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CHEMICAL AND CULTURAL MANAGEMENT STRATEGIES
FOR *RHIZOCTONIA SOLANI* KÜHN ON POTATOES IN
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DEVAN ROPPOSCH BERRY

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Master of Science degree in Plant Pathology

William W Kirk

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CHEMICAL AND CULTURAL MANAGEMENT STRATEGIES FOR *RHIZOCTONIA SOLANI* KÜHN ON POTATOES IN MICHIGAN

By

Devan Ropposch Berry

A THESIS

Submitted to
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ABSTRACT

CHEMICAL AND CULTURAL MANAGEMENT STRATEGIES FOR *RHIZOCTONIA SOLANI* KÜHN ON POTATOES IN MICHIGAN

By

Devan Ropposch Berry

Rhizoctonia solani Kühn causes stem and stolon canker as well as black scurf on potato tubers, which can reduce plant health as well as yield quality and quantity. Standard planting and fungicide application decisions were examined, as modifications may impact disease management. Current recommendations are for planting into warm soil (around 15°C) and for both a seed and early-season fungicide treatment. Three field experiments were established to examine these crop management options for multiple cultivars: planting based upon soil temperature (2004-2005, 3 temperatures), timing of seed and early-season fungicide applications (2004-2005, 1 seed treatment, 3 early-season fungicides, 3 applications), and interaction of both planting time and fungicide application (2006, 2 timings, 1 seed treatment, 2 early-season fungicides, 2 applications).

In 2004 (inoculated) and 2005 (non-inoculated) plots that were planted early (8°C at 15cm) had a significantly higher percentage of stems and stolons with cankers than plots that were planted later (either 14 or 20°C at 15cm). Also in 2004 and 2005, the use of the seed treatment, fludioxonil, regardless of additional treatments reduced the percentage of stem and stolon canker. However, the use of additional early-season fungicide treatments, regardless of chemical or application timing, was not found to be consistently effective. In 2006, a combined experiment found contradictory results for planting based upon soil temperature, but similar results for fungicide applications.

DEDICATION

I would like to dedicate this work to all of my family and friends that have continuously provided support for this, and indeed all of my endeavors. Thank you especially to my wife Karen and son Joe, my parents Jim and Karolyn Berry, my second parents Wes and Mary Summers, my mentor Dr. Willie Kirk, and my friends Rob Schafer and Donny Nguyen.

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INTRODUCTION

Host: Potato (*Solanum tuberosum*)

Importance

The potato (*Solanum tuberosum*) is the fourth most important food crop (behind corn, soybeans and wheat) in the United States, in terms of the value of production, with the 2007 growing season estimated at over 5.2 billion dollars (USDA, 2008). In addition, the potato ranks fifth (behind sugarcane, maize, wheat, rice) worldwide for the amount harvested, which was estimated at over 20 million tonnes (FAOSTAT, 2008b). Worldwide, on average, people consume 32 kilograms of potatoes per year, and in the United States people consume 63 kilograms per year (FAOSTAT, 2008a). Potatoes have been cultivated for over 5000 years, dating back to pre-Incan times in South America (Thurston, 1994). As with other important crops, there has been a great deal of research for crop protection due to pest problems associated with growing monocultures over large areas.

Basic potato plant anatomy

The potato plant is an annual, herbaceous, dicotyledonous plant that is commercially grown from vegetative seed, either whole or cut tubers. Potatoes can also be grown from botanical seed, although this method of propagation is commercially limited and used mainly by breeding programs. Meristematic tissue on the potato seed tuber gives rise to stems, stolons and roots. The stems produce pinnately compound leaves in a phyllotactic spiral pattern (Cutter, 1992). A stolon, which is a below-ground stem, produces a tuber at its apex (Peterson, 1985).

A potato tuber is a modified stem possessing leaves and axillary buds that are much reduced, shortened internodes, and radially expanded stem axis (Cutter, 1992). Tubers act as an energy sink and store carbohydrates in the form of starch granules, in varying concentrations, in amyloplasts of the parenchyma cells located throughout the tuber (Peterson, 1985). The tubers of the various cultivars can range widely on a number of attributes including tuber type, shape, taste, skin and flesh color, internal qualities, specific gravity, usage and disease or insect resistance. In addition, the plants can also vary significantly in appearance.

Pathogen problems

There are nearly 60 important diseases affecting potatoes caused by fungi, fungal-like organisms, bacteria, viruses, nematodes, plasmids, and insect toxins (Stevenson, 2001). In order for any pathogen to cause severe problems in a cropping system, three things must be present: the host, pathogen, and appropriate environmental conditions. Different pathogens affect the potato crop at different times, but all can lead to lowered yield quality and/or quantity. For most diseases, an integrated pest management strategy is used, which incorporates cultural, chemical, and biological methods.

Pathogen: *Rhizoctonia solani* Kühn

Introduction

The anamorph of the basidiomycete *Thanatephorus cucumeris* (Frank) Donk is *Rhizoctonia solani* Kühn, a ubiquitous soilborne plant pathogen, saprophyte, and is occasionally found in mycorrhizal association with orchids (Warcup, 1985). As a pathogen, *R. solani* has been reported on over 500 different genera of plants (Farr, 1989). Some of the more important anamorphic features of *R. solani* are: the production of sclerotia without differentiated rind and medulla, the lack of conidia, hyphal branching at right angles prior to septa, hyphal constrictions at the dolipore septa, multiple nuclei, no clamp connections, and the production of monilioid cells (Parmeter and Whitney, 1970). Monilioid cells and hyphae, that give rise to monilioid cells, form the loosely woven sclerotia (Tu and Kimbrough, 1975).

The species *R. solani* is part of the *Rhizoctonia* complex, which is a large grouping based upon vegetative (anamorphic) features, and has teleomorphs in multiple genera: *Helicobasidium, Thanatephorus, Ceratobasidium, Waitea, Tulasnella* and *Sebacina* (Ogoshi, 1996). The taxonomy of the teleomorphs is based primarily upon the basidiospores produced (Stalpers and Andersen, 1996).

Importance

There are a number of important disease signs and symptoms resulting from an infection by *R. solani* on potatoes. Cankers on stem and stolons (starting as sprouts), can significantly delay emergence (Frank and Leach, 1980), reduce plant stand and yields (Banville, 1989), as well as lead to increased production of misshapen, variable tuber sizes (Otrysko and Banville, 1992), and (inedible) aerial tubers. Further, sclerotia produced on the skin of daughter tubers reduce the value of fresh market tubers due to the appearance, and value of seed tubers. It is recommended that seed tubers be free of visible sclerotia, but 2 – 5% coverage can be tolerated (Secor and Johnson, 2008). If seed has more than 5% coverage, it is recommended that the seed lot be rejected due to the increased potential for disease (Powelson and Rowe, 2008).

Separation by Anastomosis Groups

Rhizoctonia solani is separated into anastomosis groups (AG), which are based upon vegetative incompatibility (Anderson 1982, Ogoshi 1987, Carling 1996). There are thirteen groups, some of which have subgroups, known as vegetative compatible populations (VCP) (Carling 1996). The more-homogenous VCPs within an AG differ for pathogenic, biochemical, or genetic characteristics (Sneh et. al. 1991, Carling 1996, Campion 2003).

When two isolates are grown on the same media, they will naturally grow in a radial fashion outward as they colonize the media. The area where the two initially come into contact can be studied under a light microscope for one of four reactions to take place. The reaction that follows dictates if the isolates are closely related, and of the same AG and VCP (most likely the same isolate); related and part of the same AG, but not the same VCP; distantly related, possibly either part of the same AG or different AGs; or not related, due to different AGs (Carling, 1996).

When isolates are of the same AG and VCP, the hyphal tips will be attracted to each other. This attraction can be detected from as far as 100 µm, as the tips will turn towards each other and meet tip to tip (Ogoshi, 1987). Once the tips come into contact with each other, growth stops, branchlike appendages are formed, the cell walls of both tips dissolve, and the protoplasts join (Ogoshi, 1987). In addition, the anastomosis point is frequently not obvious, the diameter of the anastomosis point is equal or nearly equal to the rest of the hyphae, and the anastomosing and adjacent cells may occasionally die (Carling, 1996). This interaction is now referred to as the C3 reaction (Carling, 1988).

If the two isolates are of the same AG but not the same VCP, the tips are attracted to each other, but this time the anastomosis location is obvious (Carling, 1996). The diameter of this anastomosis point is smaller than the surrounding hyphae, and the reaction always results in the death of the fused and adjacent cells (Carling, 1996). This reaction is called the C2 reaction or killing reaction (Carling 1988).

The C1 reaction occurs when two isolates, whose hyphae are distantly related, come into contact and have an apparent connection of the cell walls but no penetration of the membrane or membrane to membrane contact, and occasionally one or both of the anastomosing and adjacent cells die (Carling, 1996). Finally, with the C0 reaction, when the isolates are not related, there is simply no interaction between hyphae as they grow towards and past one another (Carling, 1996).

Host range

In addition to potatoes, from which it was first described by Kühn in 1858, the diseases caused by *R. solani* on many other important plants have been extensively reported (Parameter, 1970) and recently reviewed by Sheh et al. (1996). Most major crops are potential hosts, including rice, wheat, sugar beet, cotton, peanut, many vegetables, canola, turf grass, flower bulbs, forage and oil seed legumes, ornamentals, and forest trees (Farr et al., 1989; Sheh et al., 1996).

Some of the anastomosis groups (AGs) are rather host specific, while others can be found on a wide host range (Anderson, 1982; Gonzalez Garcia et al., 2006). *Rhizoctonia solani* AG 3 is considered host specific to potatoes and the causal agent of Rhizoctonia canker on stems, stolons and roots, as well as black scurf on the progeny tubers of potato plants (Bandy, 1988; Carling, 1989; Hill, 1989; Ogoshi, 1996; Campion

2003). In addition to AG 3, groups 1, 2, 4, 5, 8, and 9 have also been found on potatoes as sclerotia, isolated from stem and stolon cankers or from the soil around the plants (Bains and Bisht, 1995; Balali et al., 1995; Virgen-Calleros et al., 2000; Campion, 2003; Woodhall et al., 2007).

Disease cycle and infection process

The disease cycle of *R. solani* on potatoes starts in the spring with one of three scenarios: tubers are planted that have black scurf (sclerotia) on their skin; black scurf–free tubers are planted into soil containing *R. solani*, or both seed-borne and soil-borne inoculum are present. Soil-borne inoculum is found as sclerotia or mycelium that can be on nearby debris from crop residue or free in the soil matrix.

The presence of *R. solani* inoculum can reduce both yield quality and quantity (Carling, 1989; Platt, 1989; Nolte, 2003; Tsror, 2005). Both sources of inoculum are important, but there have been conflicting reports as to which is more important. Some studies have put emphasis on seed-borne inoculum sources (Banville, 1989; Carling, 1989), while others have suggested that soil-borne inoculum is more important (James and McKenzie, 1972). Tsror (2005) recently reported that both sources of inoculum are equally important, and that together cause a significantly higher level of disease severity of black scurf, than either inoculum source separately. Similarly, Frank and Leach (1980) reported that both inoculum sources are important to the overall impact of the disease, but that tuber borne inoculum may be more important for early stem pruning, while soil-borne inoculum may be more important for later season stolon pruning and production of sclerotia on tubers.

After germination of sclerotia, the mycelia grow towards plant tissues in response to exudates (Kerr, 1956; Jeger, 1996; Keijer, 1996). Once in contact with plant tissue, the mycelia grow across the surface. It is at this point that the infection process begins. The mycelia can attempt to penetrate the host in a number of ways, depending upon the location on the plant: through natural wounds or openings (stomata or lenticels); by creating an infection cushion [and eventually penetration peg(s), or appressoria (Dodman and Flentje, 1970)]. On contact with intact, healthy plant surface, the mycelium continues to grow along the surface, usually along the junction lines of the underlying epidermal cells, becomes flattened and adheres to the surface (Dodman and Flentje, 1970; Hofman and Jongbloed, 1988; Keijer, 1996). Hyphae branch in a T-shaped pattern and can either form appressoria, or with repetitive branching form infection cushions (Dodman and Flentje, 1970, Keijer, 1996). One or more infection pegs push into the host tissue from the appressoria or infection cushions via hydrostatic pressure (Keijer, 1996) and possible enzyme activity (Hofman and Jongbloed, 1988). In contrast, when the hyphae directly penetrates through a stomatal or lenticel opening, the diameter of the hyphae reduces in size to facilitate entry (Dodman and Flentje, 1970).

Following penetration, enzymes are released that lead to cell wall and cytoplasm degradation, and cell death (Bateman, 1970; Hofman and Jongbloed, 1988; Weinhold and Sinclair, 1996). Hofman and Jongbloed (1988) found that AG 3, on potato stems, caused cell death beyond the depth of colonization of the mycelia, up to 12 cells deep. As a result of the infections, light brown to black lesions form which can girdle and kill the stem, stolon, or root (Banville et al., 1996). Organs that are pruned due to severe lesions may produce secondary growth, and the cycle of growth and apical pruning has been noted to occur up to 11 times (Baker, 1970).

Infection occurs throughout the growing season (Hofman and Jongbloed, 1988), but plant shoots are most susceptible in the spring, especially between planting and emergence (Baker, 1970). Van Emden (1965) observed that sprouts that were exposed to sunlight became resistant to infection. The phenomenon of early susceptibility has been demonstrated to be caused by plant exudates, produced by young shoots and roots, which decline as the shoots age and the waxy cuticle layer builds up (Flentje et al., 1963). Older shoots can again become susceptible if the cuticle is damaged, as described in the experiments of Flentje et al. (1963).

Once the potato plants reach maturity and begin to senesce, either naturally or after herbicide application, there is an increase in the production of sclerotia on progeny tubers (Van Emden, 1965; Dijst, 1990; Banville, 1996). The production of sclerotia increases with time while the tubers remain in the soil, up to three weeks after vine desiccation (Gudmestad et al., 1979). Allington (1935) demonstrated that changes in fungal nutrition, specifically a decrease in carbohydrates, played a role in the formation of sclerotia. Later studies by Dijst (1986, 1988, 1990) have pointed to exudates of the tuber and roots as a cause of increase in sclerotia formation at the time of harvest. Potato plants exude both inhibitory and stimulatory products throughout the growing season, and after vine-kill the production of inhibitory substances decreases (Dijst, 1990). The production of stimulatory exudates continues because the roots continue to absorb water and nutrients from the soil. Dijst (1986) demonstrated that by removing the vines, or cutting the roots and stolons from the tubers, the formation of sclerotia is greatly reduced.

Rhizoctonia solani over-winters primarily as sclerotia, which appear as small, dark growths that form on the skin of the tuber, or on crop residue left in the soil. The sclerotia are commonly referred to as "black scurf" or "the dirt that won't wash off" when found on potatoes. Although the sclerotia are superficial, it is unwanted for both table stock due to the unpleasant appearance, and seed potatoes since it would not be certified as disease-free (Banville et al., 1996). Sclerotia are of little importance when found on potatoes that are bound for chipping or French fries, since the skin is pealed, thus removing the blemishes (Banville et al., 1996).

Environmental Factors

The stems and stolons of a potato plant, especially prior to emergence, are susceptible to infection by *R. solani* (Baker, 1970; Banville et al., 1996). In addition, the progeny tubers, following plant senescence are susceptible to colonization (Spencer and Fox, 1979; Dijst, 1990; Jeger, 1996). A number of environmental factors have been linked to the incidence and severity of Rhizoctonia stem and stolon canker and black scurf, with perhaps the most important being soil temperature. Soil moisture (Frank and Leach, 1980; Hide et al., 1985), pH, and soil type have also been linked to the disease, but indirectly in studies of fungicide efficacy (Hans et al., 1981; Rushdi and Jeffers, 1956).

Early studies by Richards (1921) demonstrated that *R. solani* attacks potato stems over a wide range of temperatures, between 9 and 27°C, with 18°C being the optimal temperature for stem canker incidence and severity. Further, he found that the destruction of the growing points of sprouts was highest at 12°C. Bolkan et al. (1974) furthered the study by Richards (1921) by testing different seed-borne inoculum levels over the range of temperatures. Although they did not formally quantify the macroscopic sclerotia, they did group the seed pieces as clean (no sclerotia), low, moderate, and high levels, (based upon a representative picture estimated as approximately: clean = 0 sclerotia; low = 0 – 5% surface coverage; moderate = 5 – 10% surface coverage; and high = >10% surface coverage). They found that if inoculum levels were low, stem canker severity decreased as temperature increased, from 15 to 24°C. However, when inoculum levels were higher, they found that temperature increases did not control stem canker severity. One *in vitro* study of radial growth of sclerotia from potatoes (LeClerg, 1942) showed that the optimal temperature was 25°C. This finding was supported by a study in which AG 3 was isolated (from sugar beet), and the optimal temperature for growth was found to also be 25°C (Windels et al., 1997). Carling and Leiner (1990) demonstrated that isolates of AG 3 infected potato sprouts at a temperature range from 10 to 21.1°C, and was most destructive at 10°C. However, other AGs (4, 5 and 8) tended to be more virulent to potato sprouts between 15.5 and 21.1°C (Carling and Leiner, 1990).

There is a range of temperatures at which *R. solani* can infect its various hosts, depending upon the AG. Yitbarek et al. (1988) found that while both AG 2-1 and 4 had optimal growth temperatures near 25°C (24 and 26°C, respectively), AG 2-1 was significantly more virulent on canola at lower air temperature schedules (7-8°C, night minimum-day maximum temperatures = 4-8°C night minimum-day maximum for soil temperature) than AG 4, regardless of inoculum level. Conversely, AG 4 was significantly more virulent on canola at higher air temperature schedules (26-35 °C, night minimum-day maximum; 25-36 °C for soil) regardless of inoculum level (Yitbarek et al., 1988). Chang et al.. (2004) found variation in chickpea susceptibility to the same AG 4 isolate was linked to soil temperature. In a gradient plate study, both cultivars tested were susceptible to root rot at all temperatures tested (from mean temperatures of 7.5 to 27.5°C) and susceptible to shoot infection above 10°C (Chang, 2004). Grosch and Kofoet (2003) found that the optimal growth temperature for AG 1-IB (isolated from lettuce fields) was 25°C, while virtually no growth occurred at 35°C. Dorrance et al. (2003) found that AG 2-2 IIIB was able to cause hypocotyl lesions on soybeans at all temperatures tested (20 to 32°C), with significantly more lesions at 32°C than at 20°C. In addition, all AG 2-2 IIIB isolates collected grew at 35°C (Dorrance et al., 2003).

In addition to *R. solani*, other pathogens, such as *Fusarium* spp. causing potato seed piece decay, are also important around the time of planting. Like *R. solani*, Fusarium seed piece rot is found wherever potatoes are grown. Some fungicide seed treatments, such as fludioxonil and flutolanil alone or in combination with mancozeb, are recommended for control of both *R. solani* and *Fusarium* spp. (Wharton et al. 2007b, 2007c). Cut seed pieces are particularly vulnerable to decay, since the wound provides an entry point for the pathogen. Escande and Echandi (1988) found that cut tubers that were allowed to heal for five days, provided significant protection from infection of *Fusarium* spp. and *Erwinia* spp. or their combination, compared to cut tubers that were not allowed to heal at soil temperatures of 10 and 15°C. Temperatures between 15 and 28°C are considered optimal for growth (Arora et al., 2004). Although soil temperature was not taken into account, Nolte et al. (2003) found that whole seed had significantly less seed decay caused by *Fusarium* spp. compared to cut seed pieces, but not cut and fungicide-treated pieces, over the five year study. Further, Wharton et al. (2007a) found that cut and inoculated seed pieces with a fungicide treatment up to 10 days prior to planting was effective against decay caused by *F. sambucinum.*

Management Strategies

There are three classifications for the control methods of *Rhizoctonia solani* on potatoes: biological, chemical, and cultural.

