generally greater than those in 2003 after the first sampling. In 2004, the initial dry weight increase was higher in the oilseed radish treatment during the first (10 June) sampling interval. Cereal rye treatment provided significantly higher plant dry weight increase in the second (1 July) sampling interval. There were no statistical differences in mean RGR among all treatments during the third (21 July) sampling intervals. Smooth curves were fitted Fig. 2.5 and 2.6 with celery relative growth rate and growing degree relationship for Laingsburg and Hamilton.

3.3. Celery Stalk Lengths

As expected, celery stalk length increased throughout the sampling period at both locations and years (Table 2.8, Fig. 2.8 and 2.9). In Laingsburg, celery stalks in 2004 were longer under all treatment and fertilizer rate combinations than in 2003. This was likely due to warmer temperatures in 2004. Stalk length among treatments was similar at 23 DAT. However, at 43 and 64 DAT, celery stalks were generally shorter under the system with low fertilizer rate. Under those systems, addition of oilseed radish or cereal rye improved stalk length in 2003, but did not have any positive effect in 2004. In all cases, combining cover crop with half rate of the fertilizer seemed to improve celery plant length. However, the differences were generally not significant when compared with the bare ground system containing the full or the half rate of fertilizer.

In Hamilton, celery stalk length was not affected by the cover crop treatments in 2003 (Table 2.8 and Fig. 2.9). In 2004 however, stalks were shortest in the cereal rye plots throughout the sampling period. At 31 DAT, celery stalk length was 14.7 cm in the cereal rye plot and 18.7 cm in the control plot. Early in the season, plants were taller in the oilseed radish treatments. During the final sampling date, celery stalk lengths grown in oriental and yellow mustard plots were the longest (70.3 cm each) and significantly greater than those grown under the cereal rye treatment (65.3 cm).

3.4. Celery yield

Generally, yield differences observed at both locations are attributed to original plant densities. In Laingsburg, celery yield was affected by the different treatments in both 2003 and 2004. (Table 2.10). This was observed for total and marketable yield, of the trimmed and untrimmed stalks, as well as for the number of marketable stalks.

In 2003, yields of the bare ground and hairy vetch treatments with low fertilizer rate had the lowest values in all categories. This observation indicates the importance of adequate soil fertility in celery production. For instance, total marketable plant weight before stalk trimming was 38.0 ton ha^{-1} (in the control plus low fertilizer treatment) and 37.4 ton ha^{-1} (in the hairy vetch plus low fertilizer treatment), compared to 45.4 to 70.5 ton ha^{-1} in other treatments. The combination of oilseed radish and half rate of fertilizer significantly increased yield. Moreover, yields in the oilseed radish plus half rate was greater or equal to yield of the control-full fertilizer rate. Similar results were observed with the number of marketable stalks. The highest numbers of marketable stalks were recorded in the oilseed radish (66,000 plants ha^{-1}) that received the half rate of fertilizer.

In 2004, low yields were observed in the bare ground plots receiving the low fertilizer rate. In those plots, yields were increased with increasing fertilizer rates. Also, all cover crop species improved celery yield under the low fertilizer rate program, with oilseed radish showing the greatest effects. In 2004 however, there was no benefit of the cover crops for half rate of fertilizer.

In Hamilton, celery yield was not affected by the cover crop treatments in 2003 (Table 2.11). The yields observed in 2004 were all greater than yield in 2003. In 2004, there was a greater variation in total yields among the treatments. Celery yield was reduced in the cereal rye as cover crop system. Total yield before stalk trimming was 169.0 ton ha^{-1} in the control and 159.4 ton ha^{-1} in the cereal rye plots. The yield penalty associated with cereal rye was observed in both trimmed and untrimmed marketable stalks. Higher yields were observed in the oilseed radish and yellow mustard treatments but weren't different from yields in the control plot.

3.5. Celery total soluble solids

There were no statistical differences in %-dissolved solids of celery sap grown under the various treatments (Table 2.12). In Laingsburg, the means ranged from 2.35 to 3.58 and from 3.21 to 3.57 in 2004. Similar observations were made for Hamilton experiment.

4. DISCUSSION

The aim of this work was to study the potential of cover crop inclusion into a celery production system. Additionally, we wanted to determine how the cover crops may help reduce fertilizer rates while maintaining acceptable celery growth and yield. Results indicate the cover crops tested can fit well into celery cropping systems especially for crops harvested early in the season (July – August). Under those conditions, the cover crops could produce significant biomass before being killed by frost (oilseed radish), or by herbicide or cultivation the following season (cereal rye, hairy vetch). While oilseed radish and hairy vetch biomass was stable across location and year, cereal rye biomass productions seemed to vary with growing conditions. In Hamilton for example, cereal rye biomass in 2004 was over 4 fold greater than in 2003. The main difference between the years was more rainfall directly following rye planting in 2003. Apparently, adequate soil moisture during germination and subsequent seedling establishment may be critical for cereal rye on Houghton muck soil.

Low fertilizer rate (90 kg ha^{-1} N) produced the lowest dry matter accumulation and final stalk yield, especially in the systems without cover crop. With half rate (90, 45, and 225 kg ha^{-1} N, P_2O_5, K_2O), and full (180, 90, and 450 kg ha^{-1} N, P_2O_5, K_2O) rates of fertilizer, celery growth and yield were enhanced. This result stresses the importance of not only N but also P and K in celery production. Unlike cereal rye and oilseed radish, hairy vetch cover crop did not increase celery yield under the low fertilizer rate systems. Not only was hairy vetch biomass production low but its roots showed very few nodules. Hairy vetch seed used in this study was not inoculated with rhizobium, which may explain the low nodulation on the root system. However, the same seed showed high nodule formation when grown on a sandy soil (data not shown). Future studies should test the effect of soil type on rhizobium association with hairy vetch roots.

Cereal rye enhanced celery growth and yield. However, high residue production may be detrimental to celery. When large cereal rye biomass was produced (Hamilton 2004), this resulted in stunting, yellowing, and low celery yield. Those growth inhibitory conditions may be attributed to either nutrient immobilization or allelochemical interactions. Cereal rye is known to produce allelochemicals that interfere with normal growth of several species (Barnes and Putnam, 1983; Barnes et al., 1987). Therefore, when using cereal rye as a cover crop, sufficient time should be allowed for residue decomposition prior to planting.

Oilseed radish increased celery growth and yield both under the low and half rates of fertilizer. By producing large amounts of biomass, oilseed radish probably improved microbial activity and created an environment more conducive to celery growth. Oilseed radish has been shown to produce glucosinolates, secondary metabolites that suppress weeds, nematodes, and some soil borne plant pathogens (Fahey et al., 2001). In the present study, weed competition was eliminated in all treatments with regular hand weeding. The population of plant pathogenic nematodes was low in the oilseed radish treatment (data not shown). However, nematode suppression alone may not account for the high yield observed. Through rapid growth and production of a large root system, oilseed radish can recycle N 157.2 kg ton^{-1} (Ngouajio and Mutch, 2004). Studies have documented the ability of oilseed radish to scavenge residual soil N after crop harvest (Ngouajio and Mutch, 2004). This recycled N is then released slowly to the following crop with several benefits to the crop and the environment (Baggs et al., 2000).

This work suggests that cover crops especially oilseed radish, could be integrated into celery production with associated increase in yield and reduction in fertilizer inputs. The contribution of the cover crops on soil fertility should be quantified and credited while developing fertilization programs. It is also important to determine the nutrient release curve of the cover crops in order to optimize their contribution to cropping systems. Finally, establishing and maintaining a cover crop requires investments by the farmer. Therefore a cost study would help determine the profitability of the different systems.

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Table 2.1.
Cover crop seeding rate and dry biomass (total) production in 2003 and 2004 at Laingsburg and Hamilton.

Cover crops species[x]	Seeding rate		Biomass			
	Laingsburg	Hamilton	Laingsburg		Hamilton	
			2003[y]	2004	2003	2004
	kg ha^{-1}		g m^{-2}			
Hairy vetch	39	39	181 c	114 c	147 c	-
Oilseed radish	28	28	719 a	480 a	585 a	691 b
Cereal rye	112	112	284 b	270 b	335 b	1599 a
Yellow mustard	-	22	-	-	-	822 b
Oriental mustard	-	13	-	-	-	714 b

[x] Biomass of oilseed radish, yellow mustard, and oriental mustard was evaluated in October of the year preceding the growing season (before they were kill by frost). Cereal rye and hairy vetch biomass was estimated in May prior to land preparation.
[y] All numbers within a column followed by the same letter are not statistically different ($\alpha = 0.05$).

Table 2.2.
Effects of cover crop and fertilizer rate on celery total dry weight at different dates on Houghton muck soil in Laingsburg and Hamilton during 2003 and 2004.

Cover crop and fertilizer rate[x]	2003				2004			
Laingsburg site	**0 DAT[y]**	**23 DAT[z]**	**43 DAT**	**64 DAT**	**0 DAT**	**23 DAT**	**43 DAT**	**64 DAT**
	g plant^{-1}							
Oilseed radish plus Half.	0.65	1.0 a	7.4	29.4	0.65	2.8	15.9	51.5
Cereal rye plus Half.	0.65	0.7 bc	5.5	32.6	0.65	2.9	14.2	54.9
Hairy vetch plus Half.	0.65	0.7 c	5.5	27.1	0.65	2.8	15.2	53.5
Oilseed radish plus Low	0.65	1.0 ab	5.5	27.9	0.65	2.6	13.4	43.4
Cereal rye plus Low	0.65	0.7 bc	4.4	24.4	0.65	2.8	12.1	43.5
Hairy vetch plus Low	0.65	0.8 abc	3.2	19.2	0.65	2.4	12.5	46.5
Control plus Full	0.65	0.8 abc	4.9	26.2	0.65	2.8	16.2	51.1
Control plus Half.	0.65	0.6 c	4.3	21.2	0.65	2.6	19.3	51.6
Control plus Low	0.65	0.7 c	3.4	17.2	0.65	2.2	14.1	45.4
P-value	-	*	NS	NS	-	NS	NS	NS
Hamilton site	**0 DAT**	**32 DAT**	**44 DAT**	**64 DAT**	**0 DAT**	**31 DAT**	**52 DAT**	**72 DAT**
	g plant^{-1}							
Control	0.65	13.5	35.0	57.0	0.65	3.3 ab	20.3	49.7
Hairy vetch	0.65	15.3	39.7	56.3	-	-	-	-
Oilseed radish	0.65	14.0	32.0	46.0	0.65	4.3 a	21.7	46.7
Cereal rye	0.65	14.3	37.7	55.0	0.65	1.7 c	20.3	49.7
Oriental mustard	-	-	-	-	0.65	3.7 ab	23.0	52.7
Yellow mustard	-	-	-	-	0.65	2.7 bc	21.0	62.7
P-value	-	NS	NS	NS	-	***	NS	NS

[x] Fertilizer rates are Full, Half , and Low. The full rate was 180, 90, 450 kg ha^{-1} of N, P_2O_5, and K_2O, respectively. The Half rate corresponded to 50% of the full rate. The low rate was 50% of the N applied in the full rate and no P_2O_5 and K_2O. All P_2O_5, K_2O, and 25% of N were top dressed and the remaining N side dressed in three equal applications during the season.[y] DAT is days after celery transplanting. [z] All numbers within a column and year followed by the same letter are not statistically different ($\alpha = 0.05$).

Table 2.3.

Coefficient estimates for the logistic equation $y = [a \div (1 + (x \div x_0)^b)]$ fitted with celery total dry weight data for Laingsburg and Hamilton during 2003 and 2004.

Cover crop and fertilizer rate[x]	2003[y]				2004			
	r^2	a	b	x_0	r^2	a	b	x_0
	Model coefficients							
Laingsburg site								
Oilseed radish plus Half.	0.99	110.0 E5	-2.5	8.4 E4	0.99	99.0 E5	-3.5	1.9 E4
Cereal rye plus Half.	0.99	40.0 E5	-3.3	1.9 E4	0.99	220.0 E5	-4.0	1.4 E4
Hairy vetch plus Half.	0.99	4.2 E5	-2.9	1.4 E4	0.99	290.0 E5	-3.7	2.0 E4
Oilseed radish plus Low	0.99	9.2 E5	-3.0	1.8 E4	0.99	73.0 E5	-3.5	1.8 E4
Cereal rye plus Low	0.99	9.2 E5	-3.1	1.5 E4	0.99	87.0 E5	-3.8	1.5 E4
Hairy vetch plus Low	0.99	14.0 E5	-3.3	1.6 E4	0.99	110.0 E5	-3.9	1.4 E4
Control plus Full	0.99	45.0 E5	-3.1	2.7 E4	0.99	160.0 E5	-3.5	2.3 E4
Control plus Half.	0.99	3.8 E5	-2.9	1.5 E4	0.99	126.1	-4.1	0.6 E4
Control plus Low	0.99	21.0 E5	-2.9	2.8 E4	0.99	937.9	-3.6	0.1 E4
Hamilton site								
Control	0.99	81.5	-3.9	562.5	0.99	76.3	-3.8	532.4
Hairy vetch	0.99	57.7	-4.0	494.6	-	-	-	-
Oilseed radish	0.99	65.9	-4.6	491.0	0.99	69.1	-3.5	509.6
Cereal rye	0.99	65.8	-4.7	478.5	0.99	59.5	-5.3	462.0
Oriental mustard	-	-	-	-	0.99	74.0	-4.0	499.0
Yellow mustard	-	-	-	-	0.99	104.6	-4.2	569.2

[x] Fertilizer rates are Full, Half, and Low. The full rate was 180, 90, 450 kg ha^{-1} of N, P_2O_5, and K_2O, respectively. The Half rate corresponded to 50% of the full rate. The low rate was 50% of the N applied in the full rate and no P_2O_5 and K_2O. All P_2O_5, K_2O, and 25% of N were top dressed and the remaining N side dressed in three equal applications during the season.

[y] r^2 is the coefficient of determination, *a*, is the maximal value of *y* where *y* represents biomass accumulation, *b* describes any deviation from logistic growth, x_0, is the degree day (base 10 °C) at time zero.

Table 2.4.

Effects of cover crop and fertilizer rates on celery crop growth rate (CGR) in Laingsburg and Hamilton in 2003 and 2004.

Cover crop and fertilizer rate[x]	2003[y]			2004		
Laingsburg site	**23 DAT[z]**	**43 DAT**	**64 DAT**	**23 DAT[z]**	**43 DAT**	**64 DAT**
	$g\ m^{-2}\ d^{-1}$					
Oilseed radish plus Half.	0.2 a	2.3	7.5	0.7	4.7	12.2
Cereal rye plus Half.	0.1 bc	1.7	9.3	0.7	4.1	13.9
Hairy vetch plus Half.	0.1 c	1.7	7.4	0.7	4.5	13.2
Oilseed radish plus Low	0.2 ab	1.6	7.7	0.6	3.9	10.3
Cereal rye plus Low	0.1 bc	1.3	6.8	0.7	3.3	10.8
Hairy vetch plus Low	0.2 abc	0.9	5.5	0.5	3.7	11.6
Control plus Full	0.1 abc	1.5	7.3	0.7	4.8	11.9
Control plus Half.	0.1 c	1.3	5.8	0.6	6.0	11.1
Control plus Low	0.1 c	1.0	4.7	0.5	4.3	10.7
P-value	*	NS	NS	NS	NS	NS
Hamilton site	**32 DAT**	**44 DAT**	**64 DAT**	**31 DAT**	**52 DAT**	**72 DAT**
	$g\ m^{-2}\ d^{-1}$					
Control	5.3	22.9	14.1	1.1 b	10.3	19.1
Hairy vetch	6.0	26.0	10.7	-		-
Oilseed radish	5.4	19.4	9.1	1.5 a	10.8	16.2
Cereal rye	5.4	25.2	11.4	0.4 c	11.6	18.9
Oriental mustard	-	-	-	1.1 b	12.1	19.1
Yellow mustard	-	-	-	0.9 b	11.1	27.0
P-value	NS	NS	NS	***	NS	NS

[x] Fertilizer rates are Full, Half, and Low. The full rate was 180, 90, 450 kg ha^{-1} of N, P_2O_5, and K_2O, respectively. The Half rate corresponded to 50% of the full rate. The low rate was 50% of the N applied in the full rate and no P_2O_5 and K_2O. All P_2O_5, K_2O, and 25% of N were top dressed and the remaining N side dressed in three equal applications during the season.

[y] DAT is days after celery transplanting

[z] All numbers within a column and year followed by the same letter are not statistically different ($\alpha = 0.05$).

Table 2.5.

Coefficient estimates for the logistic equation $y = [a + (1 + (x + x_0)^b)]$ fitted with celery crop growth rate (CGR) data for Laingsburg.and Hamilton in 2003 and 2004.

Cover crop and fertilizer rate[x]	2003[y]				2004			
	r^2	a	b	x_0	r^2	a	b	x_0
	Model coefficients							
Laingsburg site								
Oilseed radish plus Half.	1.00	103.9	-2.3	16.0 E2	1.00	29.9	-4.0	6.4 E2
Cereal rye plus Half.	1.00	290.0 E4	-3.1	310.0 E2	0.99	760.0 E4	-3.7	210.0 E2
Hairy vetch plus Half.	1.00	815.2	-2.7	30.0 E2	1.00	63.3	-3.7	8.4 E2
Oilseed radish plus Low	0.99	440.0 E3	-2.9	2400.0 E2	1.00	33.4	-3.7	7.3 E2
Cereal rye plus Low	0.99	380.0 E3	-3.0	200.0 E2	0.99	170.0 E4	-3.5	180.0 E2
Hairy vetch plus Low	0.99	560.0 E3	-3.4	160.0 E2	1.00	134.8	-3.7	11.0 E2
Control plus Full	0.99	150.0 E4	-2.9	340.0 E2	1.00	24.5	-4.1	5.9 E2
Control plus Half.	0.99	780.0 E3	-2.7	390.0 E2	1.00	13.2	-5.4	4.4 E2
Control plus Low	0.99	550.0 E3	-2.9	310.0 E2	1.00	18.5	-4.6	5.5 E2
Hamilton site								
Control	0.75	18.5	-60.4	3.8 E2	1.00	21.3	-5.2	4.1 E2
Hairy vetch	0.46	18.3	-61.1	3.7 E2	-	-	-	-
Oilseed radish	0.49	14.2	-60.9	3.7 E2	1.00	17.2	-5.2	3.7 E2
Cereal rye	0.53	18.2	-76.3	3.7 E2	1.00	19.3	-8.1	3.9 E2
Oriental mustard	-	-	-	-	1.00	20.0	-6.0	3.8 E2
Yellow mustard	-	-	-	-	1.00	31.9	-5.5	4.6 E2

[x] Fertilizer rates are Full, Half , and Low. The full rate was 180, 90, 450 kg ha^{-1} of N, P_2O_5, and K_2O, respectively. The Half rate corresponded to 50% of the full rate. The low rate was 50% of the N applied in the full rate and no P_2O_5 and K_2O. All P_2O_5, K_2O, and 25% of N were top dressed and the remaining N side dressed in three equal applications during the season.

[y] r^2 is the coefficient of determination, *a,* is the maximal value of *y* where *y* represents biomass accumulation, *b* describes any deviation from logistic growth, x_0, is the degree day (base 10 °C) at time zero.

Table 2. 6.
Effects of Cover Crop and Fertilizer rates on celery relative growth rate (RGR) in Laingsburg and Hamilton in 2003 and 2004.

Cover crop and fertilizer rate[x]	2003[y]			2004		
Laingsburg site	**23 DAT[z]**	**43 DAT**	**64 DAT**	**23 DAT[z]**	**43 DAT**	**64 DAT**
	ln g kg^{-1} d^{-1}					
Oilseed radish plus Half.	41.2 a	96.4	68.7	86.3	86.0 abcd	56.1
Cereal rye plus Half.	26.7 ab	98.6	86.3	87.8	79.2 cd	64.5
Hairy vetch plus Half.	24.6 b	101.9	77.1	85.3	85.7 abcd	60.0
Oilseed radish plus Low	40.6 a	84.4	78.0	83.1	81.7 bcd	56.2
Cereal rye plus Low	27.3 ab	90.6	81.5	85.4	74.2 d	61.0
Hairy vetch plus Low	32.7 ab	67.2	84.9	78.8	83.6 bcd	61.3
Control plus Full	29.3 ab	84.6	85.6	85.3	88.9 abc	54.6
Control plus Half.	18.0 b	95.1	79.6	82.1	98.8 a	48.7
Control plus Low	22.7 b	78.6	81.2	74.6	94.3 ab	55.6
P-value	*	NS	NS	NS	*	NS
Hamilton site	**32 DAT**	**44 DAT**	**64 DAT**	**31 DAT**	**52 DAT**	**72 DAT**
	ln g kg^{-1} d^{-1}					
Control	93.8	77.7	23.5	52.0 ab	84.9 b	46.0
Hairy vetch	98.3	77.7	18.2	-	-	-
Oilseed radish	95.6	67.4	18.6	60.8 a	92.0 b	39.4
Cereal rye	95.5	81.3	19.7	25.3 c	126.0 a	44.7
Oriental mustard	-	-	-	52.3 ab	92.0 b	40.6
Yellow mustard	-	-	-	42.3 b	97.2 b	54.9
P-value	NS	NS	NS	**	*	NS

[x] Fertilizer rates are Full, Half , and Low. The full rate was 180, 90, 450 kg ha^{-1} of N, P_2O_5, and K_2O, respectively. The Half rate corresponded to 50% of the full rate. The low rate was 50% of the N applied in the full rate and no P_2O_5 and K_2O. All P_2O_5, K_2O, and 25% of N were top dressed and the remaining N side dressed in three equal applications during the season. [y] DAT is days after celery transplanting. [z] All numbers within a column and year followed by the same letter are not statistically different ($\alpha = 0.05$)..

Table 2.7.

Coefficient estimates for the polynomial equation $y = y_0 + ax + bx^2$ fitted with celery relative growth rate data for Laingsburg and Hamilton in 2003 and 2004.

Cover crop and fertilizer rate[x]	2003[y]				2004			
	r^2	y_0	a	b	r^2	y_0	a	b
	Model coefficients							
Laingsburg site								
Oilseed radish plus Half.	1.0	-18.4	0.67	-10.0 E-4	1.0	31.5	0.35	-5.0 E-4
Cereal rye plus Half.	1.0	-42.4	0.77	-10.0 E-4	1.0	87.9	-0.03	-1.0 E-4
Hairy vetch plus Half.	1.0	-53.9	0.88	-12.0 E-4	1.0	36.2	0.31	-5.0 E-4
Oilseed radish plus Low	1.0	-1.2	0.46	-6.0 E-4	1.0	40.1	0.28	-4.0 E-4
Cereal rye plus Low	1.0	-33.1	0.67	-9.0 E-4	1.0	97.0	-0.04	-0.4 E -4
Hairy vetch plus Low	1.0	7.7	0.26	-2.0 E4	1.0	21.9	0.35	-5.0 E-4
Control plus Full	1.0	-20.3	0.55	-7.0 E-4	1.0	9.2	0.47	-7.0 E-4
Control plus Half.	1.0	-57.0	0.85	-11.0 E-4	1.0	-65.0	0.88	-12.0 E-4
Control plus Low	1.0	-26.9	0.54	-6.0 E2	1.0	-60.5	0.80	-10.0 E-4
Hamilton site								
Control	1.0	14.6	0.44	-6.0 E-4	1.0	-85.9	0.81	-10.0 E-4
Hairy vetch	1.0	30.4	0.41	-6.0 E-4	-	-	-	-
Oilseed radish	1.0	110.7	0.06	-3.0 E-42	1.0	-88.2	0.89	-11.0 E-4
Cereal rye	1.0	-20.6	0.60	-3.0 E-4	1.0	-353.8	2.20	-25.0 E-4
Oriental mustard	-	-	-	-	1.0	-119.2	1.00	-12.0 E-4
Yellow mustard	-	-	-	-	1.0	-162.4	1.20	-13.0 E-4

[x] Fertilizer rates are Full, Half , and Low. The full rate was 180, 90, 450 kg ha^{-1} of N, P_2O_5, and K_2O, respectively. The Half rate corresponded to 50% of the full rate. The low rate was 50% of the N applied in the full rate and no P_2O_5 and K_2O. All P_2O_5, K_2O, and 25% of N were top dressed and the remaining N side dressed in three equal applications during the season.

[y] r^2 is the coefficient of determination, and y_0, *a*, and *b* are regression coefficients.

Table 2.8.
Effects of cover crop and fertilizer rate on celery stalk length at different dates in Houghton muck soil in Laingsburg and Hamilton during 2003 and 2004.

Cover crop and fertilizer rate[x]	2003			2004		
Laingsburg site	**23 DAT[z]**	**43 DAT**	**64 DAT**	**23 DAT**	**43 DAT**	**64 DAT**
			cm			
Oilseed radish plus Half.	14.5	25.8 a	48.8 ab	20.8	41.5 a	64.0 a
Cereal rye plus Half.	14.0	24.0 ab	50.0 a	20.0	40.5 ab	63.5 a
Hairy vetch plus Half.	14.5	22.8 abc	48.0 ab	20.0	41.8 a	62.8 ab
Oilseed radish plus Low	14.3	22.0 abc	46.0 abc	20.0	38.0 bc	56.0 c
Cereal rye plus Low	14.2	21.0 abc	46.8 ab	20.3	36.8 d	58.0 c
Hairy vetch plus Low	13.3	17.0 c	42.8 bc	20.2	37.3 d	58.5 c
Control plus Full	13.5	20.8 abc	46.8 ab	19.8	40.8 a	65.0 a
Control plus Half.	13.0	19.5 bc	45.5 abc	19.5	40.0 abc	64.3 a
Control plus Low	13.5	18.0 c	40.5 c	17.8	37.5 cd	58.8 bc
P-value	NS	*	*	NS	**	***
Hamilton site	**32 DAT**	**44 DAT**	**64 DAT**	**31 DAT**	**52 DAT**	**72 DAT**
			cm			
Control	37.3	54.3	79.3	18.7 bc	45.0	66.3 ab
Hairy vetch	37.0	53.3	74.0	-	-	-
Oilseed radish	39.3	54.3	77.0	21.7 a	47.3	69.3 ab
Cereal rye	38.7	55.7	78.3	14.7 d	42.7	65.3 b
Oriental mustard	-	-	-	20.0 ab	47.3	70.3 a
Yellow mustard	-	-	-	17.7 c	46.0	70.3 a
P-value	NS	NS	NS	***	NS	*

[x] Fertilizer rates are Full, Half, and Low. The full rate was 180, 90, 450 kg ha^{-1} of N, P_2O_5, and K_2O, respectively. The Half rate corresponded to 50% of the full rate. The low rate was 50% of the N applied in the full rate and no $P_2O_5$and K_2O. All P_2O_5, K_2O, and 25% of N were top dressed and the remaining N side dressed in three equal applications during the season.
[z] All numbers within a column and year followed by the same letter are not statistically different ($\alpha = 0.05$).

