EFFECT OF PREHARVEST MANAGEMENT ON YIELD, PROCESS QUALITY, AND DISEASE DEVELOPMENT IN RUSSET BURBANK POTATOES

by

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ABSTRACT

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Phytophthora infestans (Mont) de Bary is a devastating pathogen in potato producing regions around the world. Populations of the organism in Canada shifted during the mid-1990's as the US-1 strain (A1, metalaxyl-sensitive) was displaced by the highly aggressive, US-8 strain (A2, metalaxyl-insensitive). An increase in the incidence and severity of late blight has followed. Late blight is controlled by cultural practices aimed at eliminating disease sources and by the application of foliar fungicides. Tubers can become infected at harvest from contact with blighted vines leading to severe losses in storage. In many production areas, growers desiccate vines two to three weeks prior to harvest to reduce late blight tuber rot. However, in Manitoba, because of the loss of potential yield that results from vine killing prior to harvest in a late maturing cultivar such as Russet Burbank, growers are reluctant to adopt this practice. The objective of this study was to develop recommendations for preharvest management practices that reduce storage losses due to late blight. Field trials were conducted in 1997 and 1998 to investigate the effect of vine desiccation with diquat and/or a late season application of chlorothalonil and copper hydroxide on yield, processing quality, and disease development in storage. Desiccating vines with diquat two weeks prior to harvest reduced

yield and tuber size. Compared to the untreated control, the largest reductions in marketable yield were observed for the early September harvest. By the late September harvest, however, the effect of vine killing in reducing marketable yield was less apparent. Specific gravity was lower in the vine killed treatment for all harvest dates in 1997 and in the early and mid September harvests in 1998. Vine killing did not contribute to elevated levels of reducing sugars or consistently darker fry colour at harvest or during storage. Skin-set was improved when vines were desiccated for all harvest dates in 1997 and at the early September harvest date in 1998. Vine killing reduced tuber rot in storage caused by *Fusarium* dry rot and *Pythium* leak for the early and mid September harvest dates in 1997. The incidence of late blight tuber rot was reduced in storage for the early September harvest in 1998 when vines were desiccated. The late-season application of chlorothalonil and copper hydroxide did not reduce tuber rot in storage in storage either year. Results from this study indicate that vine killing two weeks before an early to mid-September harvest is not recommended in Manitoba because of reductions in yield and specific gravity. Alternative management practices to reduce late blight tuber rot in storage should be investigated.

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1.0 INTRODUCTION

Potatoes (*Solanum tuberosum* L.) are the most valuable vegetable crop grown in Canada. Total production in 2002 was 4.65 million tonnes from 170,200 hectares with a value of $952 million (AAFC, 2004a). Production has been shifting westward in the 1990's to meet, in large part, the increased demands of an expanding processing industry. In 1993, 28% of the nation's production came from western Canada. In 2002, the western region contributed 39% of the nation's production (AAFC, 2004b).

Growth in Manitoba's potato industry has accounted for much of the shift in production. Between 1993 and 2002, Manitoba's production nearly doubled from 446,300 tonnes to 828,300 tonnes (AAFC, 2004b). In 2002, Manitoba grew 18% of the nation's production making it the second largest producer in the country. Over 88% of Manitoba's production was contracted for processing in 2002 with a value of $116 million (Manitoba Agriculture and Food, 2002).

Perhaps the most significant challenge for the expanding Manitoba potato industry has been managing late blight, caused by the fungus *Phytophthora infestans*. Rapid and significant changes in the genetic composition of *P. infestans* populations occurred during the mid-1990's in Canada (Peters et al., 1998). The existing US-1 genotype (A1 mating type, sensitive to the fungicide metalaxyl) was displaced by novel genotypes which migrated to North America from Mexico (Fry and Goodwin, 1997). Many of these new strains are of the A2 mating type, are insensitive to metalaxyl and have proven to be more aggressive on potatoes that the US-1 genotype. The predominant strain in Manitoba since 1994, US-8, is characterized by these traits.

The shift in *P. infestans* populations has resulted in more frequent and severe foliar and tuber blight, despite the increased use of foliar fungicides by growers. Researchers have reported new genotypes cause higher levels of tuber infection from a low level of foliar blight than the US-1 strain (Secor and Gudmestad, 1999). Tubers become infected with late blight during the growing season when spores are washed down from blighted vines into the hill or when immature tubers contact diseased vines at harvest (Thurston and Schultz, 1981). Tubers infected with late blight are particularly risky to store as they usually become invaded by secondary pathogens such as *Erwinia*. Severe breakdown in storage is not uncommon.

Vine desiccation two to three weeks before harvest is a recommended preharvest management practice in many production areas, particularly when foliage is infected with late blight. Vine killing is reported to reduce late blight tuber rot in storage (Stevenson, 1993).

In Manitoba, process growers don't desiccate Russet Burbank vines in order to maximize the length of the growing season for this late maturing cultivar and so increase tuber yield and size. In previous Manitoba studies, yield and specific gravity were reduced when Russet Burbank vines were desiccated before harvest (Giesel, 1985; 1986).

In most production areas, preventative fungicides are applied until vine kill. Some researchers also promote the application of fungicides in between vine kill and harvest as a means to reduce tuber infections (Secor and Gudmestad, 1999).

Manitoba growers were prematurely ending their fungicide spray programs near the close of the growing season, allowing foliar blight to develop and increasing the likelihood of tuber infection at harvest (Manitoba Agriculture, 1994).

In response to the increased prevalence of late blight in Manitoba and the need to reduce losses due to late blight in storage, potato growers and industry expressed interest in evaluating the effect of preharvest management practices on late blight tuber rot development in storage.

The objectives of the present study were: 1) to measure the yield loss and changes in tuber grade resulting from vine killing with diquat two weeks before harvest; 2) to determine the effect of vine desiccation on specific gravity; 3) to determine the effect of vine desiccation on the storage and processing quality of potatoes treated at different stages of chemical maturity; 4) to determine the effect of vine desiccation on skin-set; 5) to monitor the crop for late blight in the field and inspect tubers for rot going into storage; 6) to assess storage losses due to tuber rot as affected by vine desiccation before harvest at different stages of preharvest maturity; and 7) to assess the effectiveness of a chlorothalonil/copper hydroxide application at the time of vine killing in reducing storage losses due to tuber rot.

2.0 LITERATURE REVIEW

2.1 Potato Growth and Development

2.1.1 Introduction

The growth and development of potato plants is often described by five stages; Growth Stage I: Sprout development; Growth Stage II: Vegetative growth; Growth Stage III: Tuber Initiation; Growth Stage IV: Tuber Bulking; Growth Stage V: Maturation (Figure 2.1) (Rowe, 1993).

Many factors influence the timing of events in the growth cycle including cultivar, physiological age, climate, soil type, moisture availability, cultural practices, and pest management (Flint, 1992).

As this project focuses on the effect of management practices on potatoes in the tuber bulking and maturation stages of development, the changes that occur in tuber yield, specific gravity, sugars, and periderm in this timeframe will be discussed briefly.

2.1.2 Tuber Yield

Many factors influence potato crop growth and development, and ultimately tuber yield (Kunkel and Thornton, 1986). Some of the variables are environmental in nature and therefore out of a grower's control and include: length of growing season (frost free period), day length, light intensity, air temperature, wind, humidity and soil type. These factors determine the yield potential for a production area. Other factors affecting yield can be controlled by the grower including cultivar selection, seed quality, physiological age, seed piece size, planting date, plant population, soil compaction, timeliness of operations, moisture availability, nutrition, pest management, and harvest date. Yield is

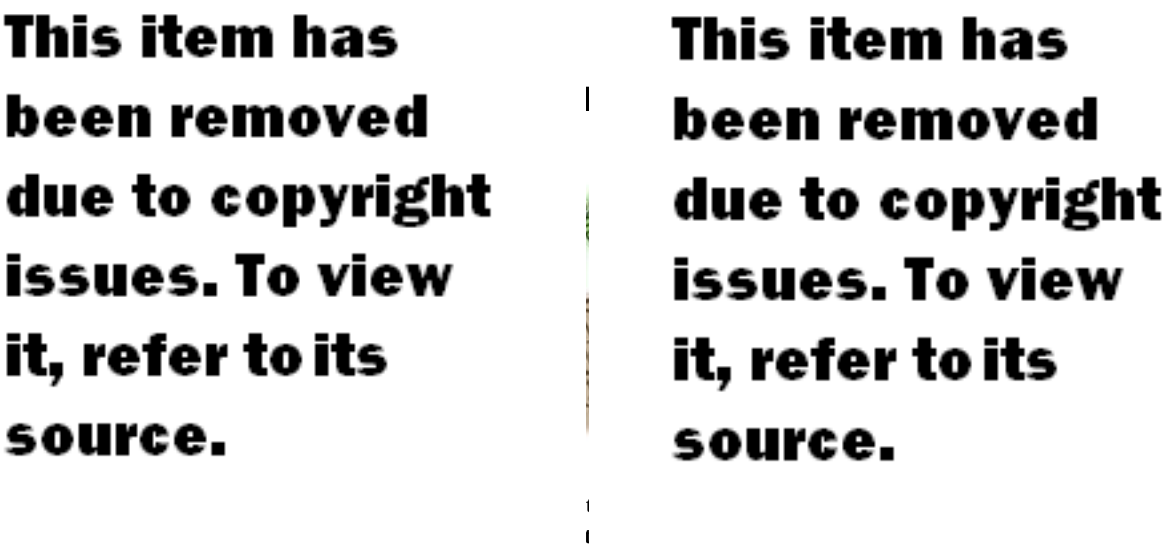


Figure 2.1. Growth stages of the potato (Rowe, 1993).

determined by the interaction of the grower's management practices within the production environment.

Providing that conditions for crop growth are near optimal, the increase in tuber yield is almost linear during the tuber bulking phase of plant development (Stage IV) (Beukema and van der Zaag, 1990). Late in the season, as the vines senesce (Stage V), photosynthesis decreases and tuber growth slows (Rowe, 1993). The rate and duration of the linear tuber growth phase determine tuber yield (Moorby and Milthorpe, 1975; Dawes et al., 1983).

The bulking rate expresses the increases in fresh tuber weight over space and time (e.g. tonnes hectare^{-1} day^{-1}) (Beukema and van der Zaag, 1990). Allen and Scott (1980) suggested that 5 tonnes ha^{-1} week^{-1} (0.71 tonnes ha^{-1} day^{-1}) was the 'normal' bulking rate for potatoes. Dwelle (2003) reported that bulking rates of 0.67 to 1.12 tonnes ha^{-1} day^{-1} were typical for Russet Burbank in southern Idaho. Menzies and Adam (1979) measured the tuber bulking rate of Russet Burbank grown in Manitoba and determined that daily tuber production decreased through September from 0.81 tonnes ha^{-1} day^{-1} in mid September to 0.22 tonnes ha^{-1} day^{-1} in late September. Giesel (1986) reported a bulking rate of 0.80 tonnes ha^{-1} day^{-1} for Russet Burbank in early September in Manitoba.

Although this discussion of tuber yield has not distinguished between total tuber yield and 'marketable yield', the distinction is important. Marketable yield describes the proportion of tuber yield that is suitable to the end-use. For processing potatoes, suitability is based on tuber size, specific gravity, french fry colour and percent defects (Stark and Love, 2003).

2.1.3 Specific Gravity

Specific gravity is a measure of tuber density used by the potato processing industry to estimate tuber solids or dry matter content (Kleinkopf et al., 1987; Storey and Davies, 1992). Potatoes with a specific gravity of 1.080 or higher (equivalent to tuber dry matter >20%) are desirable for most processed products (Stark and Love, 2003). Tubers with high dry matter are desirable for processing for a number of reasons: recovery (yield of processed product per unit of raw potatoes) is higher (Smith, 1977); the texture and flavour of the finished product is more desirable (Kleinschmidt et al., 1984); and the cost of processing is lower due to faster frying and less oil absorption (Gould, 1988). Many processing contracts offer incentives to growers for delivering high specific gravity tubers.

Tuber specific gravity can be measured by three methods: 1) weight in air – weight in water method, 2) hydrometer, and 3) brine solutions (Dean, 1994). The weight in air – weight in water method is most commonly used as it is the most versatile and accurate of the techniques (Kleinkopf et al., 1987; Burton, 1989).

The relationship between specific gravity and dry matter content has been elucidated by many researchers (van Es and Hartmans, 1987a), including Pritchard and Scanlon (1997) who developed relationships for Manitoba-grown Russet Burbank and Shepody.

Tuber dry matter content increases rapidly after tuber initiation as tubers increase in size until late in the season when tuber solids peak around the beginning of vine senescence and may actually decline if harvest is delayed after vine death (Gray and Hughes, 1978; Werner et al., 1998). Almost any factor that affects tuber growth affects

tuber specific gravity (Beukema and van der Zaag, 1990) including cultivar, climate, soil type, cultural practices (planting date, seed quality, planting density, fertility, irrigation, pest management and harvest date), and maturity. The effects of these factors and others on specific gravity have been discussed extensively by a number of authors including (Kleinschmidt et al., 1984; van Es and Hartmans, 1987a; Beukema and van der Zaag, 1990; Storey and Davies, 1992; Stark and Love, 2003).

2.1.4 Sugars

2.1.4.1 Introduction

Carbohydrates constitute about 75% (range, 63-86%) of the total dry matter found in potato tubers (Storey and Davies, 1992). Carbohydrate reserves consist largely of starch present in cells as microscopic granules called amyloplasts. Starch accounts for 70% (range, 60-80%) of tuber dry weight (Burton, 1966). Talburt et al. (1987) noted that the sugar content of potatoes is variable ranging from only trace amounts to as much as 10% of the dry weight of the tuber, but typically less than 3%. The carbohydrate balance and mechanisms for starch-sugar interconversion are significant for potatoes as the reducing sugar content is a key factor influencing acceptability for processing (van Es and Hartmans, 1987b).

Sucrose, glucose, and fructose are the principal sugars found in potatoes (van Es and Hartmans, 1987a). Considerable variation in sugar content occurs during tuber development and storage. Sucrose is a twelve-carbon, non-reducing sugar that is the primary form in which carbohydrates formed in leaves are translocated into the tubers. In tubers, sucrose is partitioned between storage as starch, structural polysaccharide, storage

as sucrose or hexose, and entry into respiratory pathways (ap Rees and Morrell, 1990). Most of the sucrose (50-70%) is converted to starch, 5-10% is converted to structural polysaccharide, and the remainder is divided between respiration and storage.

The level of the six-carbon reducing sugars, glucose and fructose, in potatoes must be low for processors to achieve the uniform, golden brown fried product colour considered desirable for chips and french fries (Gould, 1988; Walsh, 1995a). Frying at high temperature causes nonenzymatic browning of chips and french fries due to a Maillard-type reaction between the aldehyde and ketone groups of reducing sugars and the α-amino groups of nitrogenous compounds (amino acids and proteins) (Habib and Brown, 1957; Storey and Davies, 1992). Darkening and the associated bitter taste that develops when the concentration of reducing sugars is high severely reduce the quality of the finished product (van Es and Hartmans, 1987b). For chip production, the maximum allowable level of reducing sugars in tubers is 2.5 to 3 mg g^{-1} tuber fresh weight (FW) (Burton et al., 1992). Slightly higher levels are acceptable for potatoes processed into french fries (5 mg g^{-1} FW) (Burton et al., 1992). Pritchard and Adam (1994) reported that glucose levels less than 1.6 mg g^{-1} in Russet Burbank and 1.2 mg g^{-1} in Shepody were necessary to meet fry colour specifications for maximum colour bonus from Manitoba french fry processors. Pritchard and Adam (1994) demonstrated a stronger association between fry colour and glucose than with sucrose or fructose.

2.1.4.2 Sugar changes during growth

Immature tubers contain high levels of sucrose (>4 mg g^{-1}) because the rate of its translocation to the tuber exceeds the rate at which it is metabolized (Sowokinos and

Preston, 1988). As tubers approach maturity, sucrose levels decrease to a cultivar-specific value, subject to cultural practices (e.g. fertility management, disease control) and environmental factors (e.g. temperature stress, moisture stress, length of growing season) (Sowokinos, 1978; Burton, 1989). Potatoes with a sucrose content or sucrose rating of 2.5 mg g^{-1} FW or less at harvest are said be "chemically mature" and typically process acceptably from long-term storage (Nelson and Sowokinos, 1983). The sucrose content at harvest is a good indicator of processing performance out of storage because sucrose is a precursor to the reducing sugars glucose and fructose. The reducing sugar content of tubers also decreases with increasing maturity, although not to the same degree as sucrose (Mazza et al., 1983).

2.1.4.3 Sugars changes in storage

The literature is replete with references to the changes in carbohydrate that occur in stored potato tubers and the effect of these changes on processing quality. However, the mechanisms and regulation of postharvest carbohydrate metabolism in potato are still unclear (Burton et al., 1992). Writing on the challenge of studying postharvest changes in the chemical composition of potatoes, Burton et al. (1992) noted that the potato contains many potentially reactive systems of substrates and enzymes and that the very presence of complex molecules suggests the potential for continued reactions. These authors point out that even in mature tubers, where the major constituents have reached a fairly steady level, the carbohydrate component, amongst others, is believed to be in a perpetual state of change.

Davies and Viola (1992) identified four types of sugar accumulation or "sweetening" that occur postharvest in potato tubers: immaturity-based sweetening; sugar formation in association with rapid sprout growth; senescent sweetening; and low-temperature sweetening. The effect of tuber maturity on reducing sugar accumulation in storage is of particular relevance to this study.

The conversion of sucrose to reducing sugars during the early storage of chemically immature potatoes can lead to substantial accumulations of glucose and fructose (Pritchard and Adam, 1992). During tuber development sucrose levels are high, but a protein inhibitor prevents the enzyme invertase from hydrolyzing sucrose to glucose and fructose during tuber growth (Pressey, 1969). In storage, the invertase pathway is no longer blocked and sucrose is converted to reducing sugars (Richardson et al., 1990). This mechanism accounts for the dark chip and fry colours often observed early in the storage period (Mazza et al., 1983; Pritchard, 1993a). Extended preconditioning is required to lower sugars to an acceptable level in immature tubers (Pritchard and Adam, 1992; Pritchard, 1993a).

2.1.5 Periderm

2.1.5.1 Introduction

The native periderm of potato tubers, more commonly referred to as 'skin', acts as a protective barrier for the underlying tuber tissue preventing dehydration and disease invasion and reducing harvest injury (Lulai and Orr, 1994). Tuber periderm consists of three distinct tissues; phellem, phellogen and phelloderm (Reeve et al., 1969; Lulai and Freeman, 2001). The outside layer called the phellem (cork) is comprised of six to ten

layers of brick-shaped cells which develop suberized walls (Lulai, 2001). The phellem is the portion of the periderm that is generally referred to as skin (Lulai and Orr, 1994) and that confers resistance to water loss and pathogen invasion. Beneath the phellem is the phellogen (cork cambium), a single layer of meristematic cells which forms in the early stages of tuber development and divides outwardly giving rise to the phellem and inwardly forming the phelloderm (Sabba and Lulai, 2002). Phellem development varies across the tuber surface being more advanced at the stem end than the equatorial or bud regions (Lulai and Orr, 1994).

2.1.5.2 Periderm development

One of the key indicators of tuber maturity is the development of resistance to skinning injury, loosely referred to as 'skin-set', as the periderm matures (Braue et al., 1983; Lulai and Orr, 1993). Tubers with immature periderm have poor skin-set and are susceptible to scuffing abrasions or feathering during harvest and handling (Wilcockson et al., 1980; Olson et al., 2003). Consequently, promoting skin-set development is critical to limiting costly skinning-related losses for growers and processors (Lulai, 1992).

Recent research by Lulai and Freeman (2001) revealed that skinning injury results in the fracturing of cells in the phellogen and separation of the phellem from the tuber, not removal of the complete periderm as previously reported (Mohsenin, 1965; Misener, 1983). Phellogen cells in immature periderm are actively dividing and have thin walls that are easily fractured (Lulai and Freeman, 2001). As the periderm matures, meristematic activity slows, phellogen cell walls thicken, and resistance to skinning increases (Lulai and Freeman, 2001). Lulai (2002) demonstrated that these cellular

changes in the phellogen lead to the measurable development in skin-set as tubers mature. The tensile force required to tear the fabric-like layers of the phellem is relatively consistent during periderm maturation indicating that this component does not contribute to the increase in skin-set (Lulai, 2002). Previous associations made between periderm thickness (Scott and Wilcockson, 1978), suberization (de Haan, 1987), and resistance to skinning injury have been refuted (Lulai and Orr, 1993; Lulai, 2002).

In the field, producers traditionally assess skin-set by applying thumb pressure and lateral force to the surface of a freshly dug tuber in a snap-like motion (thumb-slip test) (Halderson, 1991). However, these evaluations tend to be subjective (Halderson and Henning, 1993). Researchers have used numerous methods to measure the resistance of tubers to skinning. Terman et al. (1952) spun tubers in a barrel for a determined number of revolutions and visually estimated the percentage of the tuber surfaces that were skinned. Laboratory devices were developed to determine the abrasive force (Kunkel and Edmundson, 1957) and the frictional force and downward pressure (Mohsenin, 1965) required to cause skinning. Misener (1983) measured resistance to skinning by spraying tubers with water, incrementally increasing the water pressure, until skinning occurred.

Recent progress towards developing a standardized test for tuber skin maturity is in a large part due to the skin shear strength device developed by Halderson (1991). The screwdriver-like tester is comprised of a torque wrench connected to a spring loaded shaft with a rubber tip. Skin-set is measured by pressing the rubber tip of the device against the tuber surface and applying the prescribed downward pressure through the shaft. The device is turned, exerting a torsional force to the tuber surface, until a disk of skin is sheared off. The maximum torque reading is recorded as the skin-set. Lulai and Orr

(1993) modified the Halderson skin-set testing device and refined operational procedures to develop a standard technique for measuring skin-set (Lulai, 1996a). This device has proven capable of measuring differences in the skin development patterns of potato varieties (Lulai and Orr, 1993) and the effects of cultural practices on skin-set (Lulai, 1996b). Pavlista (2002) demonstrated that there is a strong linear relationship between tuber skin resistance to shearing (as measured by the skin-set torque wrench) and tuber skinning. The simplicity and portability of the tester allows for many readings to be taken rapidly in the field (Pavlista, 2002). Skin-set measurements are affected by the test location on the tuber surface and are lowest at the bud end and highest at the stem end (Halderson and Henning, 1993; Lulai and Orr, 1993).

Several factors are known to affect skin-set development including variety, soil type, cultural practices, and environmental conditions (Braue et al., 1984; Lulai, 1997). Typically red-skinned varieties are more susceptible to skinning than russet- and white-skinned varieties because they do not develop skin-set as rapidly (Lulai, 1995; Lulai, 1996b). Enhanced periderm formation is observed on tubers grown in light to medium textured, freely draining soils (Stark and Love, 2003). Management practices that delay crop maturity, such as excessive nitrogen fertilization (Herrman et al., 1995; Lulai, 2002), hinder skin-set development. Moderate soil moisture (65 to 80% field capacity) and temperature (12 to 23°C) during tuber bulking favour the development of a uniform, mature periderm (Yamaguchi et al., 1964; Stark and Love, 2003).

2.2 Late Blight

2.2.1 Introduction

Late blight is generally regarded as the most serious disease of potatoes in the world (Fry et al., 2001). Infamous for devastating potato crops in Ireland in the 1840's; late blight resulted in widespread famine that killed 1.5 million people (Carefoot and Sprott, 1967; Fry and Goodwin, 1997). Late blight also affects some other species in the *Solanaceae* family including tomatoes and nightshade (Platt, 1999).