Biological control agents

Biological control agents are either organisms or the products of organisms that control the pathogen through antagonism, parasitism, or competition. The amendment of certain fungi into growing media, *Trichoderma harzianum*, *Verticillium biguttatum*, or *Trichoderma virens*, or bacteria, *Burkholderia cepacia* or *Bacillus subtilis*, have had varying levels of effectiveness for controlling *R. solani* (Tronsmo, 1996; Brewer and Larkin 2005; Larkin, 2001, 2002, 2007 and 2008). Another control method is inoculation with a hypovirulent strain of *R. solani* (Bandy and Tavantzis, 1990). Hypovirulent strains exhibit certain traits, like reduced growth rates, production of sclerotia and virulence that can be transferred, via anastomosis, to more virulent strains. Further, the hypovirulent strains also may induce protection or directly compete with pathogenic strains, which could be especially effective with complete coverage of the seed tuber (Bandy and Tavantzis, 1990).

Fungicides

Many plant pathogens are at least in part managed with fungicides, which is a major component of integrated pest management. The first reported use of a chemical for the control of *Rhizoctonia* was by Winston (1913), in which soil was fumigated with a mixture of steam and formalin. Since then, a number of fungicides have been tested for efficacy against *R. solani*. Multiple mercury-based products have been tested (Maine Ag. Exp. St. Bull, 1937) and used for a number of years, but all are now banned in most countries (Rich, 1983). Today, there are a variety of chemical groups that can be used against *R. solani* including: aromatic hydrocarbons, carboxamides, benzamidazoles, dicarboximides, triazoles, morpholine, phenylurea, validamycin, phenylpyrroles, and strobilurins (Kataria and Gisi, 1996). Recent fungicide efficacy tests on potatoes have focused on strobilurins (azoxystrobin, pyraclostrobin), caboxamides (flutolanil), and phenylpyrroles (fludioxonil), (Stevenson et al., 2000, 2001, 2003, 2004; Kirk et al., 2001, 2002, 2003, 2004; Bains et al., 2002; Inglis et al., 2002, 2003; Nolte et al., 2003; van den Boogert and Lutikholt, 2004).

There are four possible (registered) application timings for these fungicides for effective protection of potato plants against *R. solani*: seed treatment; soil (in furrow); foliar (around the time of emergence); and tuber pre-harvest treatment (via green crop lifting). Liquid or dust formulations of seed treatments can be applied on cut or whole seed pieces. Nolte et al. (2003) found that, over a five year period, cut and treated seed performed at least as well as whole seed that had not been treated with a fungicide. However, the study did not compare whole seed with a seed treatment compared to cut seed with the same treatment. Bains et al. (2002) examined fungicide efficacy, applied as a seed treatment, over a range of cultivars, and found that fludioxonil consistently provided control of *R. solani* black scurf and stem and stolon canker. In addition, he found that cultivar susceptibility varied, but none were resistant to either symptom.

Efficacy of in-furrow and foliar applications (around emergence), have been tested by Kirk et al. (2002, 2004, 2007, 2008) for agronomic and disease parameters comparing treatments at different application timings with the non-treated control and the industry standard of fludioxonil but few differences in efficacy were reported. Seed and soil-borne inoculum are important for stem and stolon canker, respectively (Frank and Leach, 1980). Seed treatments would therefore be expected to be most effective managing seed stem cankers, while later fungicide applications, in furrow and foliar, would be effective at managing stolon cankers. This separation is difficult, since environmental factors like soil temperature, depth of planting, soil type, and soil moisture content, play a role in persistence and efficacy of the fungicide as well as the growth of the plant and fungus.

Green crop lifting involves destroying the stems, lifting the progeny tubers so as to break up the roots and stolons, and placing the tubers back into the soil (Turkensteen et al., 1994). Just prior to the tubers being covered with soil, an application of a fungicide can be made as was tested by van den Boogert and Luttikholt (2004). However, this practice has only been experimented with in Europe, and no implementation of this practice has taken place in the United States (Kirk, *personal communication*).

Cultural practices

Cultural control measures are farming practices aimed at avoiding pathogen contact, creating environmental conditions that are unfavorable to the pathogen or avoiding conditions that are favorable, eradicating or reducing inoculum levels, and improving resistance (Agrios, 1997). There are a number of strategies that are commonly recommended for the control of Rhizoctonia stem canker *(R. solani)* that can help to relieve disease pressure; use of black-scurf free certified seed (Jeger et al., 1996), planting once the temperature of the soil has risen sufficiently in the spring (Simons and Gilligan, 1997; Secor and Gudmestad, 1999), plant green-sprout seed (Rich, 1983), use cover crops, rotate crops (Honeycutt et al., 1996), plant seed tubers close to the surface or after planting drag a chain or board to level off the hill and thus have the potatoes closer to the surface (Jeger et al., 1996), and proper management of water (Simons and Gilligan, 1997) and nutrients. Black scurf can be partially controlled by early harvesting, with the peak of sclerotia formation at about three weeks after vine destruction (Gudmestad, 1979). Dijst (1986, 1990) however, pointed out that plant exudates, in conjunction with the method of vine destruction, played the key role in the formation of black scurf on progeny tubers.

Research Goals

Integrated pest management is the key to successful and sustainable agriculture. Common recommendations for the management of *R. solani* include shallow planting in warm soil (Jeger, et al., 1996) around 15°C (Banville, 1996), planting with disease free or certified seed (Banville, 1996; Secor and Gudmestad, 1999), rotation of crops (Honeycutt et al., 1996), and the use of seed and post emergence fungicide treatments (Secor and Gudmestad, 1999). However, there are very few studies that have incorporated both cultural and chemical management strategies in potatoes. Recent studies have tested cut and fungicide treated seed against whole seed Nolte et al., (2003), and Bains et al. (2002), tested fungicide efficacy of seed treatments and cultivar susceptibility. However, no study has examined fungicide efficacy at different application times using multiple cultivars.

A series of field experiments were established that attempted to validate the prior claim of control with planting based upon soil temperature, and to test the efficacy of fungicides available and recommended for *R. solani* control. The first set of experiments

(Chapter 2), *in planta*, examined the efficacy of early-season fungicide applications alone or in combination with a seed treatment. The commonly recommended (and tested) seed treatment fludioxonil (Maxim) was tested with the early-season fungicides azoxystrobin (Amistar), flutolanil (Moncut), and pyraclostrobin (Headline). Each early-season fungicide was tested at three different application times: in-furrow, at emergence, and 14 days post emergence. The main questions this experiment attempts to address were: for effective management of the various disease symptoms, are both seed treatments and early-season treatments needed or is just one sufficient? Is there one particular fungicide that effectively manages disease symptoms better than the others, based upon measured agronomic and pathological variables? Does one particular application timing (of the early-season fungicides) provide more effective control of disease symptoms, based upon measured agronomic and pathologic variables?

The second set of experiments (Chapter 3) examined the effect of planting time based upon soil temperature among multiple varieties using three soil temperatures that can occur during the early part of the growing season; namely when soil (at 15cm depth) reached a five-day average of 8, 14, or 20°C. The main questions addressed by this approach were: does planting later result in a reduction in stem and/or stolon canker and/or black scurf, compared to early planting? Due to the shorter growing season, does planting later result in a reduction of yield? Are there differences among varieties for the effect of planting date on the incidence and severity of stem and stolon canker and black scurf?

The final experiment (Chapter 4) tested the combined effect of planting time based upon soil temperature and fungicide efficacy in four commonly grown potato varieties. The seed treatment fludioxonil, and two early-season fungicides (azoxystrobin and flutolanil) were evaluated at two possible application times. All combinations of treatments were tested in two separate plantings that occurred once the average soil temperature at 15 cm depth averaged 14 and 20°C (as described above). The questions this experiment attempted to answer were: does a particular combination of planting date and early season fungicide application result in a reduction of disease incidence and severity (stem and/or stolon canker, and/or black scurf)? Does a late planting and non-treated seed result in lower yield? Also, is one type of control, cultural (planting based upon soil temperature) or chemical (using seed/early-season fungicide(s), more effective for disease management?

CHAPTER 2
EFFECT OF FUNGICIDE AND APPLICATION TIMING ON THE INCIDENCE AND SEVERITY OF RHIZOCTONIA CANKER AND BLACK SCURF ON POTATOES

Introduction

Fungicides are the primary component of integrated management for Rhizoctonia diseases of potato. There are a wide variety of fungicides for the management of *Rhizoctonia solani* that differ in the primary target site of action as well as fungicide type and class (systemic or protective). Recent efficacy studies have tested some of these fungicides, including azoxystrobin, fludioxonil, flutolanil, iprodione, mancozeb, pencycuron, thiophanate-methyl, and thiabendazole (Bains et al., 2002; Nolte et al., 2003; van den Boogert et al., 2004). In order to have effective chemical management of Rhizoctonia stem and stolon canker and black scurf, the correct rate of the chosen fungicide as well as the best application timing must be established.

The most common timing for fungicide application is either as seed treatments on cut or whole seed, or in-furrow during planting. However, some fungicides are also labeled for applications around emergence or during cultivation. Some fungicides like flutolanil may have multiple formulations, such that it can be applied as a dust to seed pieces or sprayed in-furrow. Other fungicides, like azoxystrobin, can be sprayed in-furrow, at the time of emergence, or at hilling/cultivation. Efficacy testing of in-furrow and foliar applications around emergence showed few significant differences among treatments for agronomic and disease parameters Kirk et al. (2001, 2002, 2003, 2004, 2007a,b, 2008). Generally, all treatments tested had significantly lower disease incidence and severity when compared to the untreated control but rarely were there differences among treatments.

Fungicides should be applied at timings that maximize efficacy. Seed and soil-borne inoculum of *R. solani* are important sources of stem and stolon canker, respectively (Frank and Leach, 1980; Powelson and Rowe, 2008). Seed treatments should therefore be more effective for managing stem cankers, while later fungicide applications, in furrow and foliar, should be effective at managing stolon cankers and tuber black scurf. This separation, however, is difficult since environmental factors like soil temperature, depth of planting, soil type, and soil moisture content, play a role in persistence and efficacy of the fungicide as well as the growth of the plant and pathogen.

Field experiments were established in 2004 and 2005 to examine the effects of seed and early season fungicide applications. These early season applications were evaluated in an attempt to manage the different sources of potential inoculum. If these inoculum sources can be managed effectively, through timely fungicide applications, there could be a significant reduction in economic losses that are linked to *R. solani.*

Materials and Methods

The effects of application timing of three different fungicides (azoxystrobin, flutolanil, and pyraclostrobin) were tested over two growing seasons, 2004 and 2005 in the absence or presence of a seed treatment (fludioxonil). In addition, three application times were evaluated: in-furrow at-planting, at emergence, and 14 days post-emergence (Table 2.1). In 2004, cvs. FL1879 and Russet Norkotah were grown on Houghton muck at the Muck Soils Research Farm near Bath, MI and cv. Superior was grown on sandy loam in Antrim County, MI by a cooperating farmer. In 2005, Russet Norkotah was again grown at the Muck Soils Research Farm, and Superior was again grown, in Antrim

County, MI. These sites were chosen due to their known history of Rhizoctonia canker infection and black scurf.

Table 2.1 Treatment matrices for seed and early-season fungicides and application timings for field experiments that occurred during the 2004 and 2005 growing seasons.

	Seed Treatment	In-furrow at-planting	Emergence	14 days post emergence
1	No seed treatment	+ Azoxystrobin		
2			+ Azoxystrobin	
3				+ Azoxystrobin
4		+ Flutolanil		
5			+ Flutolanil	
6				+ Flutolanil
7		+ Pyraclostrobin		
8			+ Pyraclostrobin	
9				+ Pyraclostrobin
10				
11	+ Fludioxonil	+ Azoxystrobin		
12			+ Azoxystrobin	
13				+ Azoxystrobin
14		+ Flutolanil		
15			+ Flutolanil	
16				+ Flutolanil
17		+ Pyraclostrobin		
18			+ Pyraclostrobin	
19				+ Pyraclostrobin
20				

Single-cut potato seed tubers cv. 'Superior' were planted in sandy loam soil near Elmira, MI on 2 June, 2004 and near Mancelona, MI on 26 May, 2005 with and without fludioxinil (see below). Cut 'FL1879' seed and whole 'Russet Norkotah' seed pieces were planted in Houghton muck soil at the MSU Muck Soils Research Farm near Bath, MI on 23 June, 2004, and 1 June, 2005. The grower-cooperator at the Elmira and Mancelona sites applied all fertilizer, irrigation and pesticides for control of weeds, insects, and other pathogenic fungi as part of their farm's proprietary program.

At the Bath, MI location, fertilizer was formulated according to results of soil tests was and drilled into plots before planting in both 2004 and 2005. A permanent irrigation system was established prior to the commencement of protective fungicide sprays (for other plant pathogens) and the fields were maintained at soil moisture capacity throughout the season by frequent (minimum 5-day) irrigations.

In 2004, chlorothalonil (Bravo WS 6SC) was applied at 1.75 L/ha on a ten day interval, for a total of six applications, starting two weeks after the last application of experiment treatments. Weeds were controlled with metolachlor (Dual 8E) at 2.34 L/ha 15 DAP (days after planting), bentazon (Basagran) at 2.34 L/ha 25 and 45 DAP and sethoxydim (Poast) at 1.75 L/ha 63 DAP. Insects were controlled with imidacloprid (Admire 2F) at 1.46 L/ha at-planting, carbaryl (Sevin 80S) at 1.46 kg/ha 36 and 60 DAP, endosulfan (Thiodan 3 EC) at 2.73 L/ha 70 DAP and permethrin (Pounce 3.2EC) at 0.561kg/ha 53 DAP.

In 2005, porpamocarb hydrochloride (Previcur Flex) was applied at 1.4 L/ha on a ten day interval, for a total of four applications, starting two weeks after the last application of experiment treatments. Weeds were controlled with metolachlor (Dual 8E) at 1.2 L/ha and metribuzin (Sencor 75DF) at .67 kg/ha at planting, bentazon (Basagran) at 2.34 L/ha 27 and 45 DAP (days after planting) and sethoxydim (Poast) at 1.75 L/ha 63 DAP. Insects were controlled with thiamethoxam (Platinum) at 0.59 L/ha at-planting, cyfluthrin (Baythroid 2) at 0.146 L/ha 36 and 60 DAP.

Environmental conditions were monitored (2004, 2005) at the Muck Soils Research Farm with the onsite Michigan Automated Weather Network (MAWN, http://www.agweather.geo.msu.edu/) Campbell Scientific weather station. Of particular interest were the soil temperatures available at about 5 and 10 cm depth, air temperature, and precipitation. Although the data were not used to make experimental decisions, such as with the experiment on the effect of soil temperature at planting on varietal susceptibility (described below), the information did provide insight into experimental results. At both the Elmira (2004) and Mancelona (2005) locations a Campbell Scientific weather station was placed in the grower-cooperator field. The weather station used a CR10X data logger, and had probes for temperature (surface, 10, and 20 cm deep), and precipitation (the same as the MAWN stations described above).

At both locations, the seed pieces were planted in plots that were four rows wide (86 cm spacing between rows) and 6.1 m long, with approximately 33 cm spacing between plants give a target population of 72 plants for each plot. The experiment was replicated four times in randomized strip plot design.

The fludioxonil seed treatment was applied, in a water suspension of at a rate of 0.5mL/kg, onto the entire seed surface. Early season applications were made over the seed in-furrow, or emerged shoots/plants and applied with a single nozzle R&D spray boom delivering 46.8L/ha (551.6 kPa) and using one XR11003VS nozzle per row.

Nine parameters were measured at various stages of the growing season. Emergence was counted at all locations, from which the relative area under the emergence progress curve, RAUEPC, was calculated using the following formula:

$$\text{RAUEPC} = \frac{\Sigma(t_{i+1} - t_i) * ((E_{i+1} + E_i)/2)}{T_{total} * 100}$$

where t was the time in days after planting and E was the percentage of plant emergence (Wharton et al., 2007). Each variety had one midseason harvest (four plants per treatment), per growing season, during which time the tuber, stem and stolon numbers, and percentage of stems and stolons with greater than five percent girdling due to *R. solani* were counted and calculated. At the end of the season, plots were machine-harvested and a sample weight was taken from one row of the four row plots. In addition, 20 tubers from each plot were stored for 60 days at 10°C then evaluated for incidence and severity of black scurf on the mature tubers. The number of tubers with visible sclerotia were counted and a percentage of the sample was calculated for the incidence value. The severity index of black scurf was calculated by summing the class value assigned to each tuber (n = 20 per replicate), which was based upon the surface area covered by visible sclerotia. The severity classes used were 0 = 0%; 1 = 1 - 5%; 2 = 6 - 10%; 3 = 11 - 15%; 4 = >16% surface area. Indices of 0 to 25 cover the range 0 - 5%; 25 - 50 cover the range 6 - 10%; 51 - 75 cover the range 11 - 15%; 75 - 100 cover the range >15% surface area of the tuber with sclerotia.

Data Analyses

All data were analyzed by ANOVA and tested with Tukey's Honestly Significant Differences (HSD), $P = 0.05$ (JMP: SAS Institute, Cary, NC, USA). Response analyses were determined by the main effects analyses using the probability of difference between fungicide treatments (seed and/or early-season), application timing, and/or interaction of the treatments. Three types of response were determined; Type A= significant effect of seed treatment ($P < 0.05$) but no effect of any other factors ($P > 0.05$), (only the mean effect of seed treatment presented); Type B= significant effect of more than one factor, or factor other than seed treatment (responses to seed treatment and application type presented); Type C= no effect of any factor, no further analysis.

Results

Year

There were significant differences between the 2004 and 2005 growing seasons in both cultivars Russet Norkotah and Superior with respect to several measured parameters, (Table 2.2). The mid-season sample timings for cv. Russet Norkotah were 50 and 69 days after planting (DAP) in 2004 and 2005, respectively. Despite being planted19 days earlier, the 2004 planting of cv. Russet Norkotah yielded a significantly higher RAUEPC, number of tubers, stems and stolons. However, the 2004 planting also yielded significantly higher percentages of diseased stems and stolons. Harvest was completed 90 and 113 DAP in 2004 and 2005, respectively. Even with 23 fewer days in the growing season 2004 still had a significantly higher sample weight, but also significantly higher black scurf incidence and severity on the mature tubers.

Cv. Superior was grown in Antrim County by a grower-cooperator in both 2004 and 2005. Due to rotation of crops, the plots were located in different fields, but with similar sandy-soil type. The 2004 and 2005 mid-season harvests were 50 and 67 DAP respectively, while the fall harvests were 84 and 112 DAP. The 2005 growing season was only significantly different from the 2004 growing season with respect to three parameters; 2005 yielded significantly lower RAUEPC and higher numbers of tubers and stems.

Table 2.2 Main effects analyses (probability of difference between years: *p*=0.05) of growing season for cultivars 'Russet Norkotah' and 'Superior' on agronomic factors and disease symptoms caused by *Rhizoctonia solani* in field trials conducted at two sites in MI between 2004 and 2005.