Table 2.9.

Coefficient estimates for the logistic equation $y = [a \div (1 + (x \div x_0)^b)]$ fitted with celery stalk length data of Laingsburg and Hamilton in 2003 and 2004.

Cover crop and fertilizer rate[x]	2003[y]				2004			
	r^2	a	b	x_0	r^2	a	b	x_0
	Model coefficients							
Laingsburg site								
Oilseed radish plus Half.	0.98	440.0 E5	-1.3	200.0 E 4	1.00	170.0 E1	-1.1	110.0 E1
Cereal rye plus Half.	0.96	200.0 E5	-1.5	420.0 E 3	1.00	350.0 E5	-1.1	770.0 E4
Hairy vetch plus Half.	0.95	490.0 E5	-1.4	110.0 E 4	1.00	197.8	-1.4	111.1
Oilseed radish plus Low	0.94	200.0 E5	-1.4	770.0 E3	1.00	399.7	-1.1	331.3
Cereal rye plus Low	0.93	510.0 E5	-1.5	830.0 E3	0.99	130.0 E6	-1.1	660.0 E5
Hairy vetch plus Low	0.89	400.0 E5	-1.6	380.0 E3	0.99	970.0 E5	-1.1	410.0 E5
Control plus Full	0.94	800.0 E5	-1.5	770.0 E3	1.00	790.0 E 5	-1.2	110.0 E5
Control plus Half.	0.93	430.0 E5	-1.6	390.0 E3	0.99	120.0 E6	-1.2	140.0 E5
Control plus Low	0.90	76.0 E5	-1.4	420.0 E3	1.00	443.2	-1.3	281.8
Hamilton site								
Control	-	-	-	-	1.00	114.2	-2.3	62.6
Hairy vetch	1.00	123.6	-1.8	51.3	-	-	-	-
Oilseed radish	1.00	272.8	-1.2	137.3	1.00	144.2	-2.0	74.9
Cereal rye	1.00	145.2	-1.7	58.3	1.00	100.9	-2.8	58.1
Oriental mustard	-	-	-	-	1.00	130.2	-2.2	66.9
Yellow mustard	-	-	-	-	1.00	124.4	-2.4	64.7

[x] Fertilizer rates are Full, Half, and Low. The full rate was 180, 90, 450 kg ha^{-1} of N, P_2O_5, and K_2O, respectively. The Half rate corresponded to 50% of the full rate. The low rate was 50% of the N applied in the full rate and no P_2O_5 and K_2O. All P_2O_5, K_2O, and 25% of N were top dressed and the remaining N side dressed in three equal applications during the season.

[y] r^2 is the coefficient of determination, *a,* is the maximal value of *y* where *y* represents biomass accumulation, *b* describes any deviation from logistic growth, x_0, is the degree day (base 10 °C) at time zero.

Table 2.10.
Effects of cover crop and fertilizer on total and marketable celery yield (weight and stalk number) in Laingsburg during 2003 and 2004.

Cover crop and fertilizer rate[x]	Before trimming yield		After trimming yield	
	Total[z]	Marketable	Marketable	Marketable stalks[††]
	ton ha^{-1}			stalks ha^{-1}
2003				
Oilseed radish plus Half.	73.8 (2.8)[†] a	70.5 (4.0) a	46.0 (3.0) a	66.1 (2.3) a
Cereal rye plus Half.	65.6 (4.5) a	57.4 (6.7) ab	37.8 (5.3) ab	55.2 (4.7) abc
Hairy vetch plus Half.	63.9 (5.7) abc	57.1 (7.5) ab	36.2 (4.3) ab	59.0 (3.4) ab
Oilseed radish plus Low	62.1 (4.4) abcd	53.7 (6.4) abc	34.8 (4.7) ab	57.2 (4.4) abc
Cereal rye plus Low	53.3 (0.9) bcd	45.4 (3.4) bc	29.2 (2.2) b	54.5 (4.9) abc
Hairy vetch plus Low	49.0 (4.8) d	37.4 (5.4) c	23.9 (4.1) b	46.5 (2.5) bc
Control plus Full	57.1 (6.8) bcd	49.1 (9.4) bc	38.5 (11.1) ab	51.8 (7.4) bc
Control plus Half.	59.0 (5.5) bcd	48.4 (6.7) bc	30.5 (4.1) ab	48.2 (1.8) bc
Control plus Low	50.7 (6.5) cd	38.0 (7.8) c	24.4 (5.5) b	44.7 (5.6) c
P-value	*	*	*	*
2004				
Oilseed radish plus Half.	96.9 (5.9) ab	86.5 (7.1) a	59.0 (5.6) a	60.7 (2.9) a
Cereal rye plus Half.	101.0 (4.2) a	87.6 (5.7) a	56.3 (3.6) ab	57.2 (2.5) ab
Hairy vetch plus Half.	95.7 (6.0) ab	83.5 (9.3) a	54.4 (6.3) abc	56.3 (5.1) ab
Oilseed radish plus Low	89.9 (4.0) abc	74.8 (8.4) ab	48.8 (6.0) abcd	54.5 (5.5) abc
Cereal rye plus Low	82.5 (4.0) bc	62.6 (6.5) bc	40.1 (4.6) cd	49.1 (4.7) bcd
Hairy vetch plus Low	78.5 (1.4) c	56.4 (3.7) bc	37.0 (3.3) d	44.7 (2.3) cd
Control plus Full	98.9 (5.1) a	85.4 (6.8) a	56.5 (6.3) ab	56.3 (3.4) ab
Control plus Half.	97.0 (3.7) a	86.5 (3.8) a	57.6 (3.0) ab	59.9 (0.9) ab
Control plus Low	78.5 (4.0) c	51.3 (8.8) c	42.1 (8.3) bcd	40.2 (5.9) d
P-value	**	**	*	**

[x] Fertilizer rates are Full, Half, and Low. The full rate was 180, 90, 450 kg ha^{-1} of N, P_2O_5, and K_2O, respectively. The Half rate corresponded to 50% of the full rate. The low rate was 50% of the N applied in the full rate and no P_2O_5 and K_2O. All P_2O_5, K_2O, and 25% of N were top dressed and the remaining N side dressed in three equal applications during the season. [z] All numbers within a column and year followed by the same letter are not statistically different ($\alpha = 0.05$). [†] Standard errors of the means are parenthesized. [††] Number of stalks (x1000 stalks ha^{-1}).

Table 2.11.
Effects of cover crop and fertilizer on total and marketable celery yield (weight and stalk number) in Hamilton during 2003 and 2004.

Cover crop and fertilizer rate[x]	Before trimming yield		After trimming yield	
	Total[z]	Marketable	Marketable	Marketable stalks
	ton ha^{-1}			stalks ha^{-1} x1000
2003				
Control	160.0 (8.9)[†]	142.0 (16.9)	94.9 (9.4)	107.2 (15.5)[†]
Hairy vetch	170.5 (13.4)	155.3 (15.9)	103.6 (10.4)	111.5 (11.3)
Oilseed radish	161.7 (2.7)	133.6 (10.5)	90.0 (7.3)	98.6 (8.6)
Cereal rye	163.6 (22.0)	141.9 (26.4)	92.4 (18.7)	98.6 (8.6)
P-value	NS	NS	NS	NS
2004				
Control	169.1 (10.9) ab	146.2 (14.3) ab	102.2 (11.4) ab	105.0 (5.67)
Oilseed radish	182.0 (5.6) a	167.0 (10.1) a	118.6 (7.7) a	111.5 (7.73)
Cereal rye	159.4 (1.3) b	131.4 (10.7) b	89.0 (7.7) b	96.5 (11.13)
Oriental mustard	171.1 (5.3) ab	149.4 (3.6) ab	104.5 (2.4) ab	105.0 (2.14)
Yellow mustard	184.8 (7.8) a	163.7 (13.9) a	115.4 (9.4) a	107.2 (7.73)
P-value	*	*	*	NS

All numbers followed by the same letter are not statistically different ($\alpha = 0.05$).
[†] Standard errors of the means are parenthesized.

Table 2.12.
Effects of cover crop and fertilizer on total soluble solids on Houghton muck soil in Laingsburg and Hamilton during 2003 and 2004.

Cover crop and fertilizer rate[x]	2003	2004
	Total soluble solids %*	
Laingsburg site		
Oilseed radish plus Half.	3.4	3.2
Cereal rye plus Half.	3.3	3.6
Hairy vetch plus Half.	2.4	3.6
Oilseed radish plus Low	3.6	3.6
Cereal rye plus Low	3.4	3.5
Hairy vetch plus Low	3.0	3.6
Control plus Full	3.3	3.5
Control plus Half.	2.9	3.5
Control plus Low	3.5	3.6
P-value	NS	NS
Hamilton site		
Control	3.1	3.4
Hairy vetch	3.1	-
Oilseed radish	3.3	3.5
Cereal rye	3.4	3.4
Oriental mustard	-	3.4
Yellow mustard	-	3.5
P-value[y]	NS	NS

[x] Fertilizer rates are Full, Half, and Low. The Full rate was 180, 90, 450 kg ha^{-1} of N, P_2O_5, and K_2O, respectively. The Half rate corresponded to 50% of the full rate. The Low rate was 50% of the N applied in the full rate and no $P_2O_5$and K_2O. All P_2O_5, K_2O, and 25% of N were top dressed and the remaining N side dressed in three equal applications during the season.
[y] P-values are $P > 0.05$ (NS Non significant)

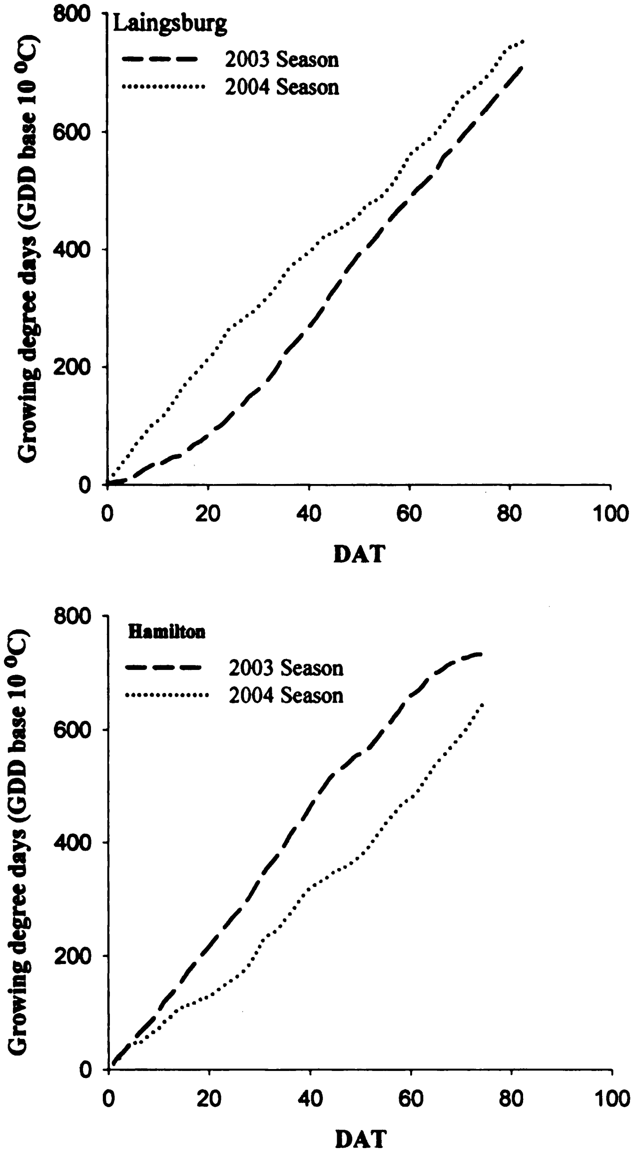

Fig. 2.1. Growing degree days (GDD base 10 °C) during celery growth in 2003 and 2004 at Laingsburg and Hamilton. Celery was transplanted on 23 May 2003 and 28 June 2004 in Laingsburg and on 13 May 2003 and 10 May 2004 in Hamilton. DAT is days after celery transplanting.

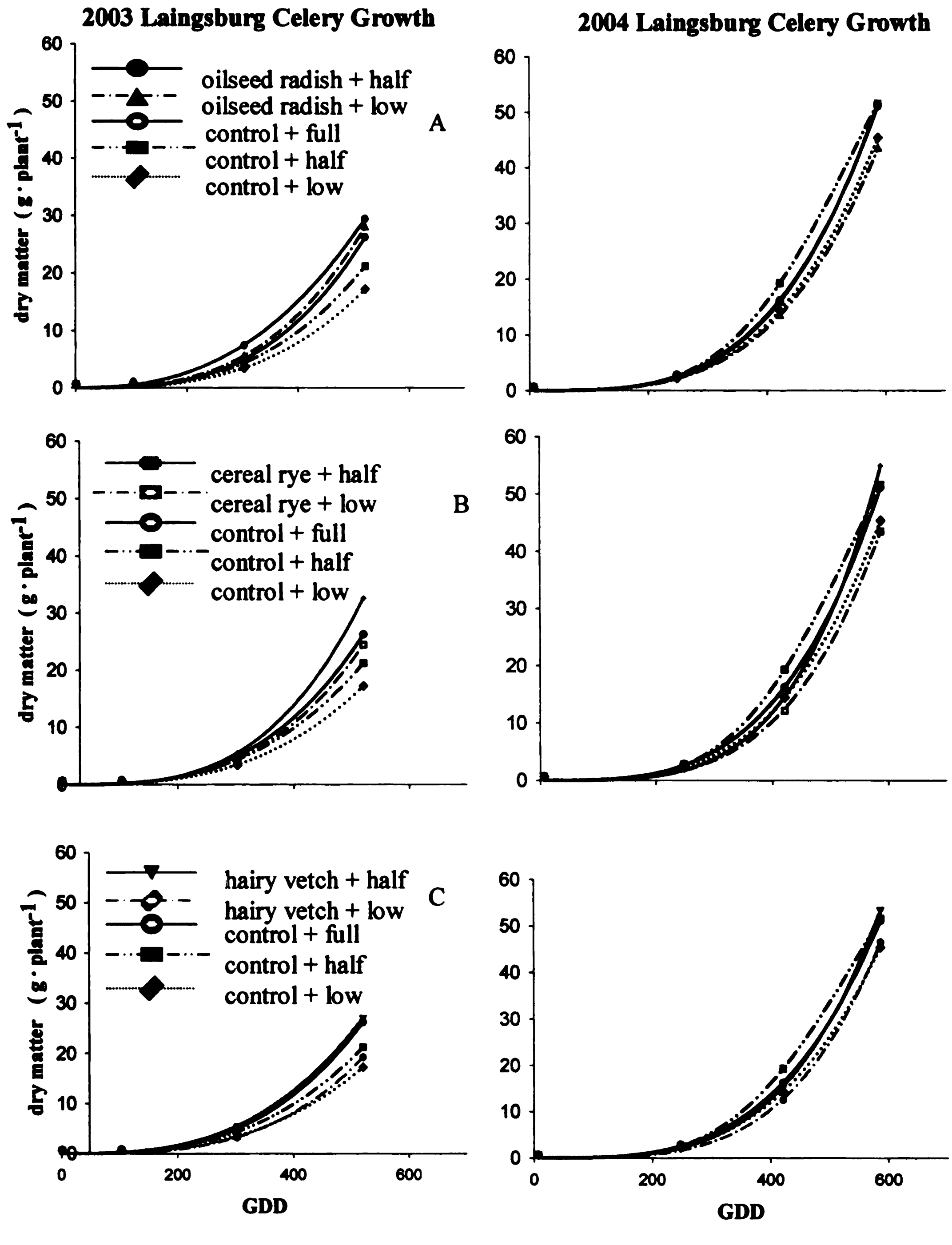

Fig. 2.2. The relationship between celery dry matter accumulation and growing degree days (GDD base 10 °C) under different cover crop: oilseed radish (a), cereal rye (b), and hairy vetch (c) and fertilization treatments during 2003-04. Observed data were fitted to a 3 parameter equation. Regression coefficients are indicated in Table 2.3.

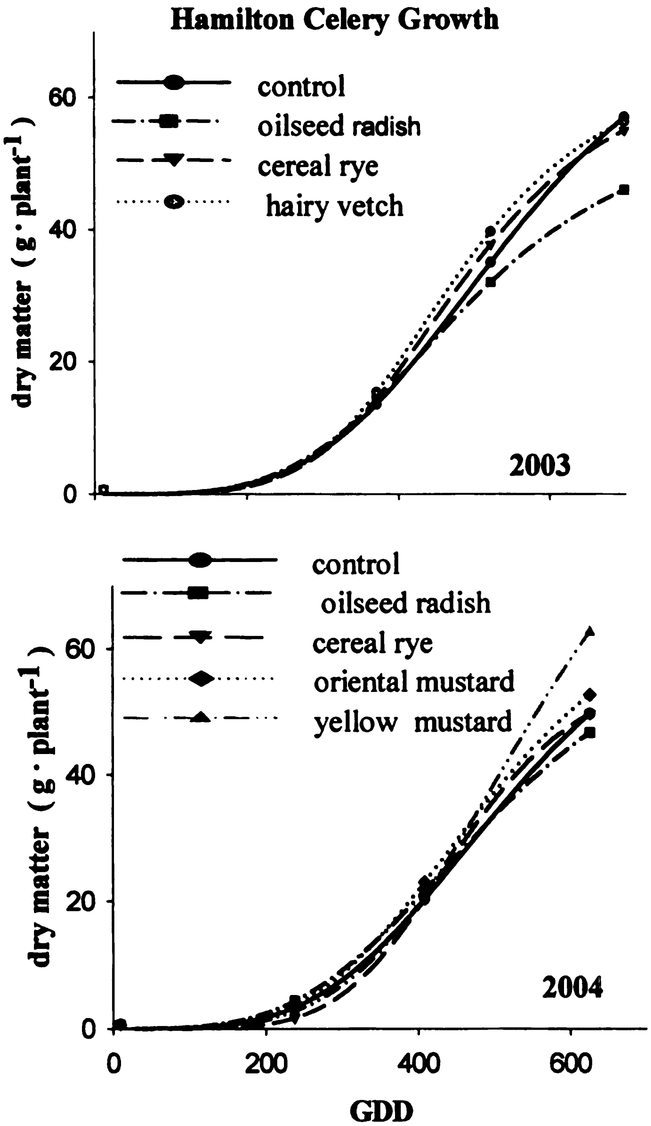

Fig. 2.3. The relationship between celery dry matter accumulation and growing degree days (GDD base 10 °C) as effected by cover crop treatments. Observed data were fitted to a 3 parameter equation. Regression coefficients are indicated in Table 2.3.

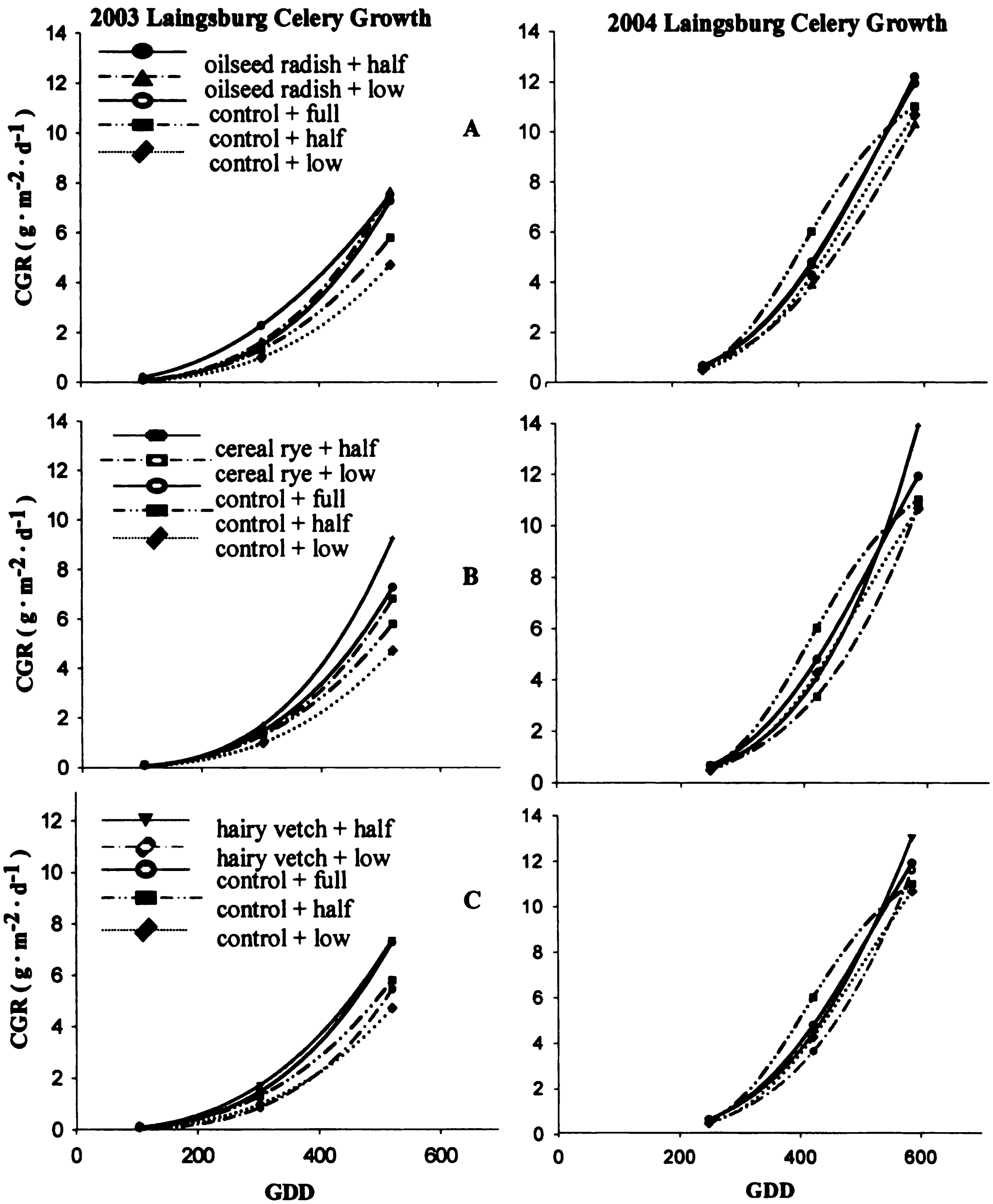

Fig. 2.4. Crop growth rate versus growing degree days under cover crop: oilseed radish (a), cereal rye (b), and hairy vetch (c) and fertilizer treatments. Observed (symbols) predicted (lines) of celery dry plant at Laingsburg. Observed data were fitted to a 3 parameter equation. Regression coefficients are indicated in Table 2.5.

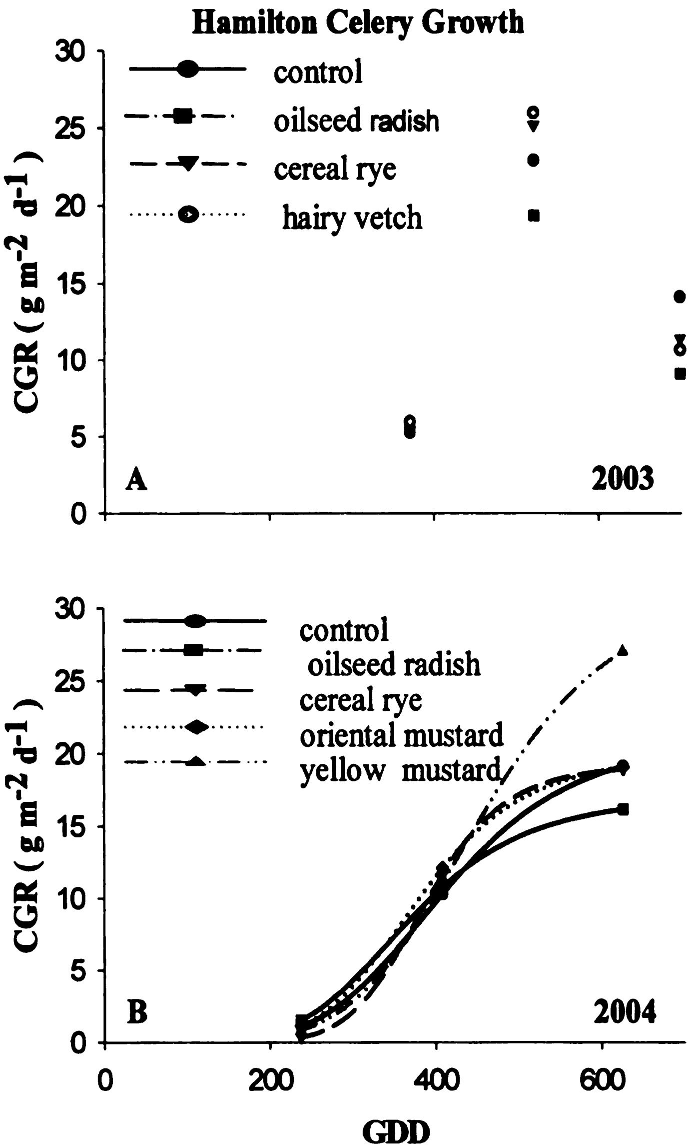

Fig. 2.5. Crop growth rate versus growing degree days under cover crop: 2003 (a) and 2004 (b) for Hamilton. Observed (symbols) predicted (lines) of celery dry plant. Predicted values for 2003 (a) regression were not fitted to logistic equation. Observed data were fitted to a 3 parameter equation. Regression coefficients are indicated in Table 2.5.