Late blight is often referred to as a "community disease" because its spread is not restricted to an individual field or a particular grower. Successful management of late blight in potatoes requires an integrated approach utilizing all available strategies at each stage of the growth cycle (Stevenson, 1993). Control strategies are directed towards disease prevention through cultural practices and foliar fungicide applications.

2.2.2 Causal Agent, Disease Cycle, and Epidemiology

Potato late blight is caused by the heterothallic oomycete, *Phytophthora infestans* (Mont.) deBary. The disease cycle of the organism is made up of two cycles – a sexual and an asexual cycle (Figure 2.2). The sexual cycle is rarely observed in North America (Glass et al., 2001).

Sexual reproduction requires the presence of both mating types (A1 and A2). Fertilization results in the production of a thick-walled resting spore called an oospore. Oospores can survive in soil for months or even years without living host tissue, even under adverse conditions (Fry and Goodwin, 1997). Moreover, they represent a means by which the organism can increase its genetic diversity and putatively, its aggressiveness.

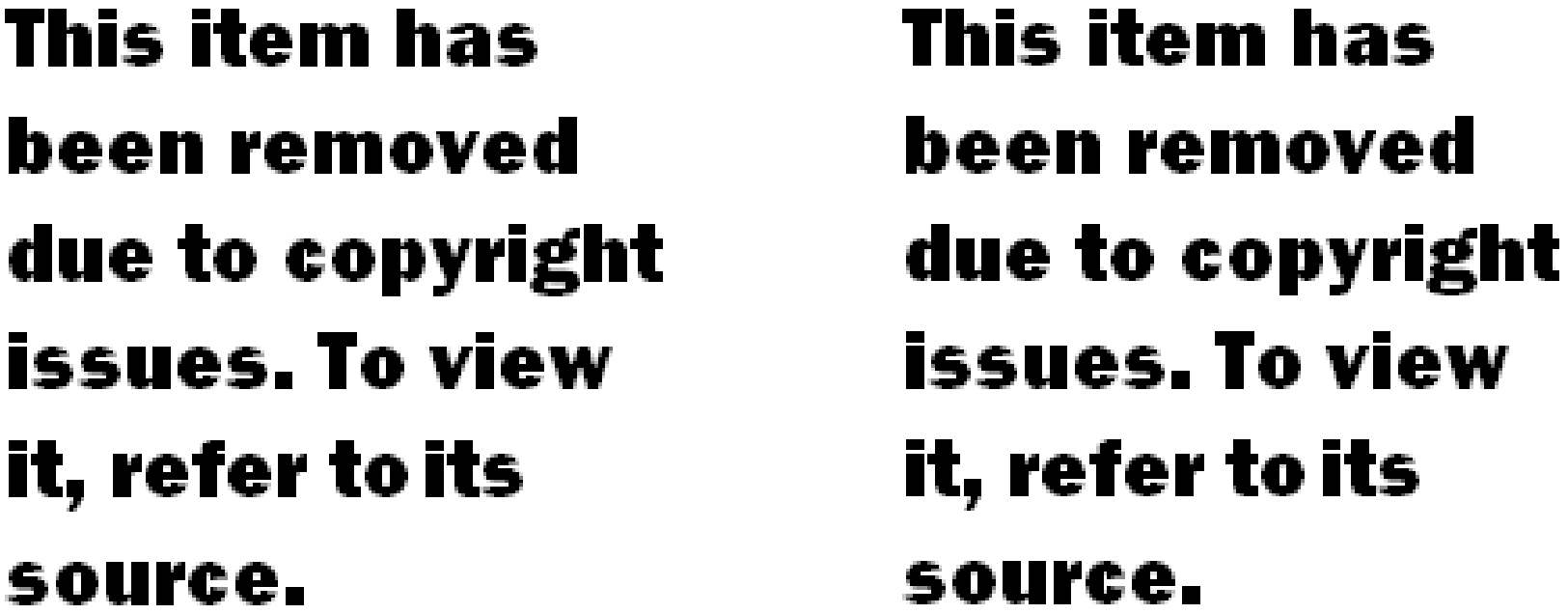


Figure 2.2. Disease cycle of *Phytophthora infestans* on potato (Agrios, 1988).

In the absence of both mating types, *Phytophthora infestans* reproduces asexually through the formation of sporangia. Sporangia are thin-walled, lemon-shaped, and produced on the tips of branched sporangiophores which grow out from infected tissue (Fry et al., 2001).

Under warm, moist conditions sporangia germinate directly and infect plant tissue by the production of a germ tube. In cooler temperatures, sporangia germinate indirectly producing 6 to 8 motile zoospores. Zoospores can swim in a water film, unlike sporangia which are dependent on wind and rain for movement. After several minutes, zoospores encyst and, on a suitable host, will germinate and penetrate the tissue by means of a germ tube.

Once inside the plant tissue, mycelia extend and begin colonizing the tissue intercellularly and form haustoria which penetrate cells to absorb nutrients.

It is the organism's efficient asexual cycle that results in the rapid destruction of foliage and aggressive spread to new hosts (Fry and Goodwin, 1997). Although the fungus can survive indefinitely as an asexual organism, as such, it is essentially an obligate parasite, requiring living host tissue.

P. infestans survives between potato crops as mycelium in infected tubers (Figure 2.2) (Thurston and Schultz, 1981). Initial sources of disease may include stored tubers intended for use as seed, blighted tubers removed during grading and dumped in cull piles, or, in some production areas, unharvested tubers that survive in the field and emerge as volunteers the following season (Fry, 1997).

Infected tubers give rise to a new epidemic when the pathogen grows into the newly developed sprouts and, under moist conditions, sporulates producing sporangia on

young leaves and stems (Stevenson, 1993). Studies confirm that the US-8 genotype can spread from infected seed and initiate foliar infections although the occurrence is thought to be rare (Lambert et al., 1998; Platt et al., 1999). Alternatively, sporangia can be produced directly on infected tubers in cull piles (Nolte et al., 2003). Even though the amount of initial inoculum is usually relatively small, it is significant because of the rapid cycling potential of this pathogen.

Sporangia produced from the initial disease source are spread between plants by rain or irrigation and by wind currents to surrounding potato fields. The spread of disease over long distances (in excess of 100 km) has been linked to sporangia carried from infected areas by moist storm systems (Peters et al., 1999).

Once established, the rate at which disease develops and the extent to which it develops are strongly influenced by the prevailing environmental conditions. Cool nights (10 to 15°C) and warm days (15 to 24°C) accompanied by high relative humidity and rain are considered ideal conditions for a late blight epidemic (Stevenson, 1993). Under these conditions the cycle of disease – infection, sporulation, and spore dispersal – can occur in less than five days and entire fields can be destroyed in less than three weeks (Fry and Goodwin, 1997).

The mechanism by which *P. infestans* infects host tissue is temperature and moisture dependant. At temperatures between 21 and 26°C and high relative humidity, sporangia germinate directly (Figure 2.2) (Stevenson, 1993). The optimum temperature for direct germination is 24°C (Thurston and Schultz, 1981). At lower temperatures (8 to 18°C) and in the presence of free moisture, sporangia germinate indirectly releasing many zoospores (Figure 2.2) (Fry et al., 2001). More sensitive to drying than sporangia,

zoospores are often spread by splashing rain drops before they encyst on host tissue and germinate (Rich, 1983). The optimum temperature for indirect germination is 12°C and at intermediate temperatures, both types of germination occur (Thurston and Schultz, 1981).

Disease development in host tissue occurs rapidly under optimal conditions (18 to 22°C) and leaf lesions become visible in 3 to 5 days (Fry et al., 2001).

Spore production begins on the undersides of infected leaves within days of the lesions being visible. When the relative humidity is near 100 percent, sporulation occurs at temperatures of 3 to 26°C, although lesions are more productive at moderate temperatures (18 to 22°C) (Stevenson, 1993). Under ideal conditions a single lesion is capable of producing as many as 300,000 sporangia per day (Legard et al., 1995).

Tubers become infected when rain carries spores from blighted vines into the soil. Infection takes place primarily through tuber eyes, lenticels, and wounds (Zan, 1962). Low soil temperatures (below 18°C) at the time of rain events increases the severity of tuber blight because this favours the release and activity of zoospores (Sato, 1979). Tubers may also be infected through contact with diseased vines at harvest. Sporangia infect tubers through skinning and harvest wounds resulting in decay when tubers are placed in storage.

2.2.3 Disease Symptoms

Phytophthora infestans can infect leaves, stem and tubers (Hodgson et al., 1973). Initial symptoms appear as small brown or black irregular-shaped lesions, often surrounded with a light green halo, that form at the margins or tips of leaves (Fry et al., 2001). Under favourable conditions, leaf lesions grow rapidly becoming circular and

brown to purplish-black in colour with pale green borders (Stevenson, 1993). As well, a white mildew growth often develops on the underside of infected leaves along the edges of active late blight lesions (Platt, 1994a). From this, the disease is disseminated to other leaves, stems and plants. In hot and dry conditions, disease spread slows and infected leaf tissues dry up (Stevenson, 1993).

A tell-tale symptom of the new strains of *P. infestans* is the brown to black stem lesions that develop at the apex of shoots and aggressively extend downward (Weingartner, 1997). These stems lesions are more tolerant of dry weather (Nolte et al., 2003).

When disease is severe, infected plants give off a foul, distinctive odor due to the rapid decay of leaf and stem tissue (PMRA, 1996).

Lesions on the surface of infected tubers are irregular in shape, purplish-brown in colour, and slightly sunken (Thurston and Schultz, 1981). Under the skin, a granular, tan to reddish-brown dry rot extends characteristically into the tuber to a depth of 1-2 cm (Platt, 1994a). In moist conditions, a mildew-like growth may occur on the surface of infected tubers. Blighted tubers are readily invaded by secondary pathogens, particularly *Erwinia* soft rot, causing rapid and severe decay in stored tubers.

Newer stains of the pathogen are more aggressive against tubers (Medina et al., 1999).

2.2.4 History of Late Blight in Manitoba

The first appearance of late blight in Canada was in the 1840's (Bourke, 1969), during the same decade that the disease ravaged the potato crop in Ireland causing

widespread famine (Carefoot and Sprott, 1967). While late blight was reported "over several hundred miles of country including Lower and Upper Canada", there is no record of the disease spreading to western Canada (Bourke, 1969).

Bisby (1938) in his book The Fungi of Manitoba and Saskatchewan records the first appearance of late blight on potatoes in Manitoba as 1927 noting that the organism "remained (presumably on stored potato tubers) over the winter and was prevalent in eastern Manitoba in 1928". Late blight was not observed again until 1941 (CPDS, 1942) but then was sighted frequently during the 1940's and 1950's (CPDS, 1943-1958). Other than a report of slight infection in 1964 (CPDS, 1965), there are no further records of late blight in the province for nearly 30 years until disease was observed in a "several" commercial fields near Winkler in 1992 (Platford, 1993).

In 1993 below average temperatures and unusually heavy rains favoured the development of late blight in Winkler, Carman and Portage (Manitoba Agriculture, 1993). Although it was thought that a return to normal rainfall and temperatures would reduce the frequency of disease outbreaks, late blight has been found in the province every year since until 2004. (Table 2.0). Late blight was found for the first time in all production areas of Manitoba in 1998 (Manitoba Agriculture, 1998a).

The emergence of late blight as a significant disease concern in Manitoba and across Canada in the 1990's has been primarily attributed to the change in the predominant strains of the pathogen (Daayf and Platt, 2000). Since 1995, the A2 clonal lineage US-8 has dominated the disease landscape in Manitoba. Research has shown that this strain is more virulent, exhibits increased aggressiveness, and is resistant to the systemic fungicide metalaxyl.

Table 2.0 Recent history of *Phytophthora infestans* in Manitoba. Incidence of disease, frequency of mating types and clonal lineages, and response to metalaxyl for isolates collected from infected potato samples.

		Mating Type [a]		Clonal Lineage [b]			Response to Metalaxyl [c]		
Year	Late Blight Observed	A1 (%)	A2 (%)	US-1 (%)	US-8 (%)	Others (%)	MS (%)	MMR (%)	MHR (%)
1992 [d]	Yes	-	-	-	-	-	-	-	-
1993 [e]	Yes	100	-	100	-	-	100	-	-
1994 [f]	Yes	85	15	70	0	30	77	23	0
1995 [g]	Yes	25	75	25	75	0	14	85	1
1996 [h]	Yes	0	100	0	100	0	14	78	8
1997 [i]	Yes	2	98	0	98	2	60	40	0
1998 [j]	Yes	0	100	0	97	3	66	24	8
1999 [k]	Yes	0	100	0	99	1	35	50	15
2000 [l]	Yes	-	-	-	-	-	-	-	-
2001 [m]	Yes	-	-	-	-	-	-	-	-
2002 [n]	Yes	-	-	-	-	-	-	-	-
2003 [o]	Yes	-	-	-	-	-	-	-	-
2004 [p]	No	-	-	-	-	-	-	-	-

[a] Numbers represent the frequency that isolates of each mating type were found in samples received (expressed as a percentage).

[b] Numbers represent the frequency that isolates of particular clonal lineages were found in samples received (expressed as a percentage).

[c] Numbers represent the frequency of three levels of response to metalaxyl of isolates in samples received (expressed as a percentage). Sensitivity to metalaxyl was tested *in vitro* and was based on the relative growth of mycelium at 100 µg/mL compared to growth at 0 µg/mL after Peters et al. (1998). MS = metalaxyl-sensitive; MMR = metalaxyl-moderately resistant; MHR = metalaxyl-highly resistant.

[d] From Platford (1993). Late blight was reported for the first time in Manitoba since 1965.

[e] From Peters et al. (1998)

[f] From Platt et al. (1995)

[g] From Platt et al. (1996)

[i] From Daayf and Platt (1998)

[j] From Daayf and Platt (2000)

[k] From Daayf and Platt (2001)

[l] From Desjardins et al. (2001)

[m] From Desjardins et al. (2002)

[n] From Desjardins et al. (2003)

[o] From Desjardins et al. (2004)

[p] From Manitoba Agriculture, Food and Rural Initiatives (2004)

In spite of more intensive management, growers have experienced substantial yield reductions in the field and losses in storage (Manitoba Agriculture, 1993, 1998a).

2.2.5 Disease Management

Effective management of late blight requires an integration of control strategies and vigilance throughout the growing season.

An integrated approach is used to manage late blight in Manitoba involving multiple strategies at each growth stage (CMAAS, 1996). These include: 1) field selection; 2) planting disease-free seed tubers; 3) growing less susceptible varieties; 4) destroying cull piles; 5) proper hilling; 6) scheduled irrigation; 7) disease forecasting; 8) scouting; 9) scheduled fungicide programs; 10) harvest management; and 11) storage management.

Field Selection

Field shape, size, and surroundings should be considered before making a choice to crop to potatoes. Small, irregularly shaped fields should be avoided as complete fungicide coverage is difficult to achieve. Fields which are bordered by shelterbelts, buildings or power lines are difficult to spray satisfactorily by plane (Stevenson, 1993). Fields with low areas where water accumulates are at higher risk of developing late blight (Nolte et al., 2000).

Planting disease-free seed tubers

Planting healthy seed is a key first step to preventing late blight (Fry et al., 2001).

Although the use of certified seed does not guarantee that tubers infected with late blight will not be present in a seed lot, it is widely recommended as a control measure (Stevenson, 1993; Platt, 1994b; Nolte et al., 2003). Movement of infected seed has been implicated in the spread of novel genotypes of late blight (Fry et al., 1993).

Growing less susceptible varieties

Host resistance is an important tool in an integrated control strategy for late blight (Forbes and Jarvis, 1994). However, the use of varieties is driven by customer and processor preference and resistant lines usually fail to match the quality characteristics of traditional varieties (PMRA, 1996). Consequently, the majority of potato varieties grown commercially in Canada are susceptible to late blight (Platt and Tai, 1998).

Inglis et al. (1996) proposed that differences in the susceptibility of commercial varieties to foliar and tuber blight could be incorporated into disease monitoring and fungicide scheduling programs. Of the two predominant varieties grown in Manitoba, Russet Burbank is more resistant than Shepody to foliar and tuber infections (Inglis et al., 1996).

Destroying cull piles

The timely elimination of cull potatoes is no less important than planting disease-free seed in reducing the amount of initial inoculum and suppressing late blight (Fry et al., 2001). Blighted tubers, removed during the grading of stored potatoes, can play a central role in initiating epidemics if not disposed of properly (Stevenson, 1993). Of

particular risk are diseased culls, collected when potatoes are shipped in early spring, which may avoid freezing temperatures, sprout, and produce spores.

Culls can be disposed using a number of methods including; 1) burying; 2) composting; 3) feeding to livestock; and 4) spreading on fields in the winter months to freeze (Stevenson, 1993). Herbicides can also be applied to culls that are sprouting. Slivers and chips produced from seed cutting should be treated similarly as they too can be a source of disease (Nolte et al., 2000).

Proper hilling

Forming high and wide hills with as few cracks in the soil as possible minimizes the exposure of tubers to spores washed down from blighted foliage (Stevenson, 1993).

Scheduled irrigation

As late blight infection requires extended periods of leaf wetness, scheduling irrigation to minimize periods of uninterrupted leaf wetness is required to avoid increasing disease risk (Stevenson, 1993). Applying more water less frequently is preferable to light, frequent applications during growth stages III and IV (Nolte et al., 2000). Time applications to allow foliage to dry before night dew formation and avoid early morning irrigation which extends the length of time that the plant canopy remains wet (Bohl et al., 2003). Don't irrigate during cool, rainy weather and manage water applications carefully in Growth Stage V (Bohl et al., 2003).

Disease Forecasting

Forecasting systems play a key role in an integrated management strategy for late blight (Fry, 1994). Several systems have been developed that identify weather conditions conducive to the late blight development so that timely fungicide applications can be made and the establishment and spread of the disease prevented (Gudmestad, 1997).

Accurately forecasting the initial appearance of late blight is critical to scheduling preventative fungicide applications for late blight. BLITECAST, or modifications of it, is the most commonly used forecast modeling system in North America for predicting when the initial outbreak of late blight will occur in an area (Gudmestad, 1997). The BLITECAST system determines severity values on the basis of temperature, relative humidity and rainfall (Stevenson, 1993). The initial protectant fungicide application is recommended once 18 severity values have accumulated as late blight is likely to occur within the next 7 to 10 days (Fry and Fohner, 1985). In years that are not favourable to late blight, BLITECAST can be used to eliminate unnecessary sprays early in the season (Fry, 1994). This model is used in preparing Manitoba Agriculture's late blight forecasts (CMAAS, 1998).

Forecasting models have also been developed that track the suitability of environmental conditions for the spread of late blight. These can be used to adjust the interval between fungicide sprays through the growing season (Gudmestad, 1997). In Manitoba, once the threshold of 18 severity values is reached, daily average temperature and leaf wetness are used to determine disease severity values (DSV) (CMAAS, 1998). The degree of change in DSV's between forecasts is used to shorten or extend the spray

interval. A rapid rate of change indicates that weather conditions have been favourable for late blight and may justify more frequent fungicide applications (CMAAS, 1998).

Manitoba Agriculture's Late Blight Forecasting Program uses weather data collected from remote automated weather stations situated across the province (CMAAS, 1998). Forecasts are updated bi-weekly and made available to growers by a toll free phone number (the Potato Disease Hotline) or via the internet. Potato disease risk maps are faxed to growers and are also available at Manitoba Agriculture, Food and Rural Initatives' website.

Scouting

Fields should be scouted regularly for late blight, particularly once forecasts have warned that disease is likely to occur. Scouting should be concentrated in areas of the field where the plant canopy is often wet including low spots, sheltered areas, center pivot wheel tracks and inside towers, and along windbreaks (Nolte et al., 2000). Areas of a field where fungicide application is difficult because of obstructions (i.e. power lines) should also be examined for symptoms. Varieties which are highly susceptible to late blight should also receive closer attention.

When late blight is detected early and damage is localized, rapid and complete destruction of these "hot spots" can slow the spread of disease. Infected areas can be plowed down, burned, or sprayed with a desiccant. Single plants that are rogued should be bagged and removed.

Early detection of the disease gives warning that late blight is in a production area and allows fungicide compounds, rates, and schedules to be adjusted pro-actively (Stevenson, 1993).

Scheduled fungicide applications

Regular fungicide applications are required to manage late blight in most production areas.

Types of Fungicides

The fungicides used for managing late blight are grouped based on their mode of action; 1) contacts; and 2) local systemics (Nolte et al., 2003).

The majority of the fungicides used against late blight are contact or protectant fungicides. To be effective these products must be applied before foliage is infected, and must be reapplied throughout the growing season to protect new plant growth and residues lost due to weathering. Contact fungicides such as mancozeb, chlorothalonil, metiram and maneb are used commonly in Manitoba to protect foliage from infection.

Unlike contact fungicides, locally systemic fungicides penetrate the foliage and move within the leaves and, to some extent, upward in the plant. These fungicides are used when the crop is in active growth and disease risk is high or when application schedules are delayed. Several products including dimetromorph, cymoxanil, and propamocarb hydrochloride, are registered for use in Manitoba. Local systemic fungicides are also applied in combination with contact fungicides.

Methods of Application

The two most common methods of applying fungicides to potato crops in North America are: 1) ground rigs; and 2) aircraft. Certain fungicides have restrictions as to how they may be applied.

Ground applications generally provide uniform fungicide coverage and are considered the best method of application (Bohl et al., 2003). Their disadvantage is the time required to cover large acreages.

Aerial applications deposit most of the fungicide in the upper canopy and rain or irrigation is required to redistribute residues down. Aircraft are also more liable to leave skips (unprotected areas) resulting from obstacles or inadequate overlap between passes.

Regardless of the method of application, fungicides must be applied preventatively, with complete crop coverage, and at the appropriate time to be effective.

Application Timing

Early-season fungicide applications are important to ensure foliage is adequately protected before conditions are favourable for disease development.

The first application should be made before plants touch across the rows or even earlier if forecasting indicates that late blight is likely to occur. When the threshold is exceeded early in the season, fungicides can be band sprayed to reduce fungicide costs.

During the growing season, spray intervals are typically 7 to 10 days for contact fungicides. Shorter spray intervals (5 days) are used during periods of rapid crop growth or when weather conditions are favourable for disease spread. The frequency of applications can be reduced when disease risk is low and environmental conditions are not favourable for disease development.

The total number of fungicide applications required during a growing season to control late blight varies between regions. Johnson et al. (1997) reported that growers in the Columbia Basin used between 8 and 12 fungicides to fend off a late blight epidemic in 1995. Growers in Manitoba typically apply a minimum of 10 fungicide sprays over a growing season although some spray as many as 16 applications to control the disease (Gilmour, 1998, 1999).

Harvest management

The importance of desiccating vines well in advance of harvest to reducing late blight tuber rot is discussed in detail in Section 2.3.9.

Storage management

Identifying the level of late blight tuber infection through careful sorting and inspection of tubers going into storage is necessary to adjust harvest planning and storage management. Remove as many blighted tubers as possible when filling the storage ensuring culls are disposed of properly (Platt, 1994b). Fields with lower levels of infection (2 to 5%) should only be stored in well-ventilated structures and monitored closely (Nolte et al., 1999). Potato lots with more than 5% infection are high-risk to store and should be processed directly from the field or, if stored, put near the front of a bin so that they can be moved quickly if tubers begin to break down (Nolte et al., 1999).

Storages with infected or potentially infected tubers should be ventilated continuously without added humidity until tubers are dry (Bohl et al., 2003). Typical preconditioning temperatures (15°C) are not advised as this favours the development of

secondary decay organisms (Stevenson, 1993). While lower storage temperature (< 8°C) and relative humidity will slow disease development in storage this may compromise processing quality.

Storages should be monitored closely, particularly in the first month, when infected tubers are most likely to show (Nolte et al., 1999; Johnson et al., 2003). Watch for the development of "hot spots", areas where tubers are breaking down, and supply additional ventilation to these areas.