	Russet Norkotah			Superior		
Variable Measured	p-value	2004	2005	p-value	2004	2005
Emergence (RAUEPC)[z]	**< 0.0001**	0.197	0.058	**< 0.0001**	0.434	0.061
Number of tubers/plant	**< 0.0001**	30.3	22.4	**< 0.0001**	19.2	27.5
Number of stems/plant	**0.0002**	4.6	3.8	0.4810	3.6	3.7
Percent of stems with girdling	0.0803	65.0	70.3	0.2177	17.5	20.3
Number of stolons/plant	**< 0.0001**	13.4	9.0	**< 0.0001**	16.3	22.3
Percent of stolons with girdling	**< 0.0001**	33.2	19.9	0.0638	7.2	9.5
Yield: metric tons/hectare	**< 0.0001**	26.8	20.2	0.2373	33.0	31.8
Black scurf incidence[y]	**< 0.0001**	48.9	23.7	0.5033	8.3	6.7
Black scurf severity[x]	**< 0.0001**	21.9	9.1	0.3669	4.0	2.9

z: RAUEPC: Relative area under the emergence progress curve (max = 100), calculated from the day of planting to the last emergence count

y: Percent incidence of tubers with sclerotia of R. solani from a sample of 20 tubers per replicate taken during fall harvest

x: Severity of black scurf (index calculated by counting the tuber number (n = 20 per replicate) falling into each class 0 = 0%; 1 = 1 - 5%; 2 = 6 - 10%; 3 = 11 - 15%; 4 = >16% surface area covered with sclerotia; these values were then multiplied by their respective class value, and combined. Indices of 0 to 25 cover the range 0 - 5%; 25 - 50 cover the range 6 - 10%; 51 - 75 cover the range 11 - 15%; 75 - 100 cover the range >15% surface area of the tuber with sclerotia

Seed and Early Season Treatments

The application of the seed treatment fludioxonil (Maxim 4FS) had some significant effects on the parameters for all varieties in both 2004 and 2005 growing seasons (Tables 2.3 – 2.6). The use of fludioxonil on seed potatoes, compared to treatments without fludioxonil (-ST), significantly increased RAUEPC (2004: cvs. FL1879 and Superior); tuber number (2004: cv. Superior); stem number (2004: all varieties); stolon number (2004: cv. Superior); sample weight (2005: cv. Russet

Norkotah); percent stems with >5% girdling (2004: cvs FL1879 and Superior); percent stolons with (>5%) girdling (2004: cvs Russet Norkotah and Superior; 2005: cv. Superior); and incidence and severity of black scurf (2004: cv. Superior). Fludioxonil use resulted in a significant reduction in the stem number (2005: cv. Superior) and sample weight (2004: cv. Superior). In addition, cv. Russet Norkotah (2005) had a significant increase in the percent of stems with >5% girdling and both incidence and severity of black scurf on the mature tubers.

In 2004, no significant differences were found among treatments for all measured parameters of cvs FL1879 and Russet Norkotah (Tables 2.3 - 2.4). However, the application of fludioxonil and pyraclostrobin at emergence or 14 days post emergence (14 DPE), on cv. Superior (Table 2.6), resulted in significantly higher numbers of tubers and stolons when compared to the non-treated control (no ST or early-season fungicide) and a portion of treatments without fludioxonil (-ST). However, pyraclostrobin (+ST) at emergence or 14 DPE was not significantly different from the treatments with fludioxonil. Similarly, pyraclostrobin (+ST) at emergence also yielded a significantly higher stem number compared to the non-treated control, and a portion of the treatments without ST, but was not significantly different from any treatment including fludioxonil seed treatment. In addition, fludioxonil and pyraclostrobin applied at emergence resulted in a higher RAUEPC compared to azoxystrobin (-ST) applied 14 DPE and pyraclostrobin (-ST) applied in-furrow but not to the non-treated control.

In 2005 on cv. Russet Norkotah, fludioxonil (ST) plus azoxystrobin applied in furrow or with flutolanil applied at emergence, (Tables 2.7 and 2.8) resulted in a significantly higher RAUEPC when compared with azoxystrobin (- ST) applied at emergence, flutolanil (- ST) applied at emergence, and pyraclostrobin (- ST) applied either in furrow or 14 DPE, but was not significantly different from the untreated control. Similarly, fludioxonil with either azoxystrobin applied at emergence or pyraclostrobin applied in-furrow resulted in a higher yield than azoxystrobin (-ST) applied 14 DPE, but was not significantly different from the untreated control. Also in 2005, pyraclostrobin (-ST) applied 14 DPE to cv. Superior had a significantly higher percent of stolons with (>5%) girdling compared with all other treatments (Tables 2.9 and 2.10).

Table 2.3 Main effects analyses (probability of difference among treatments: p=0.05) of the effect of seed and early-season fungicide treatments and application timing on agronomic factors and disease symptoms caused by *Rhizoctonia solani* in field trials conducted near Bath, MI during the 2004 growing season on cultivar 'FL1879'.

Variable Measured	Effect of seed treatment (ST) on variable p-value	Mean - ST	Mean + ST	Effect of early-season fungicide treatment on variable p-value	Effect of application timing of fungicide on variable p-value	Effect of interaction of seed, early-season and application timing on variable p-value	Analysis^{z}
Emergence (RAUEPC)^{y}	**0.0006**	0.125	0.151	0.0915	0.2775	0.1527	A
Number of tubers/plant	0.1421	35.5	40.1	0.7218	0.7179	0.9472	C
Number of stems/plant	**0.0056**	4.6	5.8	0.4940	0.1829	0.0446	C
Percent of stems with girdling	**0.0262**	44.4	32.0	0.4782	0.4725	0.1444	A
Number of stolons/plant	0.0689	44.4	51.9	0.4357	0.0919	0.6827	C
Percent of stolons with girdling	0.0888	33.8	26.1	0.2422	0.3483	0.3171	C
Yield: metric tons/hectare	0.1354	35.5	38.9	0.5608	0.9591	0.5805	C
Black scurf incidence^{x}	0.4563	62.9	58.7	0.8322	0.1805	0.7542	C
Black scurf severity^{w}	0.4565	32.5	29.8	0.9001	0.0621	0.7671	C

z: Response analysis determined by the probability of difference among fungicide treatments (seed and/or early-season), application timing, and/or interaction of the treatments. Type A= significant effect of seed treatment ($p < 0.05$) but no effect of other factors ($p > 0.05$), mean of effect of seed treatment shown only in Table 2.3. Type B= significant effect of more than one factor, or factor other than seed treatment, treatment means shown in Table 2.4; Type C= no effect of any factor, no further analysis.

y: RAUEPC: Relative area under the emergence progress curve (max = 100), calculated from the day of planting to the last emergence count

x: Percent incidence of tubers with sclerotia of R. solani from a sample of 20 tubers per replicate taken during fall harvest

w: Severity of black scurf (index calculated by counting the tuber number (n = 20 per replicate) falling into each class 0 = 0%; 1 = 1 - 5%; 2 = 6 - 10%; 3 = 11 - 15%; 4 = >16% surface area covered with sclerotia; these values were then multiplied by their respective class value, and combined. Indices of 0 to 25 cover the range 0 - 5%; 25 - 50 cover the range 6 - 10%; 51 - 75 cover the range 11 - 15%; 75 - 100 cover the range >15% surface area of the tuber with sclerotia

Table 2.4 Main effects analyses (probability of difference among treatments: p =0.05) of the effect of seed and early-season fungicide treatments and application timing on agronomic factors and disease symptoms caused by *Rhizoctonia solani* in field trials conducted near Bath, MI during the 2004 growing season on cultivar 'Russet Norkotah'.

Variable Measured	Effect of seed treatment (ST) on variable p-value	Mean - ST	Mean + ST	Effect of early-season fungicide treatment on variable p-value	Effect of application timing of fungicide on variable p-value	Effect of interaction of seed, early-season and application timing on variable p-value	Analysis[Z]
Emergence (RAUEPC)[y]	0.1211	0.195	0.200	0.8197	0.4329	0.0707	C
Number of tubers/plant	0.3109	29.4	31.3	0.1941	0.8901	0.7889	C
Number of stems/plant	**0.0312**	4.2	4.9	0.3376	0.4134	0.5140	A
Percent of stems with girdling	0.1006	69.1	60.9	0.8612	0.6991	0.1981	C
Number of stolons/plant	0.1198	12.5	14.3	0.0731	0.3518	0.5275	C
Percent of stolons with girdling	**0.0390**	37.8	28.6	0.7292	0.9935	0.2622	A
Yield: metric tons/hectare	0.6870	26.4	27.1	0.5186	0.9655	0.9721	C
Black scurf incidence[X]	0.3134	51.1	46.8	0.7324	0.7960	0.7071	C
Black scurf severity[W]	0.2780	23.2	20.5	0.7151	0.7475	0.4792	C

z: Response analysis determined by the probability of difference among fungicide treatments (seed and/or early-season), application timing, and/or interaction of the treatments. Type A= significant effect of seed treatment ($p < 0.05$) but no effect of other factors ($p > 0.05$), mean of effect of seed treatment shown only in Table 2.5. Type C= no effect of any factor, no further analysis.

y: RAUEPC: Relative area under the emergence progress curve (max = 100), calculated from the day of planting to the last emergence count

x: Percent incidence of tubers with sclerotia of R. solani from a sample of 20 tubers per replicate taken during fall harvest

w: Severity of black scurf (index calculated by counting the tuber number (n = 20 per replicate) falling into each class 0 = 0%; 1 = 1 - 5%; 2 = 6 - 10%; 3 = 11 - 15%; 4 = >16% surface area covered with sclerotia; these values were then multiplied by their respective class value, and combined. Indices of 0 to 25 cover the range 0 - 5%; 25 - 50 cover the range 6 - 10%; 51 - 75 cover the range 11 - 15%; 75 - 100 cover the range >15% surface area of the tuber with sclerotia

Table 2.5 Main effects analyses (probability of difference among treatments: p=0.05) of the effect of seed and early-season fungicide treatments and application timing agronomic factors and disease symptoms caused by *Rhizoctonia solani* in field trials conducted in Antrim Co., MI during the 2004 growing season on cultivar 'Superior'.

Variable Measured	Effect of seed treatment (ST) on variable: p-value	Mean: - ST	Mean: + ST	Effect of early-season fungicide treatment on variable: p-value	Effect of application timing of fungicide on variable: p-value	Effect of interaction of seed, early-season and application timing on variable: p-value	Analysis[z]
Emergence (RAUEPC)[y]	**0.0032**	0.422	0.446	0.4142	**0.0081**	**0.0119**	B
Number of tubers/plant	**< 0.0001**	16.2	22.1	**0.0427**	0.0597	**< 0.0001**	B
Number of stems/plant	**< 0.0001**	3.1	4.1	0.2335	0.4710	**< 0.0001**	B
Percent of stems with girdling	**< 0.0001**	24.3	10.7	0.1727	0.8217	**0.0235**	B
Number of stolons/plant	**< 0.0001**	13.4	19.2	0.0697	0.0809	**< 0.0001**	B
Percent of stolons with girdling	**0.0001**	10.7	3.6	0.5136	0.8791	**0.0067**	B
Yield: metric tons/hectare	**< 0.0001**	35.7	30.2	0.9131	0.3166	**0.0090**	B
Black scurf incidence[x]	**0.0071**	13.5	3.1	0.3459	0.2159	0.1089	A
Black scurf severity[w]	**0.0081**	6.5	1.4	0.3038	0.2382	0.1147	A

z: Response analysis determined by the probability of difference among fungicide treatments (seed and/or early-season), application timing, and/or interaction of the treatments. Type A= significant effect of seed treatment ($p < 0.05$) but no effect of other factors ($p > 0.05$), mean of effect of seed treatment shown only in Table 2.6. Type B= significant effect of more than one factor, or factor other than seed treatment, treatment means shown in Table 2.7; Type C= no effect of any factor, no further analysis.

y: RAUEPC: Relative area under the emergence progress curve (max = 100), calculated from the day of planting to the last emergence count

x: Percent incidence of tubers with sclerotia of R. solani from a sample of 20 tubers per replicate taken during fall harvest

w: Severity of black scurf (index calculated by counting the tuber number (n = 20 per replicate) falling into each class 0 = 0%; 1 = 1 - 5%; 2 = 6 - 10%; 3 = 11 - 15%; 4 = >16% surface area covered with sclerotia; these values were then multiplied by their respective class value, and combined. Indices of 0 to 25 cover the range 0 - 5%; 25 - 50 cover the range 6 - 10%; 51 - 75 cover the range 11 - 15%; 75 - 100 cover the range >15% surface area of the tuber with sclerotia

Table 2.6 Effect of seed and early-season fungicide treatments and application timing on agronomic factors and disease symptoms caused by *Rhizoctonia. solani* in field trials conducted in Antrim Co., MI during the 2004 growing season on cultivar 'Superior'.

Seed (ST) and early season (ES) treatments and application timings (AT)[z]			Emergence		Number of		Number of		Percent of		Number of		Percent of		Yield:	
ST	ES	AT	(RAUEPC)[y]		tubers per plant		stems per plant		stems with girdling		stolons per plant		stolons with girdling		metric tons/ha	
- ST	azo	IF	0.411	ab[x]	14.1	cd	2.9	bc	24.5	a	13.4	cde	9.1	ab	38.1	a
		Em	0.412	ab	16.9	a-d	3.1	abc	24.7	a	14.6	b-e	13.3	ab	32.9	a
		PE	0.393	b	14.5	cd	2.9	bc	24.0	a	12.1	de	12.6	ab	36.7	a
	flu	IF	0.410	ab	19.0	a-d	3.3	abc	41.7	a	11.6	de	23.2	ab	36.0	a
		Em	0.433	ab	20.5	a-d	3.8	abc	37.5	a	16.0	a-e	12.2	ab	33.9	a
		PE	0.437	ab	17.1	a-d	3.6	abc	16.7	a	16.9	a-e	1.0	b	37.9	a
	pyr	IF	0.393	b	14.3	cd	3.0	abc	14.1	a	11.8	de	7.7	ab	37.9	a
		Em	0.450	ab	18.8	a-d	3.1	abc	20.2	a	14.1	b-e	4.0	ab	34.5	a
		PE	0.444	ab	15.3	bcd	2.9	bc	13.5	a	12.4	de	8.0	ab	33.7	a
	none		0.437	ab	12.0	d	2.3	c	26.6	a	10.9	e	15.7	ab	35.4	a
+ ST	azo	IF	0.437	ab	22.6	abc	4.4	ab	6.9	a	19.7	a-d	3.3	ab	29.0	a
		Em	0.444	ab	20.6	a-d	3.4	abc	7.8	a	16.9	a-e	2.7	ab	27.3	a
		PE	0.467	ab	22.9	abc	4.0	abc	15.8	a	19.3	a-d	3.6	ab	31.0	a
	flu	IF	0.408	ab	23.9	ab	4.0	abc	11.3	a	18.4	a-e	2.1	b	30.2	a
		Em	0.456	ab	19.9	a-d	3.8	abc	8.3	a	18.4	a-e	3.8	ab	29.2	a
		PE	0.432	ab	19.4	a-d	4.1	abc	13.0	a	17.4	a-e	8.5	ab	29.8	a
	pyr	IF	0.420	ab	22.4	abc	3.9	abc	8.2	a	20.8	abc	1.8	b	31.1	a
		Em	0.489	a	24.8	a	4.8	a	6.4	a	23.3	a	4.5	ab	30.3	a
		PE	0.459	ab	24.8	a	4.4	ab	12.2	a	21.9	ab	4.5	ab	32.1	a
	none		0.449	ab	19.6	a-d	4.1	abc	16.9	a	16.1	a-e	1.5	b	32.2	a

z: Seed treatment: fludioxonil (Maxim 4FS) 2.37mL/45.4 kg seed. Early season treatment per 305 m: azo = azoxystrobin (Amistar 80WD) 7.09 g; flu = flutolanil (Moncut 70DF) 33.45 g; pyr = pyraclostrobin (Headline) 6.21 mL. Application timings: IF = In-furrow at planting; Em = emergence; PE = 14 days post-emergence

y: RAUEPC: Relative area under the emergence progress curve (max = 100), calculated from the day of planting to the last emergence count

x: Values followed by the same letter are not significantly different at $p = 0.05$ (Tukey's HSD)

Table 2.7 Main effects analyses (probability of difference among treatments: p=0.05) of the effect of seed and early-season fungicide treatment and application timing on agronomic factors and disease symptoms caused by *Rhizoctonia solani* in field trials conducted near Bath, MI during the 2005 growing season on cultivar 'Russet Norkotah'.

Variable Measured	Effect of seed treatment (ST) on variable p-value	Mean - ST	Mean + ST	Effect of early-season fungicide treatment on variable p-value	Effect of application timing of fungicide on variable p-value	Effect of interaction of seed, early-season and application timing on variable p-value	Analysis[z]
Emergence (RAUEPC)[y]	**< 0.0001**	0.050	0.065	0.7198	0.9778	**< 0.0001**	B
Number of tubers/plant	0.6361	22.7	22.1	0.1337	0.1351	0.1459	C
Number of stems/plant	0.6528	3.8	3.9	0.4147	0.3470	0.4749	C
Percent of stems with girdling	0.0363	66.7	73.9	0.6948	0.0702	0.0777	C
Number of stolons/plant	0.1062	9.6	8.5	0.4947	0.2757	0.4041	C
Percent of stolons with girdling	0.5356	19.0	20.7	0.1568	0.4777	**0.0321**	C
Yield: metric tons/hectare	**< 0.0001**	16.7	23.8	0.7652	0.8781	**0.0010**	B
Black scurf incidence[x]	**0.0293**	20.1	27.3	0.3188	0.0752	0.1652	A
Black scurf severity[w]	**0.0045**	7.0	11.1	0.1429	0.1198	**0.0384**	C

z: Response analysis determined by the probability of difference among fungicide treatments (seed and/or early-season), application timing, and/or interaction of the treatments. Type A= significant effect of seed treatment ($p < 0.05$) but no effect of other factors ($p > 0.05$), mean of effect of seed treatment shown only in Table 2.8. Type B= significant effect of more than one factor, or factor other than seed treatment, treatment means shown in Table 2.9; Type C= no effect of any factor, no further analysis.

y: RAUEPC: Relative area under the emergence progress curve (max = 100), calculated from the day of planting to the last emergence count

x: Percent incidence of tubers with sclerotia of R. solani from a sample of 20 tubers per replicate taken during fall harvest

w: Severity of black scurf (index calculated by counting the tuber number (n = 20 per replicate) falling into each class 0 = 0%; 1 = 1 - 5%; 2 = 6 - 10%; 3 = 11 - 15%; 4 = >16% surface area covered with sclerotia; these values were then multiplied by their respective class value, and combined. Indices of 0 to 25 cover the range 0 - 5%; 25 - 50 cover the range 6 - 10%; 51 - 75 cover the range 11 - 15%; 75 - 100 cover the range >15% surface area of the tuber with sclerotia

Table 2.8 Effect of seed and early-season fungicide treatments and application timing on agronomic factors and disease symptoms caused by *Rhizoctonia solani* in field trials conducted near Bath, MI during the 2005 growing season on cultivar 'Russet Norkotah'.