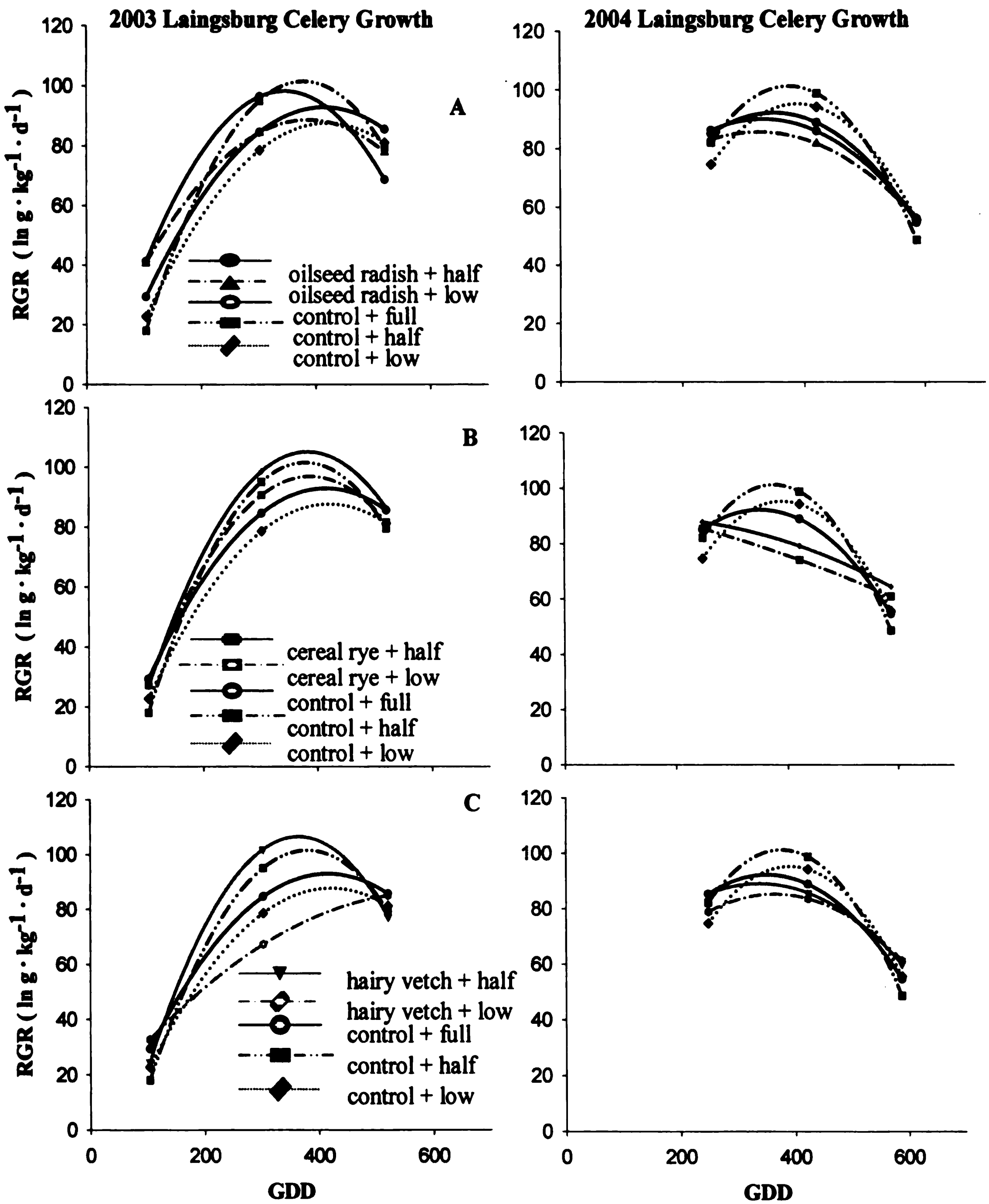

Fig. 2.6. Mean predicted relative growth rate as a function of the cumulative growing degree (GDD) after celery transplanting under cover crop: oilseed radish (a), cereal rye (b), and hairy vetch (c) and fertilizer treatments in 2003 and 2004 at Laingsburg. Regression coefficients are indicated in Table 2.7.

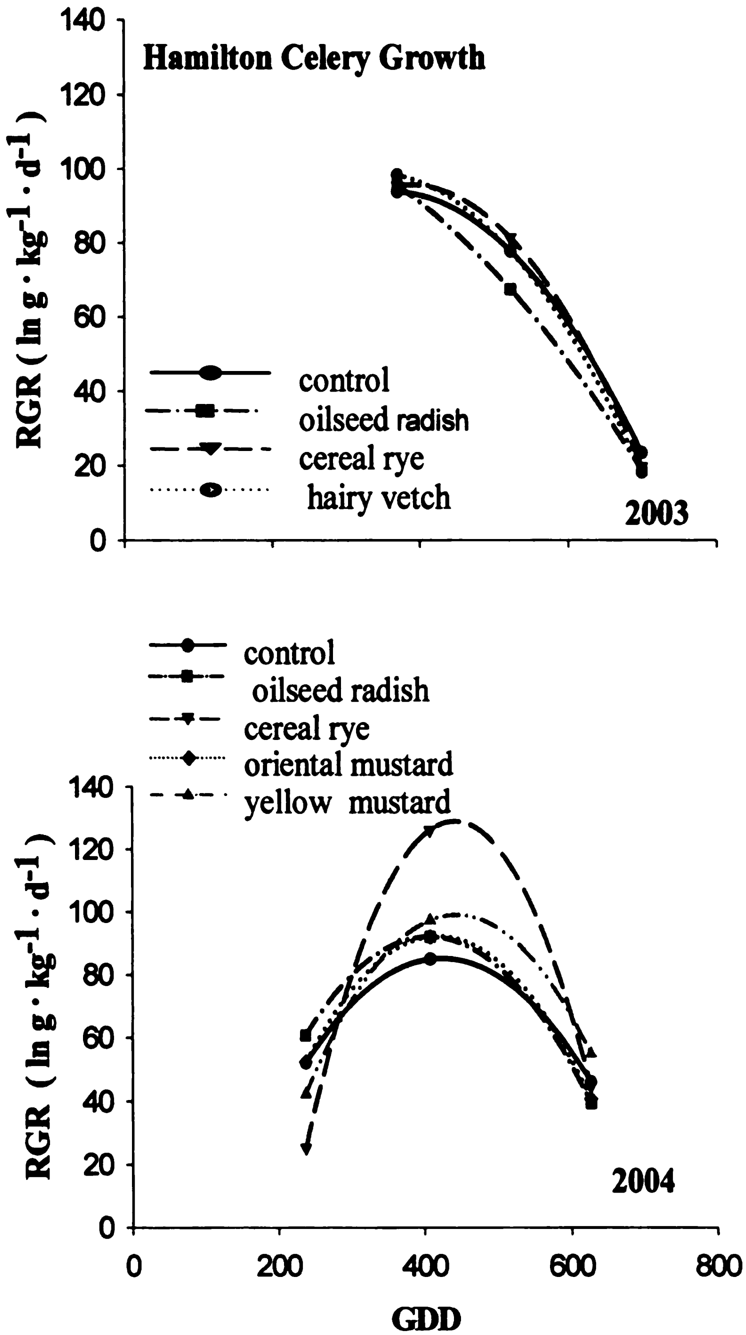

Fig. 2.7. Mean predicted relative growth rate as a function of the cumulative growing degree days (GDD) after celery transplanting in 2003 and 2004 at Hamilton. Regression coefficients are indicated in Table 2.7.

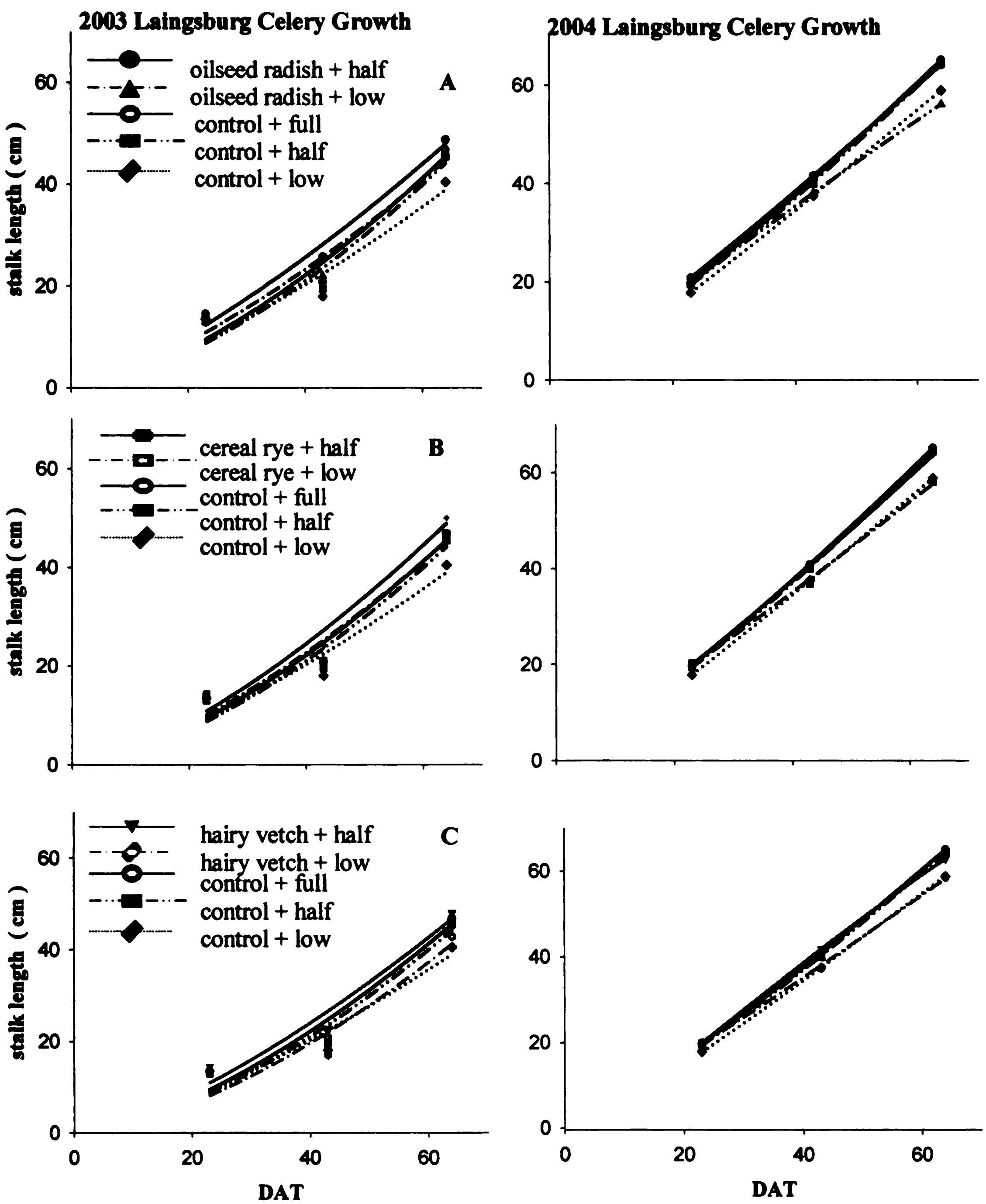

Fig. 2.8. Day after transplanting (DAT) predicted function and observed means of celery stalk length under cover crop: oilseed radish (a), cereal rye (a), and hairy vetch (c) and fertilizer treatments at Laingsburg, MI (2003 and 2004). Regression coefficients are indicated in Table 2.9.

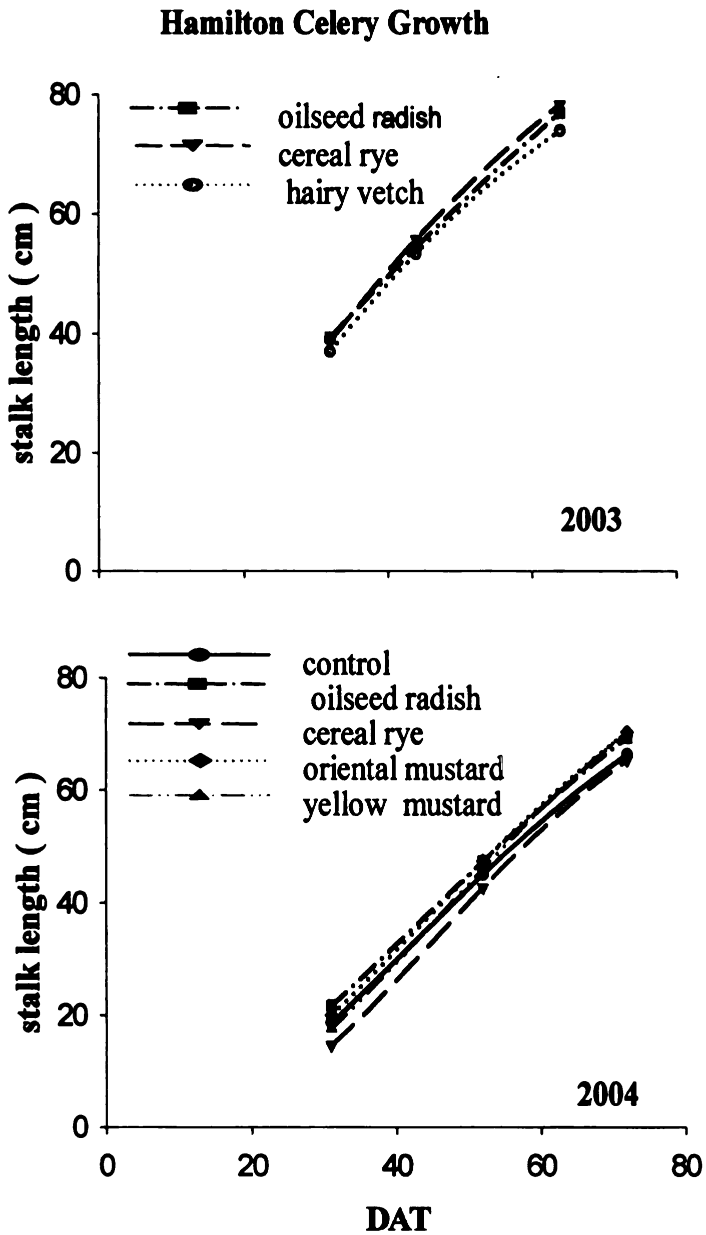

Fig. 2.9. Day after transplanting (DAT) predicted function and observed means of celery stalk length under cover crop treatments at Hamilton, MI (2003 and 2004). Regression coefficients are indicated in Table 2.9.

Chapter 3: The effects of cover crops and fertilization on soil properties and celery (*Apium graveolens* L.) on Houghton muck soil.

ABTRACT

A 2-year study conducted in Laingsburg and Hamilton, MI showed that soil nutrient composition improved under cover crop rotation system. Further, the practice of integrating cover crops was compatible with celery production. In Laingsburg, cropping systems included cover crop and fertilizer rates. The cover crops were oilseed radish, cereal rye, hairy vetch, and a bare ground control. The fertility rates were full (180, 90, and 450 kg ha^{-1} N, P_2O_5, K_2O), half (90, 45, and 225 kg ha^{-1} N, P_2O_5, K_2O), and low rate (90 kg ha^{-1} N). In Hamilton, the cover crops were oilseed radish, cereal rye, hairy vetch, yellow mustard, oriental mustard, and a bare ground control. Total dry matter production averaged 114 to 719 g m^{-2} in Laingsburg and 147 to 1599 g m^{-2} in Hamilton. There was no measurable change in soil phosphorus content. However, cover crops influenced magnesium, calcium, and potassium concentrations. Soil nitrate content was higher in plots where oilseed radish was grown. Cover cropped plots sustained higher N levels than the fallow control. The subsequent celery crop was affected by the cover crops treatments. Within individual fertilization levels, higher celery yields were recorded in the oilseed radish plots. The results of this experiment indicate the inclusion of cover crops can successfully improve the magnitude of soil mineral composition, sustain celery yield on muck soils, and can potentially reduce fertilizer inputs.

INTRODUCTION

Celery is an important commodity of vegetable production in the state of Michigan. However, intensive practices of celery cultivation with high nitrogen (N) fertilization can increase nitrate (NO_3^- N) leaching. Additionally, leaving the soil bare after harvest can increase soil erosion. Therefore, it is possible to improve soil quality and enhance celery yield by developing sustainable techniques that prevents soil erosion and reduces leaching.

Past conventional farming systems used synthetic inputs as a key component in soil fertility to improve yields (Liebman and Davis, 2000). Nitrogen as the primary limiting nutrient is an essential growth element in crop production (Di and Cameron, 2002). However, liberal nitrogen (N) fertilization in conventional vegetable farming during the early half of the twentieth century has resulted in excess-fertility conditions in many situations. Consequently, leaching and erosion has led to the loss of soil nutrients resulting in NO_3^- N accumulation of surface water and groundwater (Di and Cameron, 2002). These NO_3^- N concentration levels have generally increased in the recent past (Pang and Letey, 2000) and have in most cases exceeded acceptable contamination limits (Strebel et al., 1989; EU, 1991; Fletcher, 1991). Furthermore, developing a sustainable management strategy that reduces potential groundwater contamination resulting from leaching can conserve residual soil N and in turn, can maintain water quality and improve soil health (Muller et al., 1987; Sainju et al., 2000; Shipley et al., 1992).

A sustainable approach of managing crop residue to protect soils from erosion and nutrient leaching can provide benefits to cropping systems (Ruffo and Bollero, 2003). Replacing applied inorganic N with organic N from cover crops can reduce nitrate leaching from agricultural soils (Burket et al., 1997; Stute and Posner, 1995). Many studies have shown that N can be retained in agricultural systems by various crop management strategies such as cover crops, crop rotation, interseeding, and accessory cropping (Ditsch and Alley, 1991; Ebelhar et al., 1984; Hargrove, 1986; Hesterman et al., 1986). Thus, plant residue can play an important role in cycling of nutrients essential to production.

In addition to preventing soluble nutrients from leaching (Kelly, 1990), the use of winter cover crops in crop rotation systems can be a valuable asset in improving nutrient retention in the surface layer of intensively managed crop systems (Wyland et al., 1966). Using cover crops can potentially reduce nutrient movement within cropping systems during the winter season by increasing the amount of time the land is covered with growing vegetation (Strock et al., 2004). The rapid growth and establishment of cover crop vegetation following the fall harvest of the cash crop can reduce NO_3^- N (Meisinger et al., 1991), and thereby limit leaching. Nitrate reductions are achieved by cover crop sequestration and retention of soil residual N that can result in N provisions the following spring (Kuo et al., 1996). A number of studies have found that non-leguminous cover crops can reduce soil NO_3^- N leaching below the root zone (Lamb et al., 1985; Powlson, 1988, Martinez and Guiraud, 1990; Meisinger et al., 1991). Without vegetative cover during the winter period, precipitation increases the possibility of nutrient leaching. Therefore, using cover crops as a nutrient conservation tool can reduce groundwater contamination, and improve N-use efficiency (Baggs et al., 2000; Power and Doran, 1988).

Celery is an important vegetable crop in Michigan. Nationally, Michigan ranks second after California in celery production (6.2 % of total national production) with *c.* 890 ha of celery harvested value at $18.8 million in 2004 (USDA, 2004).

In Michigan, it is possible to integrate cover crops into celery cropping systems to establish a vegetative cover prior to the onset of frost.

The purpose of this study was to evaluate winter annual cover crops that would fit into celery production system and to assess cover crop effects on nutrient cycling. Specific objectives were to: (i) measure the effects of different cover crops on soil fertility and the possibility of reducing inorganic fertilizer inputs, (ii) determine the effects of the cover crops and fertilizer rates on celery yield, and (iii) evaluate the effect of cover crops or soil microbial activity.

2. MATERIALS AND METHODS

2.1. Experimental site

Studies were conducted during 2002 through 2004 on two sites at Michigan State University (MSU) Muck Soils Research Farm in Laingsburg, MI and at a commercial farm in Hamilton, MI. Both experiments were initiated in late summer of 2002. The soil was Houghton muck with 80 % organic matter and a range pH of 6.2 - 6.9. Temperature and rainfall data were collected from Bath and Hudsonville weather stations for Laingsburg and Hamilton studies, respectively (Fig. 3.1 and 3.2). In Laingsburg during both years, cover crops were planted in the same plot following harvests and celery was transplanted in late spring. The Hamilton experiment was conducted in different fields each year. In May of 2004, planned celery transplanting in Laingsburg was delayed due to severe rainfall (Fig. 3.2).

2.2. Laingsburg Study

The experiment had four cover crops and three fertilizer rates. The cover crops were oilseed radish (cv. diakon), cereal rye (cv. VNS), hairy vetch (cv. common), and bare ground. Establishment occurred in late summer (26 August 2002 and in 25 August 2003) following the celery crop harvest, using a broadcast method and incorporated by shallow discing. Oilseed radish, cereal rye, and hairy vetch were seeded at rates of 28, 112, and 39 kg ha^{-1}, respectively.

The 3 rates of fertilizer were: full rate (180, 90, and 450 kg ha^{-1} N, P_2O_5, K_2O), half rate (90, 45, and 225 kg ha^{-1} N, P_2O_5, K_2O), and low rate (90 kg ha^{-1} N). The full rate was the recommendation for commercial celery production on muck soils in Michigan. Each year, 25% of N and all of P, and K were broadcast during land preparation (20 May 2003 and 28 June 2004); equal amounts of the remaining N rates were applied at three subsequent side dressings during the growing season (13 June, 3 July, 25 July in 2003 and 21 July, 10 August, and 31 August in 2004). The experimental design was a randomized complete block with four replications. Treatments were combinations of cover crop and fertilizer rate and consisted of the four cover crops plus low or half rate of fertilizer. A bare ground plus high rate of fertilizer (normal practice) was also included for a total of 9 treatments. Individual plots were 4.1 m by 10.7 m and contained four rows of celery at 0.15 m in-row spacing and separated by 1.5 m buffer. Individual plots were hand weeded during the season. Celery was transplanted on 23 May 2003 and 28 June

2004. At maturity, 20 plants were harvested on 12 August 2003 and 20 September 2004. All cover crop plus fertilizer treatments were maintained in the same location throughout the duration of the study.

Soil samples were collected prior to the fertilizer top dress application on 20 May 2003, and 14 May 2004. Soil sampling was conducted by collecting 8 random cores from the top 10 cm depth in each plot. Analyses was conducted to determine soil available NO_3^-N, P, K, Mg, Ca, and total N. Celery was transplanted on 23 May 2003, and on 28 June 2004.

Microbial respiration and biomass C analysis was conducted during 2004. Biological activity potential was determined using soil microbial respiration (CO_2), (Kumar and Goh, 2000). Refrigerated soil samples were preincubated at room temperature for 15 days. Then 40 g of soil (dry weight equivalent) was put in a 500 mL jar sealed with a lid containing a rubber septum. Each sample was processed in duplicate, with one set fumigated (with chloroform) and the other non-fumigated. All samples whether fumigated or non-fumigated were opened and ventilated after 24h. A final incubation period of 5 days was observed, after which 1 mL of head space air was injected into an infra-red CO_2 (Quibit System). Soil respiration was calculated as the amount of CO_2 evolved from the non-fumigated samples. Soil microbial biomass carbon was calculated by subtracting the amount of CO_2 in the non-fumigated sample from that in the corresponding fumigated sample, and a correction factor.

2.3. *Nitrogen Leaching Assessment*

In Laingsburg, ion exchange resin (IER) bags were used to measure NO_3^-N leaching beyond celery root zone (from May 21st until August 12th, 2003). IER bags were buried in the soil to accumulate ions by binding (Binkley and Matson, 1983). The extent of accumulation of NO_3^-N enables us to estimate the relative effects of experimental treatments on N pools that have been mineralized but not immediately taken up by plant roots (Binkley et al., 1986). In 2003, IER bags were prepared by placing 4 g of equivalent weight resin (AG® 3 Anion Exchange Resin, Bio-Rad Laboratories, Hercules, CA, USA,) in nylon mesh material. At the beginning of the season, the IER bags were placed in each plot *c.* a 30 cm depth from soil surface by tunneling vertical channels near celery row, then burrowing a perpendicular tunnel beneath the row with care to avoid disturbing developing root systems and its surrounding soil environment.

2.4. *Hamilton Study*

The experiment was a complete block design with three replications. Plot sizes were 12.2 m long by 18.3 m wide. In 2003, cover crop levels, seeding rates, and sampling methods were identical to the Laingsburg site previously discussed above. In 2004, yellow mustard (cv. tilney) [*Sinapis alba* L.] and oriental mustard (cv. forge) [*Brassica juncea* (L.) *Cosson*] cover crops were also used at 22 kg ha^{-1} and 13 kg ha^{-1} seeding rates, respectively. In 2004, hairy vetch was excluded from the experiment. Cover crops were planted on 9 August 2002 and 30 August 2003. Celery transplanting dates were 13 May 2003 and 10 May 2004 in a double row raised bed system with spacing of 101 cm between consecutive beds, 31 cm between row, and 15 cm in-row spacing. Similar to the

Laingsburg site, microbial respiration and biomass C analysis was conducted during 2004 to determine biological activity potential.

DATA COLLECTION

In Laingsburg, all cover crops were sampled from two 2500 cm^{-2} areas within each plot for biomass evaluation. Cover crop dry matter (DM) was determined after drying at 75 °C until constant weight was achieved. Freezing temperatures during the winter kills oilseed radish, therefore its biomass samples were estimated prior to the October frost of each year. On the other hand, winter hardy cereal rye and hairy vetch continued growth through spring, and were killed with glyphosate [*N* – (phosphonomethyl)- glycine)]. In both years, cereal rye and hairy vetch biomass samples were collected prior to land preparation for celery transplanting. Celery plants were sampled at 23, 43, 64, and 84 days after transplanting (DAT) in 2003 and 2004. During each sampling, dry celery tissue was ground and screened through 1 mm sieve; 1 g of sieved tissue was used to extract NO_3^-N with 50 ml of 2 M KCl. Sampling was not conducted in the center two rows of each plot, as these were allocated for final crop yield estimation. Twenty plants were collected at harvest on 12 August 2003 and 20 September 2004. At harvest, celery stalks were sorted into marketable and non-marketable standards, accordingly (USDA, 1959). General marketable standards qualify as well developed, well-formed plants with stalk lengths of *c.* 0.36 m. Stalk lengths were measured from soil surface to plant crown. Processing included recording marketable before and after trimming stalk weights.