2.3 Vine Desiccation

2.3.1 Introduction

Vine desiccation before harvest is a widely used practice in commercial production areas of North America, particularly for late maturing varieties (Pavlista, 2001a; Ivany, 2004). Vines are killed to achieve a number of objectives: 1) Reduce tuber skinning at harvest (Murphy, 1968) and minimize shrinkage in storage (Misener, 1982); 2) Avert storage losses from late blight tuber rot by preventing further transfer of spores from infected vines to tubers prior to or during harvest and allowing infected tubers to rot in the soil (Thurston and Schultz, 1981); 3) Reduce bruising and mechanical injury during harvest and handling (Thornton and Sieczka, 1980); 4) Increase harvest efficiency by reducing vine quantity and weakening stolon attachment (Plissey, 1993); and 5) Vine killing is also used in the production of seed potatoes to control tuber size and minimize the late-season spread of viruses by aphids (Sanderson et al., 1984).

Vines are desiccated 10 to 21 days before the intended harvest date (Plissey, 1993; Bohl, 2003). During this time interval, tuber skin-set increases, vines decrease in

mass, and tubers loosen from stolons (Halderlie et al., 1989a). Ideally, vines are dead and dry before harvesting begins.

The drawbacks to vine desiccation include reduced tuber yield and size, lower specific gravity, and the potential for stem-end discolouration (Halderson et al., 1985a). It also increases the cost of production (Johnson et al., 2003).

2.3.2 Methods of Vine Desiccation

Potato vines can be killed before harvest in one of three ways: 1) mechanical destruction; 2) chemical desiccation, and 3) a combination of the two. In some production areas, killing frosts may desiccate potato foliage before fall harvest.

2.3.2.1 Chemical Vine Killing

In North America, chemical desiccation is the preferred method of vine kill (Halderson and Haderlie, 1986). Chemicals are a quick and effective means of killing vines and weeds before harvest. Potato vines have been killed with chemicals since the 1930's (Murphy, 1968). A range of chemicals were used in the 1950's, 60's, and 70's including sodium arsenite, di-nitro compounds, and sulphuric acid (Murphy, 1968; Smith; 1977). Until its use was restricted in 1986, the dinitrophenol herbicide, dinoseb was applied to nearly 90% of the chemically desiccated acres in the United States (Halderson and Haderlie, 1986; Haderlie et al., 1989b). Since the ban on dinoseb, diquat has become the desiccant of choice across North America (Guenther et al., 1999; Arsenault and Ivany, 2001). Other chemicals including sulphuric acid, endothal, glufosinate ammonium, paraquat and urea sulfuric acid are used on a limited basis in the

United States (Haderlie et al., 1989a). Only diquat (Reglone), endothal (Des-I-Cate), and glufosinate ammonium (Ignite/Liberty) are currently registered for potato vine killing in Canada (PMRA ELSE, 2003). Glufosinate ammonium should not be applied to potatoes grown for seed due to its effect on the vigour of daughter tubers (Ivany and Sanderson, 2001).

Cultivar (Arsenault and Ivany, 2001), plant maturity at the time of vine kill (Haderlie et al., 1989b), product type and application rate (Haderlie et al., 1989b), and environmental conditions (Mutch et al., 1984) can influence the desiccation rate of chemicals.

Studies have shown differences in the vine desiccation rates of cultivars with a number of chemicals (Mutch et al., 1984; Zeneca, 1993; Arsenault and Ivany, 2001; Ivany, 2004). Late-maturing varieties are typically more difficult to kill (Cunningham et al., 1952; Zeneca, 1993).

Immature vines are slower to desiccate than mature vines that have begun to senesce (Sanderson et al., 1984; Haderlie et al., 1989b). Stem desiccation, in particular, improves on maturing vines (Sanderson et al., 1984). Management practices which delay maturity, such as excess fertility, have also been shown to slow leaf and stem desiccation (Ivany et al., 1986).

The literature is replete with studies comparing different desiccants, rates and timing of application, and additives. Reviews by Murphy (1968) and Smith (1977) summarize potato desiccation research completed before the mid-70's. More recent studies continue to improve the understanding (Mutch et al., 1984; Haderlie et al., 1989b; Renner, 1991; Ivany and Sanderson, 2001; Pavlista, 2001b; Ivany, 2004). A ranking of

the rate of desiccation for the common desiccants is: sulfuric acid > paraquat ≥ diquat > endothal > glufosinate ammonium (Haderlie et al., 1989a; Ivany and Sanderson, 2001). Split applications of some desiccants can improve vine kill (Thornton and Sieczka, 1980; Ivany et al., 1986), particularly when desiccating immature vines (Haderlie et al., 1989b). Adding surfactants, oils, or wetting agents to vine kill sprays to improve desiccant activity has been researched (Mutch et al., 1984; Haderlie et al., 1989b; Renner, 1991; Ivany, 2004).

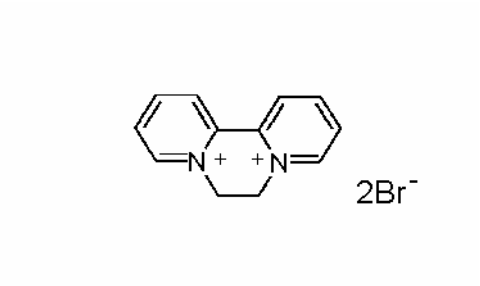
Environmental conditions at the time of application can also affect the degree of vine desiccation (Nelson et al., 1988; Haderlie et al., 1989a; Pavlista, 2001b). For some chemicals, desiccation is improved at high temperatures (Mutch et al., 1984; Haderlie et al., 1989a) and by spraying under appropriate light conditions (Pavlista, 2001b). Sulfuric acid is the only chemical desiccant which performs consistently regardless of environmental conditions (Halderlie et al., 1989a).

Compared to most mechanical methods of vine killing, chemical desiccants, excluding sulfuric acid, are less expensive (Haderlie et al., 1989a). Because of its toxicity and corrosiveness, sulfuric acid is applied by custom applicators only, using specialized equipment (Lutman, 1992).

2.3.2.1.1 Diquat

Diquat (Reglone, Syngenta) is the preferred vine desiccant in most potato-growing regions in North America (Arsenault and Ivany, 2001). In a recent survey of pesticide use in the fall potato crop production areas in the United States, diquat was the third most used pesticide, applied to 49% of the survey acres (Guenthner et al., 1998).

Diquat is a bipyridylium herbicide, available commercially as dibromide, a quaternary ammonium salt (Calderbank and Slade, 1976). Diquat dibromide is the common name for 6,7-dihydrodipyrido (1,2-α:2',1'-c) pyrazinediium dibromide (WSSA, 1994). Its chemical structure is shown below.



Diquat dibromide is used as a herbicide and desiccant in a range of crops and for the control of aquatic weeds (Calderbank and Slade, 1976). It is non-selective, quick acting and non-residual as it is strongly absorbed by soil. Its mode of action is to intercept electrons moving through photosystem I, forming diquat radicals. These in turn reduce molecular oxygen producing superoxide radicals and subsequently hydrogen peroxide. Superoxide radicals and hydrogen peroxide react together to produce hydroxyl radicals that destroy the integrity of cell membranes leading to rapid foliage wilting and desiccation (WSSA, 1994).

Diquat has been shown to be 25-30% more effective at desiccating potato vines when applied in the evening compared to spraying in the morning (Nelson et al., 1988; Morrow, 1990). Improved uptake and translocation through the vascular system result when application is made late in the day when diquat is less activated by light (Calderbank and Slade, 1976). Reduced performance has been shown at lower temperatures (Zeneca, 1993).

2.3.2.2 Mechanical Vine Killing

2.3.2.2.1 Rolling

Vine rolling before application of a chemical desiccant is a common and recommended practice in some production areas (Halderson and Haderlie, 1986, Haderlie et al., 1989a). Rollers flatten vines and stems opening the canopy so that complete and uniform spray coverage can be achieved (Haderlie et al., 1989a). Research has shown that rolling increases the rate of vine desiccation, especially when used before chemicals on immature vines (Halderson et al., 1985a, Renner, 1991). Vine rolling also seals soil cracks in the hill which reduces the risk of tuber greening following vine desiccation (Thornton and Sieczka, 1980). Vine rolling, without a follow-up application of a chemical spray, does not result in an effective vine kill (Halderson et al., 1985a). Rolling, on its own, is inexpensive (Haderlie et al., 1989a).

2.3.2.2.2 Pulling

Mechanical vine pulling is one of the few methods of top killing that provides an instant kill, regardless of the vine maturity. Consequently pulling is favoured by seed producers who must be able to, when necessary, rapidly remove the vines of immature plants to prevent the spread of aphid-transmitted viruses and to control tuber size (Misener and Everett, 1981). Vine pulling has its disadvantages however. Some stems are missed, tubers may be exposed during pulling, and vines may re-root after pulling (Misener and Everett, 1981; Halderson et al., 1988). Vine pullers are rarely used by commercial growers because of their high cost of operating relative to other methods of vine kill (Halderson and Haderlie, 1986).

2.3.2.2.3 Flailing

Flailing, also referred to as rotobeating, shredding, and chopping, like pulling, provides a near instant vine kill. Unlike pulling, the lower portions of the stems and roots are left after flailing which can result in undesirable regrowth, especially if the rotobeater is not set to chop the vines low enough (Misener and Everett, 1981; Haderlie et al., 1989a). In contrast, flail blades which are set too low or that don't match the contour of the hills can damage tubers near the soil surface (Whitney and McRae, 1992). When vines are still vigourous at the preferred time of killing, rotobeating is often used in combination with a chemical desiccant to achieve effective desiccation (Beukema and van der Zaag, 1990). Unfortunately, the operating cost of flailing is high relative to other methods of vine killing and so it is a relatively uncommon practice (Halderson and Haderlie, 1986).

2.3.2.3 Frost

Frost is an effective but unpredictable means of killing vines before harvest. Fall frosts routinely desiccate the crop in many production areas, including Manitoba. However, along with freezing temperatures comes the risk of field frost damage to tubers, and invariably tuber chilling and its subsequent detrimental effects on processing quality (Ewing, 1981). Moreover, the risk of tuber damage at harvest increases with lower soil temperatures (Plissey, 1993). Consequently, producers are not advised to wait for freezing temperatures to desiccate their vines before starting their harvest.

2.3.3 Effect of Desiccation on Yield

Vine killing prior to harvest usually reduces tuber yield and size (Nelson and Nylund, 1969; Haderlie et al., 1989a; Sanderson and Ivany, 1990). The extent to which yield is reduced by desiccation depends on a number of factors including the plant maturity at the time of vine kill, method of desiccation, and the length of time and weather conditions between vine kill and harvest (Haderlie et al., 1989a).

Killing vines in the tuber bulking stage results in lower yields and smaller tubers because the production and translocation of assimilates is restricted as the plants die (Renner, 1991). Sanderson and Ivany (1990) reported that desiccating Russet Burbank vines with diquat on Prince Edward Island before 137 days after planting (DAP) (early October) reduced tuber yield and size, whereas later applications had no effect. Other investigators have documented tuber yield and size reductions when immature plants were killed (Akeley et al., 1955, Sanderson et al., 1984; Arsenault and Ivany, 2001). Others have reported that vine killing had little or no effect on tuber yield (Ivany et al., 1986; Renner, 1991; Pavlista, 2001a). Other studies produced variable results (Halderson et al., 1985a; Haderlie et al., 1989b; Ivany and Sanderson, 2001), reflecting the declining nature of the response of yield with increasing plant maturity.

Terman et al. (1952) and Schaupmeyer (1987) reported that tuber yield is higher from plants killed with slow-acting chemicals as compared to rapid death by cutting or rotobeating, when treatments were done on the same day. These results suggest that some tuber bulking occurs in the interval between the application of a chemical desiccant and harvest. James (1989) found that tubers under desiccated vines continued to bulk up to seven days after desiccation but at a lower rate than tubers under untreated vines.

Sanderson et al. (1984) attributed yield increases following vine kill to the translocation of carbohydrates from dying vines to tubers and to water movement to tubers from active roots. Recent studies comparing chemical desiccants for their effect on tuber yield have generally shown no differences between products (Haderlie et al., 1989b; Pavlista, 2001b; Ivany and Sanderson, 2001; Ivany, 2004).

In studies in which diquat was applied before tuber bulking was completed, total yield was reduced by up to 17%, and percentage No. 1 grade by up to 10%, although typically, reductions in yield are smaller (James, 1989; Halderson et al., 1985a; Arsenault and Ivany, 2001).

Studies have shown that the effect of diquat on yield and tuber size can be even more significant under Manitoba conditions. Menzies and Adam (1979) reported that Russet Burbank desiccated with a split application of diquat in mid-September, reduced total yield by 13%, marketable yield by 21%, and yield of tubers over 283 g by 32%. Giesel (1986) found Russet Burbank vines killed in early September produced 21% less total yield, 25% less marketable yield, and 10% less yield of tubers over 283 g compared to the check treatment. Desiccating Shepody vines resulted in smaller but significant reductions in total yield and yield of tubers over 283 g (Giesel, 1995).

Growing conditions in the days between desiccation and harvest are a key factor influencing the bulking rate of green vines and, consequently, the yield deficit that results from vine killing. Warm days, cool nights, and adequate soil moisture in September can result in substantial gains in tuber size with later maturing varieties if vines are left green, especially in short-season production areas. On the other hand, if soil moisture is limiting to late season tuber growth or a killing frost occurs soon after desiccation, the effect of

vine killing on yield will be less apparent (Nelson and Nylund, 1969). Rainfall or irrigation following desiccation can also increase tuber size under desiccated vines as roots move water into tubers (Lutman, 1992).

Although the tuber yield is lower when vines are desiccated, there are generally fewer losses during harvesting as compared to green digging. When tubers are harvested from immature vines, they often remain attached to the stolon and are lost when vines are carried over the deviner chain to the ground (Zeneca, 1993). Following vine kill, tubers release better from stolons (Beukema and van der Zaag, 1990). With green digging, the volume of vines at harvest also results in carry-over losses when tubers ride on the vines. Vine killing reduces the amount of vine carried up the harvester improving the separation of vines away from tubers (Plissey, 1993).

Schoenemann (1958) suggested that by improving skin-set, reducing harvest damage, and improving storability, vine killing increased the yield of marketable potatoes. The effect of vine desiccation on these quality factors is addressed in other sections.

2.3.4 Effect of Desiccation on Specific Gravity

Typically, the specific gravity of tubers is lower when vines are chemically or mechanically killed two or more weeks before harvest (Rowberry and Johnston, 1966; Nelson and Nylund, 1969; Halderson et al., 1985a). The degree to which tuber solids are affected depends on the crop's stage of development at the time of killing, method of desiccation, and the time interval and weather conditions between vine kill and harvest (Smith, 1987; Storey and Davies, 1992).

Specific gravity increases as the growing season progresses reaching a maximum when the tubers reach physiological maturity before declining towards the end of the season (Stark and Love, 2003). Killing vines before the tubers reach physiological maturity results in lower specific gravity because there is minimal translocation of carbohydrate from leaves and stems to the tubers from dying vines (Rowberry and Johnston, 1966). Moreover, water taken up by the plant's root system following desiccation moves into the tuber reducing the percentage dry matter (Storey and Davies, 1992). In research conducted on medium- (Kennebec) and late-season (Russet Burbank) varieties, Wright and Hughes (1964) established that tubers harvested from vines defoliated in the early and mid-bulking stages are consistently lower in solids than those from vines which grow to maturity. Other investigators have documented reductions in specific gravity when bulking plants are desiccated (Terman et al., 1952; Akeley et al., 1955; Pavlista, 2001a). Conversely, in vine killing studies on mature Russet Burbank in Idaho, Halderson et al. (1988) reported no significant differences in specific gravity from tubers harvested from desiccated and untreated vines.

Chemical desiccation usually results in tubers with a slightly higher dry matter content compared with mechanical methods of vine killing because of continued translocation of assimilates from the maturing vines to the tubers (Wilcockson et al., 1985). Comparisons between chemical desiccants for their effect on specific gravity have generally shown no differences (Nelson and Nylund, 1969; Halderson et al., 1985a).

In studies where vines were desiccated with diquat before maturation, a two to seven point (0.002 to 0.007) decrease in specific gravity has been reported relative to the untreated vines (Nelson and Nylund, 1969; Halderson et al., 1985a; Johnson et al., 2003).

Studies conducted in Manitoba have measured larger reductions in tuber dry matter following vine desiccation with diquat. In a two year study with Russet Burbank, Giesel (1985, 1986) reported that desiccating vines with diquat in early September, two to three weeks before harvest, lowered specific gravity by 4 to 11 points (0.004 to 0.011) compared to the check. Killing Shepody vines in mid-August with diquat, 10 days before harvest, reduced specific gravity by 5 points (0.005) (Giesel, 1995).

The length of the time interval between vine killing and harvest and the weather conditions during this period also influence tuber dry matter. Wet conditions around the time of vine killing can lead to considerable reductions in tuber solids which may affect the suitability of the crop for processing uses (Lutman, 1992; Stark and Love, 2003). Wilcockson (1986) reported that water uptake by roots following early desiccation with diquat reduced tuber specific gravity by 1.3 points/week (0.0013/week).

2.3.5 Effect of Desiccation on Sugars

There are few reports on the effect of chemical desiccation on sugar levels at harvest and subsequently in storage (Duncun and Boyd, 1986). Sowokinos and Preston (1988) suggested that vine killing could be used to help tubers achieve chemical maturity by stopping the flow of sucrose to tubers from active vines. Halderson (1989) measured lower sucrose levels in tubers from desiccated vines than from untreated vines shortly after treatment, but there was no difference when the tubers were harvested three weeks later. Knowles et al. (2001) observed a reduction in sucrose in tubers from desiccated vines at the time of harvest in one year of research but no difference in sucrose levels in a

follow-up study in which vines were more mature. Desiccation did not affect the level of reducing sugars at harvest in studies by Halderson (1989) and Knowles et al. (2001).

Although vine killing has been shown to reduce sucrose levels at harvest, there is little evidence to suggest that this results in lower levels of reducing sugars and improved processing quality from storage. Smith (1987) reasoned that the chemical composition of tubers from desiccated and non-desiccated vines likely differed but reported that the effect of these differences on chip color was inconsistent. He suggested that weather conditions during the interval between vine killing and harvest might account for the inconsistent response. Giesel (1985) concluded that desiccation did not improve Russet Burbank fry colour out of storage. Vine desiccation resulted in significantly higher levels of reducing sugars in stored Ranger Russet tubers which accumulated earlier in the storage period (Knowles et al., 2001). Preconditioning for two weeks at 60°F was required to lower the level of reducing sugars in tubers from desiccated vines to the level observed in tubers harvested from untreated vines. Walsh (1995b) observed an immediate or delayed loss of fry colour in storage when vines were desiccated, compared to an earlier study in which vines were not killed. He concluded that since invertase activity was no longer blocked once vines were desiccated, tubers became more susceptible to low temperature sweetening and reducing sugar accumulation after harvest.

2.3.6 Effect of Desiccation on Stem-end Discolouration

Tuber stem-end discolouration (SED) is a physiological disorder typified by a shallow, brown discolouration of the tissue at the stem end of the tuber in the area of the vascular ring (Thornton, 2001). SED reduces the quality of table stock and processing

potatoes (Thornton and Sieczka, 1980). Early researchers reported increased vascular discolouration in tubers following chemical vine desiccation (Callbeck, 1948; Rich, 1950). Hoyman (1947) observed that chemicals which killed the foliage rapidly caused the most discolouration, especially when applied early in the season. Callbeck (1949) determined that plants killed while under moisture stress developed more severe vascular discolouration. While more recent research by Halderson et al. (1985b) and Haderlie et al. (1989b) has shown that rapid vine killing alone does not increase SED, both investigators found more SED when immature vines were desiccated. Several recent studies demonstrated that vine desiccation with diquat does not increase SED (Renner, 1991; Ivany and Sanderson, 2001; Ivany, 2004) while Arsenault and Ivany (2001) found that the application of diquat caused a small, but significant, increase in SED. Mechanical methods of vine killing are less likely to cause SED (Cunningham et al., 1952; Murphy, 1968).

Current recommendations to minimize SED development include avoiding vine killing water- or heat-stressed plants and vines that have not begun to senesce (Olsen et al., 2003). Irrigating before vine desiccation or waiting until rain has increased the soil moisture have been recommended to reduce the risk of SED (Murphy, 1968). Split applications of vine desiccants have also been promoted to minimize SED under sub-optimal conditions.

2.3.7 Effect of Desiccation on Skin-set

One of the strongest arguments for desiccating vines is that the practice promotes tuber skin-set (Murphy, 1968; Plissey, 1993). Typically, vines are killed 2 to 3 weeks

before harvest to allow sufficient time for periderm maturation (Haderlie et al., 1989a; Bohl, 2003). The benefits of improved skin-set in minimizing damage at harvest, and shrink and disease in stored potatoes are discussed in other sections.

A number of factors influence the development of skin-set after desiccation including cultivar, vine maturity at the time of vine kill, method of kill, and length of time and weather conditions between killing and harvest. Lulai and Orr (1993) and James (1993a) reported differences between cultivars in skin-set development following vine killing. Russet-skinned cultivars tended to develop skin-set more rapidly following vine kill (Lulai, 1997). Vine condition at the time of desiccation influences tuber maturity. Immature vines require a longer time interval between killing and harvest to reduce skinning to an acceptable level (Beukema and van der Zaag, 1990; Stark and Love, 2003). The method of vine killing also affects skin-set development. Misener (1983) reported that tubers from vines treated two weeks earlier with diquat were 25% more resistant to skinning than tubers from vines that matured naturally. Several researchers have demonstrated that chemical desiccation is more effective than vine flailing in increasing tuber skin-set (Misener, 1983; Pavlista; 2002). Following vine kill, the resistance of tubers to skinning increases approximately linearly with time (Misener, 1983; Lulai, 1993). James (1993b) measured a reduction in tuber skinning, relative to the untreated control, seven days after diquat was applied, although the level of skinning was not considered acceptable until 18-21 days after vine killing. Similar results have been reported by Pavlista (2001a, 2002). Producers, on average, allow a little less than two weeks between vine kill and harvest for tuber skins to set (Halderson and Haderlie,

1986). Wet and cool weather conditions following vine kill slow skin-set development (Stark and Love, 2003).

2.3.8 Effect of Desiccation on Weight Loss in Storage

During a 6 to 8 month storage period, tubers lose 7-10% of their weight. About 90% of this weight loss is evaporative water loss; only about 0.5% is due to respiration (Rastovski, 1987).

Skinning and bruising during harvesting significantly increase moisture loss in storage (van Es and Hartmans, 1987c). During the first few days of storage, the rate of water loss from scuffed immature tubers is 15-100 times greater than that of mature tubers with intact skin (Burton, 1978). Lulai and Orr (1995) measured the initial rate of water loss from skinned tubers to be 250-1,000 times greater than from undamaged, mature tubers. Although wound periderm formation reduces the rate of water loss, weight loss during the healing period can be substantial. James (1993a) reported a strong relationship between tuber skinning and tuber shrinkage. Tubers which had a higher percentage of skinning lost more weight in storage than tubers which had less skinning.

Since vine desiccation before harvest reduces tuber skinning and susceptibility to harvest injury, the practice has been promoted as a means to reduce weight loss in storage (Murphy, 1968; Haderlie et al., 1989a).

Misener (1982) reported that weight loss in stored Russet Burbank was reduced by an average of 20% when potatoes were desiccated 2 to 2 ½ weeks prior to harvest. Other research has shown that vine killing can reduce weight loss by up to 50% during long-term storage (Halderson and Haderlie, 1986).