Seed (ST) and early season (ES) treatments and application timings (AT)[z]			Emergence (RAUEPC)[y]		Yield: metric tons/hectare	
ST	ES	AT				
- ST	azo	IF	0.054	abcd[x]	18.8	ab
		Em	0.046	d	16.625	ab
		PE	0.052	abcd	12.425	b
	flu	IF	0.05	bcd	16.825	ab
		Em	0.046	d	17.05	ab
		PE	0.054	abcd	14.8	ab
	pyr	IF	0.048	cd	16.425	ab
		Em	0.053	abcd	20.1	ab
		PE	0.046	d	17.6	ab
	none		0.053	abcd	16.1	ab
+ ST	azo	IF	0.07	ab	23.625	ab
		Em	0.069	abc	26.775	a
		PE	0.064	abcd	24.725	ab
	flu	IF	0.059	abcd	23.625	ab
		Em	0.073	a	19.875	ab
		PE	0.064	abcd	23.2	ab
	pyr	IF	0.067	abcd	25.15	a
		Em	0.06	abcd	22.9	ab
		PE	0.062	abcd	23.875	ab
	none		0.064	abcd	24.3	ab

z: Seed treatment: fludioxonil (Maxim 4FS) 2.37mL/45.4 kg seed. Early season treatment per 305 m: azo = azoxystrobin (Amistar 80WD) 7.09 g; flu = flutolanil (Moncut 70DF) 33.45 g; pyr = pyraclostrobin (Headline) 6.21 mL. Application timings: IF = In-furrow at planting; Em = emergence; PE = 14 days post-emergence

y: RAUEPC: Relative area under the emergence progress curve (max = 100), calculated from the day of planting to the last emergence count

x: Values followed by the same letter are not significantly different at $p = 0.05$ (Tukey's HSD)

Table 2.9 Main effects analyses (probability of difference among treatments: α =0.05) of the effect of seed and early-season fungicide treatments and application timing on agronomic factors and disease symptoms caused by *Rhizoctonia solani* in field trials conducted in Antrim Co., MI during the 2005 growing season on cultivar 'Superior'.

Variable Measured	Effect of seed treatment (ST) on variable p-value	Mean - ST	Mean + ST	Effect of early-season fungicide treatment on variable p-value	Effect of application timing of fungicide on variable p-value	Effect of interaction of seed, early-season and application timing on variable p-value	Analysis^{z}
Emergence (RAUEPC)^{y}	0.6391	0.060	0.061	0.2926	0.9595	0.9708	C
Number of tubers/plant	0.6929	27.3	27.8	0.3925	0.2711	0.5373	C
Number of stems/plant	**0.0003**	4.0	3.4	0.7662	0.5337	0.2185	A
Percent of stems with girdling	0.3317	21.7	18.8	0.0673	**0.0418**	0.6042	C
Number of stolons/plant	0.1068	23.1	21.6	0.6380	0.5346	0.7758	C
Percent of stolons with girdling	**0.0019**	12.1	6.9	0.2067	0.3382	**0.0014**	B
Yield: metric tons/hectare	0.1029	30.5	33.1	0.5020	0.7968	0.7482	C
Black scurf incidence^{x}	0.1792	8.5	4.9	0.5532	0.7081	0.8898	C
Black scurf severity^{w}	0.0545	4.1	1.6	0.4252	0.8832	0.6287	C

z: Response analysis determined by the probability of difference among fungicide treatments (seed and/or early-season), application timing, and/or interaction of the treatments. Type A= significant effect of seed treatment ($p < 0.05$) but no effect of other factors ($p > 0.05$), mean of effect of seed treatment shown only in Table 2.10. Type B= significant effect of more than one factor, or factor other than seed treatment, treatment means shown in Table 2.11; Type C= no effect of any factor, no further analysis.
y: RAUEPC: Relative area under the emergence progress curve (max = 100), calculated from the day of planting to the last emergence count

x: Percent incidence of tubers with sclerotia of R. solani from a sample of 20 tubers per replicate taken during fall harvest
w: Severity of black scurf (index calculated by counting the tuber number (n = 20 per replicate) falling into each class 0 = 0%; 1 = 1 - 5%; 2 = 6 - 10%; 3 = 11 - 15%; 4 = >16% surface area covered with sclerotia; these values were then multiplied by their respective class value, and combined. Indices of 0 to 25 cover the range 0 - 5%; 25 - 50 cover the range 6 - 10%; 51 - 75 cover the range 11 - 15%; 75 - 100 cover the range >15% surface area of the tuber with sclerotia

Table 2.10 Effect of seed and early-season fungicide treatments and application timing on agronomic factors and disease symptoms caused by *Rhizoctonia solani* in field trials conducted in Antrim Co., MI during the 2005 growing season on cultivar 'Superior'.

Seed (ST) and early season (ES) treatments and application timings (AT)[z]			
ST	ES	AT	Percent of stolons with girdling
- ST	azo	IF	10.7 b[y]
		Em	9.2 b
		PE	10.1 b
	flu	IF	8.7 b
		Em	8.3 b
		PE	10.6 b
	pyr	IF	7.3 b
		Em	11.4 b
		PE	30.5 a
	none		14.2 ab
+ ST	azo	IF	5.9 b
		Em	10.9 b
		PE	5.8 b
	flu	IF	6.6 b
		Em	4.8 b
		PE	7.1 b
	pyr	IF	10.4 b
		Em	6.3 b
		PE	6.9 b
	none		4.1 b

z: Seed treatment: fludioxonil (Maxim 4FS) 2.37mL/45.4 kg seed. Early season treatment per 305 m: azo = azoxystrobin (Amistar 80WD) 7.09 g; flu = flutolanil (Moncut 70DF) 33.45 g; pyr = pyraclostrobin (Headline) 6.21 mL. Application timings: IF = In-furrow at planting; Em = emergence; PE = 14 days post-emergence

y: Values followed by the same letter are not significantly different at p = 0.05 (Tukey's HSD)

Results of similar studies

Previous studies of the diseases caused by *Rhizoctonia solani* at the MSU Muck Soils Research Farm (on cvs Pike, Snowden, or FL 1879) have included the use of the seed treatments including fludioxonil, and early season treatments of azoxystrobin, flutolanil and pyraclostrobin tested at multiple concentrations and formulations (Kirk et al., 2001, 2002, 2003, 2004, 2007a, 2007b, 2008). In most cases, the use of seed treatment fludioxonil or early-season treatments resulted in healthier plants, when compared to the non-treated control, in at least one measured variable (increased RAUEPC, canopy development, stem number, and yield; or decreased stem and stolon girdling and incidence and severity of black scurf). However, when compared to other seed or early-season fungicides tested, these treatments generally resulted in statistically similar ratings of the tested variables.

In other fungicide testing programs throughout the country, the use of fludioxonil, azoxystrobin, flutolanil and pyraclostrobin has had mixed results. During the 2003 growing season, May et al. (2004) found that flutolanil (at two rates) applied alone or in combination with fludioxonil (ST) resulted in similar ratings of *R. solani* on stems and stolons, when compared to the inoculated non-treated control. On the other hand, azoxystrobin (two formulations) applied alone or in combination with fludioxonil (ST) resulted in significantly less disease. During the 2004 growing season, Stevenson et al. (2005) found no significant differences between treatments of fludioxonil (ST) alone or in combination with early-season applications azoxystrobin or treatments with azoxystrobin or pyraclostrobin and the non-treated control for early emergence, severity of infection on stems, stolons or tubers, or yield. In addition, there were no significant differences among relevant treatments for average stem and stolon numbers. Finally, during the 2007 growing season, Zitter and Drennan (2008), found that fludioxonil (ST) or in combination with one of two concentrations of an in-furrow application of azoxystrobin resulted in a significantly lower black scurf rating compared to the non-treated control, but there were no significant differences among relevant treatments.

Discussion and Conclusions

The 2004 planting was delayed approximately three weeks due to significant rainfall (233.7 mm) in the pervious month, which led to flooding. The location of the Muck Soils Research Farm is geographically a low point for the surrounding area, and as such a backup/failure of the drainage system resulted in the entire farm being under nearly 50 cm of water for over a week. Even with the delay in planting, the agronomic differences found between the 2004 and 2005 growing seasons, for cv. Russet Norkotah, cannot be explained by meteorological data. The soil temperature at planting depth of 10 cm for a five-day average was 18.7°C on 23 June, 2004 and 15.8°C on 1 June, 2005. In spite of being planted just over three weeks later in 2004, the temperature was only 3°C higher. The two and four week average soil temperatures following planting were 19.6°C and 20.5°C in 2004 and 20.8°C and 20.7°C in 2005, respectively. Sale (1979) noted in growth chamber studies on cvs Sebago and Sequoia that "emergence was quickest at a mean temperature of about 21°C and was progressively longer as mean temperature either decreased or increased from this value." In both 2004 and 2005 growing seasons, the mean temperatures at and following planting were very close to the range of optimal temperature for emergence. This may have resulted in a faster and more uniform emergence than if the seed pieces were planted at cooler soil temperatures, thus decreasing time for initial interaction between *R. solani* and the emerging sprouts.

A possible reason for the agronomic differences in growing seasons may have been more the result of seed physiological age, something that was not accounted for. Allen and O'Brien (1986) found that an increase of time between seed breaking dormancy and planting date resulted in a quicker emergence. This faster emergence could lead to more stolons and tubers formation. All seed used had broken dormancy, but the number of days between dormancy break and planting was not recorded.

Increased disease symptoms for cv. Russet Norkotah (percent stolons with greater than five percent girdling due to *R. solani*, incidence and severity of black scurf) in 2004 may have been the result of optimal growing conditions for *R. solani* the year prior to the experiment, leading to an increased level of soil-borne inoculum. Soil inoculum levels were not measured but previous experiments at the same location have had disease signs and symptoms of *R. solani*. In addition, the selection of certified seed for the experiments ensured seed-borne inoculum less than 2% on the majority of tubers. With planting near the optimal temperature range for emergence, the stems may have been able to emerge prior to significant stem infection. However, as stolons grew, they encountered soil-borne inoculum leading to stolon girdling, and as tubers formed, black scurf occurred. Simons and Gilligan (1997) reasserted that soil-borne inoculum is more important for the development of stolon canker and black scurf, while seed-borne inoculum is more important for stem canker (Van Emden 1965; Frank & Leach 1980).

In 2004, cv. Russet Norkotah vines were desiccated on September 23 and harvested October 13 (20 days) while in 2005 vines were desiccated and harvested

August 25 and September 21 (27 days), respectively. The span of time between desiccation and harvest, especially three to seven weeks, has been shown to significantly increase the number of sclerotia per tuber (Gudmestad, 1979). In both years the final harvests were in the time span which could have resulted in an increase in tuber black scurf.

Similar to prior growing seasons at the Muck Soils Research Farm, treatments in 2004 that included the fludioxonil seed treatment had significantly less disease (percent of stems and stolons with greater than five percent girdling and black scurf incidence and severity). Treatments with fludioxonil (ST), especially on cv. Superior, produced more robust plants early in the growing season (significantly greater RAUEPC and tuber, stem and stolon numbers). However, at the end of the season the yield was significantly less for treatments with fludioxonil, which was also found by Stevenson et al. (2000, 2004).

In 2005 treatments with the fludioxonil seed treatment, on cv. Russet Norkotah, had significantly higher percent of stems with greater than five percent girdling as well as higher black scurf incidence and severity. Only in 2002 did a treatment with fludioxonil have a parameter that was significantly worse than other treatments tested including the untreated control: RAUEPC and RAUCPC (Kirk, 2003). However, other efficacy studies have also noted either significantly less healthy plants or worse disease symptoms.

The current chemical management strategy for *R. solani* is for a seed treatment (fludioxonil, flutolanil, thiophanate-methyl) or in-furrow (PCNB, azoxystrobin or flutolanil) application or both (Bird, 2008). The rationale is that the seed treatment will control the seed-borne and some soil-borne inoculum, while the in-furrow application would control mostly soil-borne inoculum. Of the early-season treatments tested, alone or in combination with the seed treatment fludioxonil, there was not one that consistently improved plant vigor (faster emergence resulting in a higher RAUEPC, increased stem, stolon, tuber number, or yield) or decreased disease incidence and severity on stems, stolons or tubers. Further, the choices of the early-season fungicide tested (azoxystrobin, flutolanil or pyraclostrobin) or the application timing (in-furrow, at emergence, or 14 days post-emergence) were not consistently significantly different from the non-treated controls.

Some of the lack of differences among treatments may have been due to interactions with the soil. The Houghton muck, at the MSU Muck Soils Research Farm, is 91.9% organic matter which is significantly higher than the sandy loam in Antrim County. Organic matter tends to adsorb pesticides, slowing the rate of leaching and volatilization, but also reduces the amount that is available for absorption by plants or target organisms. This may have lead to the limited number of significant differences found among treatments grown on muck (cvs FL1879 and Russet Norkotah). However, a comparative study of the efficacy and availability of these fungicides on different soil types has not been completed, which could provide insight.

Another possible source for the lack of visible significant differences among treatments may have been in part due to the reliance on a naturally occurring inoculum. The addition of inoculum, and a non-inoculated control, could have led to some insight on existing inoculum levels at the Muck Soils Research Farm. The application of inoculum was not an option for the sites in Antrim Co, grown by a cooperating farmer.

In a summary of nearly 50 trials, Wale (2008) found that even Rhizoctonia stem canker specific (seed and soil) treatments had variable results. For example, of the trials with azoxystrobin that examined black scurf incidence (15) and severity (11), or stem canker incidence (9) and severity (10), there was never more than 50% of the trials that resulted in significantly less disease when compared to the non-treated control (Wale, 2008). Based upon the results of this summary, these two field experiments and given consideration for the concerns stated, only use of the one treatment, whether seed or early season was necessary. However, the use of fungicides for management should not be the sole source of control, but rather part of an integrated pest management strategy.

Although the presence of *R. solani* has been noted via previous efficacy studies by Kirk et al. (2000 through 2008), the quantity, anastomosis group(s) and virulence of the soil-borne inoculum were not examined. These parameters should be evaluated for future studies at the Muck Soils Research Farm.

CHAPTER 3
EFFECT OF SOIL TEMPERATURE ON VARIETY SUSCEPTIBILITY TO THE INCIDENCE AND SEVERITY OF RHIZOCTONIA CANKER AND BLACK SCURF ON POTATOES

Introduction

The time potatoes need to reach maturity can range from 90 to around 130 days, and potatoes can be left in the ground up to one month, or more, after vine desiccation. In addition to a wide window of opportunity for harvest, a similarly large window exists for planting the potato seed pieces. Whole or cut seed pieces are generally planted once the temperature of the soil has risen sufficiently after thawing and unlikely to refreeze after seed pieces are in the ground. Many of the cultural practices involving how and when to plant seed pieces have been developed for the management of early-season diseases especially stem and stolon canker caused by *Rhizoctonia solani*.

Although current recommendations suggest not planting until the soil is 15°C, as this promotes quick emergence (Secor, 2008; Banville et al., 1996), there are few recent evaluations of the effect of soil temperature on disease incidence and severity of potato varieties. Simons and Gilligan (1997) examined three different planting times, and found that as the soil temperature increased (with later planting) the incidence and severity of stem canker decreased. However, the planting times were apparently based upon time (2 to 3 weeks apart) instead of the measured soil temperature.

In this set of experiments, the effect of soil temperature on stem and stolon canker, and black scurf incidence and severity, was examined on several potato varieties. Ten potato cultivars commonly grown in Michigan in 2004 and eight in 2005 were evaluated at three different planting times based upon the soil temperature surpassing a threshold. Planting occurred once the temperature at 15 cm (approximate planting depth) as a five day average surpassed thresholds of 8, 14 and 20°C. These temperatures were chosen to provide a testable range, within which planting was typically done in Michigan, either commercially or at the home garden level. In addition, local historical soil temperature (10cm) data (Michigan Automated Weather Network, Michigan State University: http://www.agweather.geo.msu.edu/mawn/) were examined to determine possible temperature thresholds (Figure 3.1). A five-day average was used to reduce fluctuations that could result in targeted plantings within a short (and insignificant) time period. The temperature thresholds resulted in an average of 21.5 days between plantings in 2004, and 35 days in 2005. The main questions this experiment attempted to answer were: 1) Does planting later result in a reduction in stem and/or stolon canker and/or black scurf, compared to early planting? 2) Due to the shorter growing season, does planting later result in a reduction of yield? 3) Do varieties differ for the effect of planting date on the incidence and severity of stem and stolon canker and black scurf?

Materials and Methods

The experiment was located at the Plant Pathology Farm (Michigan State University) in East Lansing, MI. The seed pieces were hand-planted into pre-hilled sandy soil in a split-plot randomized complete block design with temperature-determined planting timing as the major split. All plantings had three replications, and within each replicated plot were four rows, three meters long and spaced one meter apart. Nine seed pieces per row were spaced 30 cm apart, for a total of 36 seed pieces total per replication. Table 3.1 lists the cultivars, and their common usage, that were planted in both years.

The temperature of the soil at 15 cm (approximate planting depth) was measured hourly by a Cole-Parmer 12 channel scanning thermometer (one at each planting) and a five-day moving average of three temperature probes was calculated. This moving average was monitored, and planting occurred once the threshold of 8, 14, or 20°C was surpassed. In 2004, plantings occurred on April 19th, May 17th, and June 28th, while in 2005 they occurred on April 21st, May 9th, and June 3rd.

Plot Maintenance was similar for both growing seasons. Drip irrigation lines were setup, after planting, for each plot and used regularly to maintain adequate moisture for plant growth. Weeds were controlled by hand as needed. The fungicide propamocarb (Previcur Flex) was applied biweekly (at 1.05L/hectare) to prevent foliar late blight (*Phytophthora infestans*). Insects were controlled with one in-furrow application of imidacloprid (Admire 2F) at 1.46 L/ha at-planting.

The field was inoculated in 2004 with an AG-3 isolate of *R. solani*, MI-3, originally isolated from potato tuber sclerotia from Michigan. The isolate was grown on white millet that was twice autoclaved, for one hour on two consecutive days. 10 covered trays (23 x 40 cm) were each inoculated with one Petri plate (100 x 10mm) of the actively growing isolate. The isolate was allowed to colonize the millet seed for 21 days, after which time the inoculated millet was spread out on large (40 x 60cm) trays and dried for 3 days. One batch of 10 trays was created for each planting time and was broadcast over the section of the field to be used, just prior to cultivation and hilling for the plots. The field was not inoculated in 2005 due to contamination of the inoculum intended for the first planting.

In 2005, emergence counts were taken for each plot of each planting time, 8, 14 and 20°C, for 62, 53, and 38 days after planting, respectively. This was then converted to the relative area under the emergence progress curve (RAUEPC) for each plot. Higher values of RAUEPC indicate earlier emergence relative to the length of time in which evaluations are made.

In both 2004 and 2005, a mid-season sample from each plot was made (Table 3.2), with the exception of the third (20°C) planting in 2004. In both years samples were taken from one of the two center rows from each plot, with two plants per plot evaluated in 2004 and four plants in 2005. During this evaluation, the number of stems, stolons and tubers were counted. In addition, the incidence of cankers/girdling, caused by *R. solani*, on stems and stolons was counted and converted to a percentage of the total.

Also, in both 2004 and 2005, samples of four plants were taken at the end of the season (Table 3.2), to evaluate yield, and a subset of 20 tubers per replicate were evaluated for the incidence and severity of black scurf. Black scurf incidence was a count of the number of tubers with visible sclerotia on the skin. Black scurf severity was evaluated as the number of tubers with a specific amount of surface area covered by sclerotia. A score of 0 to 4 was possible for each tuber, with 0 = 0%; 1 = 1 - 5%; 2 = 6 - 10%; 3 = 11 – 15%; 4 = > 15% surface area of tuber covered with sclerotia. The number in each class was multiplied by the class number and summed. The sum was multiplied by a constant to be expressed as a percentage. Indices of 0 - 25 represent 0 - 5%; 26 - 50 represent 6 - 10%; 51 - 75 represent 11 - 15% and 75 - 100 >15% of the average surface area covered with sclerotia.

All data were analyzed by ANOVA and tested with Tukey's Honestly Significant Differences (HSD), p=0.05 (JMP: SAS Institute, Cary, NC, USA).

Figure 3.1 Historical soil temperatures (10cm) around planting time for potatoes
East Lansing, MI, 2000 to 2003.