In Laingsburg during 2003, IER resin bags from each plot were collected at harvest. The bags were placed in sample cups, and the NO_3^-N was extracted with 50 ml of 2 M

KCl per bag. The extract was filtered and the concentration of NO_3^-N in the extract was determined colorimetrically (Flow Solution IV,).

In Hamilton, celery plants were sampled on the 32, 44, 64, and 75 DAT in 2003 and on the 31, 52, 72, and 88 DAT in 2004. Celery dry tissue NO_3^-N was extracted with 50 ml of 2 M KCl identical to the Laingsburg extraction method. At harvest, 10 plants were collected on 29 September 2003 and 20 plants on 6 August 2004. At harvest, sorting and processing techniques were conducted similar to those discussed in the Laingsburg methodology. Soil samples were collected from each plot and underwent the similar methodologies outlined for Laingsburg in 2004.

Statistical Analysis

All data was analyzed using analysis of variance (ANOVA) PROC GLM of SAS (SAS institute, Inc. 1999). The least-square means test was used to determine the significant differences between the treatment means. Differences were defined at $P < 0.05$ for all data sets.

RESULTS

3.1. Climate

The weather conditions during the two celery-growing seasons differed greatly (Fig. 3.1). At Laingsburg, both maximum and minimum air temperatures were higher in 2004 than in 2003 (Fig. 3.1). This was due to the delay in celery transplanting until early June (warmer month) in 2004 because of high precipitation that made field operations difficult in May (Fig. 3.2).

In Hamilton, air temperatures in both years were different even though celery was transplanted at similar times. The 2003 season was warmer earlier and cooler late compared to the 2004 season.

In Laingsburg (Fig. 3.2), total rainfall from 0 to 84 DAT was 112 and 163 mm in 2003 and 2004. In 2004, most of the rainfall occurred in May during the planned transplanting that, in turn delayed field activities in Laingsburg. In Hamilton, total rainfall from transplanting to harvest was 178 (2003) and 285 (2004) mm.

3.2. Cover crop biomass production

In Laingsburg, total biomass production varied with cover crop species and growing season (Table 3.1 and Fig. 3.3). Means across cover crop biomass were lower in 2004 than in 2003. In both years, the higher cover crop biomass production was observed in the oilseed radish treatment and was statistically different from biomass measured from hairy vetch and cereal rye, respectively. In Laingsburg, oilseed radish produced the greatest biomass in both years with 719 and 480 g m^{-2} for 2003 and 2004, respectively. For cereal rye, biomass was 284 (2003) and 270 g m^{-2} (2004). Hairy vetch produced the lowest biomass with 181 g m^{-2} in 2003 and 114 g m^{-2} in 2004.

In Hamilton, the highest DM biomass yield with oilseed radish (585 g m^{-2}) in 2003 and in cereal rye (1599 g m^{-2}) treatment in 2004. In Hamilton, oilseed radish, yellow mustard and oriental mustard biomass production were similar and ranged from 691 to 822 g m^{-2}.

Generally, cereal rye biomass was lower than expected in Laingsburg and Hamilton during 2003 due to poor germination in the fall.

3.3 Soil mineral concentration

In 2003, at Laingsburg, differences in the magnitude of soil mineral concentrations were observed among fall planted cover crops in early spring soil sampling (Table 3.2). Similarly, in 2004, increases in the magnitude indicate cover crop and fertilization affected soil mineral levels. Cover crops grown in 2002 had no influence on phosphorus (P), calcium (Ca), and magnesium (Mg). However, the effects of cover crops were seen in potassium (K), residual soil nitrate (NO_3^-N) and total N.

Although, higher soil P values were observed in oilseed radish (47.0 mg kg^{-1}) and cereal rye (46.8 mg kg^{-1}), they were not different from the control (43.5 mg kg^{-1}). Magnesium concentrations ranged from 579.8 to 633.3 mg kg^{-1}. Oilseed radish cover crop increased soil K concentration. A value of 264.3 mg kg^{-1} and 167.3 mg kg^{-1} of K was found in the oilseed radish and control treatments, respectively. Plots where oilseed radish was previously grown provided significantly greater concentrations of NO_3^-N. Means averaged across cover crop indicate 65.0 mg kg^{-1} of NO_3^-N was produced in the oilseed radish treatment compared to 38.8 and 45.3 mg kg^{-1} in other treatments. Results indicate 131 kg $ha^{-1}$of N was recycled by the oilseed radish treatment in comparison to 91 kg ha^{-1} of N observed in the control.

In 2004, at Laingsburg, the effects of cover crop and fertilizer regimes did not influence phosphorus (P) concentrations (Table 3.2). The pattern of soil K indicates the oilseed radish plots receiving both low and half rate of fertilizer provided higher concentrations (444 and 473 mg kg^{-1}) in comparison to other cropping systems. As in 2003, oilseed radish increased the concentration of NO_3^-N in the soil, with 159 and 158 mg kg^{-1} in the low and half rate of fertilizer, respectively. These were significantly different from the cropping systems of control with full rate of fertilizer and cereal rye with half rate of fertilizer. Similarly, statistically greater total N accumulation was observed in the oilseed radish plots in comparison to control half and full rate of fertilizer. These differences are partly attributed to the ability of oilseed radish to recycle residual soil N.

Soil analysis was not conducted in Hamilton in 2003 because the grower cooperator applied fertilizer early. In 2004, at Hamilton, concentration of Ca and P were not significant in cover crop treatments as shown in Table 3.3. There was a significant effect of cover crop on soil K, Mg, and NO_3^-N concentrations. Soil K was increased under oriental mustard (125.4 mg kg $^{-1}$) and yellow mustard (109 mg kg $^{-1}$). Oilseed radish greatly increased the concentration of soil Mg (130.8 mg kg $^{-1}$) which was statistically higher than that of control (120.3 mg kg $^{-1}$) treatment. Oilseed radish, yellow mustard, and oriental mustard increased NO_3^-N concentration by 11 to 12 fold compared with the control. Cereal rye did not affect N concentration in the soil.

3.4. Soil microbial respiration and microbial biomass C

In Laingsburg, there were no significant differential effects of cropping systems on soil microbial respiration or on soil microbial carbon (Table 3.4 and Fig. 3.4). Soil CO_2 evolution ranged from12.4 to 16.1 μg g soil^{-1} day^{-1} and soil microbial biomass carbon ranged from 273.8 to 348.1 μg g soil^{-1}.

In Hamilton however, there was measurable differential effect of cover crops on both soil microbial respiration as well as soil microbial carbon (Table 3.4 and Fig. 3.4). Greater soil microbial respiration was observed in the cereal rye (18.4 μg g soil^{-1} day^{-1})

treatment. This was statistically different from the control (14.0 μg g $soil^{-1}$ day^{-1}) and yellow mustard (9.5 μg g $soil^{-1}$ day^{-1}) treatments. Soil samples from the yellow mustard cover crop had the lowest rate of respiration. Similar to microbial respiration, soil microbial carbon was influenced by cover crop. This may result from the rate of cover crop decomposition. Both yellow mustard (400.7 μg g $soil^{-1}$) and cereal rye (389.6 μg g $soil^{-1}$) treatments provided higher microbial carbon compared to oilseed radish and the control treatments. These values were significantly greater than those measured in the control (321.2 μg g $soil^{-1}$) as well as in the oilseed radish (305.0 μg g $soil^{-1}$) treatments.

3.5. IER NO_3^- N accumulation

In 2003, at Laingsburg, there were no statistical differences in accumulation of NO_3^- N in IER among the cover crop-fertilizer treatments at harvest (Table 3.5). Nitrate leaching is a serious problem in agricultural systems. Our results indicate that under our experimental conditions, little NO_3^- N leaching occurred during celery growing season. Nutrient leaching of organic soils occurs from runoff or leaching. This observation was true regardless of the fertilizer rate used. Therefore, most of the NO_3^- N leaching to ground water may occur between growing seasons. This hypothesis was not tested in our study. However, if that was true, it would support the use of cover crops between growing seasons to recycle residual soil NO_3^- N. Oilseed radish was very efficient at recycling NO_3^- N.

3.6. Tissue NO_3^- N concentration

In 2003 and 2004, at Laingsburg, there were no significant effects of cover crop-fertilizer cropping system on celery tissue nitrate (NO_3^- N) concentration during the growing season (Table 3.6). The lack of difference in celery tissue NO_3^- N concentration among the fertilizer rates in the control plots and among the different combinations of cover crops and fertilizer rates suggests that celery accumulate little NO_3^- N. The additional soil available nitrogen in the system with high fertility was probably take up by celery and used for growth rather than accumulated as NO_3^- N. This was reflected in the difference in celery growth and development among the treatments.

In 2003, at Hamilton, no effects of cover crop on celery NO_3^- N were detected (Table 3.6). In 2004, however, nitrate tissue concentrations varied across treatments during the first sampling date at 31 DAT. The control plot had the lowest tissue NO_3^- N concentration (58.0 mg kg^{-1}) and yellow mustard treatment the highest concentration (347.5 mg kg^{-1}). No differences among treatments were found during the remainder of the season. This result further supports the hypothesis of nitrogen utilization for celery growth rather than accumulation in tissue.

3.7. Celery yield

In Laingsburg, celery yield was affected by the different treatments in both 2003 and 2004 (Table 3.7 and Fig. 3.5, 3.6 and 3.7). This was observed for total and marketable yield, of the untrimmed and trimmed stalks, as well as for the number of marketable stalks. Across years and treatments, a higher number of marketable stalks were observed in Laingsburg during 2003.

In 2003, yields of the bare ground and hairy vetch treatments with low fertilizer rate produced the lowest values of all categories. The evaluation suggests an importance of adequate soil fertility measures in celery production. For example, plant weights of the untrimmed marketable stalks were only 38.0 ton ha^{-1} (in the control plus low fertilizer treatment) and 37.4 ton ha^{-1} (in the hairy vetch plus low fertilizer treatment), in comparison to 45.4 to 70.5 ton ha^{-1} in other treatments. The system with oilseed radish and the half rate of fertilizer significantly increased yields. Moreover, yields in the oilseed radish plus half rate were greater or equal to the yields produced by the control and full fertilizer rate. Similar observations were with marketable stalks. The highest numbers of marketable stalks were recorded in the plots previously occupied by oilseed radish (66,000 plants ha^{-1}) that received the half rate of fertilizer.

In 2004, low yields were observed in the bare ground plots receiving the low fertilizer rate. In those plots, increased yields correlated with increasing rates of fertilizers. However, cover crop systems performed similarly when receiving either the half or low fertilizer rates. The entire plot was flooded after heavy rain, which probably canceled all cover crop effects.

In Hamilton during 2003, there were no observed effects of cover crops on celery yields (Table 3.7). In 2004, the yields observed were higher than those of 2003. There was a greater variation in total yields among the treatments. Yields from cereal rye plots were reduced considerably. Total trimmed stalk weights were 102.2 ton ha^{-1} in the control and only 89.0 ton ha^{-1} in the cereal rye plots. The yield penalty associated with cereal rye was observed in both the marketable before and after trimming yields, although the latest was not evident. Higher yields were observed in the oilseed radish and yellow mustard treatments but weren't different from yields of the control plot.

DISCUSSION

Our objective was to determine whether winter annual cover crops following intensely produced celery could fit into a rotational system. Also, we sought to assess effects of cover crop and fertilization on nutrient management. Understanding how cropping system influences soil mineral composition can provide important information used in developing nutrient management strategies for Michigan celery producers.

The results presented in this paper were generated from a two year study and suggests a probable fit of the cover crops investigated. When seeded in late summer following celery harvests, a considerable cover crop stand was established and production of significant biomass occurred during early spring of the next year. The rapid establishment and growth can potentially reduce soil erosion (Bowman et al., 1998) and accumulate soil nitrogen (Odhiambo and Bomke, 2001). Schomberg and Endale (2004) reported the availability of soil N is highly dependant upon the amount of cover crop biomass produced. Additionally, Clark et al. (1995) reported a correlation with increased N content and cover crop biomass production.

Under muck soil conditions, cover crops used in this study produced significant biomass before being killed by frost (oilseed radish), or by herbicide or cultivation the following season (cereal rye, hairy vetch). Hairy vetch and oilseed radish biomass production was consistent during both seasons. However, cereal rye biomass productivity varied with growing conditions. The difference between years was more rainfall following rye planting in 2004. Low soil moisture content during germination and seedling establishment may be adverse to cereal rye growth on muck soils. Excessive moisture can however, result in poor rye establishment (Strock et al., 2004). In vegetable production, minimal residue and ease of incorporation are desirable cover crop characteristics during spring planting (Jackson et al., 1993). In this study, we observed considerable hairy vetch surface litter following incorporation that may interfere with celery transplanting. Also, timing cereal rye incorporation and celery transplanting is key to management practices.

Following the 2003 field season, beneficial effects of cropping systems were observed as an increase of soil mineral concentrations were seen. In 2004, although phosphorus remained constant across years, an increase in soil nutrient content occurred across treatments.

Soil microbial activity was affected by the cover crop treatments in Hamilton, but not affected by the treatments in Laingsburg. This differential response at the two sites is likely due to the cropping history of the sites. The Hamilton site was in continuous celery for over 10 years while Laingsburg was fallow for many years prior to the establishment of the experiment. It was therefore easier to affect soil microbial activity in the long term monoculture in Hamilton than in Laingsburg. These results support the importance of crop rotation and biodiversity in cropping systems.

While no differences in celery tissue NO_3^- N content were detected in treatments, growth and development were enhanced in the systems with high fertilizer rates. Also oilseed radish improved nitrate recycling and celery growth.

Cereal rye enhanced celery yield. However, high residue production may be detrimental to celery. When large cereal rye biomass was produced (Hamilton 2004), this resulted in stunting, yellowing, and low celery yield. The inhibition of growth may be attributed to either N immobilization or allelopathic potential. Cereal rye is known to produce allelochemicals (Barnes et al., 1987) that affect the growth of several species (Barnes and Putnam, 1983). Therefore, when using cereal rye as a cover crop, sufficient time should be allowed for residue breakdown prior to celery transplanting.

Oilseed radish increased celery yield both under the low and half rates of fertilizer. Oilseed radish produced large amounts of biomass which can create an environment more conducive to celery growth. This is in contrast to cereal rye. A study conducted by Ngouajio and Mutch, (2004) documented the ability of oilseed radish to scavenge residual soil N after crop harvest. Through rapid growth and production of a large root system, oilseed radish recycled 157.0 kg ton^{-1} of N (Ngouajio and Mutch, 2004). This recycled N is then released slowly to the following crop with several benefits to the crop and the environment (Baggs et al., 2000).

The results of this work suggests that cover crops evaluated, particularly oilseed radish, could be integrated into celery production with improved soil fertility, reduced fertilizer inputs, and increase yield. The effects of the cover crops on contribution to soil fertility between growing seasons should be further measured. Results will prove vital in development of nutrient management to address nitrate leaching. Finally, it is also important to determine the nutrient release curve of the cover crops in order to synchronize with celery crop demand and optimize their contribution to crop rotation systems.

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Table 3.1.
Cover crop seeding rate and total (above and below ground) dry biomass production in 2003 and 2004 at Laingsburg and Hamilton.

Cover crops species[x]	Seeding rate		Biomass			
	Laingsburg	Hamilton	Laingsburg		Hamilton	
			2003	2004	2003	2004
	$kg\ ha^{-1}$		$g\ m^{-2}$			
Hairy vetch	39	39	181 c[y]	114 c	147 c	-
Oilseed radish	28	28	719 a	480 a	585 a	691 b
Cereal rye	112	112	284 b	270 b	335 b	1599 a
Yellow mustard	-	22	-	-	-	822 b
Oriental mustard	-	13	-	-	-	714 b

[x] Biomass of oilseed radish, yellow mustard, and oriental mustard was evaluated in October of the year preceding the growing season (before they were kill by frost). Cereal rye and hairy vetch biomass was estimated in May prior to land preparation.
[y] All numbers within a column followed by the same letter are not statistically different ($\alpha = 0.05$, LSD).

Table 3.2.
Effects of cover crop and fertilizer on soil mineral nutrient concentration in Laingsburg during 2003 and 2004.

	Phosphorus[z]		Potassium		Magnesium		Calcium		NO_3^- N		Total N	
Cover crops[x] and fertilizer rates[y]	2003	2004	2003	2004	2003	2004	2003	2004	2003	2004	2003	2004
	mg kg^{-1}										(kg ha^{-1})	
Control plus Low	44	43	167	294	648	752	3968	5044	45 b	123	91 b	277
Hairy vetch plus Low	46	43	150	283	655	823	3750	5027	39 b	127	78 b	256
Cereal rye plus Low	47	44	175	319	633	776	3774	4988	43 b	123	85 b	249
Oilseed radish plus Low	47	52	264	444	580	714	3624	4888	65 a	159	131 a	321
Control plus Half	-	46	-	348	-	795	-	5339	-	122	-	247
Hairy vetch plus Half	-	45	-	348	-	899	-	5416	-	145	-	293
Cereal rye plus Half	-	47	-	329	-	798	-	5088	-	118	-	238
Oilseed radish plus Half	-	49	-	473	-	816	-	5303	-	158	-	318
Control plus Full	-	51	-	385	-	688	-	4450	-	111	-	223
P-value	NS	NS	NS	NS	NS	NS	NS	NS	0.0137	NS	0.0138	NS

Cover crop and soil samples were collected in spring 2003 and 2004 prior to land preparation and celery transplanting.
No fertilizer was applied prior to soil sampling in 2003.
[x] Effects result from cover crops sown in fall of 2002.
[y] Effects result from fertilization during 2003 field season and 2003 fall sown cover crops.
[z] Mean separation within columns and factors by the least square means test, $P < 0.05$.
[NS] Nonsignificant at $P > 0.05$.

Table 3.3.

Effects of cover crops on soil mineral concentration in Hamilton during 2004.

Cover crops[x]	Potassium[y]	Calcium	Magnesium	Phosphorus	NO_3^-N	Soil pH
	mg kg^{-1}					
Control	98	1138	120 b	23	7 b	6.5 a
Oilseed radish	98	1132	131 a	22	124 a	6.4 b
Cereal rye	86	1059	121 b	22	23 b	6.5 a
Oriental mustard	125	1138	121 b	23	113 a	6.3 b
Yellow mustard	109	1130	119 b	24	113 a	6.4 b
P-value	NS	NS	0.0490	NS	0.0001	0.0013

The cover crops were planted on August 30, 2003, and soil samples collected on May 10, 2004 prior to celery transplanting.

[x] Effects result from 2003 fall sown cover crops.

[y] Mean separation within columns and factors by the least square means test, $P < 0.05$.

[NS] Nonsignificant at $P > 0.05$.

Table 3.4.
Effects of cover crop and fertilizer on soil microbial activity in Laingsburg and Hamilton during 2004.

Cover crop and fertilizer rate[x]	Soil microbial respiration	Soil microbial C
	CO_2^- C (µg · g · soil^{-1} · day^{-1})	CO_2^- C (µg · g · soil^{-1})
Laingsburg		
Control plus Low	15.9 (3.1)[†]	293.8 (17.8)
Hairy vetch plus Low	16.1 (3.8)	322.2 (56.7)
Cereal rye plus Low	14.2 (2.9)	304.9 (68.3)
Oilseed radish plus Low	15.1 (2.3)	316.4 (33.1)
Control plus Half	15.9 (3.0)	329.6 (26.3)
Hairy vetch plus Half	13.3 (2.5)	311.1 (58.8)
Cereal rye plus Half	14.6 (3.0)	348.1 (53.7)
Oilseed radish plus Half	12.4 (3.8)	273.1 (47.8)
Control plus Full	13.6 (3.1)	301.8 (33.5)
P-value	NS	NS
Hamilton		
Control	14.0 (1.1) b[y]	321.2 (17.8) bc
Oilseed radish	15.6 (0.2) ab	305.0 (6.6) c
Cereal rye	18.4 (0.8) a	389.6 (35.1) a
Oriental mustard	15.9 (1.2) ab	371.6 (10.6) ab
Yellow mustard	9.5 (0.7) c	400.7 (9.3) a
P-value	0.0020	0.0277

[x] Fertilizer rates are Full, Half, and Low. The full rate was 180, 90, 450 kg ha^{-1} of N, P_2O_5, and K_2O, respectively. The half rate corresponded to 50% of the full rate. The low rate was 50% of the N applied in the full rate and no P_2O_5 and K_2O. All P_2O_5, K_2O, and 25% of N were top dressed and the remaining N side dressed in three equal applications during the season. In Laingsburg, soils were collected on September 20, 2004. No fertilizer treatments were used in Hamilton. In Hamilton, soils were collected on August 6, 2004.

[y] All numbers within a column and year followed by the same letter are not statistically different ($\alpha = 0.05$, LSD).

[†] Standard errors are parenthesized.

[NS] Nonsignificant at $P > 0.05$.

Table 3.5.
NO_3^- N accumulation by IER[x] in Laingsburg during 2003.

Cover crop and fertilizer rate[y]	mg NO_3^- N kg^{-1} resin
Control plus Low	927 (230)[z]
Hairy vetch plus Low	731 (408)
Cereal rye plus Low	623 (349)
Oilseed radish plus Low	1102 (362)
Control plus Half	493 (143)
Hairy vetch plus Half	898 (321)
Cereal rye plus Half	941 (362)
Oilseed radish plus Half	794 (404)
Control plus Full	680 (107)
P-value	NS

[x] IER refers to Ion Exchange Resin.
[y] Fertilizer rates are Full, Half, and Low. The full rate was 180, 90, 450 kg ha^{-1} of N, P_2O_5, and K_2O, respectively. The half rate corresponded to 50% of the full rate. The low rate was 50% of the N applied in the full rate and no $P_2O_5$and K_2O. All P_2O_5, K_2O, and 25% of N were top dressed and the remaining N side dressed in three equal applications during the season.
[z]Standard errors are parenthesized.
[NS] Nonsignificant at $P > 0.05$.

Table 3.6.
Effects of cover crop† and fertilizer†† on celery NO_3^- N concentration in Laingsburg and Hamilton during 2003 and 2004.

	Days after Transplanting (DAT)							
	2003[y]				2004			
Laingsburg	23[x]	43	64	84	23	43	64	84
	mg NO_3^- N kg^{-1}							
Control† plus Low††	-	620	635	469	489	556	518	359
Cereal rye plus Low	-	605	518	365	445	551	420	460
Hairy vetch plus Low	-	369	520	292	433	565	362	293
Oilseed radish plus Low	-	627	632	414	444	587	489	459
Control plus Half	-	620	439	451	376	436	275	240
Cereal rye plus Half	-	507	404	350	419	610	306	328
Hairy vetch plus Half	-	549	416	296	471	439	278	337
Oilseed radish plus Half	-	661	559	434	393	495	335	304
Control plus Full	-	546	606	352	507	583	253	219
P-value	-	NS	NS	NS	NS	NS	NS	NS

	Days after Transplanting (DAT)							
	2003[y]				2004			
Hamilton	32	44	64	75	31	52	72	88
	mg NO_3^- N kg^{-1}							
Control†	575	482	329	467	58 c	200	155	487
Hairy vetch	532	385	367	474	-	-	-	-
Oilseed radish	472	429	313	462	134 bc	336	339	197
Cereal rye	558	360	366	569	170 abc	229	233	121
Oriental mustard	-	-	-	-	264 ab	265	236	368
Yellow mustard	-	-	-	-	348 a	303	331	281
P-value	NS	NS	NS	NS	0.0458	NS	NS	NS

†† Fertilizer rates are Full, Half, and Low. The full rate was 180, 90, 450 kg ha^{-1} of N, P_2O_5, and K_2O, respectively. The half rate corresponded to 50% of the full rate. The low rate was 50% of the N applied in the full rate and no $P_2O_5$and K_2O. All P_2O_5, K_2O, and 25% of N were top dressed and the remaining N side dressed in three equal applications during the season. [x] Insufficient plant tissue for analysis.
[y] All numbers within a column and year followed by the same letter are not statistically different ($\alpha = 0.05$, LSD). [NS] Nonsignificant at $P > 0.05$.

Table 3.7.
Effects of cover crop and fertilizer on marketable celery yield in Laingsburg and Hamilton during 2003 and 2004.

Cover crop and fertilizer rate[x]	2003		2004	
	number of stalks[††] (x1000 ha^{-1})	yield (ton ha^{-1})	number of stalks[††] (x1000 ha^{-1})	yield (ton ha^{-1})
Laingsburg				
Control plus Low	44.7 (5.6) c	24.4 (5.5) b	40.2 (5.9) d	42.1 (8.3) bcd
Hairy vetch plus Low	46.5 (2.5) bc	23.9 (4.1) b	44.7 (2.3) cd	37.0 (3.3) d
Cereal rye plus Low	54.5 (4.9) abc	29.2 (2.2) b	49.1 (4.7) bcd	40.1 (4.6) cd
Oilseed radish plus Low	57.2 (4.4) abc	34.8 (4.7) ab	54.5 (5.5) abc	48.8 (6.0) abcd
Control plus Half	48.2 (1.8) bc	30.5 (4.1) ab	59.9 (0.90) ab	57.6 (3.0) ab
Hairy vetch plus Half	59.0 (3.4) ab	36.2 (4.3) ab	56.3 (5.1) ab	54.4 (6.3) abc
Cereal rye plus Half	55.2 (4.7) abc	37.8 (5.3) ab	57.2 (2.5) ab	56.3 (3.6) ab
Oilseed radish plus Half	66.1 (2.3) [†] a[y]	46.0 (3.0) a	60.7 (2.9) a	59.0 (5.6) a
Control plus Full	51.8 (7.4) bc	38.5 (11.1) ab	56.3 (3.4) ab	56.5 (6.3) ab
P-value	*	*	**	*
Hamilton				
Control	107.2 (15.5)[†] a[x]	94.9 (9.4) a	105.0 (5.67) a	102.2 (11.4) ab
Hairy vetch	111.5 (11.3) a	103.6 (10.4) a	-	-
Oilseed radish	98.6 (8.6) a	90.0 (7.3) a	111.5 (7.73) a	118.6 (7.7) a
Cereal rye	98.6 (8.6) a	92.4 (18.7) a	96.5 (11.13) a	89.0 (7.7) b
Oriental mustard	-	-	105.0 (2.14) a	104.5 (2.4) ab
Yellow mustard	-	-	107.2 (7.73) a	115.4 (9.4) a
P-value	NS	NS	NS	*

[x] Fertilizer rates are Full, Half, and Low. The full rate was 180, 90, 450 kg ha^{-1} of N, P_2O_5, and K_2O, respectively. The half rate corresponded to 50% of the full rate. The low rate was 50% of the N applied in the full rate and no P_2O_5 and K_2O. All P_2O_5, K_2O, and 25% of N were top dressed and the remaining N side dressed in three equal applications during the season. [y] All numbers within a column and year followed by the same letter are not statistically different ($\alpha = 0.05$, LSD). [†]Standard errors for the before and after category means are parenthesized. [††]stalks ha^{-1} (x1000).