Vine condition at the time of desiccation influences weight loss in storage (Iritani et al., 1977) as tubers from mature vines release less water vapor than tubers from immature vines, even in the absence of skinning (Lulai and Orr, 1994). Extending the interval between vine kill and harvest significantly reduces the weight loss from tubers in storage (Iritani et al., 1977; Misener, 1982; James, 1993a).

2.3.9 Effect of Desiccation on Late Blight Tuber Rot

There are numerous references in the literature to the merit of vine desiccation in reducing late blight tuber rot (Murphy, 1968; Thornton and Sieczka, 1980; Schwinn and Margot, 1991; Stevenson, 1993; Johnson et al., 1997). In fields where late blight is observed, the recommendation is to schedule desiccation so that vines are completely dead for 2 to 3 weeks before the crop is harvested (Stevenson, 1993; Bohl et al., 2003).

Vine killing well in advance of harvest is thought to mitigate losses from tuber blight by: 1) preventing further preharvest transmission of spores from diseased vines to tubers (Rich, 1983); 2) reducing the exposure of tubers to spores from blighted vines and infective soil at harvest (Hide and Lapwood, 1992); 3) promoting skin set (Nolte et al., 2003); and 4) allowing previously infected tubers to rot in the soil before harvest (Platt, 1994c).

Since the fungus only sporulates on living plant tissue, vine desiccation shortens the time that tubers are exposed to spores washed down from blighted foliage (Thurston and Schultz, 1981). There is no evidence that method of vine kill influences the level of late blight tuber rot, however, treatments which result in delayed or incomplete

desiccation allow continued late blight spread and increase the potential for tuber blight (Misener et al., 1990).

Increased levels of late blight tuber rot in storage occurred when tubers were harvested from vines that were infected with late blight but still green at the time of harvest (Bonde and Schultz, 1945; Walker, 1957; Thornton and Sieczka, 1980). Spores present on vines and on the soil surface cause tuber infections at harvest that develop in storage (Schwinn and Margot, 1991; Franc, 1997). The potential for contaminating tubers with spores from diseased foliage at harvest is reduced when vines are killed 2 to 3 weeks prior to harvest (Nolte et al., 2000). It is unclear to what extent delaying harvest reduces the ability of blight spores on the soil surface to infect tubers at lifting (Lacey, 1965; Deahl, 1997).

Thornton and Sieczka (1980) implicated skinning and bruising of tubers at harvest in storage breakdowns from late blight tuber rot. Others have reported a reduction in storage tuber rot when skin is well set at harvest (Scott and Wilcockson, 1978; Platt, 1994c).

Thurston and Schultz (1981) advocated killing vines two weeks before harvest so that blighted tubers could be sorted out more readily as the crop was put in storage. Others have recognized that infected tubers decay more readily following vine kill (Franc, 1997; Nolte et al., 2000; Bohl et al., 2003).

Although there is a considerable case for the use of desiccants to reduce late blight storage rot, only a few studies actually quantify the degree to which infection is reduced by this practice. In a two year study, Bonde and Schultz (1945) observed an average of 47% late blight tuber rot when tubers were dug from vines that were green but

only 3% tuber rot when vines were desiccated 10 days prior to harvest. Killing vines two days prior to harvest resulted in 12% tuber rot. Hirst et al. (1965) reported that the yield of uninfected tubers was maximized when vines were killed when approximately 5% of the foliage was blighted. Delaying desiccation increased total yield but also resulted in a higher percentage of blighted tubers at harvest (16%) compared to the vine killed plots (2%).

Cox and Large (1960) presented the case against the practice of vine desiccation to reduce late blight tuber rot concluding "it is generally uneconomic to employ haulm destruction for the purpose of preventing tuber infection before lifting". Their reasoning was that the reduction in tuber yield from early desiccation outweighed the gain in reduced tuber blight. Recent research by Johnson et al. (2003) reached similar conclusions. In five field trials, the incidence of late blight tuber rot was not significantly reduced when vines were desiccated 2 to 3 weeks before harvest. Incidence of tuber rot significantly increased when irrigation water was overapplied under center-pivot irrigation. The authors concluded that when the crop is watered properly, timely fungicide applications are made until harvest, and harvesting is done in dry weather so that desiccation is not necessary.

2.3.10 Effect of Desiccation on Other Tuber Rots

Mechanical damage and bruising of immature tubers at harvest result in costly quality losses during storage (Ewing, 1981; Plissey; 1993). Tuber skinning, cuts and bruises are entry points for storage disease organisms like *Fusarium* spp. (Fusarium dry rot) and *Pythium ultimum* (Pythium leak) that would not be able to infect tubers otherwise

(Nolte et al., 2003). Reductions in storage disease have been reported when vines were killed prior to harvest (Boyd, 1967; Hide and Lapwood, 1992).

2.3.11 Effect of Late-Season Fungicide Applications on Late Blight Tuber Rot

Tubers can become infected with late blight before harvest when spores from infected vines are washed down into the hill. Consequently, when late blight is present, fungicide applications should be continued until vines are completely dead (Stevenson, 1993).

Copper-based fungicide sprays have been reported to be effective in preventing tuber infection when applied after vine desiccation (Platt, 1994b; Manitoba Agriculture, 1997a). Copper compounds are toxic against the spore stages of late blight and, unlike most other fungicides, are not inactivated by contact with soil (Platt, 1994c).

3.0 MATERIALS AND METHODS

3.1 Crop Production Practices

Field plots of potatoes were established in 1997 at the Manitoba Crop Diversification Centre (MCDC) at Carberry, MB on a Wellwood clay loam soil. The experiment was repeated at the MCDC satellite site in Winkler, MB in 1998 on a Hochfeld fine sandy loam soil. The decision was made to relocate the trial from MCDC Carberry to MCDC Winkler for 1998 because, at the time of the study, late blight was being found earlier and more consistently in the southern production areas of the province (Platford and Kurtz, 1998). In 1997, at MCDC Carberry, the untreated check plots in an adjacent fungicide trial did not become infected with late blight until early September when environmental conditions were no longer suitable for disease spread. In comparison, late blight was detected in a field south of Winkler on July 28, 1997 (Manitoba Agriculture, 1997a).

In both years of the study, plots consisted of four 8 meter long rows. Assessments were made and the harvest was taken from the center two rows. The outside rows were treated but functioned only as border/guard rows. Additional guard rows were incorporated into the design as required to allow for travel paths for the overhead irrigation and for the application of pesticides from a tractor mounted boom. As a result, damage to the harvest rows was always minimized.

Cultural practices that favour the production of high yielding, high-quality potatoes for the Manitoba french fry processing market were followed (Tables 3.1 and 3.2) (Giesel, 1994). Fertilizer was applied at each site following recommendations based on soil test results (Table 3.1). On May 23, 1997, a 4-row planter was used to plant

Table 3.1 Summary of crop production practices on Russet Burbank potatoes grown at Carberry, MB in 1997 and Winker, MB in 1998.

	Location	
	1997 - Carberry	1998 - Winkler
Previous Crop	Alfalfa / Barley	Sorghum sudan grass
Spring Tillage	heavy harrows, roterra	field cultivator
Planting Date	May 23	May 12
Row spacing / Seed spacing	95 cm / 38 cm	100 cm / 38 cm
Fertilizer		
Broadcast (before planting)	-	May 1 179 kg N/ha 45 kg P/ha 45 kg K/ha
At Planting (banded)	May 23 13 kg N/ha 57 kg P/ha	-
Mid-Season (top-dressed)	June 25 28 kg N/ha	-
Cultivation/Hilling	June 20 July 9	June 16 June 29
Moisture*		
Rainfall	202 mm	240 mm
Irrigation	215 mm	55 mm
Harvest Date (days after planting)		
Early-September harvest	September 10 (110 DAP)	September 3 (114 DAP)
Mid-September harvest	September 17 (117 DAP)	September 10 (121 DAP)
Late-September harvest	September 24 (124 DAP)	September 17 (128 DAP)

* Cumulative rainfall and irrigation from planting to harvest

Russet Burbank seed pieces 38 cm apart. Rows were spaced 95 cm apart. On May 12, 1998, Russet Burbank seed pieces were planted 38 cm apart with a 2-row planter. Rows were spaced 100 cm apart. Russet Burbank is the main cultivar grown for the french fry potato industry in Manitoba. Cultivation and hilling were carried out as necessary (Table 3.1). Supplemental irrigation was applied, as required, during the growing season through a lateral-move overhead sprinkler irrigation system (Table 3.1). Pesticides were applied, based on local recommendations, to limit losses caused by weeds and insects (Manitoba Agriculture, 1997b, 1998b) (Table 3.2). Primary targets included green foxtail, wild oats, wild buckwheat, redroot pigweed, Colorado potato beetle, potato leafhopper, and wireworm. Plots received a standard fungicide spray program of contact and systemic products until mid-August (in 1997) or late-July (in 1998) (Table 3.2).

3.2 Experimental Design

The trials were conducted as 3 X 2 X 2 factorial experiments in a randomized complete block design, with four replications. Three late-season management factors were evaluated for their effect on potato yield and quality: time of harvest at three levels (early, mid-, and late September), vine management at two levels (control and diquat), and preharvest fungicide at two levels (unsprayed and sprayed). The twelve treatment combinations were initiated in late August in both years (Figures 3.1 and 3.2).

Harvest dates were selected so that the crop response to desiccation was observed over a range of crop maturities during the study. The three harvest dates chosen for the month of September in each year were as follows: September 10, September 17, and September 24 in 1997; and, September 3, September 10, and September 17 in 1998.

Table 3.2 Summary of pesticide applications to Russet Burbank potatoes grown at Carberry, MB in 1997 and Winker, MB in 1998.

	Location					
	1997 - Carberry			1998 - Winkler		
	Application date	Product	Application rate	Application date	Product	Application rate
Herbicide	May 9	EPTC	7.4 L/ha	May 25	sethoxydim	2.5 L/ha
	June 10	glyphosate	2.25 L/ha		metribuzin	0.373 kg/ha
		rimsulfuron	0.059 kg/ha			
	June 18	rimsulfuron	0.059 kg/ha			
	July 11	rimsulfuron	0.059 kg/ha			
Insecticide	May 23	phorate	1.9 g/m of row	July 3	endosulfan	2.0 L/ha
	July 8	carbaryl	1.2 L/ha	July 16	endosulfan	2.0 L/ha
	July 15	permethrin	0.2 L/ha			
	July 21	endosulfan	2.0 L/ha			
	August 5	carbaryl	1.2 L/ha			
Fungicide	May 23	thiophanate-methyl	0.5 kg/100 kg cut seed	May 12	thiophanate-methyl	0.5 kg/100 kg cut seed
	July 8	mancozeb	2.2 kg/ha	June 22	chlorothalonil	2.5 L/ha
	July 15	mancozeb/metalaxyl	2.5 kg/ha	June 26	chlorothalonil	2.5 L/ha
	July 21	chlorothalonil	2.5 L/ha	July 3	mancozeb/metalaxyl	2.5 kg/ha
	July 28	mancozeb	2.2 kg/ha	July 8	chlorothalonil	2.5 L/ha
	August 5	mancozeb	2.2 kg/ha	July 16	mancozeb/metalaxyl	2.5 kg/ha
	August 18	chlorothalonil	2.5 L/ha	July 24	chlorothalonil	2.5 L/ha

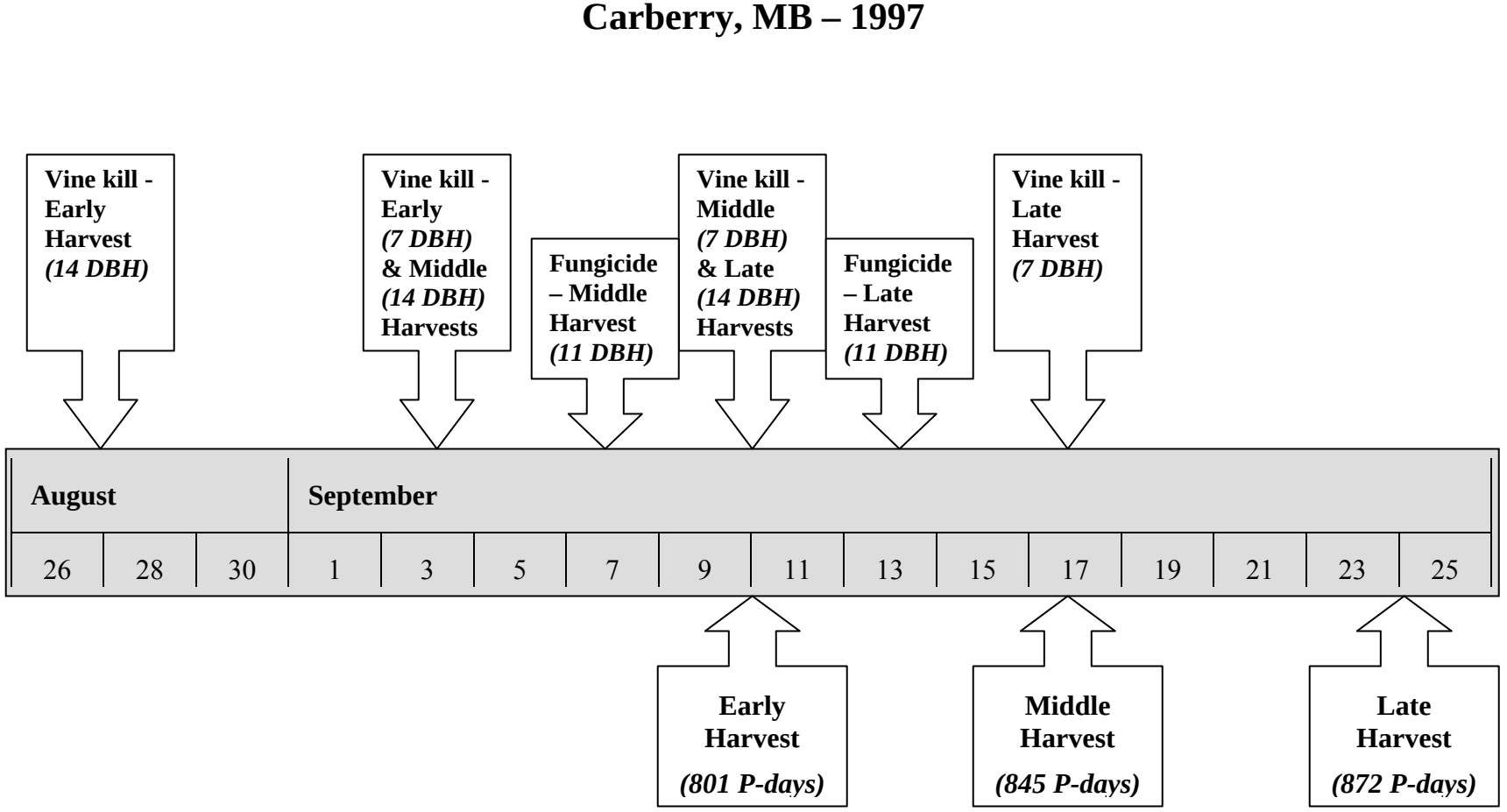


Figure 3.1. Experimental timeline – Carberry, MB – 1997. Arrows indicate the timing of preharvest management treatments and harvest. (DBH = days before harvest)

Winkler, MB – 1998

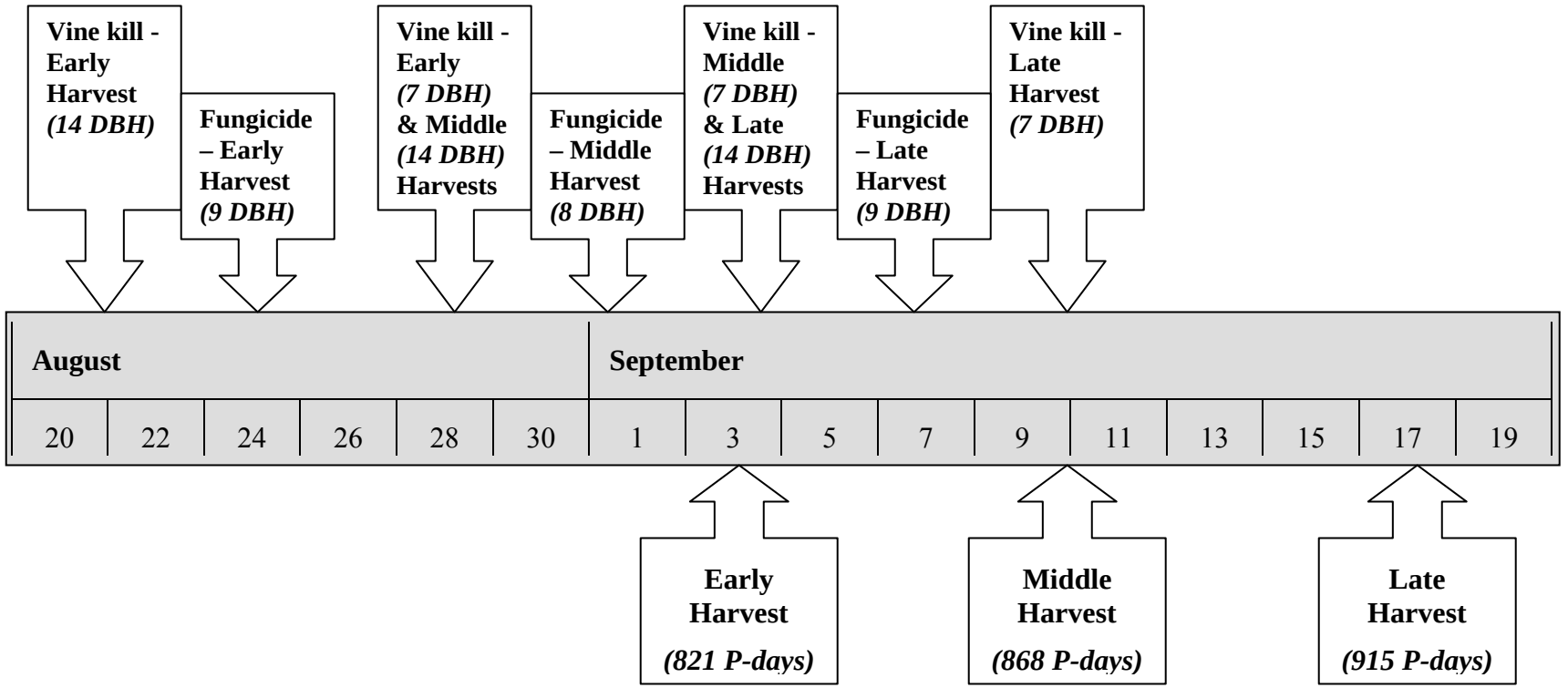


Figure 3.2. Experimental timeline – Winkler, MB – 1998. Arrows indicate the timing of preharvest management treatments and harvest. (DBH = days before harvest)

Harvest timing is also referred to as “early”, “middle” or “late” September within this document, recognizing the relative maturity of the crop at the time of harvest in each year (Figures 3.1 and 3.2).

To determine the effect of chemical desiccation, vines were either killed with diquat or allowed to senesce naturally. Vines were desiccated with a split application of diquat (Reglone Pro – 200 g L^{-1}) which was applied at 0.54 kg ai ha^{-1} fourteen days before harvest and again at 0.30 kg ai ha^{-1} seven days before harvest (label rates for a split application to dense or immature vines) (Table 3.3).

Approximately ten days before each harvest date, half of the treatments were sprayed with the fungicide combination chlorothalonil (Bravo 500 – 500 g L^{-1}) at 1.23 kg ai ha^{-1} and copper hydroxide (Kocide DF – 50% copper hydroxide) at 1.68 kg ai ha^{-1}, the other treatments were left unsprayed (Table 3.3). Plots scheduled for a later harvest date were also not sprayed with a fungicide.

Desiccant and fungicide treatments were applied with a tractor-mounted small plot sprayer which delivered a spray volume of 450 L ha^{-1} at a pressure of 275 kPa in 1997. A different small plot sprayer, used to apply the treatments in 1998, delivered a spray volume of 550 L ha^{-1} at a pressure of 550 kPa.

The experimental design was unbalanced in both years of this study due to missing treatments. In 1997, the preharvest fungicide treatment was not applied to plots in the early harvest and a misapplication of diquat resulted in a plot being discarded from the late harvest. In 1998, five of the twelve plots in the first replicate were lost due to flooding caused by a heavy rain in June.

Table 3.3 Summary of preharvest management treatments on Russet Burbank potatoes grown at Carberry, MB in 1997 and Winker, MB in 1998.

	Location			
	1997 - Carberry			
	Application date	Product	Application rate	Plots treated
Desiccant	August 27	diquat	2.72 L/ha	Early harvest - Diquat
	September 3	diquat	1.48 L/ha	Early harvest - Diquat
		diquat	2.72 L/ha	Middle harvest - Diquat
	September 10	diquat	1.48 L/ha	Middle harvest - Diquat
		diquat	2.72 L/ha	Late harvest - Diquat
	September 17	diquat	1.48 L/ha	Late harvest - Diquat
Fungicide	September 6	chlorothalonil	2.5 L/ha	Middle harvest - Fungicide
		copper hydroxide	3.36 kg/ha	
	September 13	chlorothalonil	2.5 L/ha	Late harvest - Fungicide
		copper hydroxide	3.36 kg/ha	
	1998 - Winkler			
	Application date	Product	Application rate	Plots treated
Desiccant	August 21	diquat	2.72 L/ha	Early harvest - Diquat
	August 28	diquat	1.48 L/ha	Early harvest - Diquat
		diquat	2.72 L/ha	Middle harvest - Diquat
	September 3	diquat	1.48 L/ha	Middle harvest - Diquat
		diquat	2.72 L/ha	Late harvest - Diquat
	September 10	diquat	1.48 L/ha	Late harvest - Diquat
Fungicide	August 24	chlorothalonil	2.5 L/ha	Early harvest - Fungicide
		copper hydroxide	3.36 kg/ha	
	September 2	chlorothalonil	2.5 L/ha	Late harvest - Fungicide
		copper hydroxide	3.36 kg/ha	
	September 8	chlorothalonil	2.5 L/ha	Late harvest - Fungicide
		copper hydroxide	3.36 kg/ha	

3.3 Additional Experiments – Winnipeg, 1998 and Winkler, 1999

This project included two other experiments, the results from which are not discussed within this thesis. In 1998, a field trial was set up at the Point at the University of Manitoba to act as an insurance site if late blight was not found in the research plots at MCDC Winkler. The intent was that a late blight epidemic could be initiated in the plots at the Point at any time during the growing season without endangering commercial production, due to the relative isolation of the location. However, the Point proved to be a difficult site to grow potatoes. Crop vigour was poor and Colorado potato beetles were problematic. Inoculation of border rows with a sporangia suspension of *Phytophthora infestans* in late August was not effective in initiating an epidemic even though a misting system was used to create environmental conditions suitable for disease development. In the absence of disease, preharvest management treatments were not applied and no data from this trial were collected.

In 1999, field plots were established at MCDC Winkler with the intention of gathering one last year of data on the effects of preharvest management on late blight tuber rot. Stresses on the crop during August resulted in premature decline of the crop canopy. Late blight was first sighted in the trial on September 3rd but the absence of a favourable microclimate resulted in reduced foliar disease development. No symptoms of tuber rot were observed in storage and the effects of preharvest management on tuber yield and quality were inconsistent. Consequently, results are not reported here.

3.4 Foliar Blight Assessment

Plots were oberserved regularly to monitor the onset and development of late blight. Manitoba Agriculture's late blight forecasts were used to track the favourability of weather conditions for the development of the disease (Manitoba Agriculture, 1997a, 1998c). As disease severity value (DSV) accumulations approached 15, the frequency of scouting was increased.

In 1998, as blight spread and developed in the plots during August and September, the foliar disease severity in each plot was assessed on a 3 to 6 day interval by visually rating the percentage of leaf and stem area affected by late blight. Ratings were made on the center two rows of the four row plots.