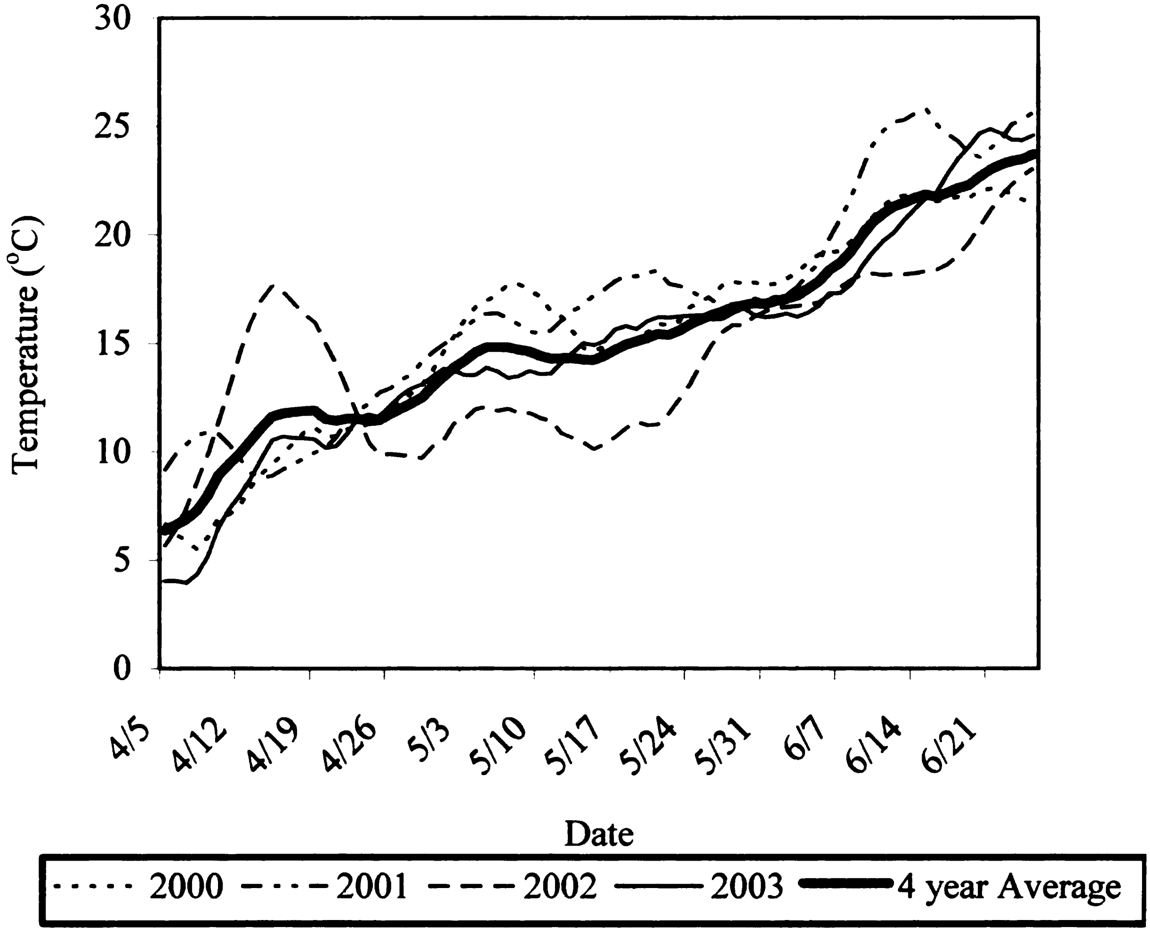


Table 3.1 Cultivars planted during the 2004 and 2005 experiments evaluating the effect of planting time, based upon soil temperature, on disease incidence and severity caused by *Rhizoctonia solani;* Plant Pathology Farm, Michigan State University, East Lansing, MI

Variety	**2004**	**2005**	**Main Use**
Atlantic	X		chip
FL1833	X		chip
FL1867	X	X	chip
FL1879	X	X	chip
Jacqueline Lee	X	X	table
Michigan Purple	X	X	table
MSI152-A		X	table (advanced breeding selection)[z]
MSI201-2PY	X		table (advanced breeding selection)
Pike	X	X	chip
Russet Norkotah	X	X	table
Snowden	X	X	chip

z: Advanced breeding selection provided by the Potato Breeding and Genetics Laboratory of Michigan State University, East Lansing, MI

Table 3.2 Important dates and relative number of days after planting (DAP) for each planting time of the 2004 and 2005 experiments evaluating the effect of planting time, based upon soil temperature, on disease incidence and severity caused by *Rhizoctonia solani.* Plant Pathology farm, Michigan State University, East Lansing, MI.

Year	Planting Temperature Threshold (^{o}C)	Temperature Threshold Surpassed	Planting date	Mid-season sampling		Vine desiccation		Fall Harvest	
				date	DAP	date	DAP	date	DAP
2004	8	4/18	4/19	7/8	80	9/17	151	10/4	168
	14	5/11	5/17	7/28	72	9/17	123	10/4	140
	20	6/10	6/28	N/A	N/A	9/17	81	10/4	98
2005	8	4/18	4/21	7/27	97	9/8	140	9/27	159
	14	5/11	5/11	7/27	77	9/8	120	9/27	139
	20	5/31	6/3	7/27	54	9/8	97	9/27	116

Results

In both 2004 and 2005 differences in several variables were found between planting times. In 2004, planting early (8°C, compared to 14°C) resulted in fewer tubers at the mid-season harvest, fewer stolons and more disease symptoms (percent of stems and stolons with girdling, and black scurf incidence and severity; Table 3.3). Planting early resulted in higher yield than at 14°C, although not significantly different than at 20°C. No significant differences were found between planting at 14°C and 20°C for black scurf incidence and severity, and yield. In 2005, planting early resulted in slower emergence (RAUEPC) and lower number of stems per plant compared to planting at 20°C and higher percent of stems and stolons with girdling and yield (Table 3.4). However, there were no differences among planting times for the number of stolons per plant or black scurf incidence or severity. In contrast to 2004, early planting in 2005 resulted in a higher number of tubers per plant.

In 2004 differences were found among cultivars for most of the agronomic variables: numbers of tubers, stems and stolons per plant (Tables 3.3 and 3.5). However, using Tukey's Honestly Significant Differences (HSD) test, the number of tubers per plant was found to be not significantly different. Also, no differences were found for any disease variables. In 2005 significant differences were found among cultivars planted for all variables tested, except the percent of stems with girdling and yield (Table 3.4 and 3.6).

The interaction of planting time and cultivar also resulted in differences in both years. In 2004 Michigan Purple had the highest number of stolons per plant and the highest yield (Tables 3.7 and 3.8). Russet Norkotah had no stems with girdling, significantly less than Atlantic's 67.6% (however neither was significantly different than any other cultivar). In 2005 Michigan Purple again had the highest number of stolons per plant (at 8°C and 14°C) and highest yield at 20°C (Tables 3.7, 3.9, and 3.10). Snowden had the highest number of stems per plant at all three plantings.

Table 3.3 Main effects analyses (probability of difference between planting times: p=0.05) of the effect of planting time and cultivar planted on agronomic factors and disease symptoms caused by *Rhizoctonia solani* in field trials at the Plant Pathology farm, Michigan State University; East Lansing, MI in 2004.

	Effect of planting time on variable				Effect of cultivar planted on variable	
Variable Tested	p-value	1) 8 °C	2) 14 °C	3) 20 °C	p-value	Analysis[z]
Number of tubers/plant[y]	**0.0050**	12.6 b[t]	19.2 a	*	**0.0302**	B
Number of stems/plant[y]	0.0532	4.0 a	4.9 a	*	**0.0007**	B
Percent of stems with girdling[x]	**0.0001**	69.7 a	45.0 b	*	0.7356	A
Number of stolons/plant[y]	**0.0392**	16.1 b	20.1 a	*	**< 0.0001**	B
Percent of stolons with girdling[x]	**0.0003**	50.3 a	33.5 b	*	0.2375	A
Black scurf incidence[w]	**< 0.0001**	85.6 a	25.4 b	14.4 b	0.7099	A
Black scurf severity[v]	**< 0.0001**	37.1 a	8.6 b	6.0 b	0.8476	A
Yield: metric tons/hectare[u]	**< 0.0001**	23.0 a	19.2 b	20.9 ab	0.8757	A

z: Response analysis determined by the probability of difference among planting times (pt) and cultivar planted. Type A= significant effect of planting time ($p < 0.05$) but no effect of cultivar planted ($p > 0.05$), mean of effect of planting time shown only in Table 3.3. Type B= significant effect of cultivar planted ($p > 0.05$), mean of effect of cultivar planted shown in Table 3.5.

y: Numbers of tubers, stems, and stolons are the average of 2 plants per replicate (3 replicates) taken 80 days after planting (dap) for pt 1; and 72 dap for pt 2

x: Percent of stems and stolons with girdling caused by *R. solani* are from an average of 2 plants per replicate (3 replicates) taken 80 dap for pt 1, and 72 dap for pt 2

w: Percent incidence of tubers with sclerotia of R. solani from a sample of 20 tubers per replicate taken 168 dap for pt 1, 140 dap for pt 2, and 98 dap for pt 3.

v: Severity of black scurf (index calculated by counting the tuber number (n = 20 per replicate) falling into each class 0 = 0%; 1 = 1 - 5%; 2 = 6 - 10%; 3 = 11 - 15%; 4 = >16% surface area covered with sclerotia; these values were then multiplied by their respective class value, and combined. Indices of 0 to 25 cover the range 0 - 5%; 25 - 50 cover the range 6 - 10%; 51 - 75 cover the range 11 - 15%; 75 - 100 cover the range >15% surface area of the tuber with sclerotia taken 168 dap for pt 1, 140 dap for pt 2, and 98 dap for pt 3.

u: Yield (metric tons/hectare) calculated from the yield of 4 plants/replicate (3 replicates); taken 168 dap for pt 1, 140 dap for pt 2, and 98 dap for pt 3.

t: Values followed by the same letter are not significantly different at p = 0.05 (Tukey's HSD Comparison)

Table 3.4 Main effects analyses (probability of difference between planting times: p=0.05) of the effect of planting time and cultivar planted on agronomic factors and disease symptoms caused by *Rhizoctonia solani* in field trials at the Plant Pathology farm, Michigan State University; East Lansing, MI in 2005.

Variable Tested	Effect of planting time on variable				Effect of cultivar planted on variable	
	p-value	1) 8 °C	2) 14 °C	3) 20 °C	p-value	Analysis[z]
Emergence (RAUEPC)[y]	**< 0.0001**	0.0446 a[s]	0.0437 a	0.0307 b	**< 0.0001**	B
Number of tubers/plant[x]	**0.0004**	18.5 a	13.4 b	15.3 b	**< 0.0001**	B
Number of stems/plant[x]	**0.0015**	3.9 b	4.2 b	5.2 a	**< 0.0001**	B
Percent of stems with girdling[w]	**< 0.0001**	51.8 a	33.4 b	11.3 c	0.0599	A
Number of stolons/plant[x]	0.4494	19.3 a	17.0 a	18.0 a	**< 0.0001**	B
Percent of stolons with girdling[w]	**< 0.0001**	33.7 a	32.4 a	15.5 b	**< 0.0001**	B
Black scurf incidence[v]	0.6988	10.8 a	12.3 a	9.0 a	**0.0028**	B
Black scurf severity[u]	0.8379	3.6 a	4.6 a	3.8 a	**0.0084**	B
Yield: metric tons/hectare[t]	0.1937	31.7 a	24.8 ab	20.7 b	0.3735	A

z: Response analysis determined by the probability of difference among planting times (pt) and cultivar planted. Type A= significant effect of planting time ($p < 0.05$) but no effect of cultivar planted ($p > 0.05$), mean of effect of planting time shown only in Table 3.4. Type B= significant effect of cultivar planted ($p > 0.05$), mean of effect of cultivar planted shown in Table 3.6.

y: RAUEPC: Relative area under the emergence progress curve (max = 100), calculated from the day of planting to 62 days after planting (dap) for pt 1, 53 dap for pt 2, and 38 dap for pt 3

x: Numbers of tubers, stems, and stolons are the average of 4 plants per replicate (3 replicates) taken 97 days after planting (dap) for pt 1, 77 dap for pt 2, and 54 dap for pt 3

w: Percent of stems and stolons with girdling caused by *R. solani* are from an average of 4 plants per replicate (3 replicates) taken 97 dap for pt 1, 77 dap for pt 2, and 54 dap for pt 3

v: Percent incidence of tubers with sclerotia of R. solani from a sample of 20 tubers per replicate taken 159 dap for pt 1, 139 dap for pt 2, and 116 dap for pt 3.

u: Severity of black scurf (index calculated by counting the tuber number (n = 20 per replicate) falling into each class 0 = 0%; 1 = 1 - 5%; 2 = 6 - 10%; 3 = 11 - 15%; 4 = >16% surface area covered with sclerotia; these values were then multiplied by their respective class value, and combined. Indices of 0 to 25 cover the range 0 - 5%; 25 - 50 cover the range 6 - 10%; 51 - 75 cover the range 11 - 15%; 75 - 100 cover the range >15% surface area of the tuber with sclerotia taken 159 dap for pt 1, 139 dap for pt 2, and 116 dap for pt 3.

t: Yield (metric tons/hectare) calculated from the yield of 4 plants/replicate (3 replicates); taken 159 dap for pt 1, 139 dap for pt 2, and 116 dap for pt 3.

s: Values followed by the same letter are not significantly different at p = 0.05 (Tukey's HSD Comparison)

Table 3.5 Effect of cultivar planted on agronomic factors in field studies at the Plant Pathology farm, Michigan State University; East Lansing, MI in 2004.

Cultivar planted	Number of tubers/plant^{z}		Number of stems/plant^{z}		Number of stolons/plant^{z}	
Atlantic	8.2	a^{y}	3.6	b	11.8	c
FL1833	14.9	a	4.7	ab	20.6	abc
FL1867	11.3	a	3.8	b	14.4	bc
FL1879	17.4	a	4.8	ab	25.8	ab
Jacqueline Lee	14.7	a	3.4	b	14.3	bc
Michigan Purple	21.5	a	5.0	ab	26.9	a
MSI201-2PY	22.3	a	7.3	a	23.1	abc
Pike	10.8	a	2.8	b	12.8	c
Russet Norkotah	14.2	a	4.0	b	11.3	c
Snowden	23.8	a	5.5	ab	19.8	abc

z: Numbers of tubers, stems, and stolons are the average of 2 plants per replicate (3 replicates) taken 80 days after planting (dap) for pt 1; and 72 dap for pt 2

y: Values followed by the same letter are not significantly different at $p = 0.05$ (Tukey's HSD Comparison)

Table 3.6 Effect of cultivar planted on agronomic factors and disease symptoms caused by *Rhizoctonia solani* in field studies at the Plant Pathology farm, Michigan State University; East Lansing, MI in 2005.

Cultivar planted	Emergence (RAUEPC)[z]		Number of tubers/plant[y]		Number of stems/plant[y]		Number of stolons/plant[y]	
FL1867	0.0381	b[x]	14.1	bcd	4.5	bc	15.3	cd
FL1879	0.0492	a	16.9	bc	5.4	ab	25.8	ab
Jacqueline Lee	0.0278	cd	14.3	bcd	3.7	bc	15.1	cd
Michigan Purple	0.0478	a	23.8	a	4.1	bc	29.9	a
MSI152-A	0.0202	d	12.1	cd	3.5	c	14.6	cd
Pike	0.0344	bc	9.5	d	3.3	c	11.6	d
Russet Norkotah	0.0480	a	16.3	bc	4.2	bc	12.2	d
Snowden	0.0516	a	19.5	ab	6.3	a	20.9	bc

	Percent of stolons with girdling[w]		Black scurf incidence[v]		Black scurf severity[u]	
FL1867	36.1	ab	9.4	ab	3.5	ab
FL1879	32.4	abc	10.6	ab	3.5	ab
Jacqueline Lee	30.9	abcd	7.5	ab	2.3	b
Michigan Purple	12.2	d	2.8	b	1.0	b
MSI152-A	15.0	cd	4.2	b	1.0	b
Pike	19.9	bcd	7.2	b	3.5	ab
Russet Norkotah	39.5	a	17.8	ab	5.3	ab
Snowden	33.0	abc	24.4	a	10.8	a

z: RAUEPC: Relative area under the emergence progress curve (max = 100), calculated from the day of planting to 62 days after planting (dap) for pt 1, 53 dap for pt 2, and 38 dap for pt 3

y: Numbers of tubers, stems, and stolons are the average of 4 plants per replicate (3 replicates) taken 97 days after planting (dap) for pt 1, 77 dap for pt 2, and 54 dap for pt 3

x: Values followed by the same letter are not significantly different at $p = 0.05$ (Tukey's HSD Comparison)

w: Percent of stems and stolons with girdling caused by *R. solani* are from an average of 4 plants per replicate (3 replicates) taken 97 dap for pt 1, 77 dap for pt 2, and 54 dap for pt 3

v: Percent incidence of tubers with sclerotia of R. solani from a sample of 20 tubers per replicate taken 168 dap for pt 1, 140 dap for pt 2, and 98 dap for pt 3.

u: Severity of black scurf (index calculated by counting the tuber number (n = 20 per replicate) falling into each class 0 = 0%; 1 = 1 - 5%; 2 = 6 - 10%; 3 = 11 - 15%; 4 = >16% surface area covered with sclerotia; these values were then multiplied by their respective class value, and combined. Indices of 0 to 25 cover the range 0 - 5%; 25 - 50 cover the range 6 - 10%; 51 - 75 cover the range 11 - 15%; 75 - 100 cover the range >15% surface area of the tuber with sclerotia taken 159 dap for pt 1, 139 dap for pt 2, and 116 dap for pt 3.

Table 3.7 Main effects analyses (probability of difference: p=0.05) of the interaction between planting time and cultivar planted on agronomic factor and disease symptoms caused by *Rhizoctonia solani* in field trials at the Plant Pathology farm, Michigan State University; East Lansing, MI in 2004 a 2005.