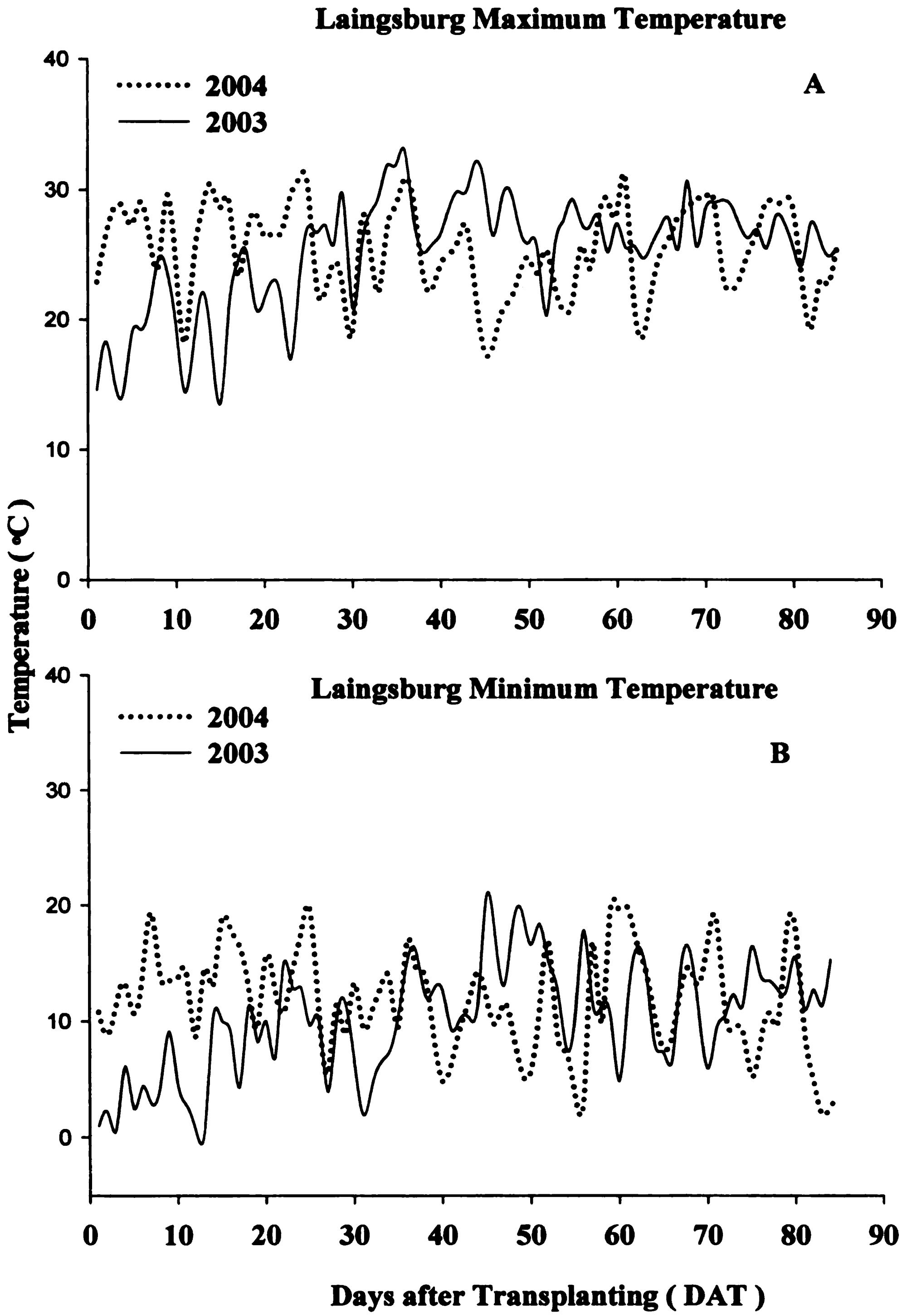

Fig. 3.1. Daily maximum (A) and minimum (B) temperature of Laingsburg during celery growth season in 2003 and 2004. Celery transplanted on 23 May 2003 and 28 June 2004 in Laingsburg. Data recorded in Bath weather station.

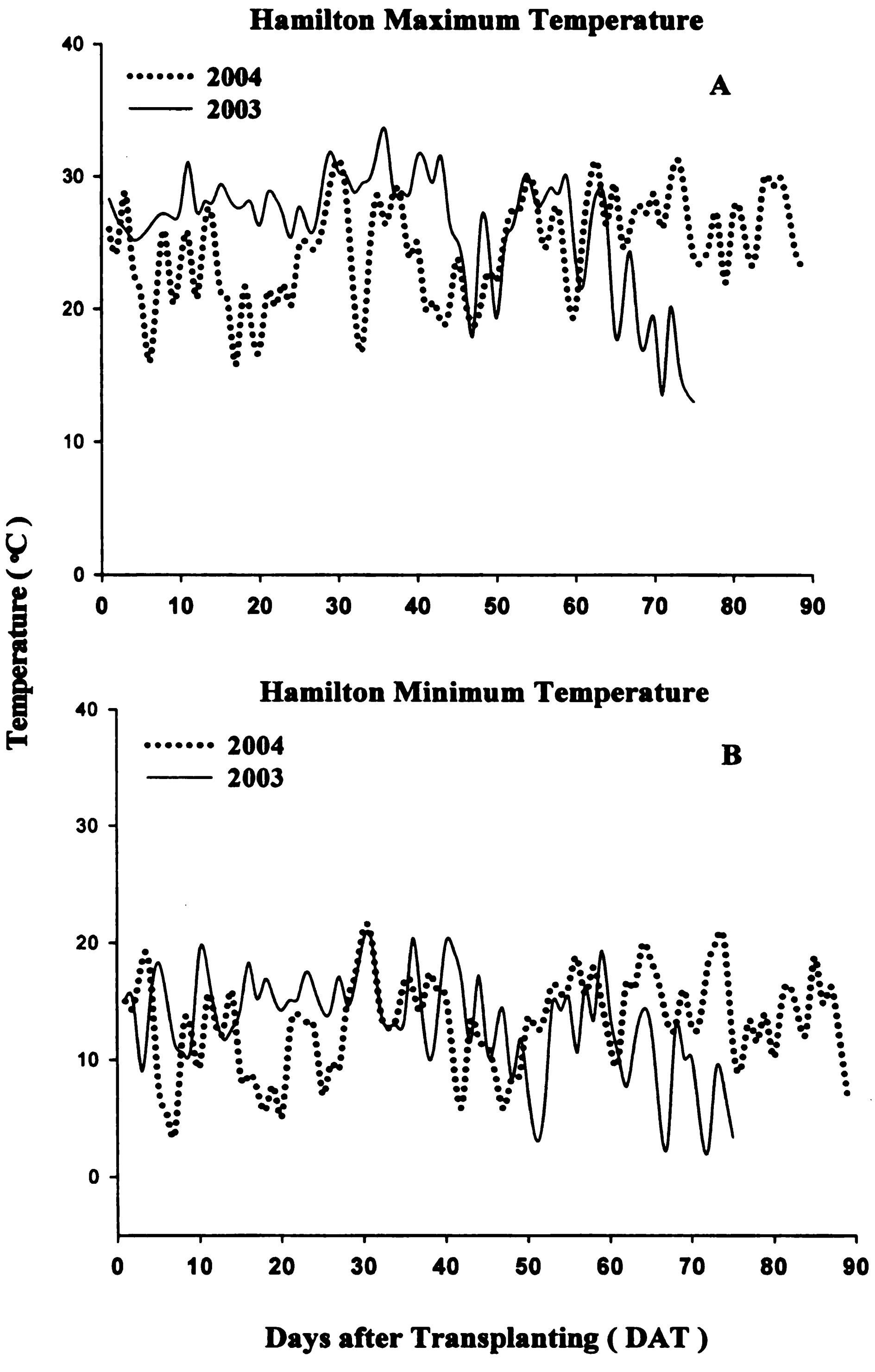

Fig. 3.2. Daily maximum (A) and minimum (B) temperature of Hamilton during celery growth season in 2003 and 2004. Celery transplanted on 13 May 2003 and 10 May 2004 in Hamilton. Data recorded in Hudsonville weather station.

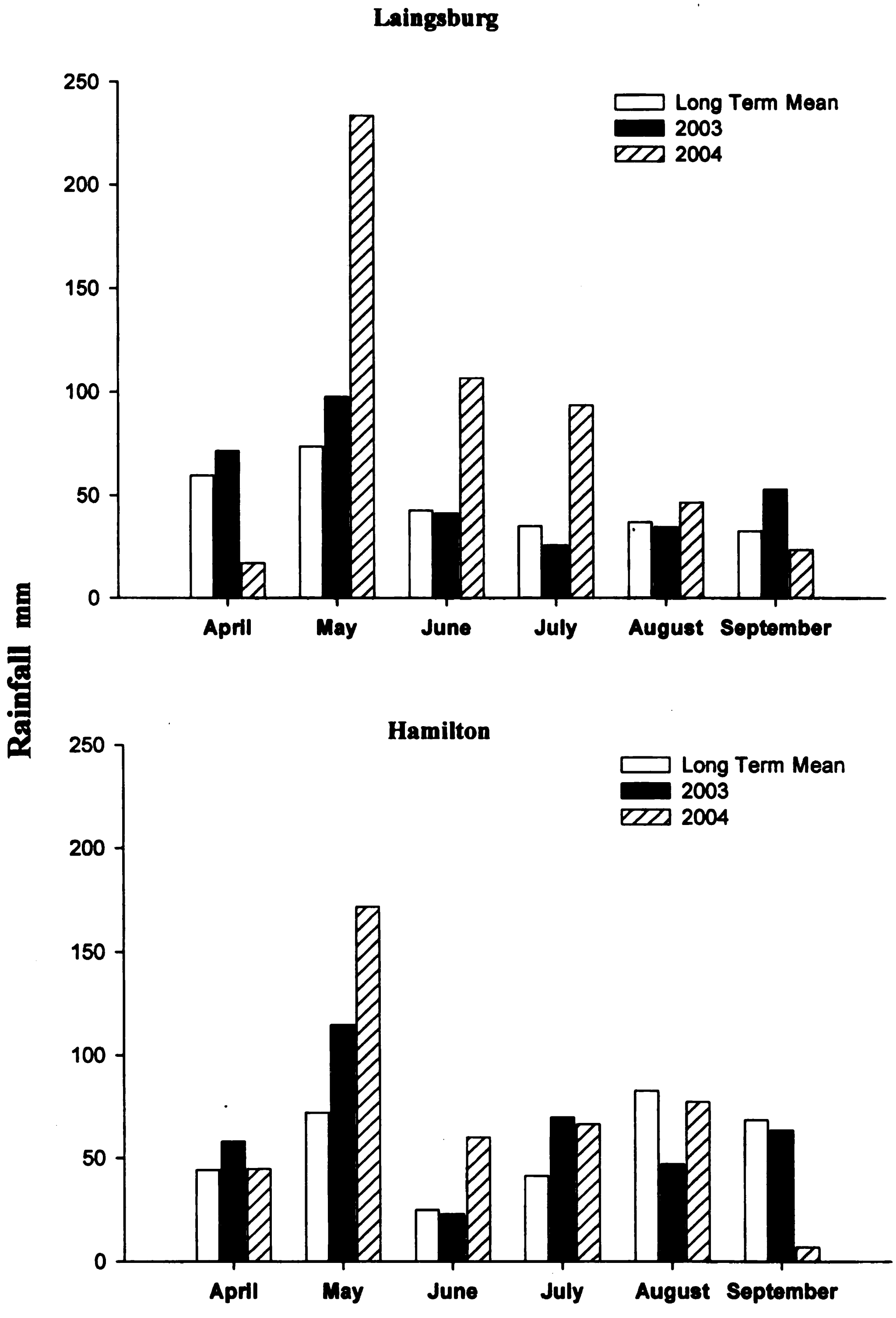

Fig. 3.3. Total monthly rainfall at Laingsburg and Hamilton during celery growth season in 2003 and 2004. Data recorded in Bath and Hudsonville weather stations. The long term means are from 2001-2003 in Laingsburg and Hamilton.

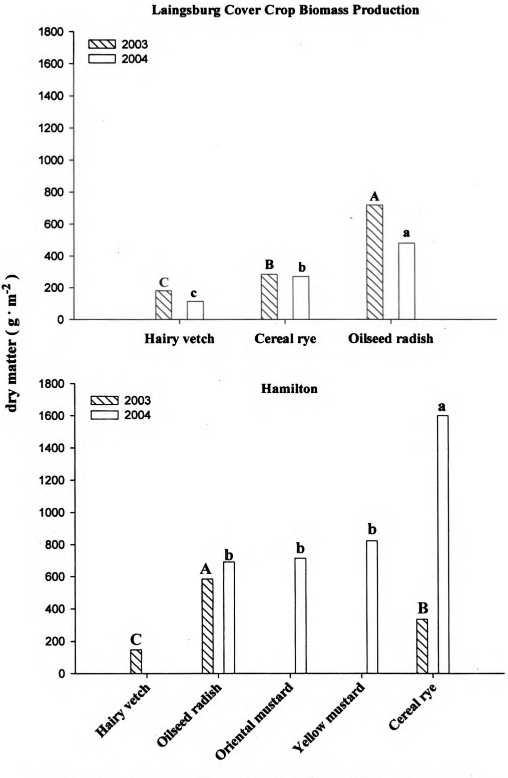

Fig. 3.4. Cover crop (total) biomass yield in 2003 and 2004 growing seasons. In Hamilton, mustards were not seeded in 2003 nor was hairy vetch in 2004.

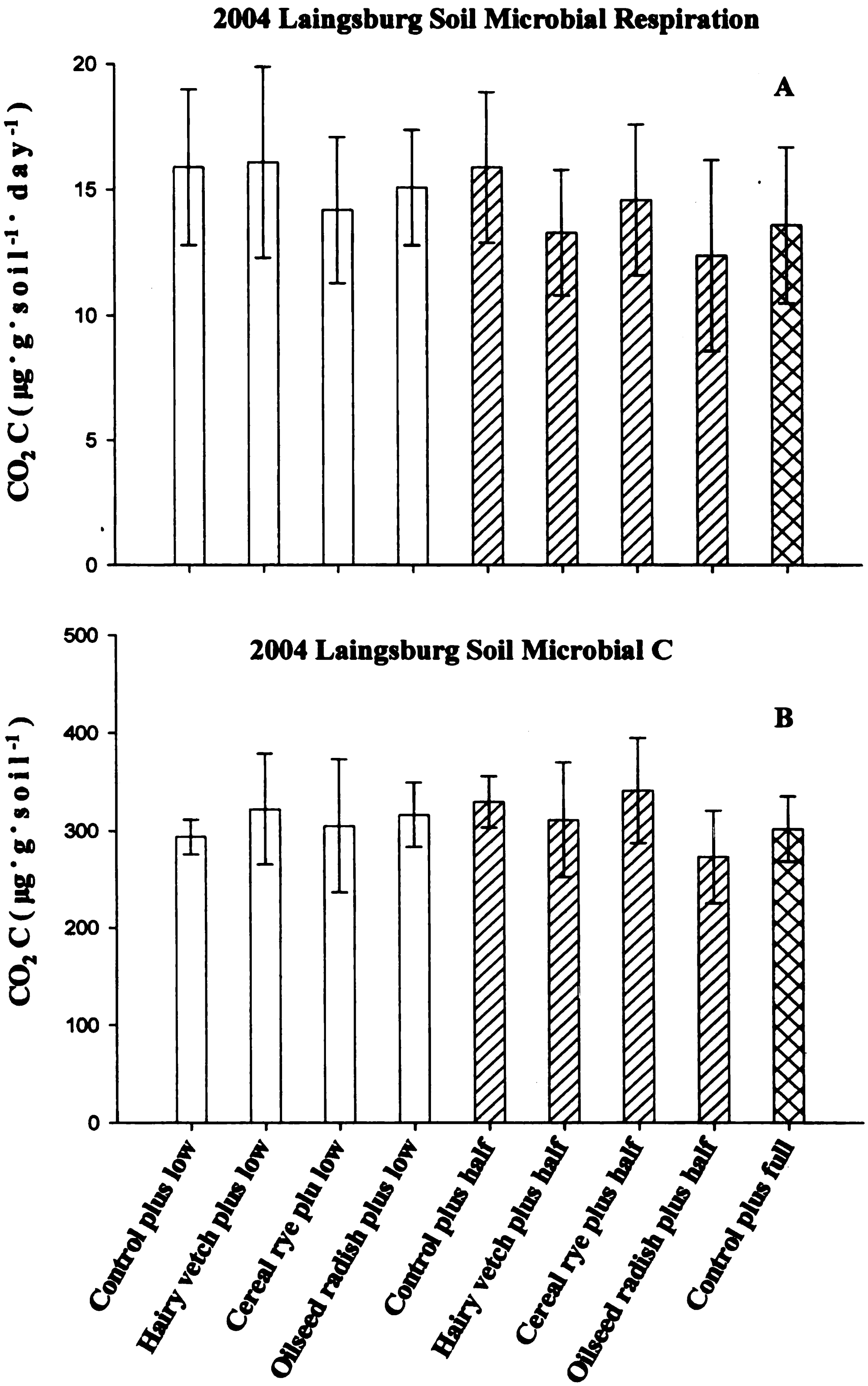

Fig. 3.5. Laingsburg microbial soil respiration (A) and microbial biomass C (B) during celery growing season in 2004.

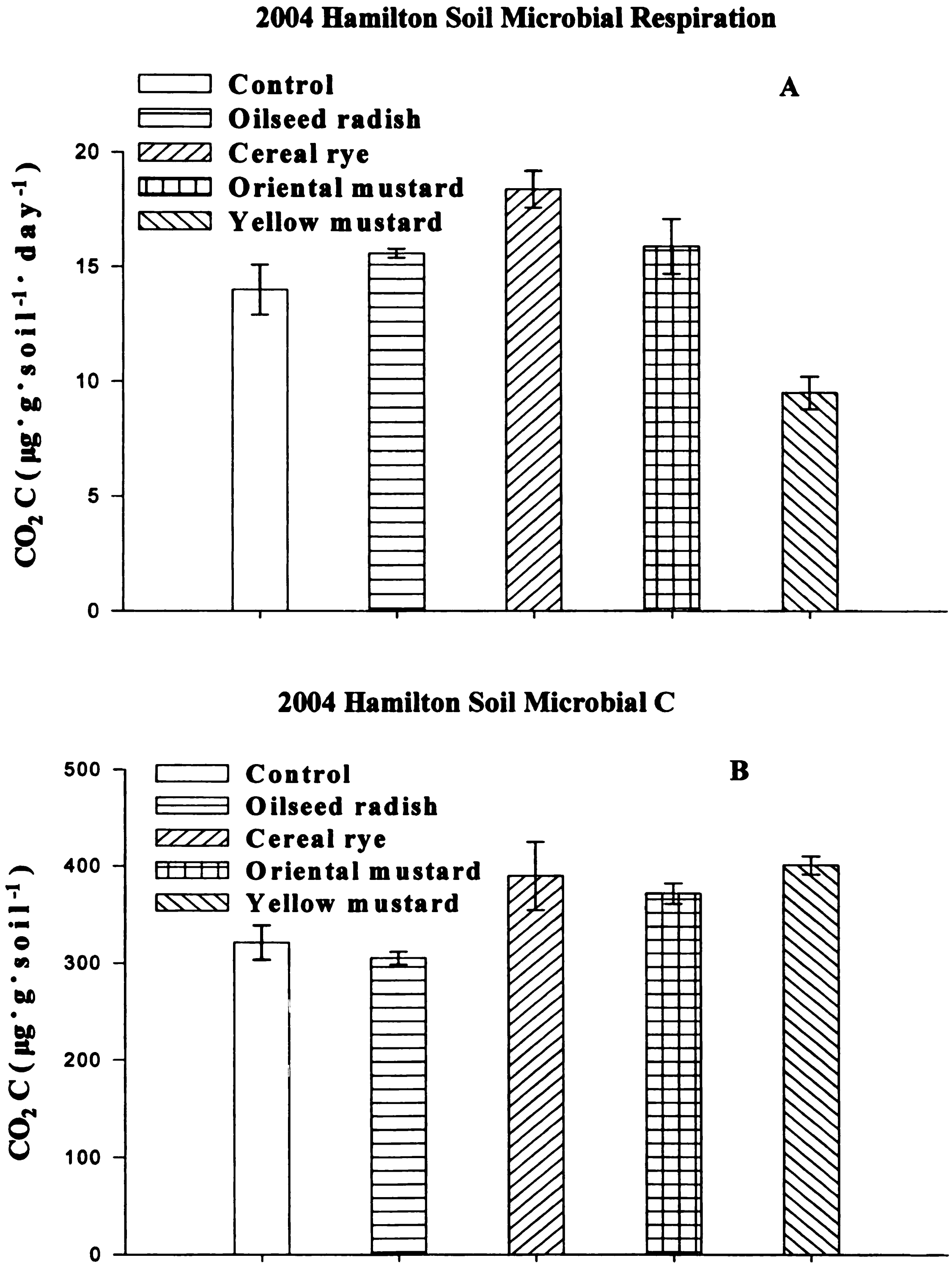

Fig. 3.6. Hamilton microbial soil respiration (A) and microbial biomass C (B) during celery growing season in 2004.

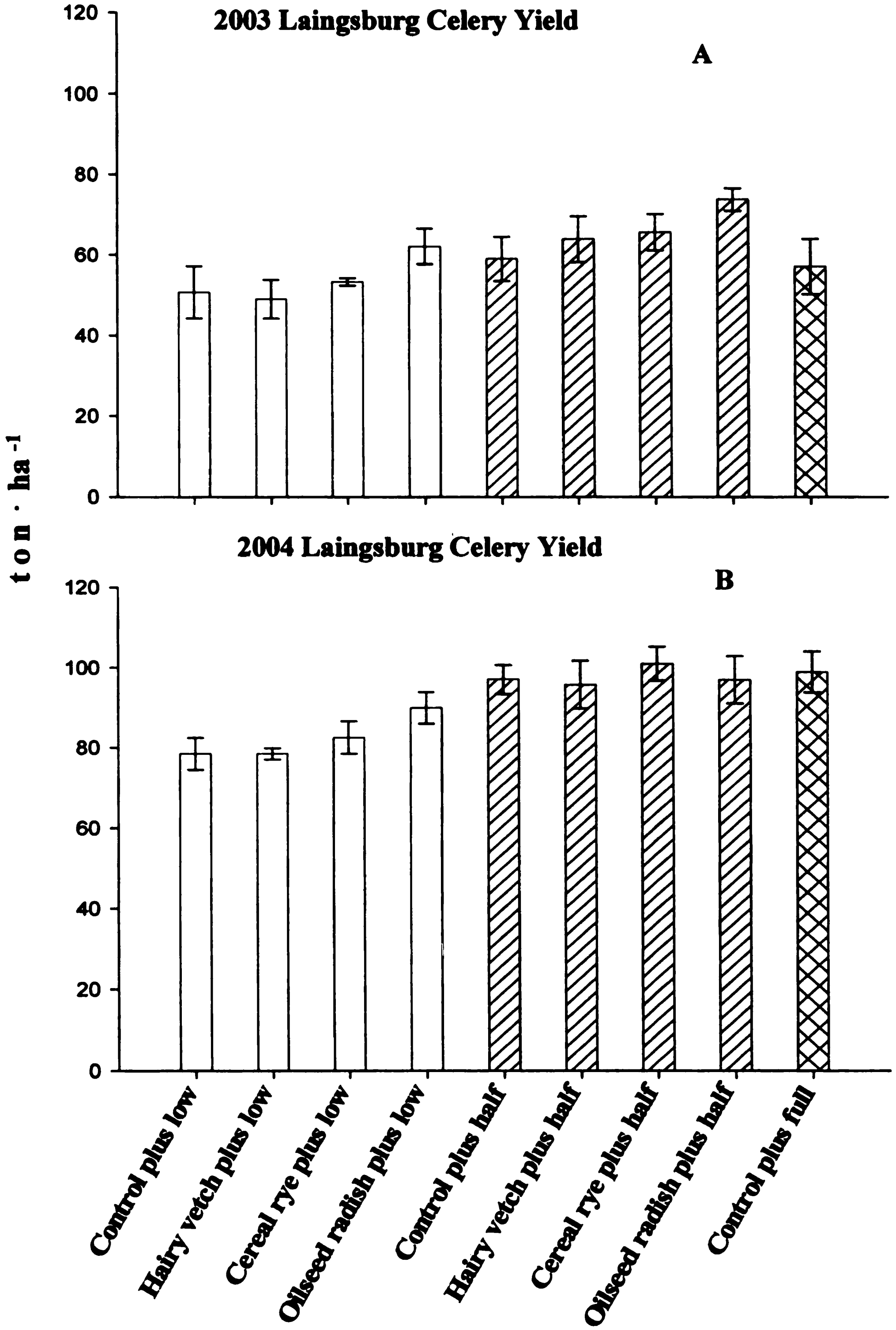

Fig. 3.7. Celery total yield before trimming stalks as influenced by cover crop and fertilization in 2003 (A) and 2004 (B) at Laingsburg. Means separation by the least squares means test, $P < 0.05$.