The use of established illustrated late blight assessment keys (James, 1971 - Key No. 3.1.1; Cruickshank et al., 1982) was considered but such aids, based on observations of foliar disease symptoms caused by the old A1 mating type strains, were found unsuitable. Furthermore, descriptive field keys such as those devised by the British Mycological Society (Anonymous, 1947) and James (1971 - Key No. 3.1.2), were evaluated but found to be inadequate in describing foliar disease development of the US-8 strain of late blight.

3.5 Tuber Yield and Size

Plots were machine harvested using a single-row potato harvester. The two center rows of each four-row plot were lifted. Within two days of harvesting, tubers were graded into the following categories: undersized (<50 mm diameter), marketable (>50 mm), and bonus (>283 g). Yields are reported in tonnes ha^{-1} (tonnes per hectare). Undersized and

bonus yields are expressed as a percentage of the total yield. Since the frequency of knobs, greening, and other tuber deformities was low, they were not culled out.

For both years of the study, tuber bulking rates during September were determined by computing average yield increases between treatments and across harvest dates.

3.6 Specific Gravity

The specific gravity of tubers was determined soon after harvest using the weight in air – weight in water method. A twelve tuber (1.5 to 2.5 kg) sample was selected at random from the marketable grade of each treatment, washed, and left overnight at room temperature (20ºC) to dry. The following day, tuber samples were weighed, first in air and then reweighed in water that was also at room temperature. The specific gravity of each sample was calculated using the following formula;

$$\text{Specific Gravity} = \frac{\text{weight in air (g)}}{\text{weight in air (g)} - \text{weight in water (g)}}$$

Before statistical analysis, specific gravity readings were converted by subtracting by 1 and multiplying by 1000.

3.7 Process Quality

3.7.1 Sugars

3.7.1.1 Sampling

Beginning in mid-August, representative tubers were hand-dug from random plants in each replicate and tuber sugars determined as a measure of chemical maturity.

Samples were taken weekly until harvest to establish a sucrose profile for each year. This information was used in determining the timing of the initial desiccation treatment.

Sugar levels were determined for all treatments following harvest and three times from storage (fall – 6-8 weeks after harvest; winter – 17-19 weeks after harvest; and spring – 28-31 weeks after harvest) for a total of four sampling dates.

3.7.1.2 Sugar Extraction

Five average-sized tubers were washed and peeled. For pre-harvest sugar determinations, tubers were sliced longitudinally into quarters and a 200 g sample consisting of approximately ¼ of each tuber was weighed. For harvest and storage sugar extractions, a 200 g sample of raw french fry strips (approximately 25 fries) was used.

An Olympic fruit and vegetable juicer (Model 1000; Omega Products Inc., Harrisburg, PA, USA) was used to extract the juice from the sample. The juicer was rinsed three times with 80 mL aliquots of cold distilled water to wash the sugars from the pulp; water was then added until the extract volume totaled 400 mL. After stirring, the extract was allowed to settle for 1 hour at 4°C. A 25 mL sample was removed and analyzed immediately or frozen at -20°C for analysis at a later date. Between extractions, pulp was removed and the juicer washed out 2-3 times with distilled water.

3.7.1.3 Sugar Analysis

Tuber glucose and sucrose content were measured using a YSI glucose analyzer (Model 2000; Yellow Springs Instrument Co., Inc., Yellow Springs, OH, USA). This instrument measures the β-D-glucose concentration using an immobilized glucose

oxidase membrane system (Mazza, 1983a). Sucrose content was calculated by measuring the difference in the β-D-glucose concentration in samples following the addition of the enzyme invertase (Sowokinos et al., 1985).

For each sample, 5-7 mL of juice extract were poured into a test tube (designated GLU). To determine the sucrose concentration for each sample, 1 mL of the extract was drawn out and added to a separate test tube (designated GLUINV). An invertase solution was prepared by dissolving 0.7 g of invertase from baker's yeast (I-4504 (500 units/mg); Sigma-Aldrich Canada Ltd., Oakville, ON, Canada) per 100 mL of buffer. To each GLUINV test tube, 1 mL of invertase solution was added. Samples were mixed and left for 30 minutes at room temperature to allow for complete hydrolysis of the sucrose into glucose. The hydrolysis of 1 g of sucrose yields 0.526 g of glucose (Sowokinos et al., 1985).

An automatic sampling device measured 0.7 mL of extract from each test tube and, following analysis, the instrument reported the glucose content of each sample in g/L. The analyzer was set to calibrate automatically with a standard glucose solution (1.8 g/L) at the beginning of analysis and after every five samples.

Tuber glucose and sucrose content (on a fresh weight basis) were calculated using the following formulae;

$$\text{Glucose content (mg/g)} = \frac{\text{GLU (g/L) x sample volume (L)}}{\text{fresh weight of tuber sample (g) x } 0.001}$$

$$\text{Sucrose content (mg/g)} = \frac{[2 \times \text{GLUINV}] - \text{GLU (g/L) x sample volume (L)}}{\text{fresh weight of tuber sample (g) x } 0.526}$$

3.7.2 French Fry Colour

At harvest and periodically throughout the storage period (fall – 6-8 weeks after harvest; winter – 17-19 weeks after harvest; and spring – 28-31 weeks after harvest), strips taken from five tubers in each treatment were fried to assess their suitability for processing into french fries. French fry colour was determined on strips taken from the same tubers used for sugar analysis.

Washed and hand-peeled tubers were cut longitudinally into 1 cm^2 strips using a mechanical french fry cutter. Five longitudinal strips were removed from the center of each tuber and fried in vegetable oil for 2.75 min at 190ºC. After frying, the colour appearance of each of the 25 fries was visually assessed and scored using the USDA Colour Standards for Frozen French Fried Potatoes (Anonymous, 1988). To simplify calculations, the chart ratings 000, 00, 0, 1, 2, 3, and 4 were converted to nonzero ratings of 1, 2, 3, 4, 5, 6, and 7, respectively, where 1 corresponds to the lightest fry colour (Pritchard and Adam, 1994). Fry colour is presented as the average colour of 25 strips. Earlier research has shown that a fry colour of 3.5 (on the 1-7 colour scale) or lower is required to attain maximum fry colour bonus on processing contracts in Manitoba (Pritchard and Adam, 1994).

3.7.3 Stem-end Discolouration

Tubers used for sugar analysis and french fry colour determinations were also evaluated for stem-end discolouration. Discolouration was visually scored when tubers were peeled.

3.8 Skin-set

The skin-set measuring device used was a modified torque wrench described by Lulai and Orr (1993) (Figure 3.3). It measures the torsional force required to shear a disk of skin from the tuber. Following the advice of Lulai (personal communication), a number of adjustments were made to the operational protocol outlined by Lulai and Orr (1993). To prevent slippage of the rubber test tip on the tuber surface, the contact force of the tester was increased from 53 to 76 Newtons. Fresh size 1 rubber test tube stoppers were used as tester tips. This provided a larger area of skin contact (1.54 cm^2) during testing (compared to the size 0 test tube stoppers). The rubber tip of the testing device was wiped clean between measurements and changed frequently. Reference to the updated methodology was made by Lulai (2002).

In both years, skin-set measurements, measured in inch-ounces (in•oz), were taken on each of the three harvest dates to establish a time course for skin-set development through September. Ten average sized tubers were collected from each plot. Three measurements of skin-set were obtained from the midsection of each tuber, halfway between the stem and bud ends. Tuber skin-set (in•oz) was recorded as the average of these three readings. Readings were converted to millinewton-meters (mN•m) for reporting (1 in·oz = 7.06155 m•Nm). In total, approximately 1440 individual measurements were made in 1997, 1470 in 1998. In 1997, preharvest skin-set measurements were also obtained September 3rd from tubers collected from the control and desiccated treatments (seven days after the first application of diquat).

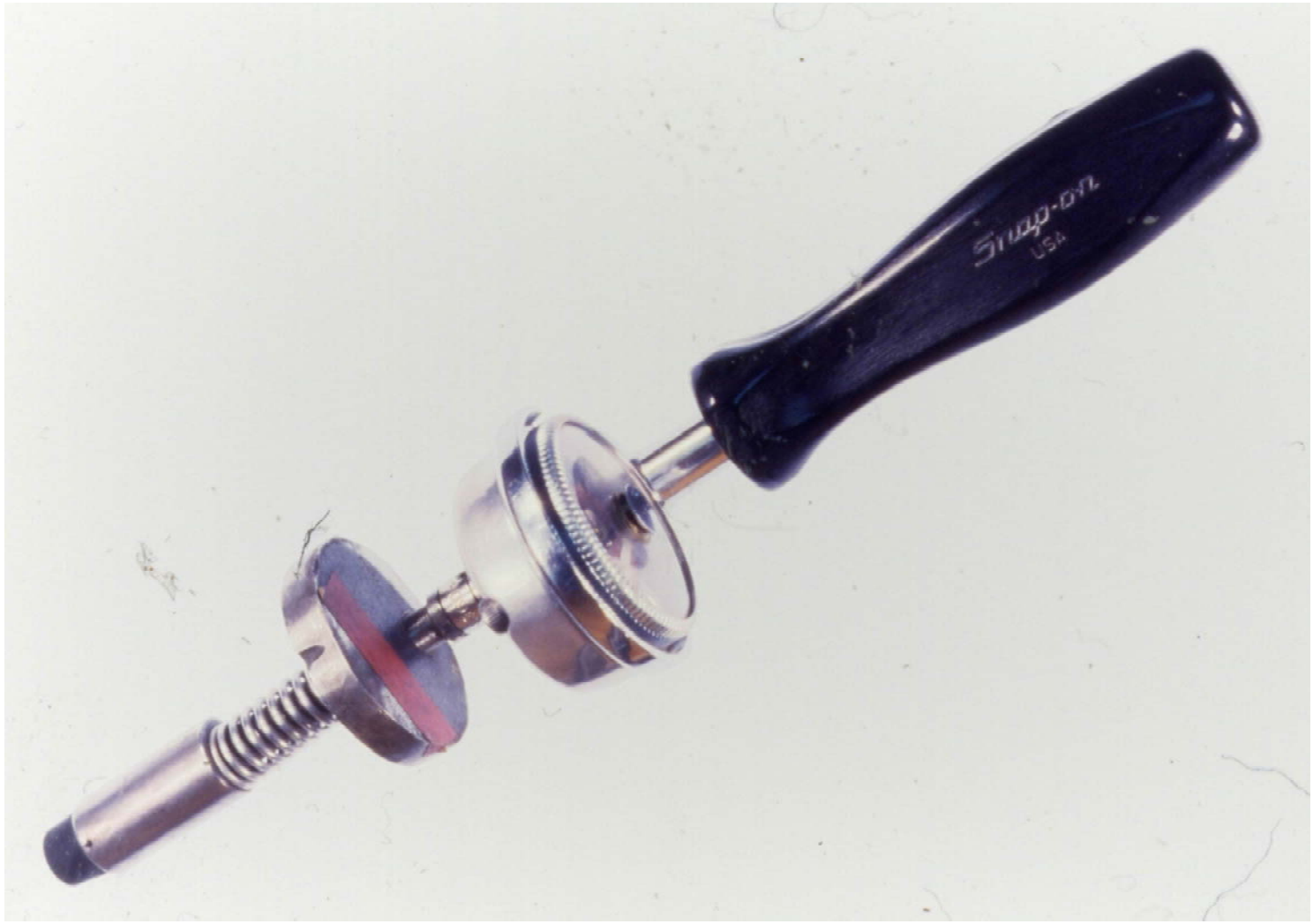


Figure 3.3. Modified torque wrench used to measure tuber skin-set (after Lulai and Orr, 1993).

3.9 Storage

After grading, tubers were placed in storage at the University of Manitoba Horticulture Research Storage Facility and preconditioned at 15°C, 95% relative humidity for two weeks. Storage temperature was subsequently lowered by 1°C per week to 8°C and 90% relative humidity for the holding period. Tubers were not sprout-inhibited.

3.10 Tuber Rot Assessment

In both years of this study, a random sub-sample of marketable tubers was stored for each treatment replicate to monitor the development of storage diseases. Approximately 12 kg of tubers were held in plastic crates at 15°C and 95% relative humidity to encourage the development of storage rots. Samples were examined throughout the storage period and the incidence and severity of rot was visually assessed. Confirmation of the identity of the rot-causing organisms was made through isolations in the Plant Pathology laboratory.

3.11 Weight Loss

In 1998, the effect of desiccation and time of harvest on the weight lost from tubers during the storage period was determined. From each treatment a sub-sample of marketable tubers weighing approximately 10 kg was collected during grading and placed in a perforated nylon sack. After an initial weight was recorded, these samples were placed in storage conditions as described in Section 3.9. The weight loss samples

were reweighed throughout the storage period and the percentage weight loss calculated. Weight loss data was not collected during the 1997 storage season.

3.12 Environmental Monitoring

At MCDC Carberry, in 1997, a weather station equipped with a 21X micrologger (Campbell Scientific, Logan, UT) collected hourly measurements of minimum and maximum air temperature, relative humidity, and rainfall.

At Winkler, in 1998, minimum and maximum air temperature, relative humidity, and rainfall were recorded daily with an A730MD remote measuring station (Adcon Telemetry, Boca Raton, FL) located near the experimental site.

The heat units (P-days) accumulated between planting and harvest were calculated as an additional indicator of crop maturity (Sands, et al., 1979). Conceptually similar to growing degree days, the P-day function has an optimum temperature of 21°C and limiting temperatures of 7 and 30°C (Figure 3.4).

The following formulae were used to determine daily P-day accumulation from hourly and daily air temperature data:

Equation 1

$$P(T) = 0 \text{ when } T < 7^{O}C$$

$$P(T) = 10\left[1 - \frac{(T - 21^{O}C)^2}{(21-7)^2}\right] \text{ when } 7 \le T < 21^{O}C$$

$$P(T) = 10\left[1 - \frac{(T - 21^{O}C)^2}{(30-21)^2}\right] \text{ when } 21 \le T < 30^{O}C$$

$$P(T) = 0 \text{ when } T \ge 30^{O}C$$

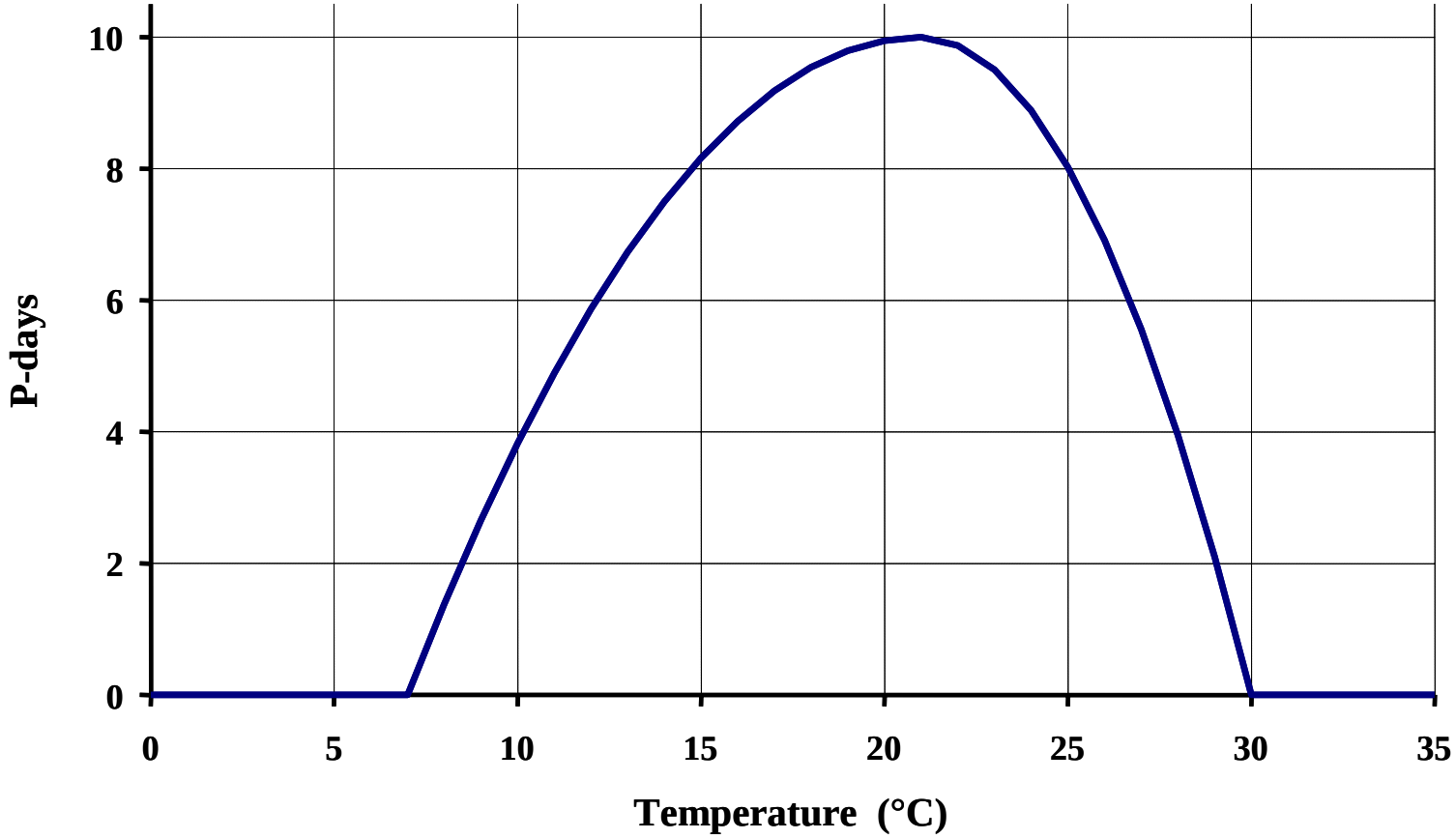


Figure 3.4. P-days as a function of temperature (Sands et al., 1979).

Equation 2

$$PDay = \left(\frac{1}{24}\right)\left[5P(T_{min}) + 8P\left(\frac{2T_{min}}{3} + \frac{T_{max}}{3}\right) + 8P\left(\frac{2T_{max}}{3} + \frac{T_{max}}{3}\right) + 3P(T_{max})\right]$$

Equation 1 was used in 1997 to calculate the accumulation of thermal time for one-hour periods. The daily P-day accumulation was determined by summing up the hourly P-day accumulations and dividing by a factor of twenty-four.

In 1998, when only daily minimum (T_{min}) and maximum (T_{max}) air temperatures were available, Equations 1 and 2 were used to calculate the accumulation of P-days for a 24-hour period.

3.13 Statistical Analysis

Data were subjected to ANOVA using the SAS General Linear Model (GLM) procedure (SAS Institute Inc., Cary, NC). Due to missing values, least squares means (LSMEANS) are reported to account for the imbalance. Differences between treatments were determined using single degree-of-freedom contrasts for preplanned comparisons. Treatment effects were considered to be significant if $P < 0.05$.

The results for each year are presented separately as significant year X harvest date, year X desiccation and year X fungicide interactions would have made pooling the data, for most variables, statistically invalid (Appendix – Table 1).

In determining the significance of treatment effects, models were initially run with all possible sources of variation included as part of the model statement. As is often

the case, the two- and three-way replicate interactions (i.e. replicate X harvest date and replicate X harvest date X desiccation) were non-significant. Since these interactions are independent estimates of the experimental error, it is common practice to pool the replicate interactions with the error term to obtain a more precise estimate of the true experimental error. As this generally reduces the value for the error mean square and affords a more precise test of treatment effects, it is often possible to determine that certain effects are significant when they would have tested otherwise.

Repeated Measures ANOVA was used to examine the response of sugar levels, french fry colour, and weight loss to preharvest management and harvest date over the storage period. Results are reported for the between-subjects main effects (harvest date, desiccation, and fungicide) and between-subjects interaction effects (harvest date X desiccation, etc.). The results of tests of the within-subjects main effect of time of sampling and its interactions were consistent for all factors. Time of sampling was significant indicating that sample time influenced processing quality from storage. The interaction of harvest date and time of sampling was also consistently significant indicating that the influence of time of sampling on processing quality from storage depended on the harvest date.

4.0 RESULTS AND DISCUSSION

4.1 Foliar Disease Development

4.1.1 Carberry – 1997

Late blight was not identified in the field trial in 1997 even though most plots received no fungicide application after August 18th. Conditions in the Carberry area were suitable for the development of late blight (Table 4.1), however, late blight was not found in surrounding commercial fields until the first week in September (Manitoba Agriculture, 1997a). Late blight symptoms were also observed in mid-September in the check treatment of a fungicide efficacy evaluation that was adjacent to the trial site at MCDC Carberry. Unfortunately, environmental conditions at that time were not conducive to disease spread (Table 4.1).

4.1.2 Winkler – 1998

The decision to relocate the trial from Carberry to Winkler in 1998 was made to ensure more reliable disease pressure. In 1997, there were a number of confirmed cases of late blight in the Winkler area by late-July and, at the end of the season, the potato blight severity index for the region (96-105) was more than twice that of Carberry (36-40) (Manitoba Agriculture, 1997a).

In 1998, prolonged periods of cool, wet weather in June created favourable conditions for late blight. The threshold of 18 severity values was exceeded in Winkler by June 25th (Table 4.1), 3 weeks earlier than normal (Manitoba Agriculture, 1998c). The first fungicide application, chlorothalonil, was made at the trial site on June 22nd.

Table 4.1 Potato Late Blight Disease Severity Index for Carberry, MB (1997) and Winker, MB (1998).

	Location	
	1997 - Carberry [a]	1998 - Winkler [b]
June 18	-	13 - 17
June 25	-	22 - 24
July 2	-	31 - 34
July 9	-	41 - 45
July 16	-	46 - 50
July 23	-	56 - 60
July 30	23 - 27	61 - 70
August 6	31 - 35	71 - 80
August 13	31 - 35	81 - 90
August 20	31 - 35	81 - 90
August 27	31 - 35	91 - 100
September 3	36 - 40	91 - 100
September 10	36 - 40	94 - 110
September 17	36 - 40	-

[a] From Potato Disease Severity Risk Maps prepared for the Carberry region by Manitoba Agriculture (1997a).

[b] From Potato Disease Severity Risk Maps prepared for the Carman, Morden, and Winker region by Manitoba Agriculture (1998c).

The first cases of late blight were reported in the Winkler area in early July, approximately 10 days after the diseases severity threshold was exceeded. Infected plants were observed in a commercial field adjacent to the trial site on July 16th. The fungicide program of alternating applications of the contact fungicide chlorothalonil and the contact/systemic tank-mix of mancozeb/metalaxyl on a 4 to 8 day schedule prevented late blight infections at the trial site until July 26th when a number of stem infections were observed in the guard rows between plots 5 and 6 in the 4th replicate.

In an attempt to encourage even disease development throughout the trial, blighted spreader plants were planted on July 31st between each plot in the guard rows. These greenhouse-grown plants had been inoculated with a spore suspension of US-8 *Phytophthora infestans*. Additionally, no further fungicide applications were made after July 24th until the end of the season allowing the epidemic to progress unchecked.

Favourable weather conditions (Figures 4.1 and 4.2) and loss of fungicide protection due to weathering encouraged disease progress in early August.

The rate of foliar disease development was quantified by repeated assessments of the percentage of leaf and stem area affected by late blight in each plot beginning in mid-August (Figure 4.3). The epidemic moved rapidly through the logistic phase in late August. When the level of foliar blight was assessed on September 10th, disease severity ranged from 95 to 100% making it difficult to distinguish between the control and vine-killed treatments. These results illustrate the devastating capabilities of late blight when left unchecked. Disease progressed from levels which were barely detectable to virtually 100% in less than one month.