Variable Tested	2004: Effect of the interaction of planting time and cultivar on variable 1) 8 °C	2) 14 °C	3) 20 °C	Analysis[z]	2005: Effect of the interaction of planting time and cultivar on variable 1) 8 °C	2) 14 °C	3) 20 °C	Analysis
Emergence (RAUEPC)[y]	*	*	*	*	**< 0.0001**	**< 0.0001**	**< 0.0001**	C
Number of tubers/plant[x]	0.1711	0.1064	*	A	**0.0003**	**< 0.0001**	0.0735	C
Number of stems/plant[x]	0.2072	**0.0012**	*	B	**0.0038**	**< 0.0001**	**0.0012**	C
Percent of stems with girdling[w]	0.1143	**0.0060**	*	B	**0.0061**	**0.0042**	**0.0463**	D
Number of stolons/plant[x]	**0.0034**	**0.0002**	*	B	**< 0.0001**	**< 0.0001**	0.1155	C
Percent of stolons with girdling[w]	0.0616	0.5885	*	A	**< 0.0001**	**0.0012**	**0.0010**	D
Black scurf incidence[v]	0.5825	0.1793	0.1030	A	0.4605	0.1296	**0.0059**	D
Black scurf severity[u]	0.2570	0.2386	0.0619	A	0.5161	0.1177	**0.0275**	D
Yield: metric tons/hectare[t]	0.6225	**0.0002**	**0.0435**	B	0.4458	0.0854	**0.0264**	C

z: Response analysis determined by the probability of differences with the interaction of planting time (pt) and cultivar (cv). Type A (2004)= no significant interaction of pt and cv ($p < 0.05$), no further analysis. Type B (2004)= significant interaction of pt and cv ($p > 0.05$), mean of interaction pt of cv planted shown in Table 3.8. Type C (2005)= significant interaction of pt and cv of an agronomic factor, mean of interaction of pt and cv shov in Table 3.9. Type D (2005)= significant interaction of pt and cv of disease symptoms caused by *R. solani*, mean of interaction of pt and cv shown in Table 3.10.

y: RAUEPC: Relative area under the emergence progress curve (max = 100), calculated from the day of planting to 62 days after planting (dap) for p 53 dap for pt 2, and 38 dap for pt 3 (2005 only)

x: Numbers of tubers, stems, and stolons are the average of 2 (2004) or 4 (2005) plants per replicate (3 replicates) 2004: taken 80 dap for pt 1, and 72 dap for pt 2; 2005: taken 97 days after planting (dap) for pt 1, 77 dap for pt 2, and 54 dap for pt 3

w: Percent of stems and stolons with girdling caused by *R. solani* are from an average of 2 (2004) or 4 (2005) plants per replicate (3 replicates) 2004: taken 80 dap for pt 1, and 72 dap for pt 2; 2005: taken 97 days after planting (dap) for pt 1, 77 dap for pt 2, and 54 dap for pt 3

v: Percent incidence of tubers with sclerotia of R. solani from a sample of 20 tubers per replicate (3 replicates) 2004: taken 168 dap for pt 1, 140 dap pt 2, and 98 dap for pt 3; 2005: taken 159 dap for pt 1, 139 dap for pt 2, and 116 dap for pt 3

u: Severity of black scurf (index calculated by counting the tuber number (n = 20 per replicate) falling into each class 0 = 0%; 1 = 1 - 5%; 2 = 6 - 10% 3 = 11 - 15%; 4 = >16% surface area covered with sclerotia; these values were then multiplied by their respective class value, and combined. Indices 0 to 25 cover the range 0 - 5%; 25 - 50 cover the range 6 - 10%; 51 - 75 cover the range 11 - 15%; 75 - 100 cover the range >15% surface area of the tuber with sclerotia taken 168 dap for pt 1, 140 dap for pt 2, and 98 dap for pt 3; 2005: taken 159 dap for pt 1, 139 dap for pt 2, and 116 dap for pt 3

t: Yield (metric tons/hectare) calculated from the yield of 4 plants/replicate (3 replicates); taken 159 dap for pt 1, 139 dap for pt 2, and 116 dap for pt

Table 3.8 Interaction effect between planting time and cultivar on select agronomic factors and disease symptoms caused by *Rhizoctonia solani* during field studies at the Plant Pathology farm, Michigan State University; East Lansing, MI in 2004.

	Timing 1 (8°C)	Timing 2 (14°C)				Timing 3 (20°C)
Cultivar	Number of stolons/plant[z]	Number of stems/plant[z]	Number of stolons/plant[z]	Yield: metric tons/hectare[y]	Percent of stems with girdling[z]	Yield: metric tons/hectare[y]
Atlantic	9.5 b[x]	3.8 b	14.0 b	15.0 c	67.6 a[w]	24.6 a
FL1833	15.0 b	5.3 ab	26.2 ab	22.0 abc	26.9 ab	20.1 a
FL1867	11.5 b	4.5 b	17.3 ab	15.8 bc	58.1 ab	17.6 a
FL1879	17.5 ab	6.3 ab	34.2 a	26.0 ab	41.9 ab	18.2 a
Jacqueline Lee	14.2 b	3.2 b	14.3 b	17.6 bc	52.7 ab	24.4 a
Michigan Purple	31.0 a	4.5 b	22.8 ab	29.1 a	64.7 ab	29.3 a
MSI201-2PY	19.5 ab	9.5 a	26.7 ab	21.1 abc	49.6 ab	20.4 a
Pike	13.8 b	2.5 b	11.8 b	12.7 c	31.3 ab	19.1 a
Russet Norkotah	13.2 b	4.0 b	9.5 b	14.2 c	0.0 b	17.0 a
Snowden	16.0 ab	5.7 ab	23.7 ab	18.1 bc	56.7 ab	18.5 a

z: Numbers of tubers, stems, and stolons are the average of 2 plants per replicate (3 replicates) taken 80 days after planting (dap) for pt 1; and 72 dap for pt 2

y: Yield (metric tons/hectare) calculated from the yield of 4 plants/replicate (3 replicates); taken 168 dap for pt 1, 140 dap for pt 2, and 98 dap for pt 3.

x: Values followed by the same letter are not significantly different at $p = 0.05$ (Tukey's HSD Comparison)

Table 3.9 Interaction effect between planting time and cultivar on agronomic factors during field studies at the Plant Pathology farm, Michigan State University; East Lansing, MI in 2005.

Planting Temperature	Cultivar	Emergence (RAUEPC)[z]	Number of tubers/plant[y]	Number of stems/plant[y]	Number of stolons/plant[y]	Yield: metric tons/hectare[x]
1) 8 °C	FL1867	0.0448 cd[w]	17.9 b	4.6 a	16.8 b	33.8 a
	FL1879	0.0571 ab	16.9 b	5.0 a	31.2 a	37.4 a
	Jacqueline Lee	0.0324 ef	18.4 ab	4.2 ab	16.8 b	21.6 a
	Michigan Purple	0.0625 a	27.8 a	3.6 ab	34.3 a	45.3 a
	MSI152-A	0.0310 f	18.6 ab	3.9 ab	16.6 b	25.2 a
	Pike	0.0365 def	11.3 b	2.1 b	11.7 b	24.5 a
	Russet Norkotah	0.0413 de	16.5 b	3.3 ab	9.5 b	31.7 a
	Snowden	0.0512 bc	20.5 ab	4.4 a	17.3 b	33.8 a
2) 14 °C	FL1867	0.0458 abcd	11.4 bcd	5.3 ab	17.7 bc	23.0 a
	FL1879	0.0525 ab	16.8 abc	3.9 bc	24.5 b	23.7 a
	Jacqueline Lee	0.0371 de	9.8 bcd	3.0 c	10.5 cd	13.7 a
	Michigan Purple	0.0404 cd	23.8 a	4.5 bc	36.8 a	38.1 a
	MSI152-A	0.0278 e	4.5 d	3.3 bc	9.8 cd	10.1 a
	Pike	0.0430 bcd	8.8 cd	3.8 bc	11.3 cd	25.2 a
	Russet Norkotah	0.0493 abc	13.9 bc	3.8 bc	5.3 d	33.1 a
	Snowden	0.0537 a	18.3 ab	6.2 a	19.8 bc	31.7 a
3) 20 °C	FL1867	0.0238 d	13.0 a	3.6 b	11.3 a	10.8 b
	FL1879	0.0380 c	17.0 a	7.4 ab	21.7 a	18.7 ab
	Jacqueline Lee	0.0138 d	14.9 a	3.9 ab	19.5 a	6.5 b
	Michigan Purple	0.0405 bc	17.5 a	4.4 ab	13.1 a	37.4 a
	MSI152-A	0.0020 e	13.6 a	3.1 b	18.6 a	*
	Pike	0.0238 d	8.5 a	4.0 b	11.8 a	18.0 ab
	Russet Norkotah	0.0535 a	18.3 a	5.6 ab	21.8 a	23.0 ab
	Snowden	0.0500 ab	19.7 a	8.3 a	25.5 a	25.9 ab

z: RAUEPC: Relative area under the emergence progress curve (max = 100), calculated from the day of planting to 62 days after planting (dap) for pt 1, 53 dap for pt 2, and 38 dap for pt 3

y: Numbers of tubers, stems, and stolons are the average of 4 plants per replicate (3 replicates) taken 97 days after planting (dap) for pt 1, 77 dap for pt 2, and 54 dap for pt 3

x: Yield (metric tons/hectare) calculated from the yield of 4 plants/replicate (3 replicates); taken 159 dap for pt 1, 139 dap for pt 2, and 116 dap for pt 3.

w: Values followed by the same letter are not significantly different at $p = 0.05$ (Tukey's HSD Comparison)

Table 3.10 Interaction effect between planting time and cultivar on disease symptoms caused by *Rhizoctonia solani* during field studies at the Plant Pathology farm, Michigan State University; East Lansing, MI in 2005.

Planting Temperature	Cultivar	Percent of stems with girdling[z]		Percent of stolons with girdling[z]		Black scurf incidence[y]		Black scurf severity[x]	
8°C	FL1867	49.9	ab[w]	54.0	a	16.7	a	7.5	a
	FL1879	23.8	b	49.1	a	18.3	a	5.8	a
	Jacqueline Lee	41.2	ab	30.8	abc	13.3	a	4.6	a
	Michigan Purple	61.7	a	22.9	bc	3.3	a	0.8	a
	MSI152-A	43.8	ab	9.6	c	5.0	a	1.3	a
	Pike	63.9	a	14.0	c	1.7	a	0.4	a
	Russet Norkotah	62.9	a	39.6	ab	13.3	a	4.2	a
	Snowden	66.9	a	49.8	a	15.0	a	4.6	a
14°C	FL1867	41.5	ab	43.7	ab	8.3	a	2.1	a
	FL1879	41.3	ab	33.7	abc	8.3	a	2.1	a
	Jacqueline Lee	19.0	b	23.2	abc	1.7	a	0.4	a
	Michigan Purple	23.1	ab	9.0	c	5.0	a	2.1	a
	MSI152-A	38.8	ab	18.9	bc	3.3	a	0.8	a
	Pike	30.7	ab	32.8	abc	20.0	a	10.0	a
	Russet Norkotah	59.2	a	57.1	a	20.0	a	5.8	a
	Snowden	13.3	b	40.4	abc	31.7	a	13.3	a
20°C	FL1867	23.2	a	15.3	b	3.3	b	0.8	b
	FL1879	1.7	a	9.5	b	5.0	ab	2.5	ab
	Jacqueline Lee	1.8	a	42.5	a	7.5	ab	1.9	ab
	Michigan Purple	10.8	a	0.8	b	0.0	b	0.0	b
	MSI152-A	31.7	a	17.2	ab	*		*	
	Pike	13.2	a	12.8	b	0.0	b	0.0	b
	Russet Norkotah	9.0	a	21.9	ab	20.0	ab	5.8	ab
	Snowden	2.8	a	8.9	b	26.7	a	14.6	a

z: Percent of stems and stolons with girdling caused by *R. solani* are from an average of 4 (2005) plants per replicate (3 replicates) taken 97 days after planting (dap) for pt 1, 77 dap for pt 2, and 54 dap for pt 3.
y: Percent incidence of tubers with sclerotia of R. solani from a sample of 20 tubers per replicate (3 replicates) taken 159 dap for pt 1, 139 dap for pt 2, and 116 dap for pt 3
x: Severity of black scurf (index calculated by counting the tuber number (n = 20 per replicate) falling into each class 0 = 0%; 1 = 1 - 5%; 2 = 6 - 10%; 3 = 11 - 15%; 4 = >16% surface area covered with sclerotia; these values were then multiplied by their respective class value, and combined. Indices of 0 to 25 cover the range 0 - 5%; 25 - 50 cover the range 6 - 10%; 51 - 75 cover the range 11 - 15%; 75 - 100 cover the range >15% surface area of the tuber with sclerotia taken 159 dap for pt 1, 139 dap for pt 2, and 116 dap for pt 3
w: Values followed by the same letter are not significantly different at $p = 0.05$ (Tukey's HSD Comparison)

Discussion and Conclusions

Planting early in the spring, when soil temperatures are relatively low (around 8°C) resulted in more disease symptoms and less healthy plants. This general result was found among planting times both in the presence (2004) and absence (2005) of additional inoculum. The differences among planting times for percent of stems and stolons with girdling is most likely the result of two factors, soil temperature and inoculum. Bolkan et al. (1974) found that infection of potato shoots decreased with increasing temperature (15, 18, 21, 24°C) when (tuber-borne) inoculum levels were "low", but did not change with "moderate" and "high" levels of inoculum. Similarly, Simons and Gilligan (1997) found that later dates of planting resulted in a decrease of stem canker (girdling), especially with a "high" level of inoculum (AG-3). Also, Carling and Leiner (1990) found that isolates of AG-3 were able to attack potato sprouts at all three temperatures tested (10, 15.5, and 21.1°C), but caused significantly more damage at 10°C. The results of the 2004 and 2005 growing seasons agree with previous findings, that as the soil temperature at planting increases, the incidence of stem and stolon canker decreases. In 2005, there may have been sufficient inoculum either already in the soil or on the seed to cause Rhizoctonia diseases. This was especially evident in 2005, when no inoculum was incorporated prior to planting, and significant differences were still found for percent of stems and stolons with girdling. Potatoes had been planted in the field used many times prior to 2004, and although not measured in this field, it would be expected that the level of soil-borne inoculum would have built up over time.

While the presence or absence of additional inoculum may not have played a major role in the percent of stem and stolon canker, it may have made the difference for the significant differences among planting times for black scurf incidence and severity. In 2005, when supplemental inoculum was not added, there were no differences among planting times for black scurf. The significant differences of black scurf incidence and severity found among planting times in 2004 may have two possible sources. First, there was likely an increase in inoculum level, both naturally over the course of the growing season, and as a result of the addition of the inoculum prior to planting. Tsror and Peretz-Alon (2005) found that black scurf incidence and severity were higher when both seed and soil-borne inoculum were present than either inoculum source separately. In addition, the level of inoculum present was also positively correlated with the incidence and severity of black scurf on progeny tubers (Tsror and Peretz-Alon, 2005). Second, the plots of the early planting were more physically mature at vine desiccation. Although the 17 days between vine desiccation and harvest falls within the recommended time frame to harvest of within three weeks (Gudmestad et al., 1979), the early planting of 2004 was already senescing at vine desiccation. This fact may have increased the likelihood that the increased inoculum would form sclerotia, triggered by the reduction of plant exudates (Spencer and Fox, 1979).

Growing seasons vary considerably in Michigan, depending upon location, and waiting to plant until the soil warms to 14 or 20°C may result in a significantly shorter growing season, which could negatively affect the yield. In both years, the early planting (around 8°C) resulted in higher yield. While this is expected when considering the length of the growing season, it is in contrast to the early planting having significantly higher percent of stems and stolons with girdling in both 2004 and 2005. It is expected that if there is significantly high level of disease pressure that the yield would be decreased, as a number of researchers have reported significant yield losses (Banville et al., 1996). All planting times were vine desiccated and harvested on the same dates. Had the later plantings been allowed to continue growing until natural senescence, differences in yield may not have been found.

Differences among varieties were expected, with the majority being agronomic factors, such as tuber, stem and stolon number and yield. No variety was noted as resistant to *R. solani* prior to the experiments and all had stem and stolon canker as well as black scurf to varying degrees. As to sorting out the varieties in terms of recommendations for planting, it would require a number of factors to be assessed. Some factors needing evaluation include: the end-product that the potatoes will become (chip processing or table stock; the level of known disease pressures present in the field (*R. solani, Phytophthora infestans, Streptomyces scabies* etc.); the maturity of the particular variety (early, moderate, or late); the harvest window (prior to, at or after senescence); and the level of management (cost/energy).

These experiments did confirm previous findings of reduced disease incidence and severity with later planting. A point of improvement in this experiment may be the testing of the method for establishing planting thresholds. The five day average was chosen to minimize large fluctuations in temperature, but other timeframes could be tested. A larger number of days averaged would continue to smooth the trend of increasing temperature, while a shorter one could lead to premature planting. Another point for improvement would be to use a vine desiccation and harvest date based upon the maturity of the plot, instead of the date of the first planting. While this would not affect stem and stolon canker, it could positively impact the yield of later plantings.

CHAPTER 4
EFFECT OF FUNGICIDE APPLICATION TIMING AND SOIL TEMPERATURE AT PLANTING ON VARIETY SUSCEPTIBILITY TO THE INCIDENCE AND SEVERITY OF RHIZOCTONIA CANKER AND BLACK SCURF ON POTATOES

Introduction

The combination of chemical and cultural control strategies, as part of an integrated pest management strategy, is generally the most effective and sustainable method of disease management. The final experiment, in 2006, tested the combined effect of fungicide efficacy and planting time based upon soil temperature, with multiple varieties, for the management of diseases caused by *Rhizoctonia solani*. As this experiment incorporated both cultural and chemical control strategies, it more closely resembled actual practices that could be utilized by Michigan potato growers. Treatments from the previous experiments (see Chapters 2 and 3) were combined and tested for their efficacy. Two temperature thresholds were used, 14 and 20°C to trigger the planting of four cultivars (commonly grown in Michigan). In addition to the seed treatment (fludioxonil), two early-season applications (in-furrow and 14 days post-emergence) were evaluated for two of the previously tested fungicides (azoxystrobin and flutolanil). The main questions this experiment attempted to answer were: 1) Does a particular combination of planting date and early season fungicide application result in a reduction of disease incidence and severity (stem and/or stolon canker, and/or black scurf)? 2) Does a late planting and non-treated seed result in lower yield? 3) Is one type of control, cultural (planting based upon soil temperature) or chemical (using seed/early-season fungicide(s), more effective at disease management?

Materials and methods

The potato cultivars FL1833, FL1879, Russet Norkotah, and Superior were planted at the Michigan State University Muck Soils Research Farm, Bath, MI. All cultivars were tested for the control of Rhizoctonia disease symptoms under identical chemical regimes at two planting times. Within each regime, the efficacy of the seed treatment fludioxonil (Maxim) alone or in combination with one of two additional fungicides, azoxystrobin (Amistar) and flutolanil (Moncut) were examined. The additional fungicides were tested at two application times, at-planting in-furrow and 14 days after emergence.

Seed pieces were planted once the soil temperature at a 10 cm depth surpassed a threshold of a five-day average of 14°C (threshold surpassed 4 May 2006, planted 9 May 2006) or 20°C (threshold surpassed 30 May 2006, planted 1 June 2006). The soil temperature was monitored with the onsite weather station (Michigan Automated Weather Network; Michigan State University, East Lansing, MI; http://www.agweather.geo.msu.edu/mawn/). Data was regularly downloaded and daily and five-day averages were calculated.

Except for the cultivar Superior, which was cut prior to seed treatment, whole seed was treated with the Maxim seed treatment one day prior to planting. Seed pieces were planted in Houghton muck soil at the Michigan State University Muck Soils Research Farm, Bath, MI on 9 May (timing 1) and 1 June (timing 2), into two rows by 4.6 meter plots (approximately 30.5 cm between plants give a target population of 30 plants per plot at 1 m row spacing) replicated three times in a randomized strip block design.

The fludioxonil seed treatment was applied, in a water suspension at a rate of 0.5mL/kg, and applied onto the entire seed surface. In-furrow applications were made over the seed at-planting, applied with a single nozzle R&D spray boom delivering 46.8L/ha (551.6 kPa) and using one XR11003VS nozzle per row.

Table 4.1 Experimental layout (for one of four potato cultivars: FL1833, FL1879, Russet Norkotah, and Superior) for the study of the effects of soil temperature at planting, the use of a seed treatment, additional fungicide and the application timing of the additional fungicide on agronomic factors and disease symptoms, caused by *Rhizoctonia solani,* in field trials at the Muck Soils Research Farm, Michigan State University; Bath, MI in 2006.