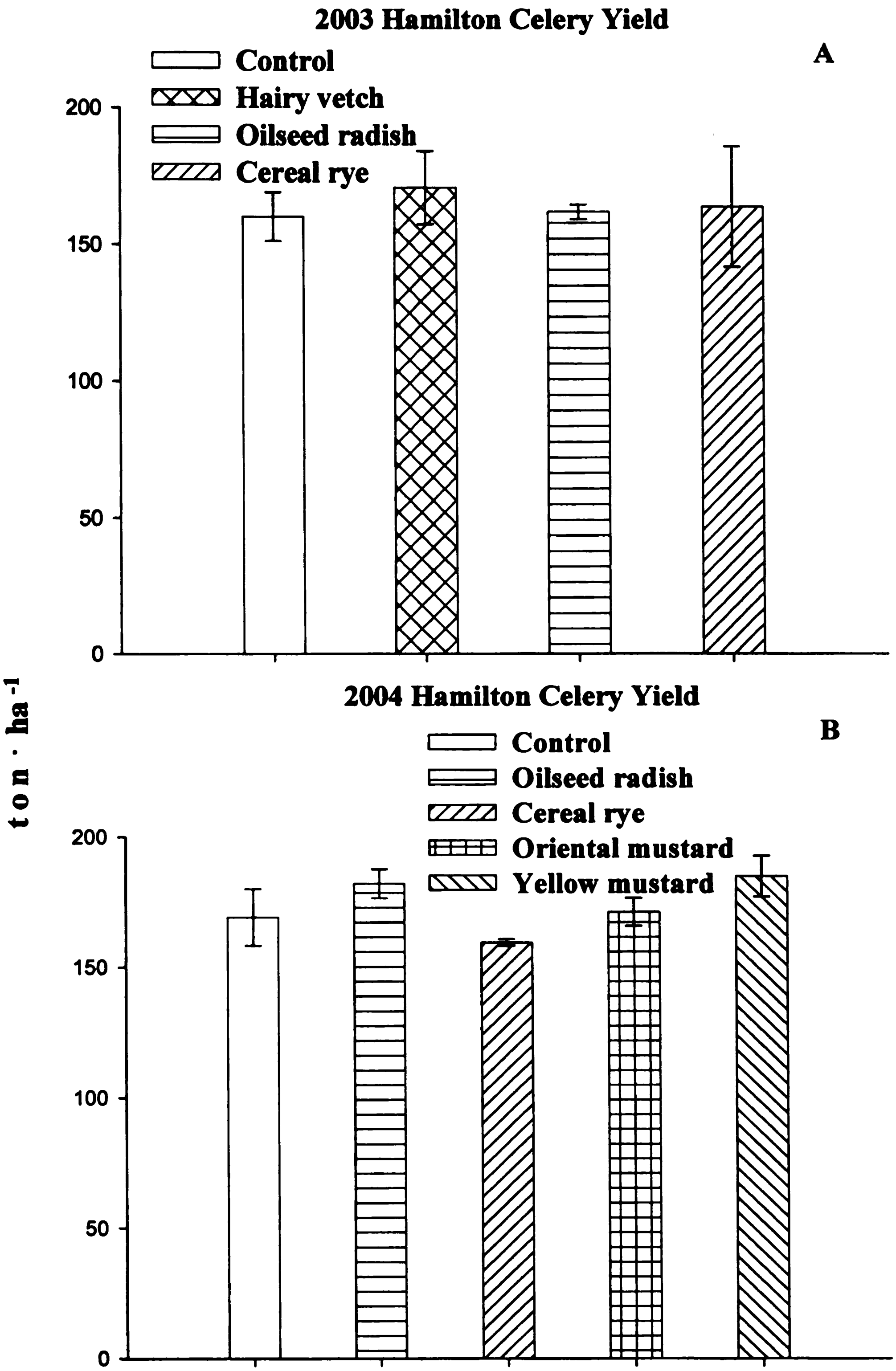

Fig. 3.8. Celery total yield before trimming stalks as influenced by cover crop and fertilization in 2003 (A) and 2004 (B) at Hamilton. Means separation by the least squares means test, $P < 0.05$.

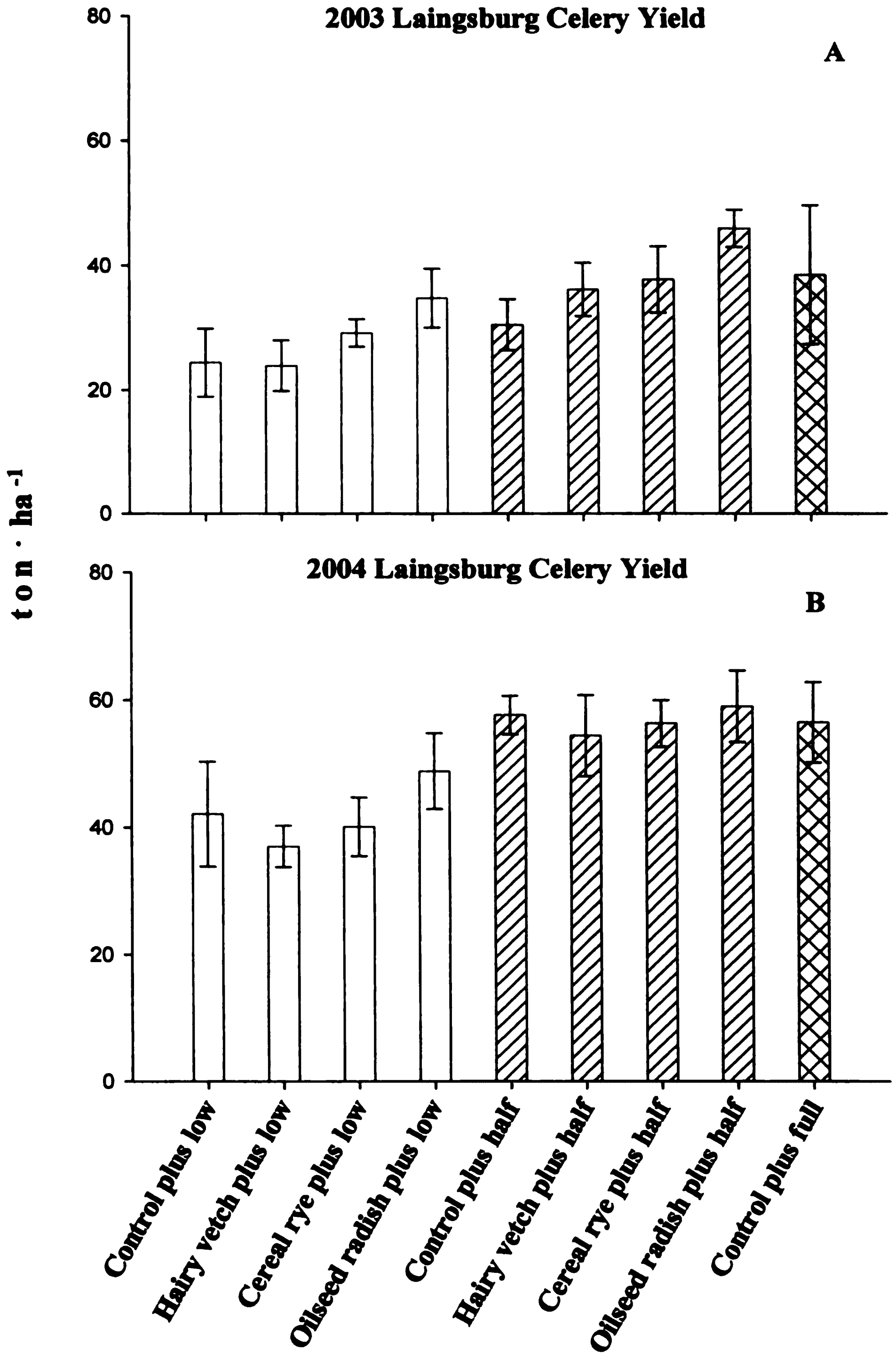

Fig. 3.9. Celery marketable yield after trimming stalks as influenced by cover crop and fertilization in 2003 (A) and 2004 (B) at Laingsburg. Means separation by the least squares means test, $P < 0.05$.

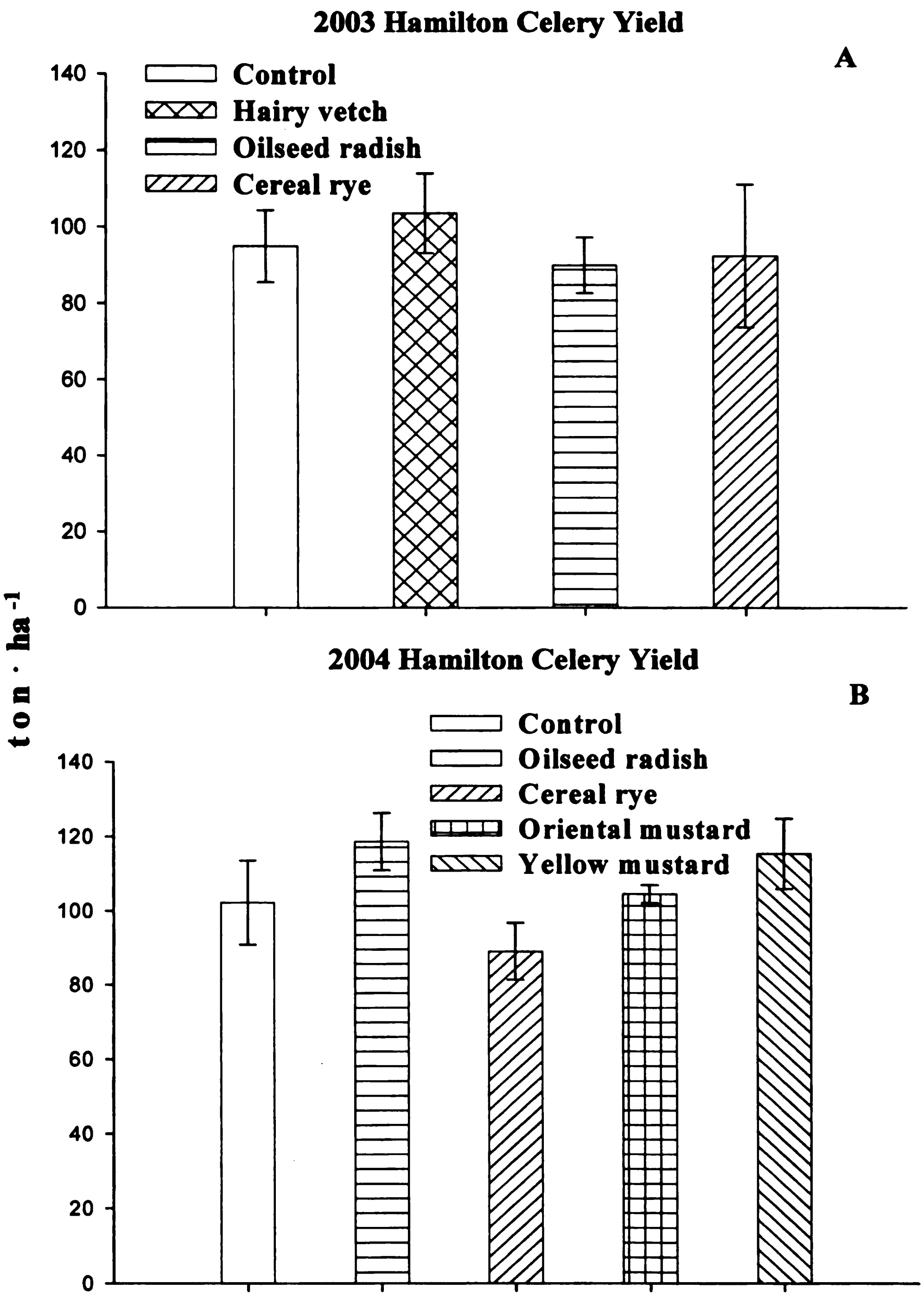

Fig. 3.10. Celery marketable yield after trimming stalks as influenced by cover crop in 2003 (A) and 2004 (B) at Hamilton. Means separation by the least squares means test, $P < 0.05$.

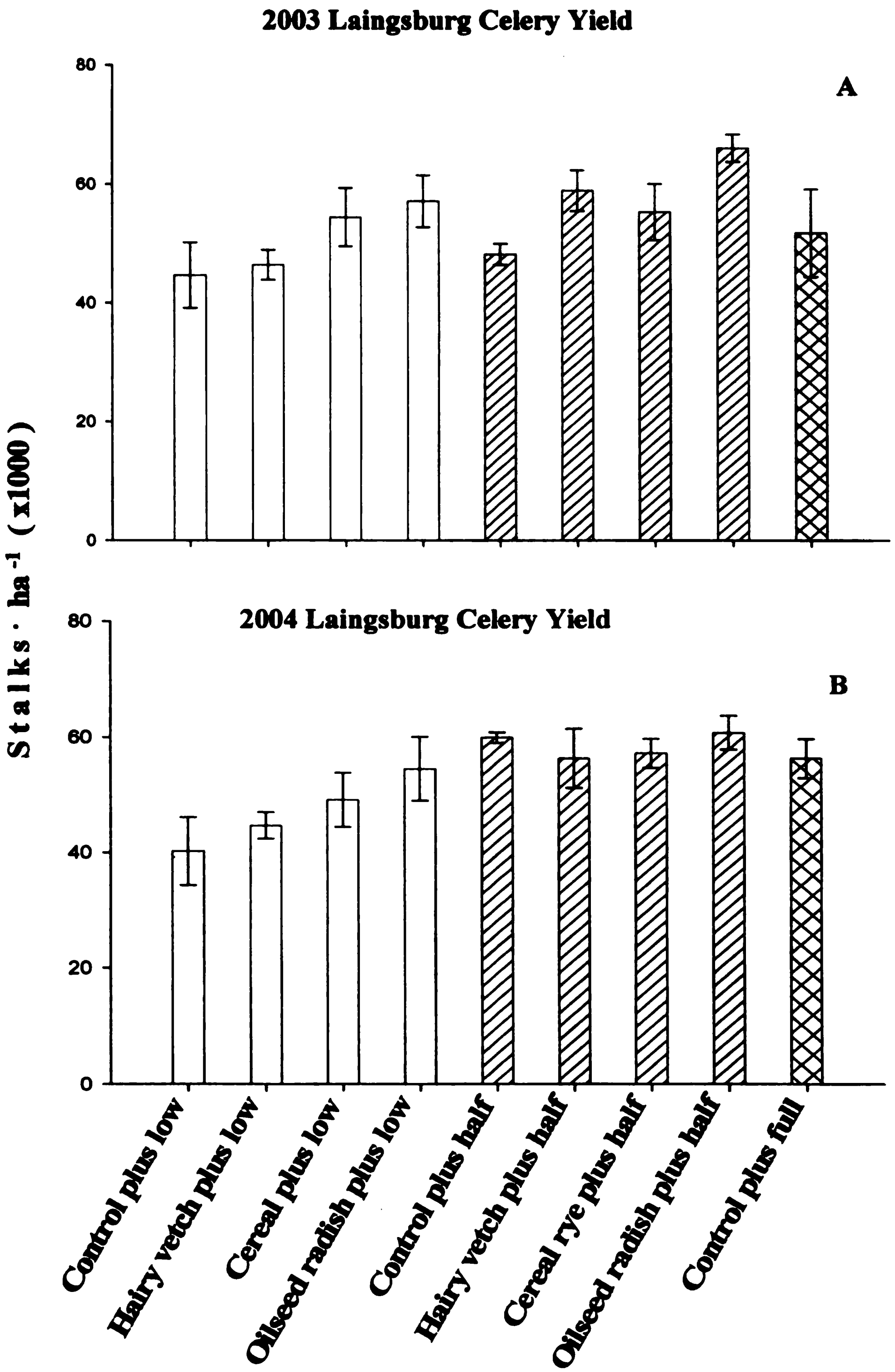

Fig. 3.11. Number of marketable celery stalks as influenced by cover crops and fertilization in 2003 (A) and 2004 (B) at Laingsburg. Means separation by the least square means test, $P < 0.05$.

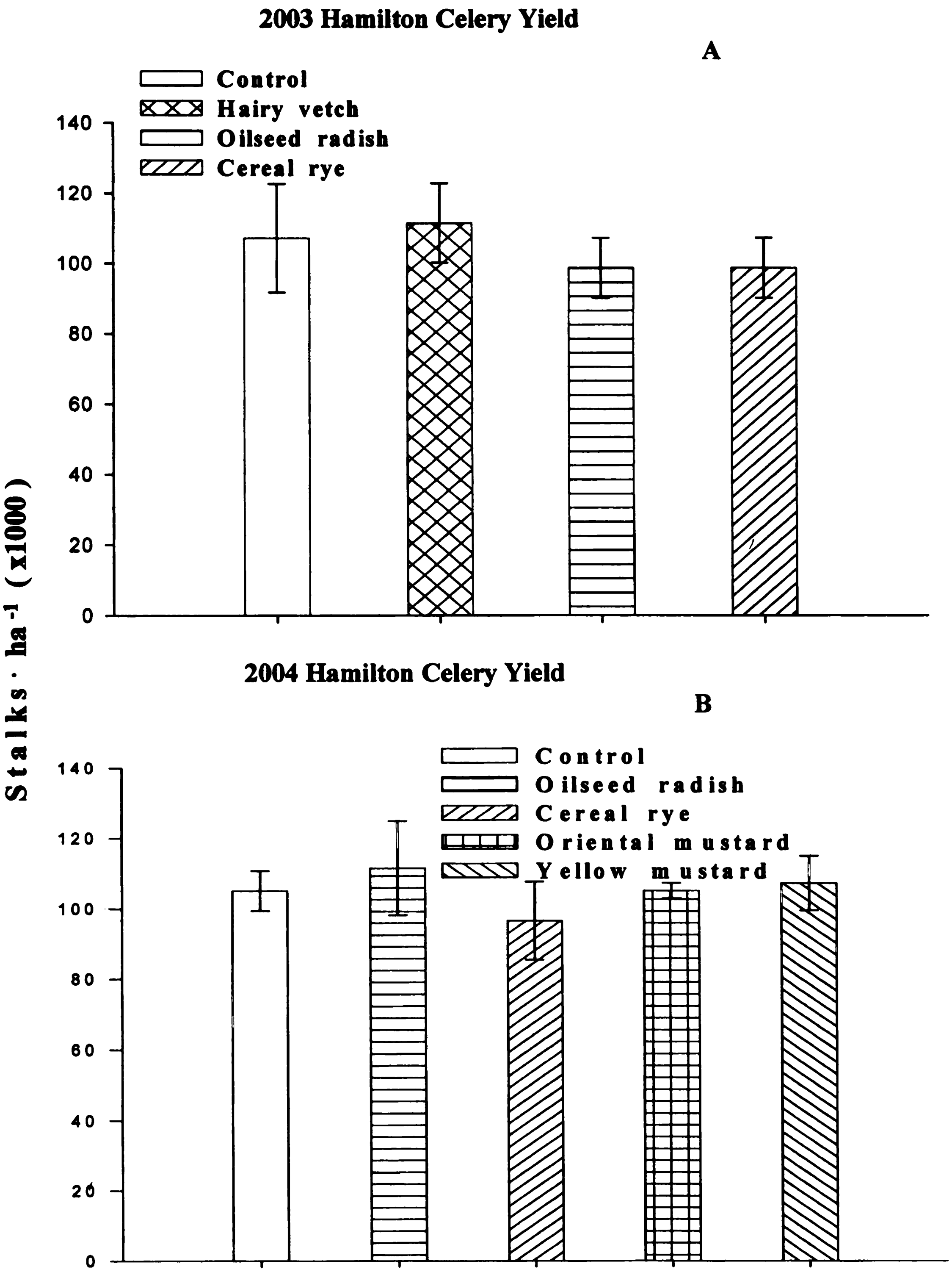

Fig. 3.12. Number of marketable celery stalks as influenced by cover crops in 2003 (A) and 2004 (B) at Hamilton. Means separation by the least square means test, $P < 0.05$.

Chapter 4: Integration of cover crops and fertilizer rates for weed management in celery (*Apium graveolens* L.).

ABSTRACT

A number of studies have shown that weed suppression can be improved using cover crops and different fertilization strategies. However, little is known about these effects on weed population dynamics on high organic matter (>80% OM) soils. Field studies were carried out in Laingsburg, MI from 2002 to 2004 on Houghton muck soil to assess the impacts of cover crops and soil fertility regimes on weed populations and celery yield. The cover crops were oilseed radish, cereal rye, hairy vetch, and a bare ground control. The fertility rates were full (180, 90, and 450 kg ha^{-1} N, P_2O_5, K_2O), half (90, 45, and 225 kg ha^{-1} N, P_2O_5, K_2O), and low rate (90 kg ha^{-1} N). Each cover crop treatment was combined with the low or half rate of fertilizer. An additional treatment with bare ground plus the full rate of fertilizer was added as standard practice. Treatments were maintained in the same location for the duration of the study. Major weed species were common chickweed, prostrate pigweed, shepherd's-purse, common purslane, and yellow nutsedge. Each year, oilseed radish consistently produced the greatest biomass and provided over 98% early season weed suppression. Hairy vetch and cereal rye provided over 75% weed suppression in early spring. Unlike the 2003 season, weed populations were affected by the soil fertility level during the 2004 growing season. Weed biomass increased as fertilizer rate increased, but total density was not affected. Within individual fertility levels, higher celery yields were recorded in the oilseed radish plots. For example, in the low fertility rate, celery yield was 34.8, 29.2, 23.9, and 24.4 ton

ha^{-1} in the oilseed radish, cereal rye, hairy vetch, and control plots, respectively in 2003. Overall, the results of this experiment indicate that cover crops can successfully improve weed management and celery yield on muck soils, while allowing reduction of fertilizer inputs.

INTRODUCTION

Michigan is the second largest producer of fresh market and processing celery after California (USDA 2005). In 2004, 931 ha of celery were planted in Michigan, and total crop value was estimated at $19 million. Michigan growers rely on intensive celery production systems. Most of the production is conducted on Houghton muck soil with short-term rotations. The lack of long-term rotations has led to a resurgence of troublesome weeds and has diminished soil fertility levels. Currently, Michigan producers are becoming increasingly interested in a more comprehensive weed and fertility management approaches that address these concerns. Cover crops have shown many benefits when used between growing seasons (Mutch and Snapp 2003; Ngouajio and Mennan 2005; Teasdale 1998). One of the objectives of using annual cover crops in temperate regions is to manage the soil with over-wintering species that produce considerable biomass during the spring. Winter annual cover crops are planted in late summer or fall, become established before winter, and produce most biomass during early spring before planting a summer crop (Teasdale 1996).

Cover crops can be used as a potential tool in restoring soil fertility and reducing weed competition in cropping systems. However, due to the short growing season, Michigan producers are limited to selection and timing options of cover crop as a planting challenge. Early transplanting of celery is harvested in mid July to early August and can allow for rapid establishment of vegetation prior to the fall frost. Therefore, selection of cover crops is critical. Oilseed radish is a cool season cover crop that can be planted in Michigan after harvest of a warm season cash crop. Cereal rye and hairy vetch are winter annual cover crops that can consistently perform well in Northern climates.

Winter annual cover crops are best adapted to areas where there is a sufficient establishment period in the fall and soil moisture is not limiting in the spring (Teasdale 1996). In Michigan, there is a small window following harvest of most vegetables when cover crops can be introduced and established prior to the onset of cool climates. Exploiting these cover crop niches could allow improving weed control and soil fertility management approaches (Snapp et al. 2005).

The use of cover crops in sustainable farming systems has been a common practice for many years (Burket et al. 1997). Cover crop usage is well documented and includes: erosion control, reduced runoff, improved infiltration, soil moisture retention, and improved soil tilth, (Blevins et al. 1990; Hall et al. 1984; Robinson and Dunham 1954; Teasdale 1996; Teasdale and Mohler 1993; Utomo et al. 1990). In addition to the many benefits, cover crops can also provide weed control (Gallandt et al. 1999; Ngouajio and Mutch 2004; Williams et al. 1998), and improve soil fertility (Kuo and Jellum 2002; Ranells and Wagger 1996).

The management of weeds is vital to the success of sustainable farming systems. The principal goal of using cover crops for weed control is replacing an unmanageable weed population with a manageable cover crop (Teasdale, 1996). Cover crops effectively suppress weeds by competition and changing environmental factors that affect moisture used for weed germination (Fisk et al. 2001), emergence, and establishment (Liebman and Davis 2000). Residue biomass in the form of plant litter alters physical parameters of soils and can significantly influence plant communities (Facelli and Pickett 1991) by inhibiting the emergence of most plant species (Teasdale and Mohler 2000). Cover crop residue can also modify environmental conditions that have an impact on weed communities. Altered environmental conditions include changes in soil temperature, decrease in soil moisture, as well as release of allelopathic chemicals and/or physical impediments to weed seedlings (Facelli and Pickett 1991; Fisk et al. 2001; Teasdale 1996; Teasdale and Mohler 1993).

Nitrogen (N) fertilizers are important nutrient input sources used in vegetable production to enhance crop yields. However, nutrients may promote growth of crops (Everaats 1992) as well as weeds (Sindel and Michael 1992; Teyker et al. 1991). The ability of weeds to efficiently use and assimilate minerals can lead to interference with crops (Blackshaw et al. 2004; DiTomaso 1995; Sibuga and Bandeen 1980). The ensuing competition favoring weeds in most scenarios results from vigorous weed seedlings and is a detriment to crop yields (Dhima and Eleftherohorinos 2001). Increasing crop competitiveness during such interactions is an important component of strategic fertility systems, particularly within weed management programs. Cultural practices using reduced fertility levels (Dyck and Liebman 1994) and fertilizer placement (Melander and Jorgensen 2003) have been used successfully to manage weeds.

To our knowledge, no study has focused on the effect of cover crops and fertilizer regimes on weed population on muck soil in general and celery in particular. Because of the high organic matter content of muck soil and the high soil fertility requirements of celery, integration of cover crops and fertilization regimes may have significant effects on weed populations and celery yield. For this reason, this research was conducted to: (i) evaluate the potential for integrating cover crops into a celery production system, (ii) measure the effects of cover crops and soil fertility on weed populations, and (iii) evaluate celery yield as affected by cover crops and fertilization.

MATERIALS AND METHODS

Experimental Site

This study was conducted on a Houghton muck soil with 80 % organic matter and pH of 6.2-6.9 from 2002 to 2004. The experimental site was located on Michigan State University's Muck Soils Research Farm in Laingsburg, MI. The initial experiment was established in summer of 2002 on land that was previously fallow during the summer.

The experiment had four cover crops and three fertilizer rates. Cover crop treatments were oilseed radish (cv. diakon), cereal rye (cv. VNS), hairy vetch (cv. common), and bare ground. Establishment occurred in late summer (26 August 2002 and in 25 August 2003) following the celery crop harvest, using a broadcast method and incorporated by shallow discing. Oilseed radish, cereal rye, and hairy vetch were seeded at rates of 28, 112, and 39 kg ha^{-1}, respectively.