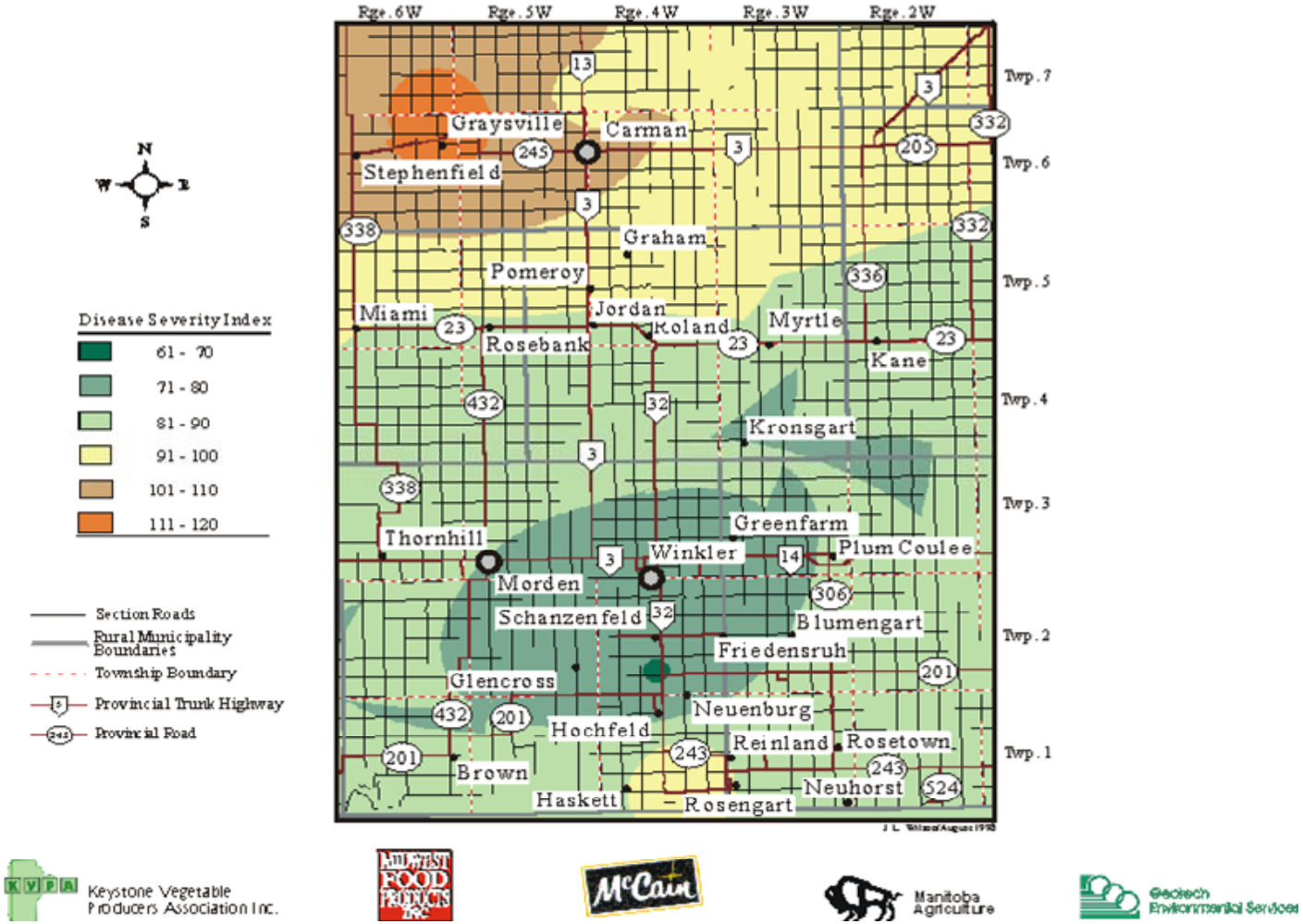


Figure 4.1. Potato Late Blight Disease Severity Index for the Carman, Morden, and Winkler region; August 6, 1998 (Manitoba Agriculture, 1998c). MCDC Winkler is located near Schanzenfeld.

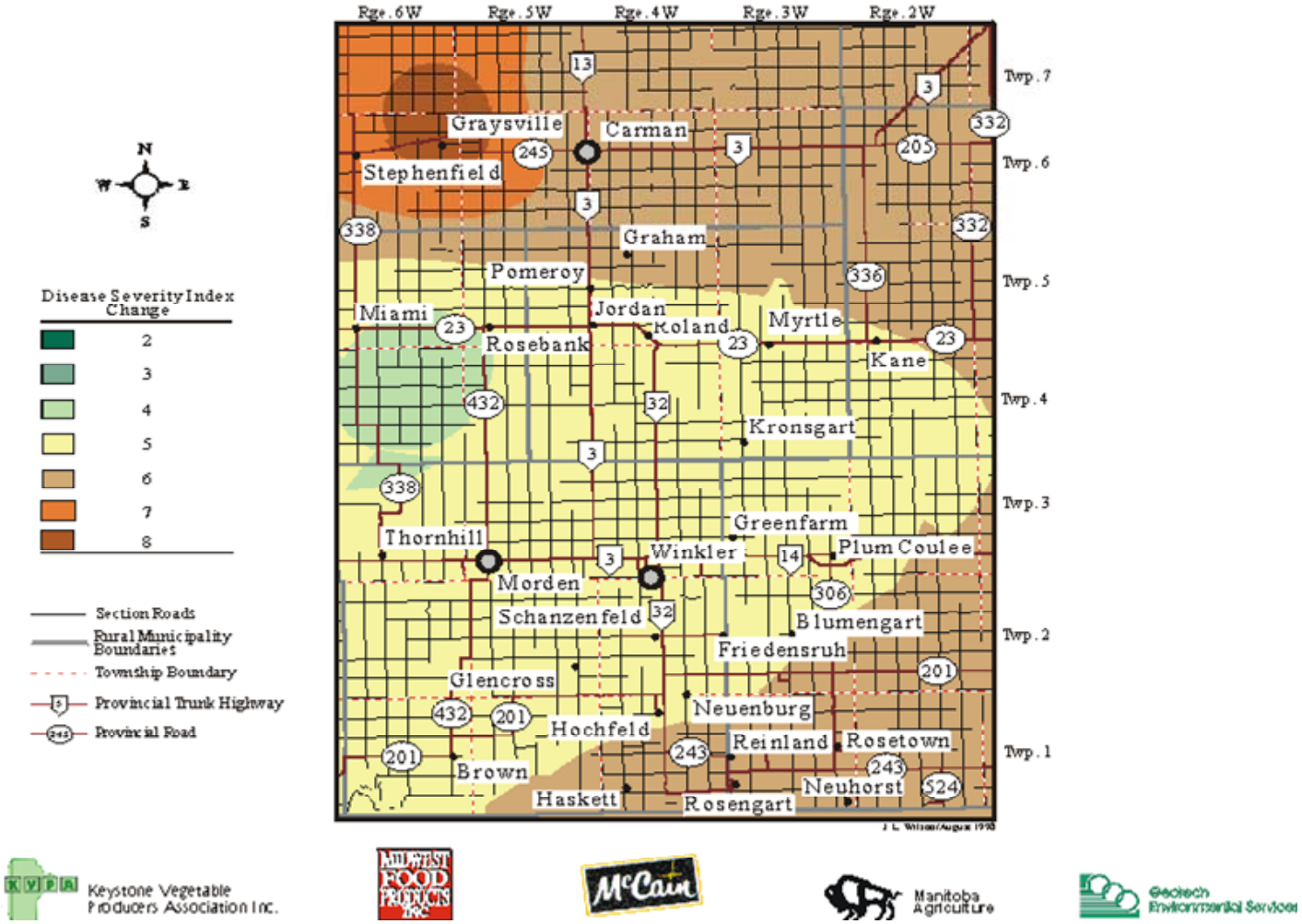


Figure 4.2. Change in Potato Late Blight Disease Severity Index for the Carman, Morden, and Winkler region; August 4 to 6, 1998 (Manitoba Agriculture, 1998c).

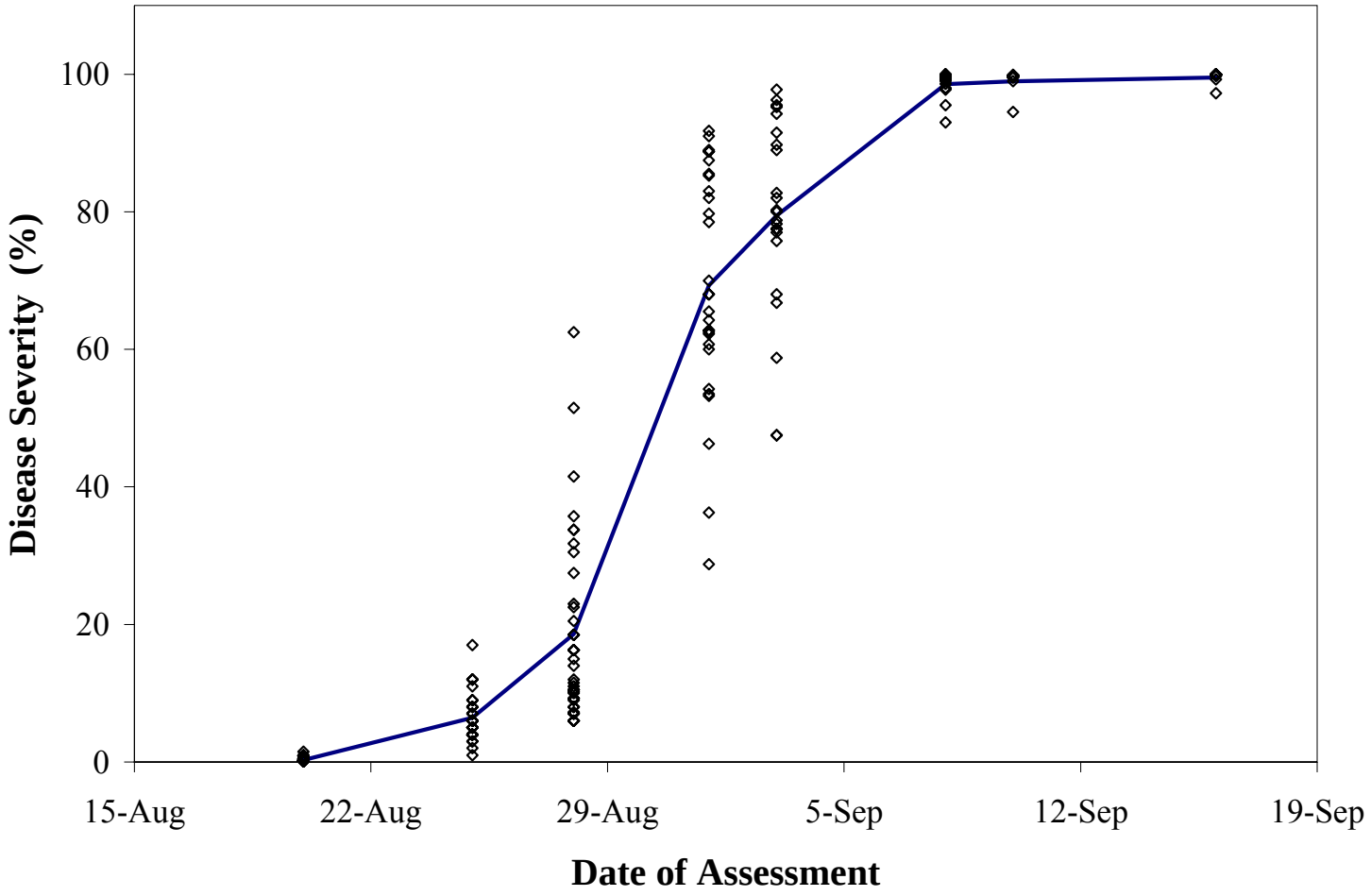


Figure 4.3. Foliar late blight progress curve for Winkler, MB in 1998. Each data point represents the disease severity of one plot on the assessment date. The solid line marks the trendline for all plots over the assessment period.

Despite efforts to establish the disease evenly across the trial site, the development of late blight was variable between plots and across replicates (Figures 4.3 and 4.4). For example, when disease severity was assessed on August 28th, the level of foliar blight ranged from 6 to 62% across the trial (Figure 4.3). Disease progress was delayed in the 1st replicate and noticeably quicker in the 4th replicate (Figure 4.4). Variation in disease intensity between plots in a replicate is a concern because the underlying variability confounds differences in treatment effects. Variation in disease progress between replicates is less of an issue. In fact, it could be argued to be advantageous in that it allows for observation of treatment responses over a range of disease pressures.

With the variability in disease progress between plots over time, the possibility existed that treatment responses were being masked. Attempts were made to characterize and adjust for differences in disease progress between plots of a replicate in order to increase the precision of treatment comparisons. However, the use of covariance-type analysis was confounded by the fact that the length of the epidemic differed in each plot depending on the time of harvest and whether or not the vines were desiccated. Consequently, adjusting the treatment responses based on AUDPC (area under the disease progress curve) or RAUDPC (AUDPC adjusted for time) as the covariate was not effective.

One useful approach for quantifying the variation in disease progress between replicates was the application of growth curve models. Following the procedure used by Campbell and Madden (1990) to fit growth curve models to epidemics of potato late blight, selected disease progress data from each replicate was fitted to two different

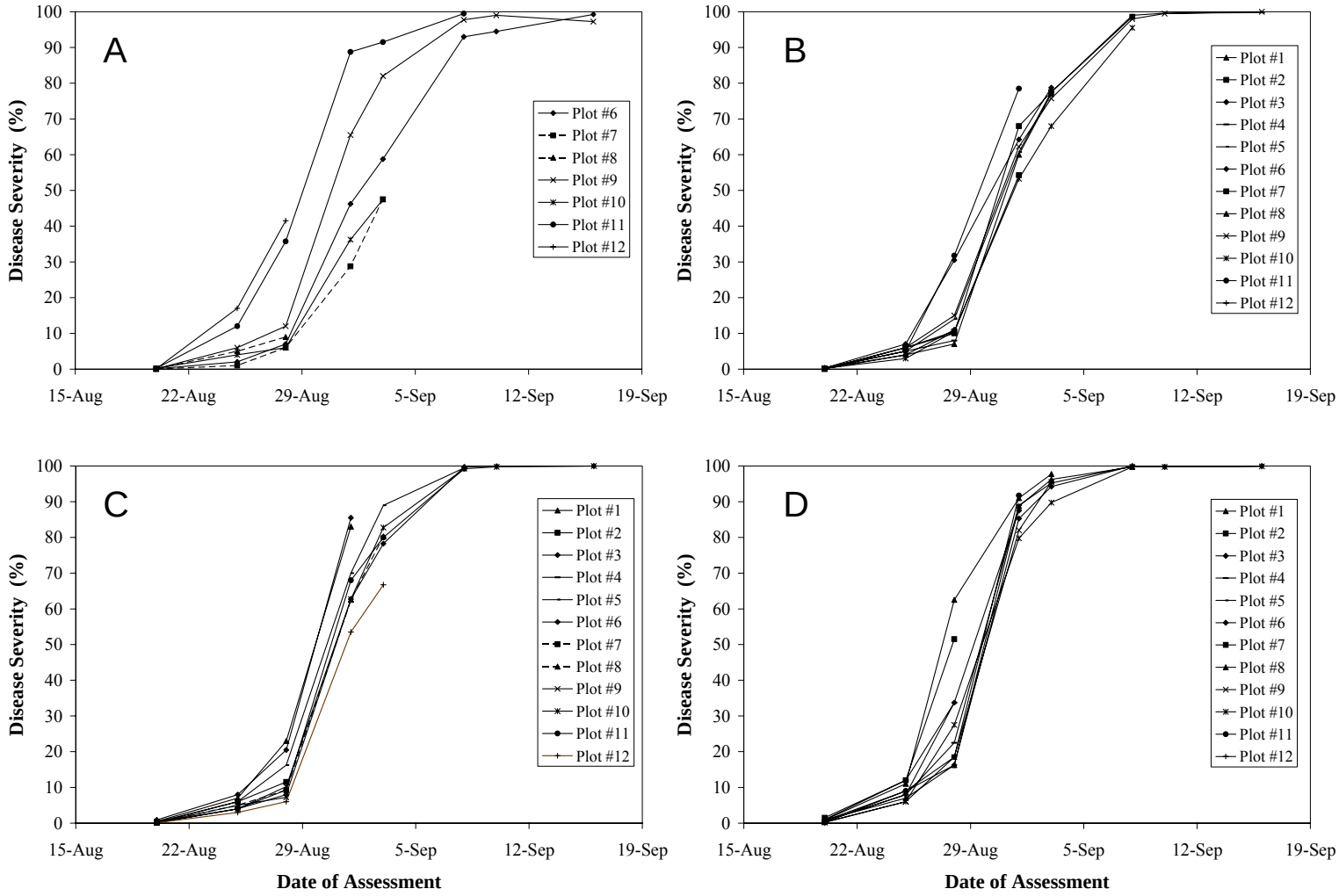


Figure 4.4. Foliar late blight progress curves by replicate for Winkler, MB in 1998. (A) Replicate 1. (B) Replicate 2. (C) Replicate 3. (D) Replicate 4.

models - logistic and Gompertz. Other models such as the exponential and monomolecular were not tested because of their obvious lack of fit.

From a thorough evaluation of the models, the conclusion was reached that the logistic model described the progress of foliar blight in each replicate better than the Gompertz model. A number of factors were considered in determining the adequacy of a model in describing disease development through time. The R^2 value, which is an indication of the degree of association between disease severity and date, was higher for the logistic (0.96) than the Gompertz (0.92) model. The mean square error for error (MSE), which is an estimate of the variance around the predicted curve, was lower for the logistic (0.77) than the Gompertz (0.78). Additionally, the residual plot of the estimates provided from the Gompertz model was not random but rather had an undesirable pattern.

The logistic equation describes a S-shaped growth curve where dY_t/dt (the absolute rate of disease increase) is proportional to the amount of disease at any given time (Y_t) multiplied by a logistic rate constant (r_L) and a correction factor dependent on the proportion of plants already infected ($1-Y_t$).

Based on the parameter estimates generated from regression analysis using SAS, Figure 4.5 was generated. The disease level at time t (Y_t) was calculated using the following equation;

$$Y_t = 1 / [1 + \exp(-\{\ln[Y_0/(1-Y_0)] + r_L t\})]$$

The logistic curves for each replicate have been charted based on values of r_L and Y_0 generated by the regression analysis.

The fact that fitting the disease progress data to the logistic model yielded a highly significant relationship between disease severity and date is not unexpected. The

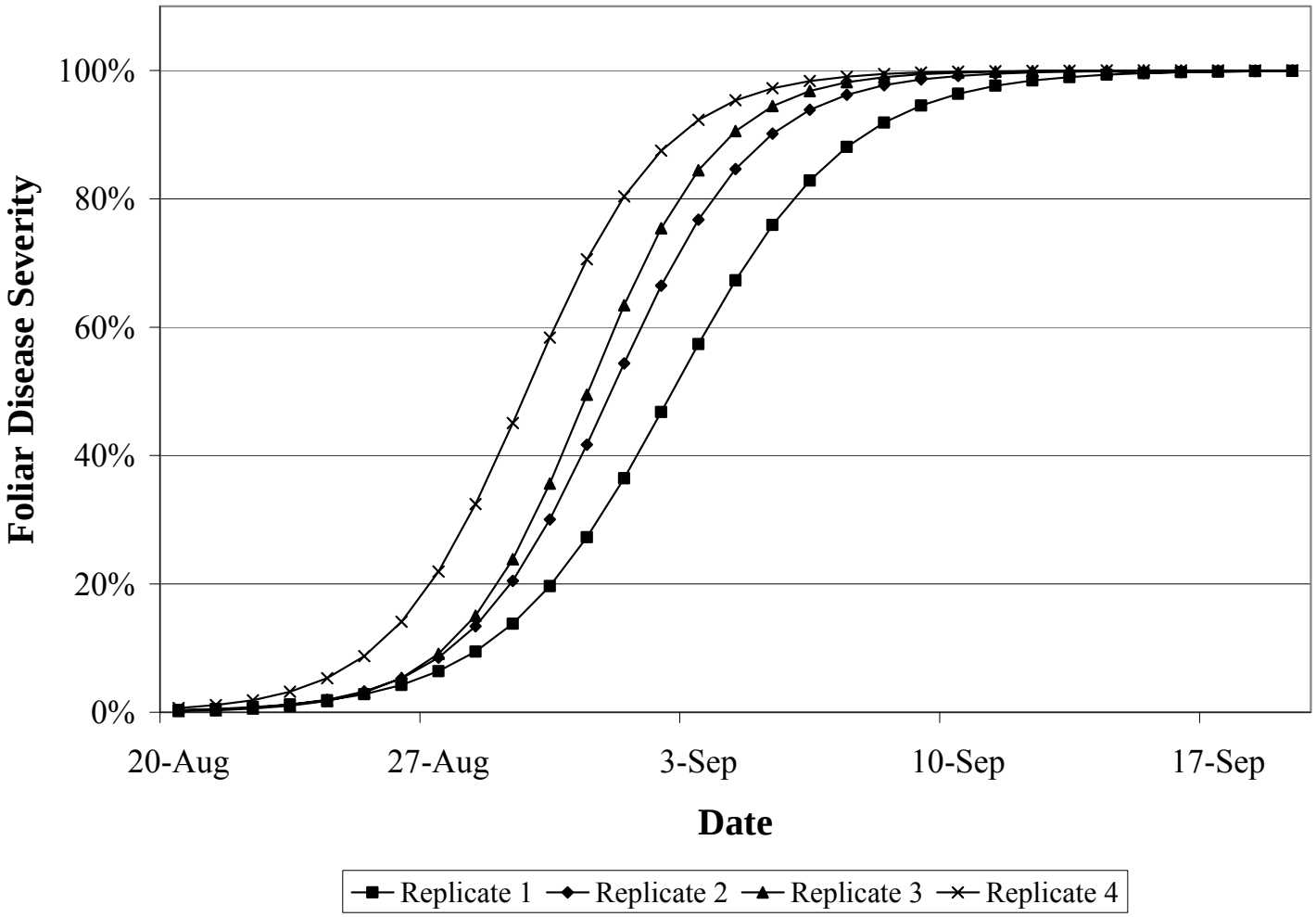


Figure 4.5. Foliar late blight progress curves fit to a logistic function for each replicate in Winkler, MB in 1998.

logistic model is used frequently by plant pathologists in describing disease progress, especially with polycyclic epidemics (e.g. late blight). Analyzing disease progress with the logistic model confirmed that there were significant differences in disease progress between replicates ($p = 0.028$) (data not shown).

4.2 Tuber Yield

Tuber yield and grade are two of the factors which determine crop value. In a typical french fry processing contract, tubers less than 50 mm in diameter are considered 'undersize' for which the grower receives no payment. In addition, incentives are often paid for deliveries which meet certain tuber size requirements. In the years of this study, Manitoba processors paid a bonus based on the percentage of large tubers weighing over 284 g (10 oz). Consequently, Manitoba process growers have targeted bigger tubers to maximize 'bonus' and minimize the yield of small potatoes. Results are presented for each component of tuber yield separately followed by a common discussion.

4.2.1 Total Yield

Total yield varied between treatments in both study years, ranging from 31.8 to 45.5 tonnes ha^{-1} in 1997 and 32.1 to 43.1 tonnes ha^{-1} in 1998 (data not shown). Total yield was not significantly different ($p = 0.23$) in 1997 (40.8 tonnes ha^{-1}) and 1998 (39.2 tonnes ha^{-1}) (Table A.1).

The analysis of variance in the total yield data from 1997 showed a significant harvest date X desiccation interaction ($p = 0.014$) (Table 4.2). Desiccation caused a greater reduction in total yield at the early harvest date than at the middle or late harvest

Table 4.2. Analysis of variance and associated contrasts for effects of harvest date and preharvest management on the yield of Russet Burbank potatoes grown at Carberry, MB in 1997.