Treatment	Soil temperature threshold at planting	Seed treatment	Application timing for additional fungicide: In-furrow	Application timing for additional fungicide: 14 day post-emergence
1	14°C	Yes	Amistar	
2				Amistar
3			Moncut	
4				Moncut
5				
6		No	Amistar	
7				Amistar
8			Moncut	
9				Moncut
10				
11	20°C	Yes	Amistar	
12				Amistar
13			Moncut	
14				Moncut
15				
16		No	Amistar	
17				Amistar
18			Moncut	
19				Moncut
20				

Fertilizer was drilled into plots before planting, formulated according to results of soil tests at the Bath, MI location. Porpamocarb hydrochloride (Previcur Flex) was applied at 1.4 L/ha on a ten day interval, total of four applications, starting two weeks after the last application of experiment treatments. A permanent irrigation system was established prior to the commencement of fungicide sprays and the fields were maintained at soil moisture capacity throughout the season by frequent (minimum 5-day) irrigations. Weeds were controlled with metolachlor (Dual 8E) at 2.34 L/ha and metribuzin (Sencor 75DF) at .67 kg/ha at planting, bentazon (Basagran) at 2.34 L/ha 27 and 45 DAP (days after planting) and sethoxydim (Poast) at 1.75 L/ha 63 DAP. Insects were controlled with thiamethoxam (Platinum) at 0.59 L/ha at-planting, cyfluthrin (Baythroid 2) at .146 L/ha 36 and 60 DAP.

Emergence was rated as the number of plants breaking the soil surface or fully emerged after planting. The rate of emergence was estimated as the area under the plant emergence curve (max=100) from the day of planting until 45 DAP for planting 1 (14°C) and 28 DAP for planting 2 (20°C). Tuber, stem and stolon numbers, and percentages of stems and stolons with girdling caused by *R. solani* were measured via a destructive mid-season harvest (4 plants per replication) at 69 DAP (timing 1) and 61 DAP (timing 2). Vines were killed with Reglone 2EC (1 pt/A) on 25 August and 20 progeny tubers were harvested from each plot on 15 September and the individual treatment replications were washed and assessed for black scurf (*R. solani*) incidence (%) and severity. Severity of black scurf was measured as an index calculated by counting the number of tubers (n = 20) falling in class 0 = 0%; 1 = 1 - 5%; 2 = 6 -10%; 3 = 11 – 15%; 4 = > 15% surface area of tuber covered with sclerotia. The number in each class was multiplied by the class number and summed. Indices of 0 - 25 represent 0 - 5%; 26 - 50 represent 6 - 10%; 51 - 75 represent 11 - 15% and 75 - 100 >15% surface area covered with sclerotia.

Results

Tubers planted once the soil at 10 cm surpassed a five day average of 20°C resulted in significantly faster emergence, higher average number of stems, higher percentage of stems and stolons with girdling, and black scurf incidence and severity (Table 4.2). Of the four cultivars planted, plots of Russet Norkotah resulted in significantly faster emergence, higher average number of stems per plant and percent of stems with girdling (Table 4.3). In addition, plots of Superior had a significantly slower emergence and lower average number of stolons per plant. Plots of FL1833 had significantly lower average number of stems per plant, and plots of FL1879 had significantly lower percent of stolons with girdling when compared to the other cultivars planted.

The use of the seed treatment fludioxonil, compared to no seed treatment used, resulted in significantly higher average number of stems and stolons per plant, and significantly lower percent of stolons with girdling (Table 4.4). The use of azoxystrobin resulted in a significantly lower average number of stolons per plant, when compared to no additional fungicide being used (Table 4.5). However, in terms of average number of stolons per plant, there was no significant difference between plots with azoxystrobin and flutolanil. Also, plots with flutolanil resulted in significantly lower percent of stolons with girdling when compared to plots with no additional fungicide, but there was no significant difference between plots with flutolanil and plots with azoxystrobin. Fungicides that were applied in-furrow resulted in significantly lower average number of stolons per plant, compared to no additional fungicide applied, but were not significantly different from fungicides applied 14 days after emergence (Table 4.6). Also, fungicides that were applied 14 days after emergence resulted in significantly lower percent of stolons with girdling, compared to no additional fungicide applied, but were not significantly different than fungicides applied in furrow.

The interaction of these treatments (planting based upon soil temperature, seed treatment, additional fungicide, and the timing of application of the fungicide) resulted in a number of significant differences within each cultivar (Tables 4.7 – 4.11). However, there was not a single (combined) treatment that proved more effective for *R. solani* management or improved agronomic variables on all cultivars.

Table 4.2 Main effects analyses (probability of difference: p=0.05) of the effect of soil temperature at planting on agronomic factors and disease symptoms caused by *Rhizoctonia solani* in field trials at the Muck Soils Research Farm, Michigan State University; Bath, MI in 2006.

Variable	p-value	Effect of planting date on variable 14°C (5/9/2006)		20°C (6/1/2006)	
RAUEPC (emergence)^{z}	**0.0496**	0.0626	b^{u}	0.0653	a
Number of stems^{y}	**0.0007**	2.9	b	3.3	a
Percent of stems with girdling^{x}	**<0.0001**	30.0	b	61.3	a
Number of stolons^{y}	0.1433	19.4	a	18.0	a
Percent of stolons with girdling^{x}	**<0.0001**	16.8	b	24.0	a
Black scurf incidence^{w}	**0.0009**	13.4	b	21.7	a
Black scurf severity^{v}	**<0.0001**	4.0	b	8.5	a

z: RAUEPC: Relative area under the emergence progress curve (max = 100), calculated from the day of planting to 45 days after planting (dap) for planting time (pt) 1, and 28 dap for pt 2

y: Numbers of stems and stolons are the average of 4 plants per replicate (3 replicates) taken 69dap for pt 1; and 61 dap for pt 2

x: Percent of stems and stolons with girdling caused by *R. solani* are from an average of 4 plants per replicate (3 replicates) taken 69 dap for pt 1, and 61 dap for pt 2

w: Percent incidence of tubers with sclerotia of *R. solani* from a sample of 20 tubers per replicate taken 129 dap for pt 1, and 106 dap for pt 2

v: Severity of black scurf (index calculated by counting the tuber number (n = 20 per replicate) falling into each class 0 = 0%; 1 = 1 - 5%; 2 = 6 - 10%; 3 = 11 - 15%; 4 = >16% surface area covered with sclerotia; these values were then multiplied by their respective class value, and combined. Indices of 0 to 25 cover the range 0 - 5%; 25 - 50 cover the range 6 - 10%; 51 - 75 cover the range 11 - 15%; 75 - 100 cover the range >15% surface area of the tuber with sclerotia taken 129 dap for pt 1, and 106 dap for pt 2

u: Values followed by the same letter are not significantly different at p = 0.05 (Tukey's HSD Comparison)

Table 4.3 Main effects analyses (probability of difference: p=0.05) of the effect of cultivar planted on agronomic factors and disease symptoms caused by *Rhizoctonia solani* in field trials at the Muck Soils Research Farm, Michigan State University; Bath, MI in 2006.

		Effect of cultivar planted on variable							
Variable	p-value	FL1833		FL1879		Russet Norkotah		Superior	
RAUEPC (emergence)[z]	**<0.0001**	0.0661	b[u]	0.0656	b	0.0715	a	0.0527	c
Number of stems[y]	**<0.0001**	1.9	d	3.3	b	4.7	a	2.6	c
Percent of stems with girdling[x]	**<0.0001**	44.9	b	40.3	b	60.1	a	37.2	b
Number of stolons[y]	**<0.0001**	17.4	b	32.3	a	15.0	b	10.0	c
Percent of stolons with girdling[x]	**<0.0001**	20.8	b	16.0	c	26.3	a	18.6	bc
Black scurf incidence[w]	0.2462	18.5	a	21.3	a	15.3	a	14.9	a
Black scurf severity[v]	**0.0488**	7.4	a	7.8	a	5.6	a	4.0	a

z: RAUEPC: Relative area under the emergence progress curve (max = 100), calculated from the day of planting to 45 days after planting (dap) for planting time (pt) 1, and 28 dap for pt 2

y: Numbers of stems and stolons are the average of 4 plants per replicate (3 replicates) taken 69dap for pt 1; and 61 dap for pt 2

x: Percent of stems and stolons with girdling caused by *R. solani* are from an average of 4 plants per replicate (3 replicates) taken 69 dap for pt 1, and 61 dap for pt 2.

w: Percent incidence of tubers with sclerotia of *R. solani* from a sample of 20 tubers per replicate taken 129 dap for pt 1, and 106 dap for pt 2

v: Severity of black scurf (index calculated by counting the tuber number (n = 20 per replicate) falling into each class 0 = 0%; 1 = 1 - 5%; 2 = 6 - 10%; 3 = 11 - 15%; 4 = >16% surface area covered with sclerotia; these values were then multiplied by their respective class value, and combined. Indices of 0 to 25 cover the range 0 - 5%; 25 - 50 cover the range 6 - 10%; 51 - 75 cover the range 11 - 15%; 75 - 100 cover the range >15% surface area of the tuber with sclerotia taken 129 dap for pt 1, and 106 dap for pt 2

u: Values followed by the same letter are not significantly different at p = 0.05 (Tukey's HSD Comparison)

Table 4.4 Main effects analyses (probability of difference: p=0.05) of the effect of the use of the seed treatment Maxim (fludioxonil) on agronomic factors and disease symptoms caused by *Rhizoctonia solani* in field trials at the Muck Soils Research Farm, Michigan State University; Bath, MI in 2006.

Variable	Effect of seed treatment applied on variable				
	p-value	Maxim		None	
RAUEPC (emergence)[z]	0.3581	0.0646	a[u]	0.0633	a
Number of stems[y]	**0.0001**	3.4	a	2.9	b
Percent of stems with girdling[x]	0.1244	43.6	a	47.6	a
Number of stolons[y]	**0.0001**	20.6	a	16.7	b
Percent of stolons with girdling[x]	**<0.0001**	16.7	b	24.1	a
Black scurf incidence[w]	0.2347	16.1	a	19.1	a
Black scurf severity[v]	0.6087	6.0	a	6.5	a

z: RAUEPC: Relative area under the emergence progress curve (max = 100), calculated from the day of planting to 45 days after planting (dap) for planting time (pt) 1, and 28 dap for pt 2.

y: Numbers of stems and stolons are the average of 4 plants per replicate (3 replicates) taken 69dap for pt 1; and 61 dap for pt 2.

x: Percent of stems and stolons with girdling caused by *R. solani* are from an average of 4 plants per replicate (3 replicates) taken 69 dap for pt 1, and 61 dap for pt 2.

w: Percent incidence of tubers with sclerotia of *R. solani* from a sample of 20 tubers per replicate taken 129 dap for pt 1, and 106 dap for pt 2

v: Severity of black scurf (index calculated by counting the tuber number (n = 20 per replicate) falling into each class 0 = 0%; 1 = 1 - 5%; 2 = 6 - 10%; 3 = 11 - 15%; 4 = >16% surface area covered with sclerotia; these values were then multiplied by their respective class value, and combined. Indices of 0 to 25 cover the range 0 - 5%; 25 - 50 cover the range 6 - 10%; 51 - 75 cover the range 11 - 15%; 75 - 100 cover the range >15% surface area of the tuber with sclerotia taken 129 dap for pt 1, and 106 dap for pt 2

u: Values followed by the same letter are not significantly different at p = 0.05 (Tukey's HSD Comparison)

Table 4.5 Main effects analyses (probability of difference: p=0.05) of the effect of use of additional fungicide (Amistar: azoxystrobin, or Moncut: pyraclostrobin) on agronomic factors and disease symptoms caused by *Rhizoctonia solani* in field trials at the Muck Soils Research Farm, Michigan State University; Bath, MI in 2006.

	Effect of additional fungicide applied on variable						
Variable	p-value	Amistar		Moncut		None	
RAUEPC (emergence)[z]	0.6591	0.0642	a[u]	0.0633	a	0.0648	a
Number of stems[y]	0.0740	3.1	a	3.0	a	3.4	a
Percent of stems with girdling[x]	0.8446	44.8	a	46.4	a	45.8	a
Number of stolons[y]	**0.0257**	17.4	b	18.9	ab	20.9	a
Percent of stolons with girdling[x]	**0.0253**	20.0	ab	19.1	b	23.9	a
Black scurf incidence[w]	0.7698	20.2	a	15.3	a	16.7	a
Black scurf severity[v]	0.8535	7.2	a	5.2	a	6.4	a

z: RAUEPC: Relative area under the emergence progress curve (max = 100), calculated from the day of planting to 45 days after planting (dap) for planting time (pt) 1, and 28 dap for pt 2

y: Numbers of stems and stolons are the average of 4 plants per replicate (3 replicates) taken 69dap for pt 1; and 61 dap for pt 2

x: Percent of stems and stolons with girdling caused by *R. solani* are from an average of 4 plants per replicate (3 replicates) taken 69 dap for pt 1, and 61 dap for pt 2.

w: Percent incidence of tubers with sclerotia of *R. solani* from a sample of 20 tubers per replicate taken 129 dap for pt 1, and 106 dap for pt 2

v: Severity of black scurf (index calculated by counting the tuber number (n = 20 per replicate) falling into each class 0 = 0%; 1 = 1 - 5%; 2 = 6 - 10%; 3 = 11 - 15%; 4 = >16% surface area covered with sclerotia; these values were then multiplied by their respective class value, and combined. Indices of 0 to 25 cover the range 0 - 5%; 25 - 50 cover the range 6 - 10%; 51 - 75 cover the range 11 - 15%; 75 - 100 cover the range >15% surface area of the tuber with sclerotia taken 129 dap for pt 1, and 106 dap for pt 2

u: Values followed by the same letter are not significantly different at p = 0.05 (Tukey's HSD Comparison)

Table 4.6 Main effects analyses (probability of difference: p=0.05) of the effect of application timing of additional fungicide on agronomic factors and disease symptoms caused by *Rhizoctonia solani* in field trials at the Muck Soils Research Farm, Michigan State University; Bath, MI in 2006.

Variable	p-value	Effect of application timing of additional fungicide on variable: In furrow		14 days post emergence		No application	
RAUEPC (emergence)[z]	0.8237	0.0631	a[u]	0.0644	a	0.0648	a
Number of stems[y]	0.1013	3.1	a	3.0	a	3.4	a
Percent of stems with girdling[x]	0.6167	47.0	a	44.2	a	45.8	a
Number of stolons[y]	**0.0179**	17.2	b	19.0	ab	20.9	a
Percent of stolons with girdling[x]	**0.0175**	20.3	ab	18.8	b	23.9	a
Black scurf incidence[w]	0.9618	16.9	a	18.6	a	16.7	a
Black scurf severity[v]	0.9809	5.8	a	6.7	a	6.4	a

z: RAUEPC: Relative area under the emergence progress curve (max = 100), calculated from the day of planting to 45 days after planting (dap) for planting time (pt) 1, and 28 dap for pt 2

y: Numbers of stems and stolons are the average of 4 plants per replicate (3 replicates) taken 69dap for pt 1; and 61 dap for pt 2

x: Percent of stems and stolons with girdling caused by *R. solani* are from an average of 4 plants per replicate (3 replicates) taken 69 dap for pt 1, and 61 dap for pt 2

w: Percent incidence of tubers with sclerotia of *R. solani* from a sample of 20 tubers per replicate taken 129 dap for pt 1, and 106 dap for pt 2

v: Severity of black scurf (index calculated by counting the tuber number (n = 20 per replicate) falling into each class 0 = 0%; 1 = 1 - 5%; 2 = 6 - 10%; 3 = 11 - 15%; 4 = >16% surface area covered with sclerotia; these values were then multiplied by their respective class value, and combined. Indices of 0 to 25 cover the range 0 - 5%; 25 - 50 cover the range 6 - 10%; 51 - 75 cover the range 11 - 15%; 75 - 100 cover the range >15% surface area of the tuber with sclerotia taken 129 dap for pt 1, and 106 dap for pt 2

u: Values followed by the same letter are not significantly different at p = 0.05 (Tukey's HSD Comparison)

Table 4.7 Main effects analyses (probability of difference: p=0.05) of the interactive effect of soil temperature at planting, seed treatment, additional fungicide and application time, on the cultivar planted for agronomic factors and disease symptoms caused by *Rhizoctonia solani* in field trials at the Muck Soils Research Farm, Michigan State University; Bath, MI in 2006.

	Effect of interaction of planting date, seed treatment, additional fungicide and application time on variable							
	FL1833		FL1879		Russet Norkotah		Superior	
Variable	p-value	analysis[z]	p-value	analysis	p-value	analysis	p-value	analysis
RAUEPC (emergence)[y]	**0.0007**	A	**<0.0001**	B	**0.0005**	C	**0.0012**	D
Number of stems[x]	0.1048	E	0.0802	E	0.8496	E	**<0.0001**	D
Percent of stems with girdling[w]	**<0.0001**	A	**<0.0001**	B	**<0.0001**	C	**0.0062**	D
Number of stolons[x]	**0.0196**	A	**0.0004**	B	**<0.0001**	C	0.1355	E
Percent of stolons with girdling[w]	**0.0013**	A	**<0.0001**	B	**<0.0001**	C	**0.0033**	D
Black scurf incidence[v]	0.4240	E	0.4669	E	0.8951	E	0.7557	E
Black scurf severity[u]	0.2209	E	0.2356	E	0.7700	E	0.7085	E

z: Response analysis determined by the probability of difference among treatments (interaction of soil temperature at planting, seed treatment, additional fungicide, and application timing of additional fungicide) for each cultivar planted. Type A= significant effect of treatment ($p < 0.05$) with the cultivar FL1833, mean of treatment effect on variable shown Table 4.8. Type B= significant effect of treatment ($p < 0.05$) with the cultivar FL1879, mean of treatment effect on variable shown Table 4.9. Type C= significant effect of treatment ($p < 0.05$) with the cultivar Russet Norkotah, mean of treatment effect on variable shown Table 4.10. Type D= significant effect of treatment ($p < 0.05$) with the cultivar Superior, mean of treatment effect on variable shown Table 4.11. Type E= no significant effect of treatment ($p > 0.05$), no further analysis.

y: RAUEPC: Relative area under the emergence progress curve (max = 100), calculated from the day of planting to 45 days after planting (dap) for planting date (pd) 1, and 28 dap for pt 2.

x: Numbers of stems and stolons are the average of 4 plants per replicate (3 replicates) taken 69dap for pt 1; and 61 dap for pt 2

w: Percent of stems and stolons with girdling caused by *R. solani* are from an average of 4 plants per replicate (3 replicates) taken 69 dap for pt 1, and 61 dap for pt 2

v: Percent incidence of tubers with sclerotia of *R. solani* from a sample of 20 tubers per replicate taken 129 dap for pt 1, and 106 dap for pt 2

u: Severity of black scurf (index calculated by counting the tuber number (n = 20 per replicate) falling into each class 0 = 0%; 1 = 1 - 5%; 2 = 6 - 10%; 3 = 11 - 15%; 4 = >16% surface area covered with sclerotia; these values were then multiplied by their respective class value, and combined. Indices of 0 to 25 cover the range 0 - 5%; 25 - 50 cover the range 6 - 10%; 51 - 75 cover the range 11 - 15%; 75 - 100 cover the range >15% surface area of the tuber with sclerotia taken 129 dap for pt 1, and 106 dap for pt 2

Table 4.8 Effect of the interaction of soil temperature at planting, seed treatment, additional fungicide and application time, on the cultivar FL1833 for agronomic factors and disease symptoms caused by *Rhizoctonia solani* in field trials at the Muck Soils Research Farm, Michigan State University; Bath, MI in 2006.