The 3 rates of fertilizer were: full rate (180, 90, and 450 kg ha^{-1} N, P_2O_5, K_2O), half rate (90, 45, and 225 kg ha^{-1} N, P_2O_5, K_2O), and low rate (90 kg ha^{-1} N). The full rate was the recommendation for commercial celery production on muck soils in Michigan. Each year, 25% of N and all of P, and K were broadcast during land preparation (20 May 2003 and 28 June 2004); equal amounts of the remaining N rates were applied at three subsequent side dressings during the growing season (13 June, 3 July, 25 July in 2003 and 21 July, 10 August, and 31 August in 2004). The experimental design was a randomized complete block with four replications. Treatments were combinations of cover crop and fertilizer rate and consisted of the four cover crop plus low or half rate of fertilizer. A bare ground plus high rate of fertilizer (normal practice) was also included for a total of 9 treatments. Individual plots were 4.1 m by 10.7 m and contained four rows of celery at 0.15 m in-row spacing and separated by 1.5 m buffer. Individual plots were hand weeded during the season and a 1m^{-2} area was maintained undisturbed throughout the season for weed assessment. Celery was transplanted on 23 May 2003 and 28 June 2004. At maturity, 20 plants were harvested on 12 August 2003 and 20 September 2004. All cover crop and fertilizer treatments were maintained in the same location throughout the duration of the study.

DATA COLLECTION

Cover crop total biomass was collected from each plot in 2003 and 2004 growing seasons using a randomly placed 50- by 50-cm quadrat. Oilseed radish is ill adapted to freezing temperatures thus; biomass sampled on October 2002 and 2003 prior to being frost killed. Because hairy vetch and rye are winter hardy, their biomass was sampled the following spring (8 May 2003 and 6 May 2004). Cereal rye, hairy vetch, and weeds in other treatments were then killed with glyphosate prior to land preparation. Cover crop biomass was determined after oven drying at 75 ^{o}C until constant weight was achieved.

Winter annual weed density was assessed in all plots using a randomly placed 50- by 50-cm quadrat per plot each year (May 6 in 2003, and May 8 in 2004) prior to cover crop incorporation, fertilizer application, and land preparation. The effect of cover crops and fertilizer on weed populations was determined during the growing season. Weed density and dry weight were assessed twice: following celery transplanting (on June 18, and July 9 in 2003 and July 21, and August 18 in 2004) before each fertilizer side dressing. Sampling was conducted as described above. The Weeds were separated by species, and then all species were combined and dried at 75 ^{o}C until constant weight was obtained for dry biomass measurement. To avoid weed interference with celery, weed evaluations were conducted on undisturbed, permanently established microplots within each experimental unit. During the 2003 and 2004 growing season, hand weeding and hoeing were used to maintain weed free celery plots following each weed survey.

Celery harvest was manually conducted in the two center rows of each plot in 2003 and 2004. At harvest, plants were separated into marketable and non-marketable yields, according to market standards. Generally, marketable plants are qualified as well developed; well-formed plants with a minimum stalk length of 30 cm (USDA 1959). Stalk length was measured from soil surface to plant crown. Stalk weight was measured before trimming and after trimming in each category.

Statistical Analysis

Data on weed density and species composition were transformed to the $\log_{10}$ to meet homogeneity of variance and normality assumptions of ANOVA (Laufenberg et al. 2005). A value of 0.001 was added to all data to adjust zero for transformation. All data were then back transformed for clarity of presentation and tables. ANOVA was conducted on all data using the PROC GLM of SAS and means separated using Fisher's Protected LSD at 5 % probability level (SAS Institute, Inc. 1999). Species richness was determined by using the number of weed species retrieved from respective plots (Ngouajio and Mennan 2005). Cover crop biomass, weed variables, and celery yield data are presented separately for each year because of significant year by treatment interactions.

RESULTS AND DISCUSSION

Climate

The weather conditions during the two celery-growing seasons differed greatly (Figures 4.1 and 4.2). Because of excessive rainfall (234 mm) in May of 2004, celery transplanting was delayed until June 28. Consequently, both daily maximum and minimum temperatures were higher in 2004 than in 2003 (Figure 4.2). At celery transplanting, maximum daily temperature was below 15 °C in 2003 and above 20 °C in 2004.

Cover Crop Biomass Production

Oilseed radish produced the greatest biomass in both years, with 7,186 and 4,797 kg ha^{-1} in 2003 and 2004, respectively (Figure 4.3). Cereal rye and hairy vetch produced 2,839 and 1,808 kg ha^{-1}, respectively in 2003, and 2,699 and 1,044 kg ha^{-1}, respectively in 2004. Unlike oilseed radish that was killed by frost in late fall, both cereal rye and hairy vetch continued growth until spring killed with glyphosate. Hairy vetch developed an extensive root system that persisted after land preparation and interfered with celery transplanting.

Effects of Cover Crop and Fertilizer on Weed Density and Species Composition

Weed density varied with year (Table 4.1). However, oilseed radish provided the greatest weed suppression in both 2003 and 2004 for evaluations conducted in May prior to land preparation. In 2003, weed density was 264 plants m^{-2} in the control plot and only 21 plants m^{-2} in the oilseed radish plot. Weed density in the cereal rye, and hairy vetch plots was 91 and 117 plants m^{-2}, respectively, and were significantly lower than weed density in the bare ground plot. Similar results were obtained in 2004 during the first evaluation in May 6. Oilseed radish plots had the lowest weed densities, regardless of the fertility level. Densities ranged from 49 to 51 plants m^{-2} in the oilseed radish plots compared with 200 to 313 plants m^{-2} in the control plots. The fertilization regime used in the previous crop did not translate into significant differences in weed infestations in 2004. However, there was a general tendency in all treatments (except cereal rye) for greater weed densities as the fertility levels increased.

In-season weed suppression also varied with year (Table 4.1). In 2003, evaluations conducted in June 18 (28 DAT, days after transplanting) showed more weeds in the oilseed radish plots, compared with the control plots with high rate of the fertilizer. Weed densities were 853 m^{-2} in the oilseed radish plus low fertilizer, 723 plants in the oilseed radish plus half fertilizer, and only 309 in the control plus full fertilizer. All other treatments had equivalent weed infestations. No differences in weed densities were observed for second in-season evaluation in 2003 and both in-season evaluations in 2004.

The prevalent species during the growing season were common chickweed (*Stellaria media*), common purslane (*Portulaca oleracea*), prostrate pigweed (*Amaranthus blitoides*), shepherd's-purse (*Capsella bursa-pastoris*), and yellow nutsedge (*Cyperus esculentus*) (Figure 4.4). During the growing season, the major weed species present in the experimental plot and their relative contribution to total populations changed as the season progressed (Figure 4.4). In May and early June when maximum air temperature was below 15 °C, the prominent species was common chickweed. By the end of June, a significant shift in weed population occurred. Most of the chickweed populations were replaced by prostrate pigweed and common purslane. From July to August the population of pigweed declined while that of common purslane increased. Finally, in August when air temperature started to decline, the population of chickweed started to increase again in the plots. It is important to note that weed populations observed at successive dates were from different flushes since the entire plot was weeded after each evaluation. The simultaneous presence of both winter annual and warm season weeds on Michigan organic soils makes weed control highly challenging. Common chickweed, prostrate pigweed, and common purslane were the most important species. Yellow nutsedge is another troublesome weed in muck soil in Michigan (Zandstra 2005), but was only recorded in significant numbers in May of 2004. Early in the season, common chickweed accounted for 52 and 84 % of the total population in 2003 and 2004 (Figure 4.4). Common purslane although less, contributed 21 and 47 % (2003) and 84 and 76 % (2004) of the total weed population.

In 2003, oilseed radish significantly reduced the density of common chickweed and shepherds purse in early spring (Table 4.2). Cereal rye also reduced the density of shepherd's-purse. However, during the growing season, none of the major weed species was affected by the treatments. In 2004, weed suppression in early spring was similar to 2003 observations (Table 4.3). Common chickweed was suppressed in the oilseed radish plots, and yellow nutsedge in both oilseed radish and cereal rye plots. During the season, the only weed that was affected by the treatments was common chickweed for evaluation conducted on August 18, when its density was lowest in plots previously grown with oilseed radish and subjected to the low fertilizer rate regime.

Weed species richness (number of species) was not affected by the treatments in 2003 (Table 4.4). The largest number of weed species was observed for evaluations conducted in mid season (June 18) in 2003. In 2004, the number of weed species in early spring was affected by the treatments. Irrespective of the fertilizer rate, oilseed radish and cereal rye plots had fewer species (1 to 1.3) than the other treatments (1.8 to 2.3 species). As in 2003, no treatment effect was observed on weed species richness during the growing season.

Effects of Cover Crop and Fertilizer on Weed Dry Biomass

Weed biomass varied with year, cover crop, and fertilizer treatments (Table 4.5). The effects of cover crop on winter annual weeds were more pronounced during the first evaluations in both years ($P \leq 0.05$). In 2003, the first weed evaluation conducted on May 8 showed high level of weed suppression by the cover crops, with oilseed radish exhibiting the greatest suppressive effects. Weed biomass was 101.2 g m^{-2}, in the bare ground treatment, compared to 0.3, 15.3, and 31.3 g m^{-2}, respectively in the oilseed radish, cereal rye, and hairy vetch treatments. Since this was the first year of the experiment, no effect of fertilizer level was possible. During celery growing season, weed biomass in all treatments was similar, indicating no carryover effects of the cover crops and no effect of soil fertility levels.

In 2004, the ability of the cover crops to reduce spring weed populations was confirmed with May's evaluation. The greatest weed biomass (193 g m^{-2}) was observed in the bare ground plot where the highest rate of fertilizer was applied the previous season. This verifies Dhima and Eleftherohorinos (2001) results of a weed dry weight increase with nitrogen fertilization. Oilseed radish showed the least weed biomass, regardless of the applied fertilizer rate. Unlike 2003, there was a carryover effect of the cover crops and fertilizer effects during the celery growing season in 2004. Weed biomass assessed on July 21 (23 DAT) showed the greatest weed biomass in the bare ground treatment that received the full rate of fertilizer (225 g m^{-2}). This was followed by hairy vetch and the bare ground treatments, each combined with 50% fertilizer rate. All other treatments had comparable weed biomass. The final weed evaluation conducted on August (72 DAT) show no differences among treatments.

Effects of Cover Crop and Fertilizer on Celery Yield

Celery yield was affected by the different treatments in both 2003 and 2004 (Figures 4.5 and 4.6). This was observed for total and marketable yield, of the untrimmed and trimmed stalks, as well as for the number of marketable stalks.

In 2003, yields from the control and hairy vetch plots receiving the low fertility rate, produced the lowest values in all categories. This observation indicates the importance of adequate soil nutrient amendment in intensely grown celery production. For example, total marketable plant weight before stalk trimming was 38.0 ton ha^{-1} (in the control plus low fertility treatment) and 37.4 ton ha^{-1} (in the hairy vetch plus low fertility treatment), compared to 45.4 to 70.5 ton ha^{-1} in other treatments. The combination of oilseed radish and half rate of fertilizer significantly increased yield. Moreover, yields in the oilseed radish plus the half rate were greater than or equal to yield of the control and full fertility rates. Similar results were observed with the number of marketable stalks

(Figure 4.7). The highest numbers of marketable stalks were recorded in the oilseed radish (66,000 plants ha^{-1}) that received the half rate of fertilizer.

In 2004, low yields were observed in all systems receiving the low fertility rate. Oilseed radish cover crop increased yield in those treatments. For example, total marketable yield (before stalk trimming) was 89.9 ton ha^{-1} with oilseed radish and the low fertility rate in comparison to 78.5 ton ha^{-1} with the bare ground system. Similar results were found true for the number of marketable stalks. However, in 2004, there was no observed yield benefit noted when the cover crops were combined with the half rate of fertility. Similarly, applying a full rate of fertilizer to the bare ground plot did not improve yield over the cover crop systems with half rate of fertilizer.

The objective of this work was to improve celery cropping systems with cover crops. Also, we sought to determine how weed populations and celery yield are affected by different cover crops and soil fertility levels. Results of this study indicate a possible fit of the evaluated cover crops in celery production, particularly, in systems where harvests occur in July or early August. In this study, cover crops sown in late August rapidly established, providing considerable soil cover during winter and biomass in the following spring. Teasdale and Daughtry (1993), documented early spring weed control by cover crops that were used in their study. Mohler and Teasdale (1993), and Ngouajio et al. (2003) in their respective studies showed increase in weed control as cover crop biomass increased. Additionally, Fisk et al. (2001) observed cover crop biomass negatively affected weed density. A dense carpet of cover crop mechanically inhibits weed germination and emergence (Teasdale 1996).

Under muck soil conditions, cover crops used in this study produced significant biomass before being killed by frost (oilseed radish), or by herbicide or cultivation the following season (cereal rye, hairy vetch). Oilseed radish did not over-winter, while the other cover crops continued growth to the following spring. Oilseed radish and hairy vetch biomass was stable across years. On the other hand, cereal rye biomass productivity varied with growing conditions. The primary difference between the years was more rainfall following rye planting in 2004. Apparently, adequate soil moisture during germination and subsequent seedling establishment may be critical for cereal rye on muck soils.

Although, the cover crops reduced weed densities in spring, there was no significant effect of the cover crops and level of soil fertility on weed density during celery growing season. Most studies documenting low weed densities in the cover crop systems during cash crop growth had normally left high residue on the soil surface (Williams et al. 1998). In this study, all residues were incorporated into the soil, therefore reducing their physical effects on weed seed germination. In 2004 however, the high fertilizer rate favored weed growth as indicated by the greater biomass in the control plots early in the growing season. This observation suggests that high fertility does not affect seed germination but seedling growth. This is in contrast to observations of Agenbag and Villiers (1989) who suggested that fertilization, may affect weed seed dormancy. Several studies have reported reduced weed infestations under low fertilization programs (Alkamper 1976; AmpongNyarko and DeDatta 1993; Banks et al. 1976; DiTomaso 1995). Following those studies, fertilizer banding as a weed control strategy has been recommended in weed management programs (DiTomaso 1995). Crimson clover, hairy vetch, and other cover crops have been reported to reduce weed infestations in cropping systems (Dyck and Liebman 1994; Ngouajio and Mennan 2005; Williams et al. 1998). These are legume cover crops that increase soil N fertility. However, the mechanism of weed suppression may be more complex than simple soil fertility modification.

Therefore, by using different cover crop and fertilization practices, Michigan producers can reduce weed densities in celery production that, in turn will increase crop competitiveness and thereby increase their potential for optimal crop yields. Increased vegetative growth by cover crops during the winter season can also provide soil N (Hargrove 1986; Kuo et al. 1997). Oilseed radish increased celery growth and yield both under the low and half rates of fertilizer. By producing large amounts of biomass, oilseed radish can improve microbial activity and create an environment more conducive to celery growth. Oilseed radish has been shown to produce glucosinolates (Fahey et al. 2001), secondary metabolites that suppress weeds, nematodes, and some soil borne plant pathogens.

Cereal rye enhanced celery growth and yield. However, high residue production may be detrimental to celery. When large cereal rye biomass was produced (data not shown), this resulted in stunting, yellowing, and low celery yield. Those growth inhibitory conditions may be attributed to either nutrient immobilization or allelochemical interactions. Cereal rye is known to produce allelochemicals (Barnes et al. 1987) that interfere with normal growth of several species (Barnes and Putnam, 1983).

This work suggests that cover crop, especially oilseed radish, could be integrated into celery production with associated weed suppression, increase in yield, and reduction in fertilizer inputs. The effects of the cover crops on weed populations and contribution to soil fertility should be quantified and credited while developing weed management and fertilization programs. It is also important to determine the nutrient release curve of the cover crops in order to synchronize with crop demand and optimize their contribution to celery crop rotation systems. Finally, establishing and maintaining a cover crop requires investments by the farmer. Therefore a cost study would help determine the profitability of the different systems.

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Table 4.1.
Effects of cover crop and fertilizer rate on total weed density at different dates in Houghton muck soil during Summer 2003 and 2004[a].

Cover crop and fertilizer rate [b]	2003			2004		
	May 8	June 18	July 9	May 6	July 21	August 18
	plants m^{-2}					
Control plus Low	264 a [c]	346	148	200 abc	531	263
Oilseed radish plus Low	21 c	853	209	49 d	434	201
Cereal rye plus Low	91 b	516	123	84 bcd	492	298
Hairy vetch plus Low	117 b	529	182	180 ab	390	278
Control plus Half	n/a [d]	383	124	259 ab	520	193
Oilseed radish plus Half	n/a	723	129	51 d	328	225
Cereal rye plus Half	n/a	536	131	75 cd	349	161
Hairy vetch plus Half	n/a	397	219	209 abc	404	257
Control plus Full	n/a	309	151	313 a	326	191
P-value [e]	***	NS	NS	***	NS	NS

[a] All data (plus a value of 0.001 to adjust zeros) were transformed to the $\log_{10}$ prior to ANOVA and then back transformed for clarity of presentation.
[b] Fertilizer rates are Full, Half, and Low. The full rate was 180, 90, 450 kg ha^{-1} of N, P_2O_5, and K_2O, respectively. The half rate corresponded to 50% of the full rate. The low rate was 50% of the N applied in the full rate and no P_2O_5 and K_2O. All P_2O_5, K_2O, and 25% of N were top dressed and the remaining N side dressed in three equal applications during the season.
[c] All numbers within a column and year followed by the same letter are not statistically different ($\alpha = 0.05$).
[d] Not applicable (n/a) because fertilizer treatments were not applied during summer 2002.
[e] P-values are $P > 0.05$ (NS Non significant), $P < 0.05$ (*), $P < 0.01$ (**), and $P < 0.001$ (***)

Table 4.2.
Effects of cover crop and fertilizer rate on weed species composition in Houghton muck soil during celery growing season 2003[a].

Cover crop and fertilizer rate[b]	May 8			June 18				July 9			
	STEME[c]	CAPBP	Other	STEME	POROL	AMABL	Other	STEME	POROL	AMABL	Other
	plants m^{-2}										
Control plus Low	89 a[d]	133 a	43 a	80	117	102	47	17	93	34	21
Oilseed radish plus Low	20 b	1 c	0 b	408	169	156	120	44	101	53	19
Cereal rye plus Low	81 a	7 b	3 ab	238	125	60	93	19	63	32	11
Hairy vetch plus Low	66 a	25 a	26 a	167	70	94	198	39	69	41	44
Control plus Half	n/a[e]	n/a	n/a	117	108	111	47	13	64	43	6
Oilseed radish plus Half	n/a	n/a	n/a	351	140	102	130	13	84	29	10
Cereal rye plus Half	n/a	n/a	n/a	273	103	92	68	19	65	35	13
Hairy vetch plus Half	n/a	n/a	n/a	146	85	80	86	12	110	72	
Control plus Full	n/a	n/a	n/a	73	109	81	43	3	87	57	7
P-value[f]	***	***	***	NS	NS	NS	NS	NS	NS	NS	NS

[a] All data (plus a value of 0.001 to adjust zeros) were transformed to the $\log_{10}$ prior to ANOVA and then back transformed for clarity of presentation.
[b] Fertilizer rates are Full, Half, and Low. The full rate was 180, 90, 450 kg ha^{-1} of N, P_2O_5, and K_2O, respectively. The half rate corresponded to 50% of the full rate. The low rate was 50% of the N applied in the full rate and no P_2O_5 and K_2O. All P_2O_5, K_2O, and 25% of N were top dressed and the remaining N side dressed in three equal applications during the season.
[c] Five digit Bayer code: STEME is chickweed (*Stellaria media*), CAPBP is shepherds purse (*Capsella bursa-pastoris*), POROL is common purslane (*Portulaca oleracea*), AMABL is prostrate pigweed (*Amaranthus blitoides*).
[d] All numbers within a column and year followed by the same letter are not statistically different ($\alpha = 0.05$).
[e] Not applicable (n/a) because fertilizer treatments were not applied during summer 2002.
[f] P-values are $P > 0.05$ (NS Non significant), $P < 0.05$ (*), $P < 0.01$ (**), and $P < 0.001$ (***).

Table 4.3.

Effects of cover crop and fertilizer rate on weed species composition in Houghton muck soil during celery growing season 2004[a].

Cover crop and fertilizer rate [b]	May 6			July 21			August 18			
	STEME[c]	CYPES	Other	POROL	AMABL	Other	STEME	POROL	AMABL	Other
	plants m^{-2}									
Control plus Low	147 [d]	49 ab	4 ab	436	86	3	14 bc	19	226	4
Oilseed radish plus Low	49	0 c	0 b	360	70	2	1 c	17	181	2
Cereal rye plus Low	84	0 c	0 b	454	33	5	10 ab	24	262	2
Hairy vetch plus Low	155	21 abc	4 ab	310	63	10	53 a	24	200	1
Control plus Half	180	59 ab	20 a	440	64	9	26 a	16	145	6
Oilseed radish plus Half	47	4 bc	0 b	252	61	1	23 a	23	179	0
Cereal rye plus Half	75	0 c	0 b	315	24	1	22 ab	15	123	1
Hairy vetch plus Half	202	7 a	0 b	345	35	10	31 a	27	195	4
Control plus Full	237	70 ab	6 ab	269	51	2	23 a	14	141	13
P-value [e]	NS	**	*	NS	NS	NS	**	NS	NS	NS

[a] All data (plus a value of 0.001 to adjust zeros) were transformed to the $\log_{10}$ prior to ANOVA and then back transformed for clarity of presentation.

[b] Fertilizer rates are Full, Half, and Low. The full rate was 180, 90, 450 kg ha^{-1} of N, P_2O_5, and K_2O, respectively. The half rate corresponded to 50% of the full rate. The low rate was 50% of the N applied in the full rate and no P_2O_5 and K_2O. All P_2O_5, K_2O, and 25% of N were top dressed and the remaining N side dressed in three equal applications during the season.

[c] Five digit Bayer code: STEME is chickweed (*Stellaria media*), CYPES is yellow nutsedge (*Cyperus esculentus*), POROL is common purslane (*Portulaca oleracea*), AMABL is prostrate pigweed (*Amaranthus blitoides*).

[d] All numbers within a column and year followed by the same letter are not statistically different ($\alpha = 0.05$).

[e] P-values are $P > 0.05$ (NS Non significant), $P < 0.05$ (*), $P < 0.01$ (**), and $P < 0.001$ (***).

Table 4.4.
Effects of cover crop and fertilizer rate on <u>number of weed species</u> in Houghton muck soil during Summer 2003 and 2004 [a].

Cover crop and fertilizer rate [b]	2003			2004		
	May 8	June 18	July 9	May 6	July 21	August 18
	# of species m^{-2}					
Control plus Low	2.3 [c]	5.0	3.8	2.3 a	3.8	4.3
Oilseed radish plus Low	0.5	6.0	5.3	1.0 c	3.3	3.3
Cereal rye plus Low	1.3	6.0	3.5	1.0 c	3.0	4.5
Hairy vetch plus Low	2.5	6.0	4.8	2.0 ab	4.0	4.3
Control plus Half	n/a [d]	6.0	3.5	2.3 a	3.5	3.5
Oilseed radish plus Half	n/a	6.0	3.8	1.3 bc	3.0	3.5
Cereal rye plus Half	n/a	5.0	4.3	1.0 c	3.3	3.5
Hairy vetch plus Half	n/a	6.0	5.0	1.8 ab	4.8	3.8
Control plus Full	n/a	6.0	4.0	2.3 a	4.3	4.0
P-value [e]	NS	NS	NS	**	NS	NS

[a] All data (plus a value of 0.001 to adjust zeros) were transformed to the $\log_{10}$ prior to ANOVA and then back transformed for clarity of presentation.
[b] Fertilizer rates are Full, Half, and Low. The full rate was 180, 90, 450 kg ha^{-1} of N, P_2O_5, and K_2O, respectively. The half rate corresponded to 50% of the full rate. The low rate was 50% of the N applied in the full rate and no P_2O_5 and K_2O. All P_2O_5, K_2O, and 25% of N were top dressed and the remaining N side dressed in three equal applications during the season. [c] All numbers within a column and year followed by the same letter are not statistically different ($\alpha = 0.05$).
[d] Not applicable (n/a) because fertilizer treatments were not applied during summer 2002.
[e] P-values are $P > 0.05$ (NS Non significant), $P < 0.05$ (*), $P < 0.01$ (**), and $P < 0.001$ (***).

Table 4.5.
Effects of cover crop and fertilizer rate on weed dry biomass at different dates in Houghton muck soil during Summer 2003 and 2004.

Cover crop and fertilizer rate [a]	2003			2004		
	May 8 [b]	June 18	July 9	May 6	July 21	August 18
	$g\ m^{-2}$					
Control plus Low	101.2 a	5.0	31.7	152.6 ab	132.0 c	42.5
Oilseed radish plus Low	0.3 b	15.6	91.6	0.6 d	147.5 c	27.0
Cereal rye plus Low	15.3 b	8.9	59.6	20.8 c	172.0 bc	44.5
Hairy vetch plus Low	31.3 ab	9.9	49.1	44.7 bc	139.5 c	49.5
Control plus Half	n/a [c]	5.8	79.4	118.1 abc	222.0 ab	55.0
Oilseed radish plus Half	n/a	16.9	44.8	0.9 d	160.0 c	34.0
Cereal rye plus Half	n/a	9.9	66.4	32.2 bc	144.5 c	39.0
Hairy vetch plus Half	n/a	9.0	83.9	72.1 bc	225.0 ab	52.0
Control plus Full	n/a	5.0	76.4	193.0 a	255.0 a	26.5
P-value [d]	**	NS	NS	***	**	NS

[a] Fertilizer rates are Full, Half, and Low. The full rate was 180, 90, 450 kg ha^{-1} of N, P_2O_5, and K_2O, respectively. The half rate corresponded to 50% of the full rate. The low rate was 50% of the N applied in the full rate and no P_2O_5 and K_2O. All P_2O_5, K_2O, and 25% of N were top dressed and the remaining N side dressed in three equal applications during the season.

[b] All numbers within a column and year followed by the same letter are not statistically different ($\alpha = 0.05$).

[c] Not applicable (n/a) because fertilizer treatments were not applied during summer 2002.

[d] P-values are $P > 0.05$ (NS Non significant), $P < 0.05$ (*), $P < 0.01$ (**), and $P < 0.001$ (***).