Source of variation	df	Mean Square			
		Total Yield	Marketable Yield	Undersized Yield	Bonus Yield
Replication (BLOCK)	3	27.21 *	18.65 NS	1.51 NS	32.09 NS
Harvest Date (HVST)	2	84.03 ***	87.26 ***	7.34 NS	239.47 **
Desiccation (VINE)	1	340.30 ***	360.31 ***	28.26 **	439.73 ***
HVST X VINE	2	30.50 *	26.80 *	3.24 NS	33.05 NS
Preharvest Fungicide (FUNG)	1	0.04 NS	0.11 NS	0.05 NS	10.28 NS
HVST X FUNG	1	3.44 NS	2.86 NS	0.02 NS	4.71 NS
VINE X FUNG	1	2.36 NS	1.66 NS	0.22 NS	13.19 NS
HVST X VINE X FUNG	1	3.67 NS	6.52 NS	3.61 NS	17.96 NS
Error	26	6.04	6.35	3.33	26.83
Contrast	df	Mean Square			
		Total Yield	Marketable Yield	Undersized Yield	Bonus Yield
Early Harvest - Control vs Diquat	1	195.43 ***	205.30 ***	21.01 *	197.45 *
Middle Harvest - Control vs Diquat	1	152.02 ***	142.84 ***	2.24 NS	216.62 **
Late Harvest - Control vs Diquat	1	33.54 *	46.37 *	11.61 NS	49.46 NS
CV (%)		6.04	6.74	22.15	18.90

***,**,*, and NS indicate significance at 0.001, 0.01 and 0.05 levels of probability and not significant, respectively.

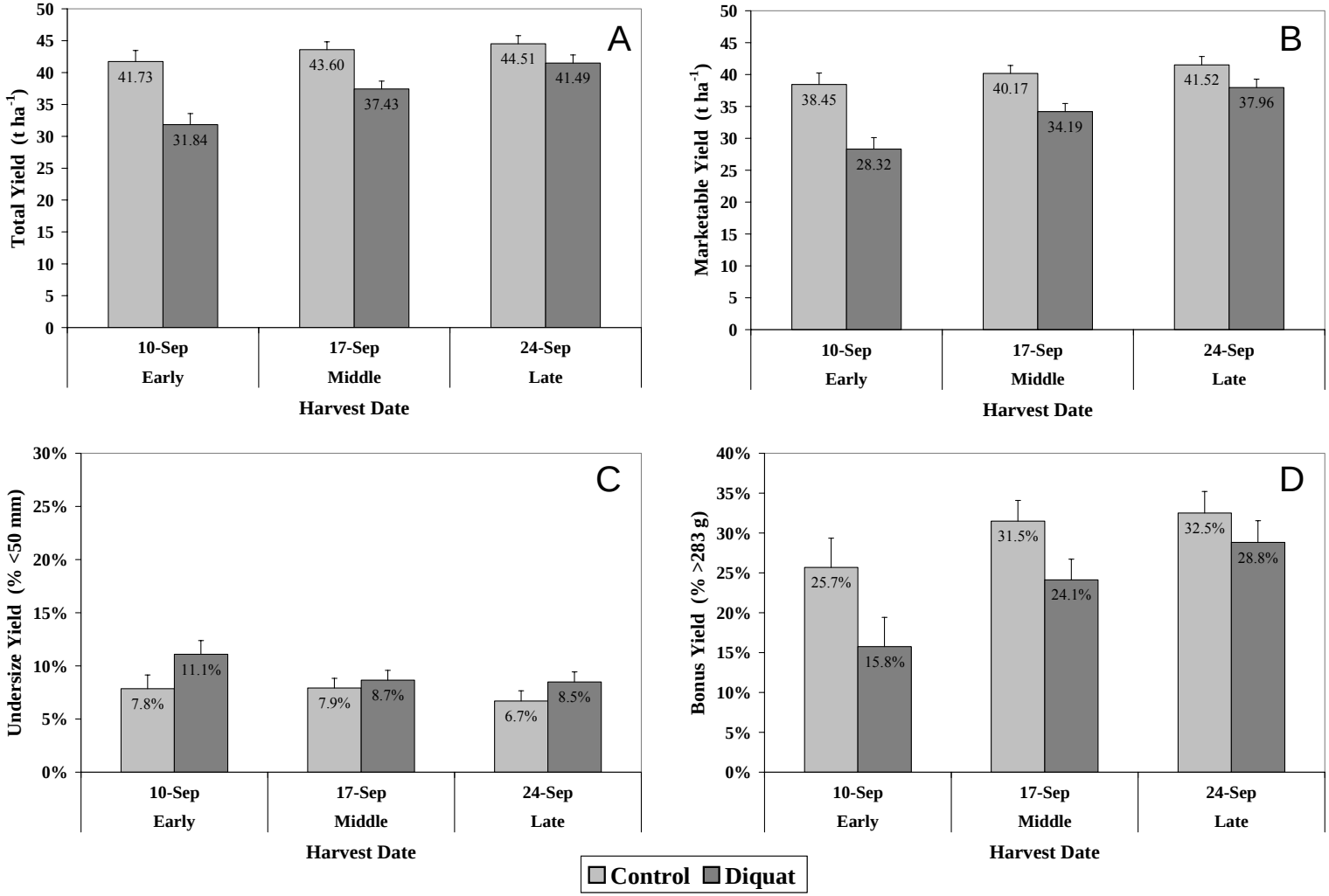


Figure 4.6. Tuber yield components as influenced by desiccation at Carberry, MB in 1997. (A) Total Yield. (B) Marketable Yield. (C) Undersize Yield. (D) Bonus Yield. (Bars represent SEM).

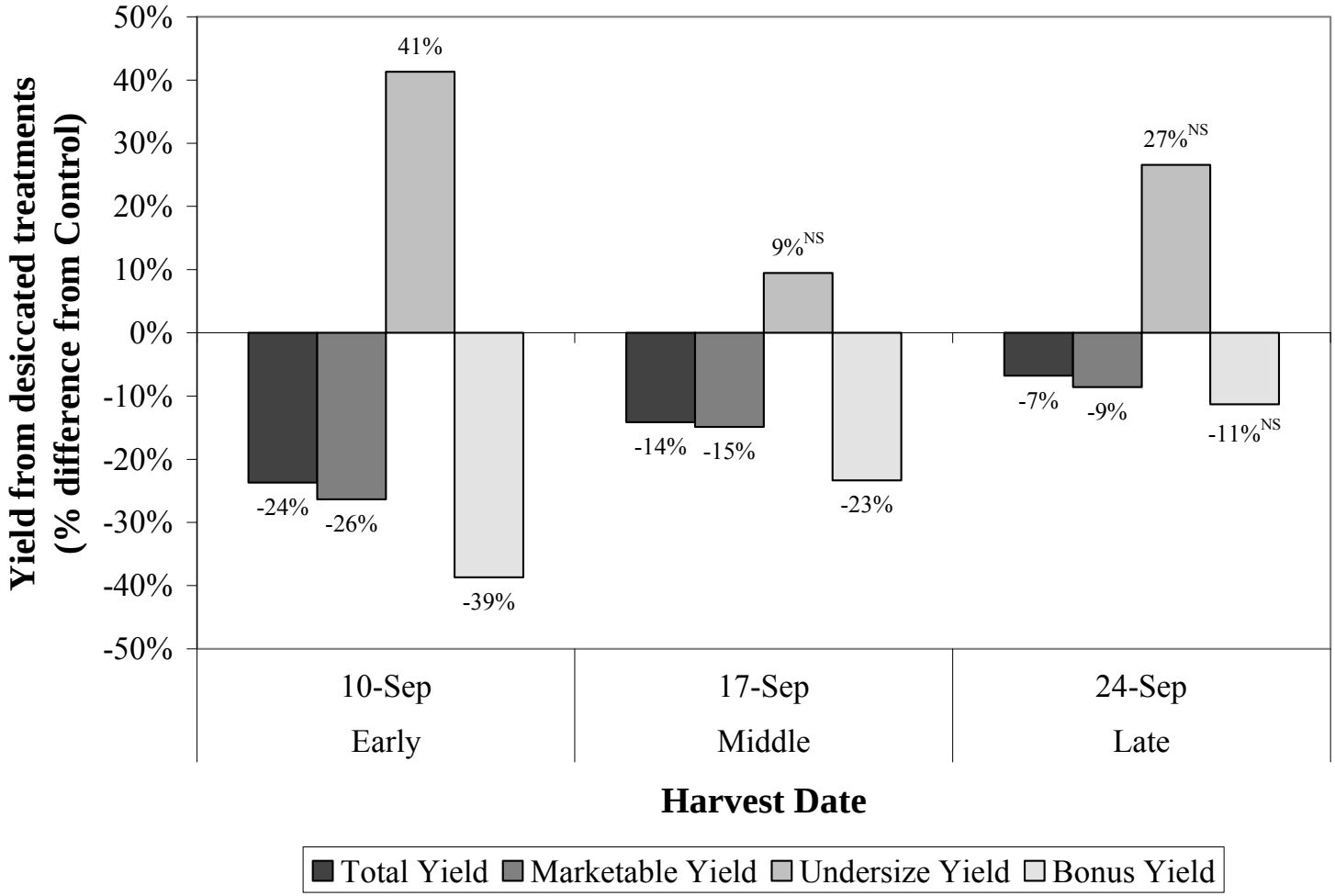


Figure 4.7. Effect of desiccation on tuber yield components at Carberry, MB in 1997. Yield differences which are not statistically significant ($p>0.05$) are labeled NS.

dates (Figure 4.6A). Since the interaction is not detecting a difference in the direction of the response of total yield to desiccation but rather a change in the degree of response, a discussion of the highly significant responses to the main effects of harvest date ($p = <0.0001$) and desiccation ($p = <0.0001$) is still warranted (Table 4.2). Mean total yield increased from 36.8 tonnes ha^{-1} at the early harvest date to 40.5 tonnes ha^{-1} and 43.0 tonnes ha^{-1} at the middle and late harvest dates, respectively. The average total yield of potatoes in the non-desiccated controls (43.6 tonnes ha^{-1}) was 13% higher than in the desiccated treatments (37.9 tonnes ha^{-1}). Vine killing reduced total yield by 24% at the early harvest date, 14% at the middle harvest date, and 7% at the late harvest date (Figure 4.7). The reduction in total yield was significant at all harvest dates (Table 4.2). Total yield differed significantly ($p = 0.011$) between replicates (Table 4.2). Total tuber yield was highest in the second replicate (43.1 tonnes ha^{-1}; data not shown). The late season fungicide application had no effect on total yield in 1997 ($p = 0.94$) (Table 4.2).

In 1998, total yield was significantly affected by harvest date ($p = 0.039$) and desiccation ($p = 0.003$) (Table 4.3). The interaction of these main effects was not significant ($p = 0.21$) although the effect of desiccation on total yield clearly decreases with later harvest date (Figure 4.8A). Mean total yield increased from 37.2 tonnes ha^{-1} at the early harvest date to 39.2 tonnes ha^{-1} and 41.3 tonnes ha^{-1} at the middle and late harvest dates, respectively. The average total yield was 9% higher from the untreated controls (41.2 tonnes ha^{-1}) than the vine-killed treatments (37.3 tonnes ha^{-1}). Desiccation reduced total yield by 17% at the early harvest date, 8% at the middle harvest date, and 4% at the late harvest date (Figure 4.9), although the difference was only significant at the early harvest date ($p = 0.004$) (Table 4.3). Total yield differed significantly

Table 4.3. Analysis of variance and associated contrasts for effects of harvest date and preharvest management on the yield of Russet Burbank potatoes grown at Winkler, MB in 1998.

Source of variation	df	Mean Square			
		Total Yield	Marketable Yield	Undersized Yield	Bonus Yield
Replication (BLOCK)	3	57.30 *	42.18 *	49.79 *	6.77 NS
Harvest Date (HVST)	2	52.20 *	46.13 *	22.43 NS	12.54 NS
Desiccation (VINE)	1	158.65 **	93.16 **	0.04 NS	29.20 NS
HVST X VINE	2	23.77 NS	14.88 NS	0.53 NS	0.98 NS
Preharvest Fungicide (FUNG)	1	3.73 NS	0.41 NS	27.18 NS	17.75 NS
HVST X FUNG	2	0.38 NS	0.56 NS	9.63 NS	19.58 NS
VINE X FUNG	1	2.02 NS	9.28 NS	22.35 NS	6.71 NS
HVST X VINE X FUNG	2	11.07 NS	12.43 NS	7.99 NS	23.49 NS
Error	28	14.35	12.17	12.71	8.30
Contrast	df	Mean Square			
		Total Yield	Marketable Yield	Undersized Yield	Bonus Yield
Early Harvest - Control vs Diquat	1	143.33 **	84.43 *	0.00 NS	14.70 NS
Middle Harvest - Control vs Diquat	1	32.08 NS	21.94 NS	0.25 NS	9.86 NS
Late Harvest - Control vs Diquat	1	12.75 NS	5.57 NS	0.88 NS	5.26 NS
CV (%)		9.58	11.42	15.61	33.79

***,**,*, and NS indicate significance at 0.001, 0.01 and 0.05 levels of probability and not significant, respectively.

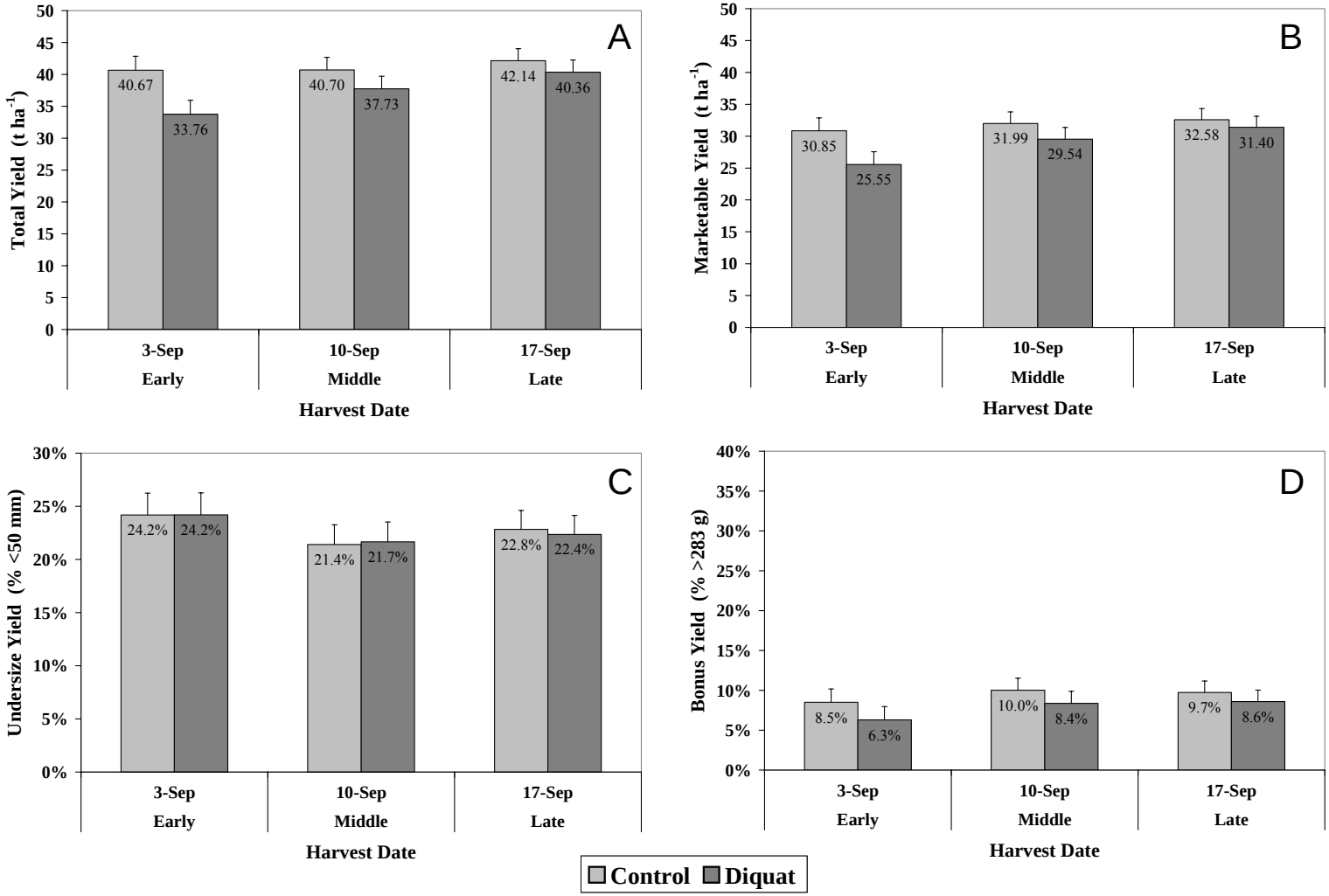


Figure 4.8. Tuber yield components as influenced by desiccation at Winkler, MB in 1998. (A) Total Yield. (B) Marketable Yield. (C) Undersize Yield. (D) Bonus Yield. (Bars represent SEM).

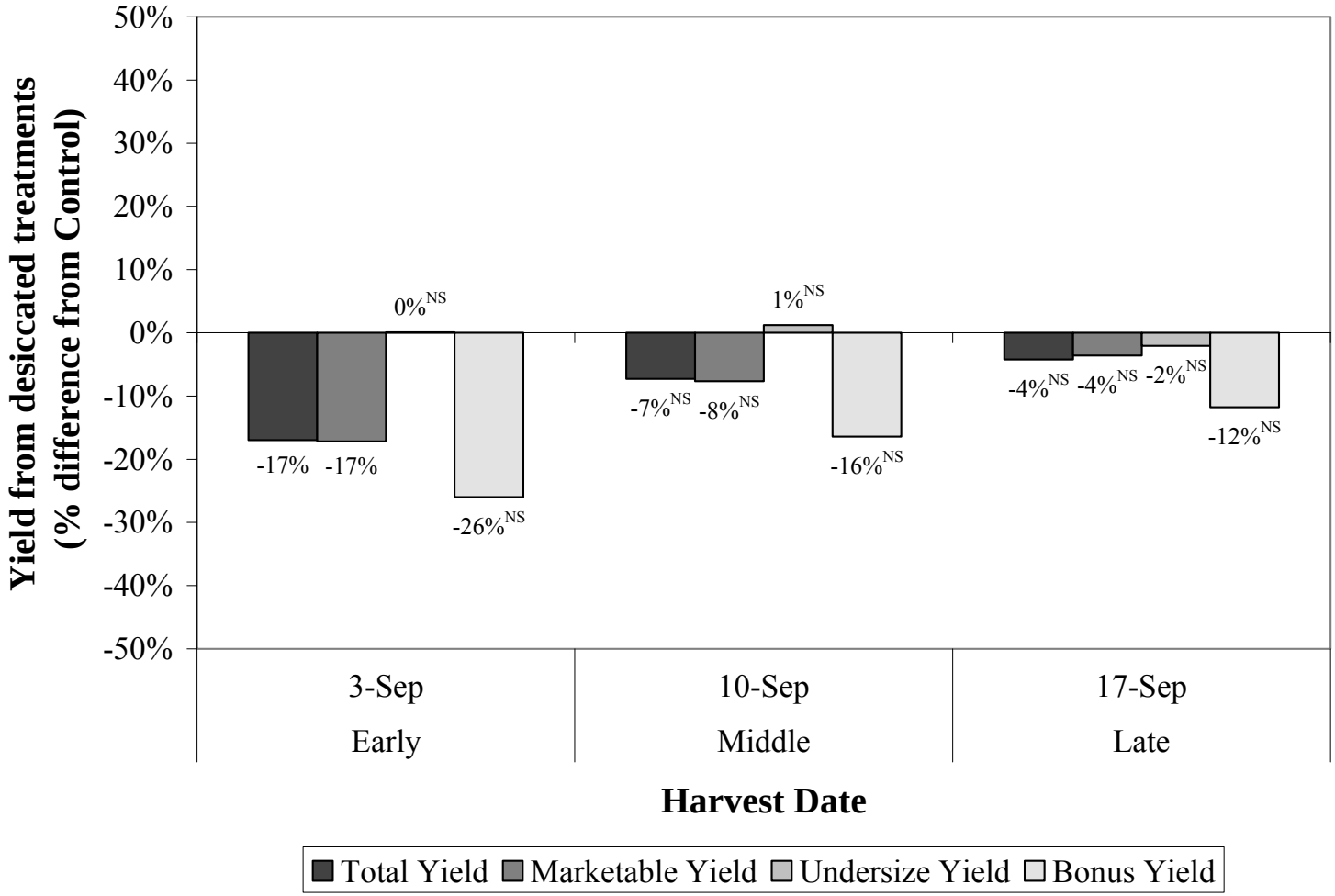


Figure 4.9. Effect of desiccation on tuber yield components at Winkler, MB in 1998. Yield differences which are not statistically significant ($p>0.05$) are labeled NS.

(p = 0.017) between replicates in 1998 (Table 4.3). Total yields were highest in the third replicate (42.6 tonnes ha^{-1}; data not shown). Application of a late season fungicide application had no effect on total yield in 1998 (p = 0.61) (Table 4.3).

4.2.2 Marketable Yield

Yield of marketable-sized tubers (>50 mm) varied with treatment in both study years ranging from 28.3 to 42.6 tonnes ha^{-1} in 1997 and 24.5 to 33.0 tonnes ha^{-1} in 1998 (data not shown). Marketable yield was significantly higher (p = <0.0001) in 1997 (37.4 tonnes ha^{-1}) than in 1998 (30.3 tonnes ha^{-1}) (Table A.1).

The analysis of variance of marketable yield revealed a significant harvest date X desiccation interaction (p = 0.026) in 1997 (Table 4.2). Consideration of the marketable yield data (Figure 4.6B) reveals that the interaction effect arises from a difference in the magnitude of response to desiccation between harvest dates. Vine killing reduced marketable yield more at the early harvest date than the middle or late harvest dates. Consequently, a discussion of the highly significant responses to the main effects of harvest date (p = <0.0001) and desiccation (p = <0.0001) is warranted (Table 4.2). Mean marketable yield increased from 33.4 tonnes ha^{-1} at the early harvest date to 37.2 tonnes ha^{-1} and 39.7 tonnes ha^{-1} at the middle and late harvest dates, respectively. The average yield of marketable tubers was 14% higher from the untreated controls (40.4 tonnes ha^{-1}) than the vine-killed treatments (34.5 tonnes ha^{-1}). Desiccation reduced marketable yield by 26% at the early harvest date, 15% at the middle harvest date, and 9% at the late harvest date (Figure 4.7). The reduction in yield was significant at all harvest dates (Table

4.2). Application of a late season fungicide application had no effect on marketable yield in 1997 ($p = 0.90$) (Table 4.2).

In 1998, marketable yield was again significantly affected by harvest date ($p = 0.035$) and desiccation ($p = 0.001$) (Table 4.3). Although the interaction of these main effects was not significant ($p = 0.31$), it is evident that the effect of desiccation on marketable yield decreased with later harvest date (Figure 4.8B). The mean yield of marketable tubers increased from 28.2 tonnes ha^{-1} at the early harvest date to 30.8 tonnes ha^{-1} and 32.0 tonnes ha^{-1} at the middle and late harvest dates, respectively. Vine-killed treatments produced, on average, a 9% lower marketable yield (28.8 tonnes ha^{-1}) than the non-desiccated controls (31.8 tonnes ha^{-1}). Desiccation reduced marketable yield by 17% at the early harvest date, 8% at the middle harvest date, and 4% at the late harvest date (Figure 4.9), although the difference was only significant at the early harvest date ($p = 0.014$) (Table 4.3). Marketable yield differed significantly ($p = 0.029$) between replicates (Table 4.3). Yields of marketable grade tubers were lowest in the fourth replicate (28.4 tonnes ha^{-1}; data not shown). A late season fungicide application had no effect on marketable yield in 1998 ($p = 0.86$) (Table 4.3).