Temperature threshold for planting	Seed treatment	Additional fungicide treatment	Application time[z]	RAUEPC (emergence)[y]		Percent of stems with girdling[x]		Number of stolons[w]		Percent of stolons with girdling[x]	
14°C	Maxim	Amistar	I.F.	0.0627	abc[v]	0.0	fg	16.7	ab	10.9	c
			14 D.P.E.	0.0613	abc	43.1	abcdefg	16.6	ab	16.7	abc
		Moncut	I.F.	0.0593	bc	34.7	bcdefg	21.1	ab	18.9	abc
			14 D.P.E.	0.0520	c	0.0	fg	13.1	b	6.9	c
		None	N/A	0.0647	abc	41.7	abcdefg	18.6	ab	23.9	abc
	None	Amistar	I.F.	0.0667	abc	25.0	cdefg	17.4	ab	18.4	abc
			14 D.P.E.	0.0617	abc	18.8	defg	17.0	ab	23.1	abc
		Moncut	I.F.	0.0650	abc	6.9	fg	18.9	ab	19.0	abc
			14 D.P.E.	0.0640	abc	13.2	efg	17.0	ab	13.9	bc
		None	N/A	0.0637	abc	30.6	bcdefg	26.9	a	17.3	abc
20°C	Maxim	Amistar	I.F.	0.0737	ab	87.5	a	16.1	ab	20.2	abc
			14 D.P.E.	0.0707	ab	60.0	abcde	16.8	ab	19.0	abc
		Moncut	I.F.	0.0757	a	72.5	abc	18.3	ab	24.1	abc
			14 D.P.E.	0.0730	ab	82.0	ab	19.0	ab	25.4	abc
		None	N/A	0.0710	ab	70.1	abcd	21.3	ab	39.5	a
	None	Amistar	I.F.	0.0687	ab	66.7	abcd	12.7	b	23.0	abc
			14 D.P.E.	0.0667	abc	56.9	abcdef	14.3	ab	19.1	abc
		Moncut	I.F.	0.0697	ab	40.6	abcdefg	16.8	ab	22.2	abc
			14 D.P.E.	0.0667	abc	46.5	abcdefg	18.0	ab	18.1	abc
		None	N/A	0.0643	abc	87.5	a	11.3	b	36.3	ab

z: Application times were I.F., in furrow at planting, 14 D.P.E.; 14 days post-emergence; N/A, none applied

y: RAUEPC: Relative area under the emergence progress curve (max = 100), calculated from the day of planting to 45 days after planting (dap) for planting time (pt) 1 (at 14°C), and 28 dap for pt 2 (at 20°C).

x: Percent of stems and stolons with girdling caused by *R. solani* are from an average of 4 plants per replicate (3 replicates) taken 69 dap for pt 1, and 61 dap for pt 2.

w: Number of stolons are the average of 4 plants per replicate (3 replicates) taken 69dap for pt 1; and 61 dap for pt 2.

v: Values followed by the same letter are not significantly different at p = 0.05 (Tukey's HSD Comparison)

Table 4.9 Effect of the interaction of soil temperature at planting, seed treatment, additional fungicide and application time, on the cultivar FL1879 for agronomic factors and disease symptoms caused by *Rhizoctonia solani* in field trials at the Muck Soils Research Farm, Michigan State University; Bath, MI in 2006.

Temperature threshold for planting	Seed treatment	Additional fungicide treatment	Application time[z]	RAUEPC (emergence)[y]		Percent of stems with girdling[x]		Number of stolons[w]		Percent of stolons with girdling[x]	
14°C	Maxim	Amistar	I.F.	0.0637	bcd[v]	33.2	bcdef	46.5	a	13.0	bcde
			14 D.P.E.	0.0620	bcde	20.3	cdef	31.7	ab	9.8	cde
		Moncut	I.F.	0.0663	abcd	19.8	cdef	35.5	ab	13.2	abcde
			14 D.P.E.	0.0693	abcd	31.5	bcdef	33.0	ab	13.5	abcde
		None	N/A	0.0687	abcd	38.5	bcdef	33.2	ab	17.8	abcde
	None	Amistar	I.F.	0.0707	abcd	0.0	f	21.0	ab	2.9	e
			14 D.P.E.	0.0663	abcd	4.2	ef	22.0	ab	7.3	de
		Moncut	I.F.	0.0653	abcd	20.8	cdef	16.8	b	6.9	de
			14 D.P.E.	0.0670	abcd	29.2	bcdef	22.1	ab	32.4	ab
		None	N/A	0.0653	abcd	8.3	def	24.9	ab	9.8	cde
20°C	Maxim	Amistar	I.F.	0.0467	f	62.8	abc	24.1	ab	19.6	abcde
			14 D.P.E.	0.0487	ef	35.3	bcdef	44.9	a	12.5	cde
		Moncut	I.F.	0.0583	def	57.3	abcd	43.6	ab	15.3	abcde
			14 D.P.E.	0.0603	cde	56.2	abcd	48.0	a	11.3	cde
		None	N/A	0.0647	bcd	52.6	abcde	34.2	ab	16.6	abcde
	None	Amistar	I.F.	0.0740	ab	44.0	abcdef	38.1	ab	18.4	abcde
			14 D.P.E.	0.0787	a	77.9	ab	35.3	ab	32.7	a
		Moncut	I.F.	0.0703	abcd	47.8	abcdef	30.8	ab	15.1	abcde
			14 D.P.E.	0.0737	abc	77.2	ab	33.1	ab	27.5	abc
		None	N/A	0.0713	abcd	88.9	a	27.7	ab	24.5	abcd

z: Application times were I.F., in furrow at planting, 14 D.P.E.; 14 days post-emergence; N/A, none applied

y: RAUEPC: Relative area under the emergence progress curve (max = 100), calculated from the day of planting to 45 days after planting (dap) for planting time (pt) 1 (at 14°C), and 28 dap for pt 2 (at 20°C).

x: Percent of stems and stolons with girdling caused by *R. solani* are from an average of 4 plants per replicate (3 replicates) taken 69 dap for pt 1, and 61 dap for pt 2.

w: Number of stolons are the average of 4 plants per replicate (3 replicates) taken 69dap for pt 1; and 61 dap for pt 2.

v: Values followed by the same letter are not significantly different at $p = 0.05$ (Tukey's HSD Comparison)

Table 4.10 Effect of the interaction of soil temperature at planting, seed treatment, additional fungicide and application time, on the cultivar Russet Norkotah for agronomic factors and disease symptoms caused by *Rhizoctonia solani* in field trials at the Muck Soils Research Farm, Michigan State University; Bath, MI in 2006.

Temperature threshold for planting	Seed treatment	Additional fungicide treatment	Application time[z]	RAUEPC (emergence)[y]		Percent of stems with girdling[x]		Number of stolons[w]		Percent of stolons with girdling[x]	
14°C	Maxim	Amistar	I.F.	0.0667	b[v]	39.1	abc	17.3	abc	11.0	e
			14 D.P.E.	0.0703	ab	33.8	c	22.3	a	15.8	bcde
		Moncut	I.F.	0.0713	ab	44.6	abc	22.9	a	22.2	abcde
			14 D.P.E.	0.0703	ab	41.0	abc	23.8	a	9.2	e
		None	N/A	0.0710	ab	45.2	abc	23.0	a	10.2	e
	None	Amistar	I.F.	0.0687	b	38.6	bc	16.8	abcd	17.2	bcde
			14 D.P.E.	0.0683	b	52.6	abc	21.2	ab	33.3	abcde
		Moncut	I.F.	0.0683	b	53.6	abc	17.1	abcd	35.7	abcde
			14 D.P.E.	0.0677	b	73.1	abc	16.1	abcd	21.6	abcde
		None	N/A	0.0680	b	67.0	abc	17.8	abc	34.0	abcde
20°C	Maxim	Amistar	I.F.	0.0753	ab	54.1	abc	10.5	bcd	13.7	de
			14 D.P.E.	0.0697	b	63.8	abc	12.7	abcd	18.8	abcde
		Moncut	I.F.	0.0757	ab	56.5	abc	14.5	abcd	15.7	cde
			14 D.P.E.	0.0713	ab	67.0	abc	10.1	bcd	22.2	abcde
		None	N/A	0.0737	ab	70.4	abc	10.3	bcd	25.0	abcde
	None	Amistar	I.F.	0.0803	a	71.8	abc	9.4	cd	18.9	abcde
			14 D.P.E.	0.0743	ab	81.7	ab	8.7	cd	52.7	a
		Moncut	I.F.	0.0767	ab	85.5	ab	12.6	abcd	48.1	abcd
			14 D.P.E.	0.0703	ab	86.1	a	6.7	cd	51.2	abc
		None	N/A	0.0727	ab	77.0	abc	5.7	d	51.0	ab

z: Application times were I.F., in furrow at planting, 14 D.P.E.; 14 days post-emergence; N/A, none applied
y: RAUEPC: Relative area under the emergence progress curve (max = 100), calculated from the day of planting to 45 days after planting (dap) for planting time (pt) 1 (at 14°C), and 28 dap for pt 2 (at 20°C).
x: Percent of stems and stolons with girdling caused by *R. solani* are from an average of 4 plants per replicate (3 replicates) taken 69 dap for pt 1, and 61 dap for pt 2.
w: Number of stolons are the average of 4 plants per replicate (3 replicates) taken 69dap for pt 1; and 61 dap for pt 2.
v: Values followed by the same letter are not significantly different at $p = 0.05$ (Tukey's HSD Comparison)

Table 4.11 Effect of the interaction of soil temperature at planting, seed treatment, additional fungicide and application time, on the cultivar Superior for agronomic factors and disease symptoms caused by *Rhizoctonia solani* in field trials at the Muck Soils Research Farm, Michigan State University; Bath, MI in 2006.

Temperature threshold for planting	Seed treatment	Additional fungicide treatment	Application time[z]	RAUEPC (emergence)[y]		Number of stems[w]		Percent of stolons with girdling[x]	
14°C	Maxim	Amistar	I.F.	0.0457	ab[v]	2.3	abcd	9.2	b
			14 D.P.E.	0.0647	ab	1.8	cd	16.8	ab
		Moncut	I.F.	0.0583	ab	2.4	abcd	12.3	ab
			14 D.P.E.	0.0603	ab	2.3	abcd	19.0	ab
		None	N/A	0.0547	ab	2.3	abcd	14.1	ab
	None	Amistar	I.F.	0.0433	ab	1.8	bcd	24.8	ab
			14 D.P.E.	0.0473	ab	2.3	abcd	29.3	ab
		Moncut	I.F.	0.0443	ab	1.9	bcd	24.9	ab
			14 D.P.E.	0.0513	ab	2.2	bcd	10.7	b
		None	N/A	0.0570	ab	1.3	d	6.5	b
20°C	Maxim	Amistar	I.F.	0.0543	ab	4.0	a	14.2	ab
			14 D.P.E.	0.0627	ab	2.9	abcd	19.5	ab
		Moncut	I.F.	0.0690	a	3.6	ab	15.7	ab
			14 D.P.E.	0.0593	ab	3.3	abc	15.1	ab
		None	N/A	0.0667	ab	3.3	abc	15.1	ab
	None	Amistar	I.F.	0.0457	ab	3.5	abc	15.1	ab
			14 D.P.E.	0.0427	ab	1.8	bcd	22.0	ab
		Moncut	I.F.	0.0413	ab	3.1	abcd	26.6	ab
			14 D.P.E.	0.0447	ab	2.5	abcd	37.0	a
		None	N/A	0.0397	b	2.8	abcd	23.8	ab

z: Application times were I.F., in furrow at planting, 14 D.P.E.; 14 days post-emergence; N/A, none applied
y: RAUEPC: Relative area under the emergence progress curve (max = 100), calculated from the day of planting to 45 days after planting (dap) for planting time (pt) 1 (at 14°C), and 28 dap for pt 2 (at 20°C).
x: Percent of stems and stolons with girdling caused by *R. solani* are from an average of 4 plants per replicate (3 replicates) taken 69 dap for pt 1, and 61 dap for pt 2.

w: Number of stolons are the average of 4 plants per replicate (3 replicates) taken 69dap for pt 1; and 61 dap for pt 2.
v: Values followed by the same letter are not significantly different at $p = 0.05$ (Tukey's HSD Comparison)

Discussion and conclusions

A combination of treatments were selected from the previous trials (see Chapters 2 and 3), so as to provide a realistic range of management strategies currently available to potato growers in Michigan. Plantings of potatoes, from large commercial growers down to home gardeners, tend to take place (in Michigan) between late April and mid June, depending upon location and environmental conditions. Soil temperature at planting depth can vary significantly among locations, with northern regions of Michigan ranging between 5 and 15°C, and southern regions ranging between 10 and 20°C.

In the case of the Muck Soils Research Farm, the moisture content of the soil is also an important factor in the decision to plant. The farm regularly has saturated soil for a significant portion of the planting time, due to its geographical location and history as a eutrophied lake. As a result, planting potatoes at that location usually occurs in late May through June, and thus only the planting thresholds of 14 and 20°C were applicable in 2006 (see Figure 4.1). Also, a more shallow (10cm instead of 15cm) planting was used, which corresponded to the soil temperature data (10cm) collected from the on-site MAWN weather station.

Contrary to previous findings (see Chapter 3), the later planting at 20°C resulted in significantly more early-season disease symptoms. This finding was also in contrast to other research that found later plantings to have reduced levels of stem and/or stolon canker (Simons and Gilligan, 1997). Bolkan et al. (1974) found that infection of potato shoots decreased with increasing temperature (15, 18, 21, 24°C tested) when (tuberborne) inoculum levels were "low", but did not change with "moderate" and "high" levels of inoculum. Although AG-3 is considered the most important anastomosis group for potatoes, others including AG-4, -5, and -8 have also been shown to readily cause infection to sprouts and stolons (Carling and Leiner, 1990). One possible reason for the increase in disease symptoms at later planting, instead of the predicted decrease, could be the presence in reasonable quantity of an AG other than AG-3. Cultures of AG-3 have been shown to cause more disease symptoms at lower soil temperatures. Carling and Leiner (1990) found that while AG-3 damaged shoots and roots at the three temperatures tested (10, 15.5 and 21.1°C), it caused significantly more damage at 10 °C. In addition, AG-5 significantly damaged sprouts at 15.5 and 21.1°C, and AG-8 caused damage to roots at all three temperatures (Carling and Leiner, 1990).

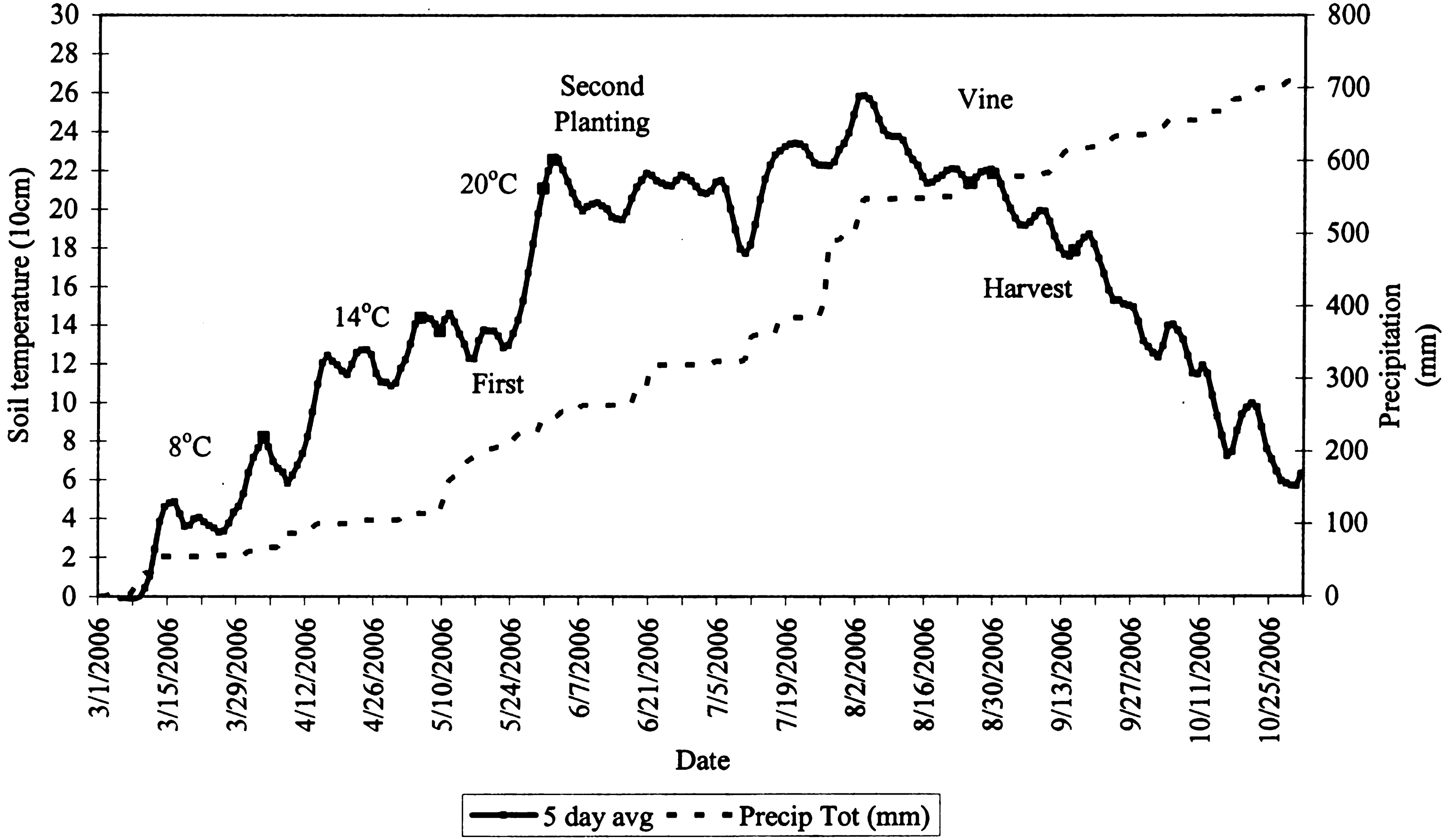
Following the previous fungicide efficacy studies of 2004 and 2005 (see Chapter 2), the use of the seed treatment fludioxonil (Maxim) was again found to be effective against *R. solani*. In 2006, the use of the fungicide did significantly reduce the incidence of stolon girdling, but was not effective against stem girdling. In addition, no single treatment or combination of treatments proved to be effective against disease symptoms for all cultivars planted or soil temperatures at planting. In a summary of nearly 50 trials, Wale (2008) found that even Rhizoctonia stem canker specific (seed and soil) treatments had variable results. Based upon the results of this experiment and the experiments of 2004 and 2005, only use of the one treatment, whether seed or early season was necessary. However, the use of fungicides for management should not be the sole source of control, but rather part of an integrated pest management strategy.

The lack of differences among treatments for black scurf incidence and severity, as well as no yield data reported was the result of significant rainfall prior to harvest. The potato crop was subjected to fully saturated soil for a significant length of time, which resulted in many tubers succumbing to the disease pressure of bacterial soft rot (*Erwinia carotovora* subsp. *carotovora*).

Future Investigations

The management strategies for *R. solani* should continue to be evaluated for possible improvement over current methods. The integration of a pest management plan with chemical and cultural components is most likely the best strategy. In similar studies in the future, the combination of planting based upon soil temperature and chemical control should be reexamined, with multiple seed treatments. Also, some of the available biocontrol agents should be tested for potential efficacy compared to the current standards. The populations of soilborne *R. solani* should be ascertained prior to and following the study at each location. Also, the use of inoculum (multiple AGs, either alone or in combination) should be incorporated into the soil prior to planting in future studies.

Figure 4.1 Five day average of soil temperature (10cm) and precipitation total (mm) Muck Soils Research Farm, Michigan State University; Bath, MI, 2006.



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