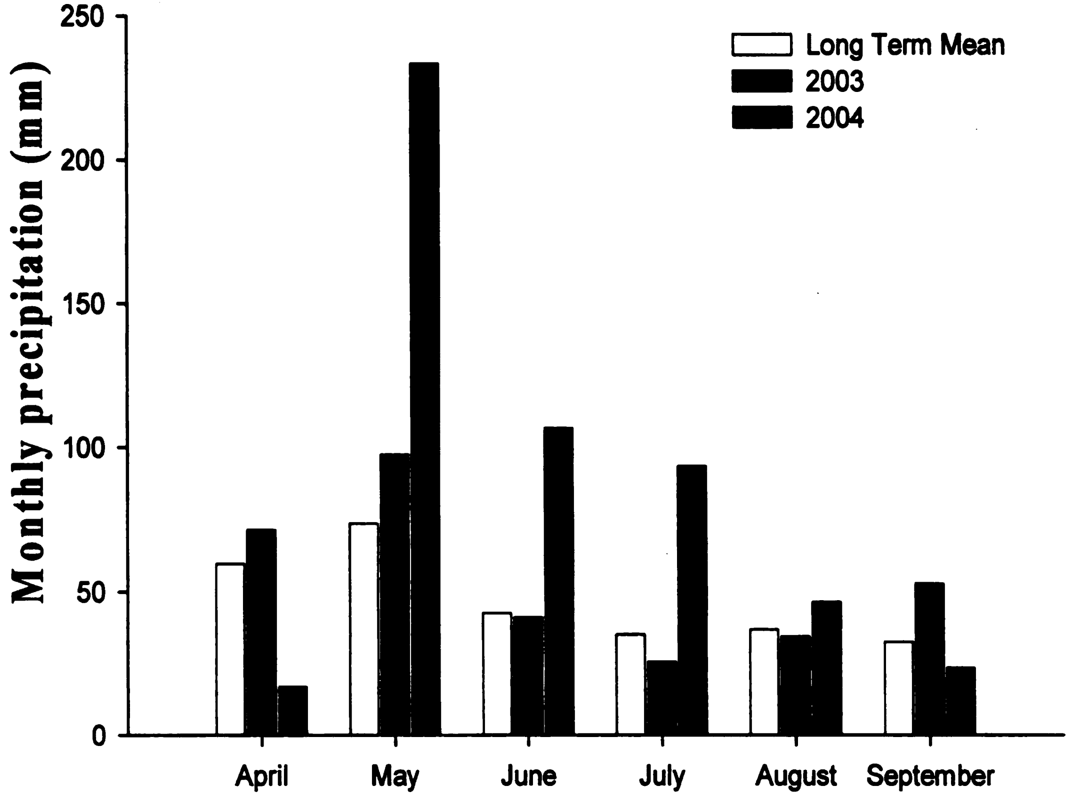

FIGURE 4.1. Total monthly precipitation. Data recorded in Bath weather station located at the experimental site. Long term mean rainfall available were from 2001-2003.

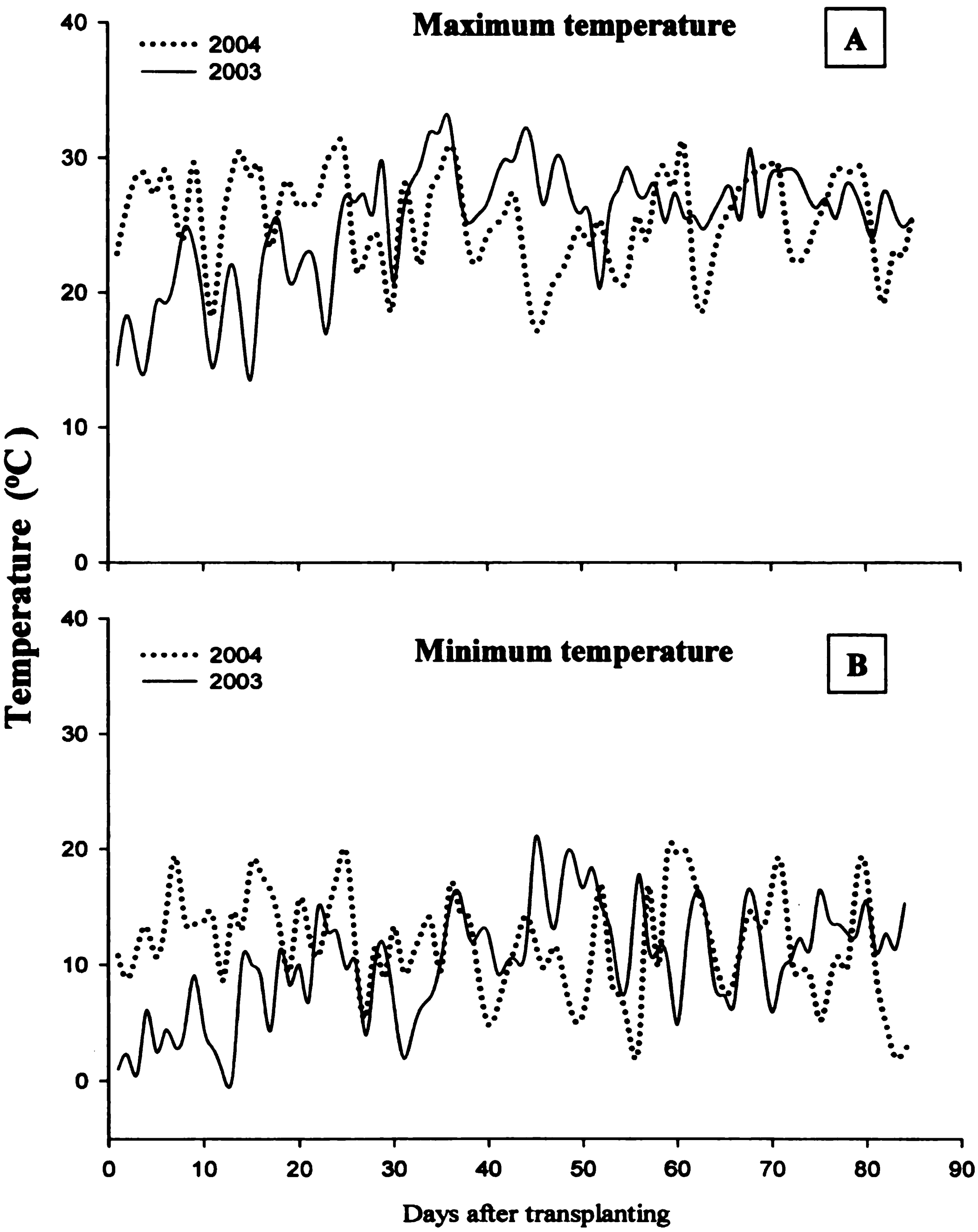

FIGURE 4.2. Daily maximum (A) and minimum (B) temperature at different days after transplanting (DAT) during celery growth in 2003 and 2004. Celery transplanted on 23 May 2003 and 28 June 2004 in Laingsburg and. Data recorded in Bath weather station located at the experimental site.

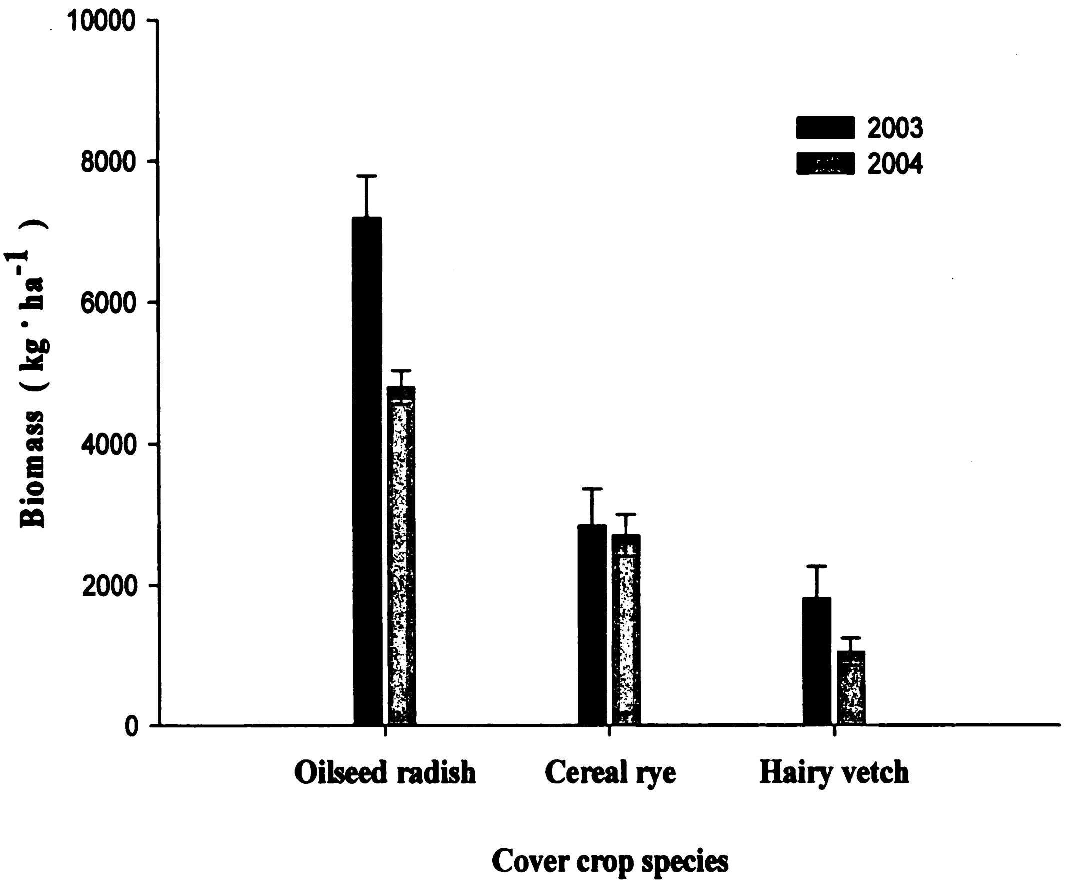

FIGURE 4.3. Biomass production (kg · ha^{-1}) by the cover crops prior to incorporation and transplanting of celery in 2003 and 2004. Vertical bars represent standard errors of the means. Biomass of oilseed radish was measured in October of the year preceding the growing season (before they were killed by frost). Cereal rye and hairy vetch biomass was estimated in May prior to land preparation.

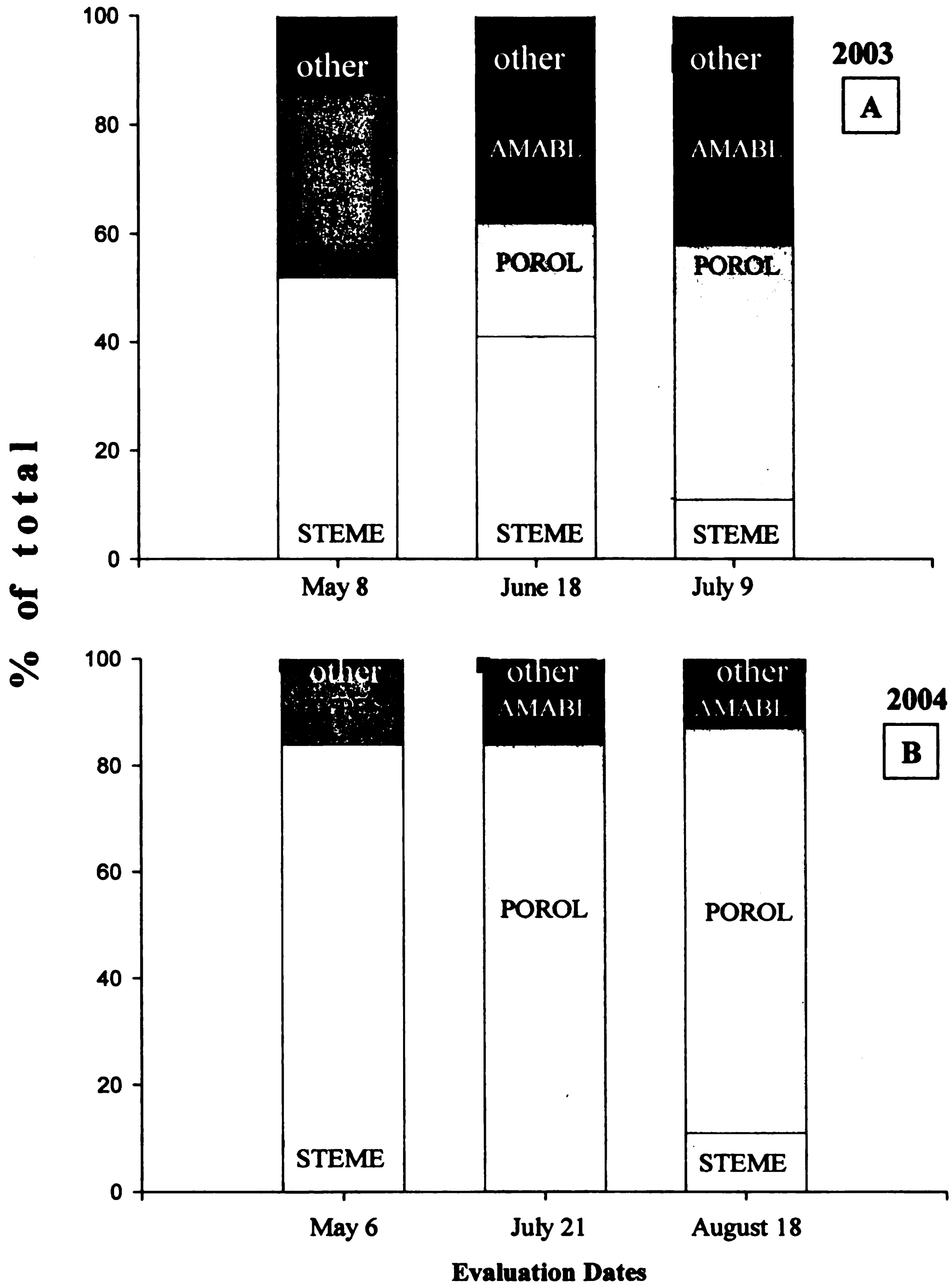

FIGURE 4.4. Major weed species and contribution to total weed density in 2003 (A) and 2004 (B). Other includes all species contributing less than 10 % to total weed density.

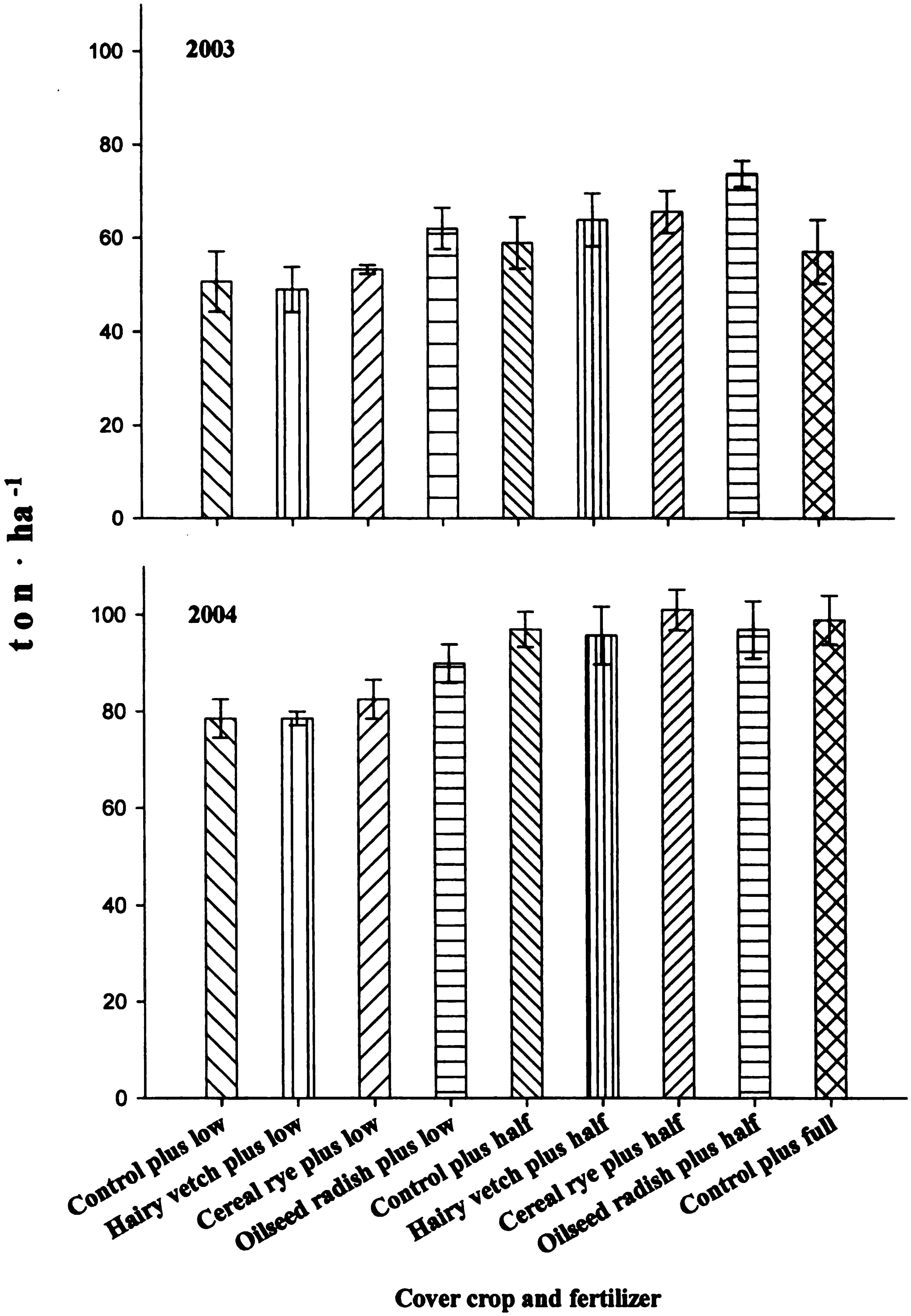

FIGURE 4.5. Total before trimming celery yield as influenced by cover crop and fertilization in 2003 and 2004. Fertilizer rates are Low (90 kg ha^{-1} N), Half (90, 45, and 225 kg ha^{-1} N, P_2O_5, K_2O), and Full (180, 90, and 450 kg ha^{-1} N, P_2O_5, K_2O).

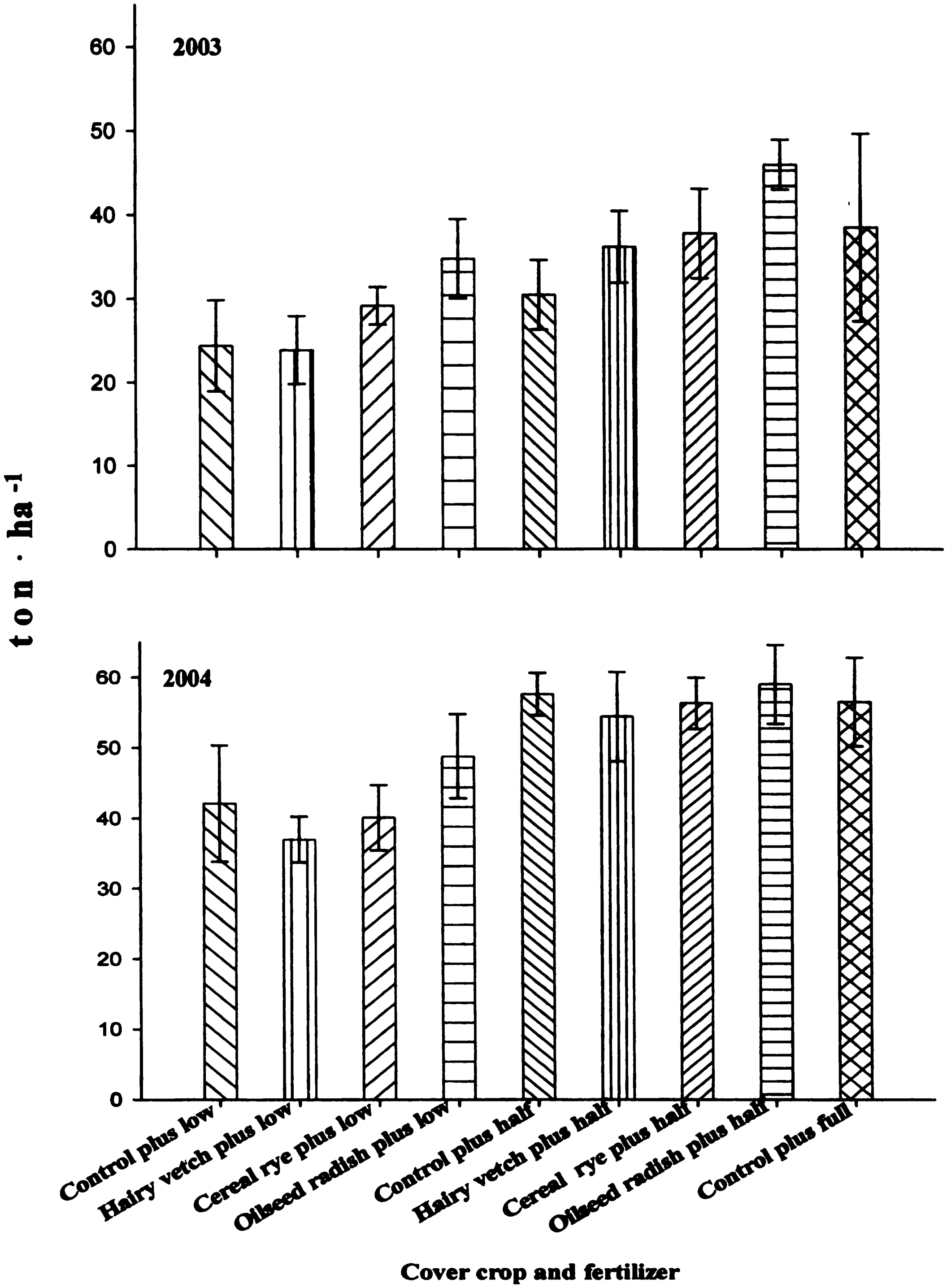

FIGURE 4.6. Marketable after trimming celery yield as influenced by cover crop and fertilization in 2003 and 2004. Fertilizer rates are Low (90 kg ha^{-1} N), Half (90, 45, and 225 kg ha^{-1} N, P_2O_5, K_2O), and Full (180, 90, and 450 kg ha^{-1} N, P_2O_5, K_2O).

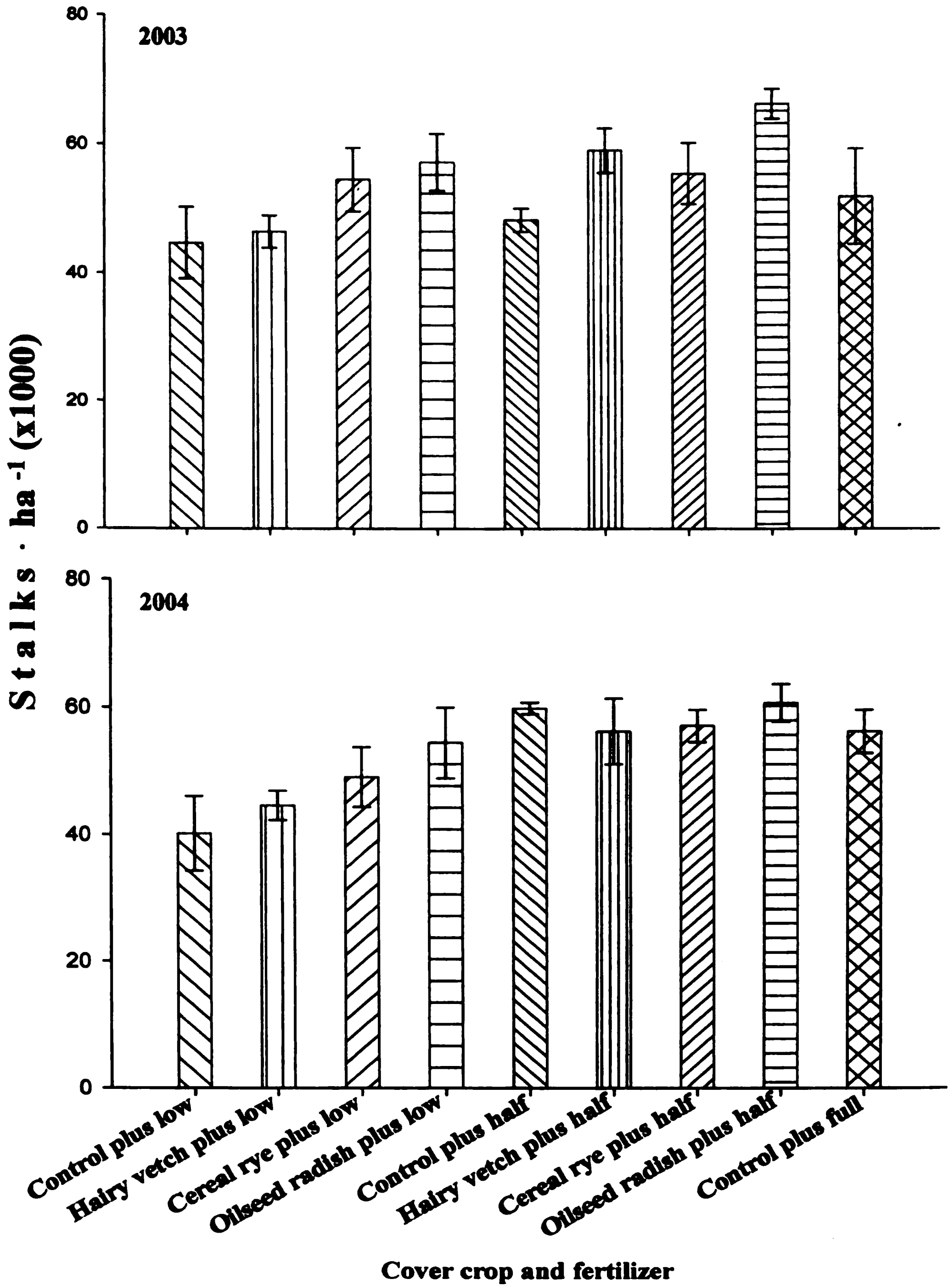

FIGURE 4.7. Number of marketable celery stalks as influenced by cover crops and fertilization in 2003 and 2004.