4.2.3 Undersize Yield

The yield of undersized tubers (<50 mm diameter) harvested from treatments was expressed as a percentage of the total yield and ranged from 6.4 to 11.1% in 1997 and 20.3 to 27.1% in 1998 (data not shown). Percent undersize was significantly higher ($p = <0.0001$) in 1998 (22.8%) compared to 1997 (8.2%) (Table A.1).

Desiccating vines with diquat significantly affected ($p = 0.0072$) the yield of undersized tubers in 1997 (Table 4.2; Figure 4.6C). Overall, the vine-killed treatments yielded a higher percentage of undersized tubers (9.1%) than the control treatments (7.4%). Desiccation increased the yield of undersized tubers at all harvest dates (Figure 4.7), although the difference (41%) was only significant ($p = 0.019$) at the early harvest date (Table 4.2). The late season fungicide application had no effect on undersize yield in 1997 ($p = 0.90$) (Table 4.2).

Yield of undersized tubers was not significantly affected by harvest date ($p = 0.19$), desiccation ($p = 0.95$), or late season fungicide ($p = 0.15$) in 1998 (Table 4.3; Figure 4.8C). Percent undersize differed significantly ($p = 0.019$) between replicates (Table 4.3). The yield of undersized tubers was highest in the fourth replicate (25.8%; data not shown).

4.2.4 Bonus Yield

The yield of bonus grade tubers varied between treatments and years; 15.8 to 33.0% in 1997 and 5.5 to 11.5% in 1998 (data not shown). The yield of tubers over 283 g was significantly higher ($p = <0.0001$) in 1997 (27.5%) than in 1998 (8.6%) (Table A.1).

Date of harvest and desiccation had highly significant effects on the yield of bonus grade tubers in 1997 ($p = 0.001$ and $p = 0.0004$, respectively) (Table 4.2; Figure 4.6D). The mean yield of tubers over 283 g increased from 20.7% at the early harvest date to 27.8% and 30.7% at the middle and late harvest dates, respectively. The average bonus yield was 21% lower from the desiccated treatments (24.3%) compared to the control treatments (30.7%). Desiccation reduced the yield of bonus grade tubers more at

the early harvest date (39%) than at the middle harvest date (23%) or late harvest date (11%), although the difference was not significant ($p = 0.19$) in the late harvest (Figure 4.7). Application of a late season fungicide had no effect on bonus yield in 1997 ($p = 0.59$) (Table 4.2).

The yield of bonus grade tubers was not significantly affected by harvest date ($p = 0.24$), desiccation ($p = 0.07$), or late season fungicide ($p = 0.15$) in 1998 (Table 4.3; Figure 4.8D). However, the control treatments did consistently yield more bonus size tubers than those treatments which were desiccated and there was an upward trend in yield of tubers over 283 g with later harvest date (Figure 4.8D).

4.2.5 Rate of Tuber Bulking

The tuber bulking rate of non-desiccated vines during September was determined by calculating the marketable yield increase of treatments between successive harvest dates. Over the three September harvest dates, tuber bulking rate was significantly higher ($p = 0.008$) in 1997 (0.45 tonnes ha^{-1} day^{-1}) than in 1998 (0.27 tonnes ha^{-1} day^{-1}).

In 1997, the rate at which marketable yield developed decreased almost linearly from 0.84 tonnes ha^{-1} day^{-1} on August 31st to 0.54 tonnes ha^{-1} day^{-1} on September 7th and 0.19 tonnes ha^{-1} day^{-1} on September 21st (Figure 4.10A).

In 1998, the rate of marketable yield increase was markedly lower but followed a similar trend (Figure 4.10B). Tuber bulking rates fell from 0.57 tonnes ha^{-1} day^{-1} on August 25th to 0.27 tonnes ha^{-1} day^{-1} on September 1st and 0.08 tonnes ha^{-1} day^{-1} on September 14th.

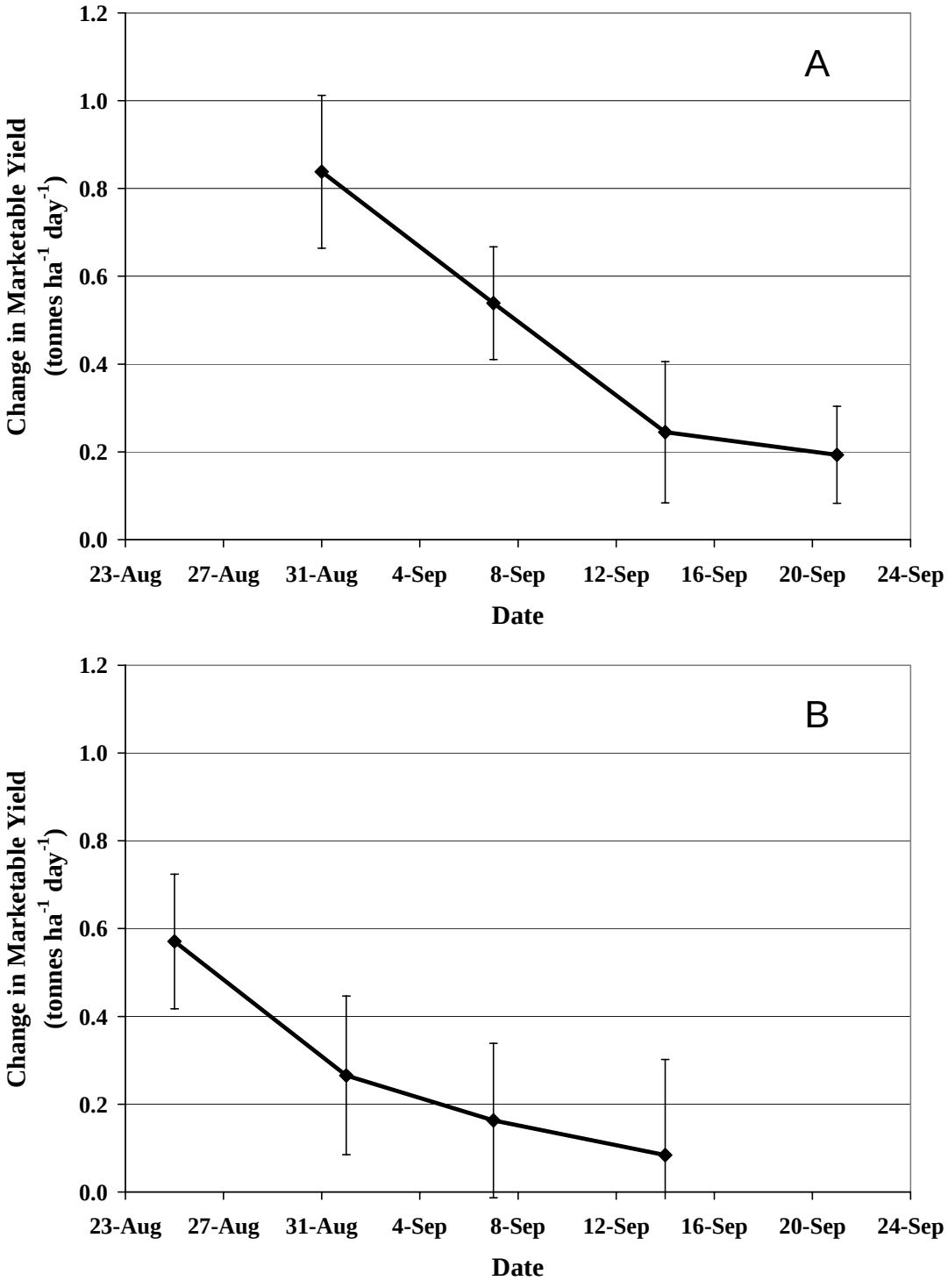


Figure 4.10. Tuber bulking rate at Carberry, MB in 1997 (A) and Winkler, MB in 1998 (B). (Values are means of 2 observations and bars represent SEM).

A number of factors complicate the interpretation of the tuber yield results for this study. Tuber numbers per plant were higher in 1998 than in 1997 resulting in a smaller tuber profile. Consequently, although total yield was similar in the two years of this study, marketable and bonus yield were significantly lower in 1998 compared to 1997. Moreover, the yield potential of the 1998 crop was never fully realized due to the development of late blight in the trial that caused the rapid senescence of vines in all treatments in late August and early September (Section 4.1). Due to the loss of photosynthetic area, tuber bulking rates in the control treatments were lower in 1998 than in 1997 and, as a result, the effect of desiccation on yield and size was diminished.

Vine killing with diquat significantly reduced total and marketable yield at all three harvest dates in 1997. Vines killed on August 27th showed the largest reductions in total and marketable yield (24% and 26%, respectively). Delaying vine kill by 2 weeks to September 10th decreased its effect on total and marketable yield (7% and 9%, respectively). Previous Manitoba experiments showed that vine killing Russet Burbank in early and mid-September reduced total yield by 21% and 13% and marketable yield by 25% and 21%, respectively (Menzies and Adam, 1979; Giesel, 1986). In this study, similar reductions in total yield were observed in 1997 but only when vines were desiccated ten day to two weeks earlier in the season. The effect of desiccation on yield was less evident in 1998 and only significant when vine killing on August 21st reduced total and marketable yield by 17%. The smaller reductions in total and marketable yield observed in 1997 and 1998 suggest that tubers were bulking at a slower rate in September compared to these earlier studies. Indeed, the bulking rates reported by Giesel (1986) for early September (0.80 tonnes ha^{-1} day^{-1}) and Menzies and Adam (1979) for mid-

September (0.81 tonnes ha^{-1} day^{-1}) were almost twice as high as the rate observed in this study in early September in 1997 and threefold higher than the tuber bulking rate in early September, 1998. The drop observed in the tuber bulking rate through September in both years of this study suggests that plants were shifting from the linear tuber growth phase to the maturation phase over this time period (Rowe, 1993). Many different environmental and cultural factors account for the timing of shifts in potato development (Flint, 1992). Menzies and Adam (1979) noted that their trial site had been 'heavily fertilized' and that vine growth was 'extensive'. Excessive nitrogen application favours vine growth and can delay tuber initiation and bulking by 10 days or more (Dwelle, 2003). Consequently, vine killing resulted in large yield losses, even when vines were killed relatively late in the growing season. Although non-desiccated vines remained healthy until harvest in 1997, crop development was evidently more advanced than was the case in the previous Manitoba studies. In 1998, the rapid development of late blight clearly limited the length of the tuber bulking phase. Large (1952) reported that tuber growth stopped when 75% of the vine was destroyed. This level of disease severity was measured September 3rd (Figure 4.3); consequently, the effect of vine killing on yield was minimal at the late harvest in 1998. Accurately assessing the stage of crop development (maturity) at the time of desiccation is critical to minimizing the magnitude of yield loss.

Desiccation reduces marketable tuber yield in two ways. It prevents some tubers from reaching marketable size, thereby increasing undersize tuber yield. It also limits the growth of marketable sized tubers, decreasing bonus yield.

The effect of vine killing on the yield of undersized tubers was inconsistent. Undersize yield was higher in 1997 when vines were desiccated, although the difference

was only significant at the early vine-kill date. In 1998, desiccation had no effect on undersize yield. Menzies and Adam (1979) reported that desiccation increased the yield of undersized tubers while other researchers have not always reported a difference (Giesel, 1986). The inconsistency in the response might be explained by variations in the partitioning of assimilates to different size classes of tubers. In 1998, the yield of undersized tubers was significantly higher in the fourth replicate, where disease progression was quickest. This result supports the conclusion that disease development was a factor in the higher yield of undersized tubers in 1998.

Desiccation resulted in consistent reductions in the yield of tubers over 283 g in both years of this study although the differences were not significant at the late harvest date in 1997 and at all harvest dates in 1998. Previous Manitoba studies (Menzies and Adam; 1979; Giesel, 1986) also reported reductions in bonus yield when vines were desiccated.

Increased losses during commercial harvesting have been reported when tubers are harvested from green vines due to poor separation of vines from tubers (Plissey, 1993). The small-plot harvester used in this study did not replicate a commercial harvester, consequently, carry-over losses were not a factor in this study.

4.3 Specific Gravity

Specific gravity of harvested tubers varied with treatment in both study years ranging from 1.071 to 1.083 in 1997 and 1.075 to 1.082 in 1998 (data not shown). Average specific gravity was significantly higher ($p = <0.0001$) in 1998 (1.079) than in 1997 (1.077) (Table A.1). The higher tuber dry matter content in 1998 reflects the

advanced maturity of the trial in 1998 compared to 1997. The average P-day accumulation at harvest was 29 P-days higher in 1998 (868 P-days) than in 1997 (839 P-days) (Figure A.1).

Specific gravity was significantly affected by harvest date ($p = 0.015$) and desiccation ($p = <0.0001$) in 1997 (Table 4.4). The interaction of harvest date and desiccation was not significant ($p = 0.85$) so these main effects are discussed independently. Specific gravity increased from 1.074 at the early harvest date to 1.077 and 1.078 at the middle and late harvest dates, respectively. Overall, specific gravity was 6 points higher in the untreated controls (1.080) than the vine-killed treatments (1.074). Desiccation reduced specific gravity by 6 points at the early harvest date, 7 points at the middle harvest date, and 6 points at the late harvest date (Figure 4.11A). The reduction in specific gravity was significant at all harvest dates (Table 4.4). The late season application of chlorothalonil and copper hydroxide also had a significant effect ($p = 0.016$) on tuber dry matter content. Specific gravity was consistently lower in the fungicide-treated plots (Figure 4.11B), although the difference was only significant ($p = 0.022$) at the middle harvest date (Table 4.4). Specific gravity also differed significantly ($p = 0.042$) between replicates. Tuber solids were highest in the fourth replicate (1.079; data not shown).

The interaction of the harvest date and desiccation main effects was statistically significant in 1998 ($p = 0.014$) (Table 4.5). The response of specific gravity to vine killing was not consistent across harvests (Figure 4.12). Consequently, the highly significant desiccation effect ($p = 0.003$) is overlooked and only the simple effects reported. At the early harvest date, the specific gravity of tubers from the desiccated

Table 4.4. Analysis of variance and associated contrasts for effects of harvest date and preharvest management on the specific gravity of Russet Burbank potatoes grown at Carberry, MB in 1997.

Source of variation	df	Mean Square
Replication (BLOCK)	3	40.4205494 *
Harvest Date (HVST)	2	64.1783894 *
Desiccation (VINE)	1	384.9091494 ***
HVST X VINE	2	2.1549940 NS
Preharvest Fungicide (FUNG)	1	85.7481518 *
HVST X FUNG	1	7.8562934 NS
VINE X FUNG	1	0.8649660 NS
HVST X VINE X FUNG	1	0.2310722 NS
Error	26	12.8797120
Contrast	**df**	**Mean Square**
Early Harvest - Control vs Diquat	1	78.7512500 *
Middle Harvest - Control vs Diquat	1	205.2056250 ***
Late Harvest - Control vs Diquat	1	117.4824984 **
Middle Harvest - No Preharvest Fungicide vs Preharvest Fungicide	1	76.1256250 *
Late Harvest - No Preharvest Fungicide vs Preharvest Fungicide	1	19.9638544 NS
CV (%)		4.67

***,**,*, and NS indicate significance at 0.001, 0.01 and 0.05 levels of probability and not significant, respectively.

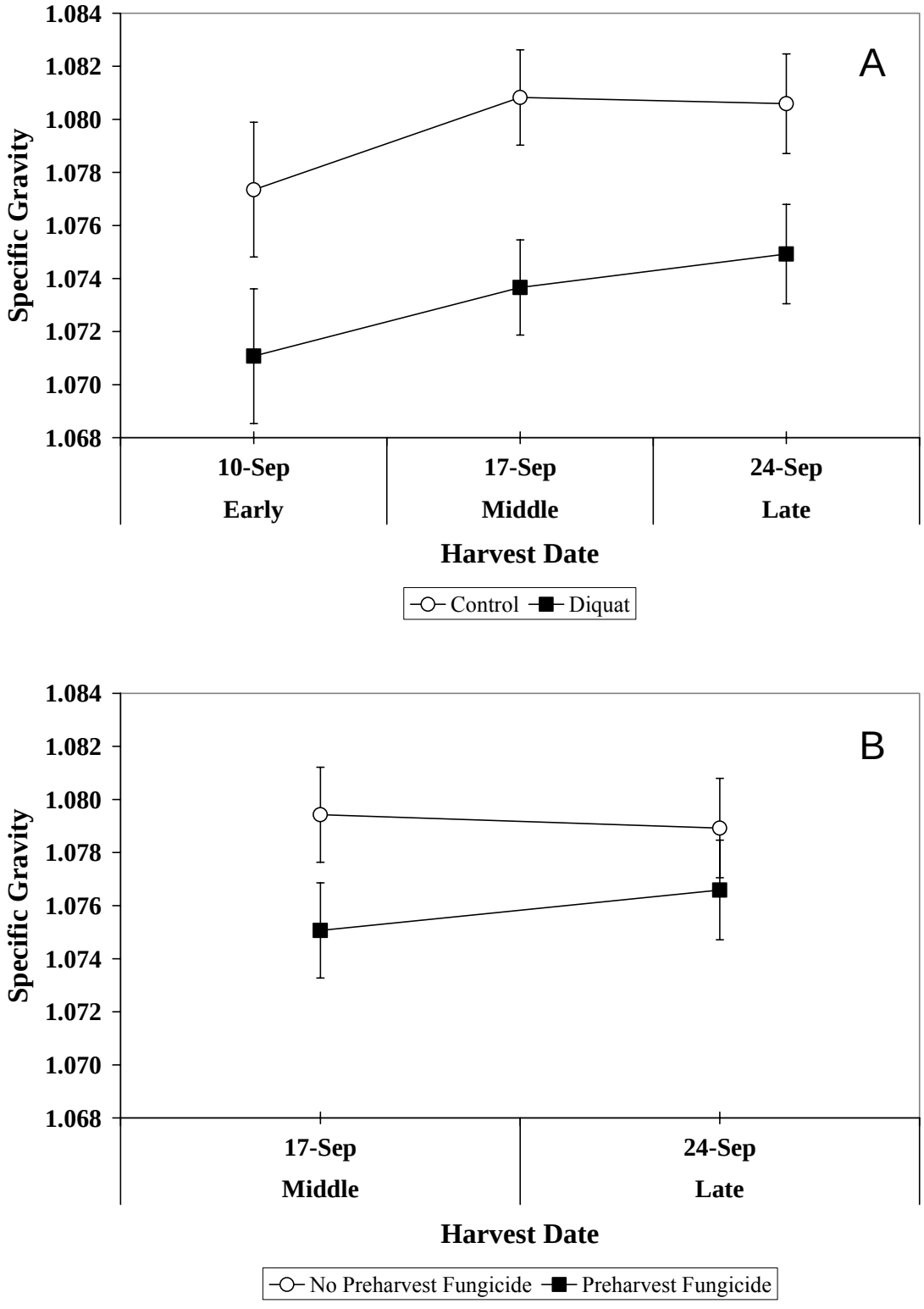


Figure 4.11. Specific gravity as influenced by desiccation (A) and late season fungicide (B) at Carberry, MB in 1997. (Bars represent SEM).

Table 4.5. Analysis of variance and associated contrasts for effects of harvest date and preharvest management on the specific gravity of Russet Burbank potatoes grown at Winkler, MB in 1998.

Source of variation	df	Mean Square
Replication (BLOCK)	3	80.7039550 ***
Harvest Date (HVST)	2	7.3466522 NS
Desiccation (VINE)	1	46.8138905 **
HVST X VINE	2	22.7291922 *
Preharvest Fungicide (FUNG)	1	2.9822239 NS
HVST X FUNG	2	7.7419065 NS
VINE X FUNG	1	0.3028836 NS
HVST X VINE X FUNG	2	4.6109116 NS
Error	28	4.5556774
Contrast	**df**	**Mean Square**
Early Harvest - Control vs Diquat	1	77.0133333 ***
Middle Harvest - Control vs Diquat	1	5.4168168 NS
Late Harvest - Control vs Diquat	1	0.0100000 NS
CV (%)		2.69

***,**,*, and NS indicate significance at 0.001, 0.01 and 0.05 levels of probability and not significant, respectively.

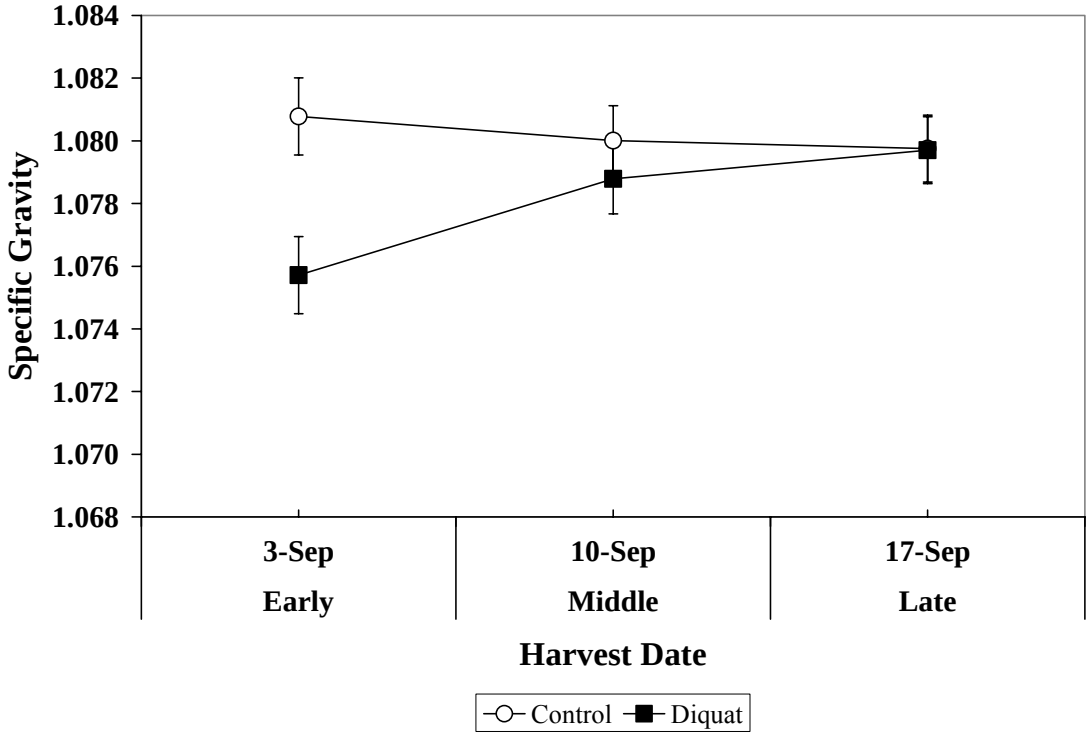


Figure 4.12. Specific gravity as influenced by desiccation at Winkler, MB in 1998. (Bars represent SEM).

treatments (1.076) was significantly lower than that of the untreated control (1.081) ($p = 0.0003$). At the middle and late September harvest dates, tuber solids were higher in the control than the vine-killed treatment, however, the differences were not significant, ($p = 0.28$ and $p = 0.96$, respectively) (Table 4.5). Specific gravity differed significantly ($p = <0.0001$) between replicates. Tuber solids were lowest in the fourth replicate (data not presented). The highly significant replicate effect is attributable to variations in disease progress and canopy decline between replicates. Application of a late season fungicide application had no effect on specific gravity in 1998 ($p = 0.43$) (Table 4.5).

Tuber specific gravity was lowered by 4 to 7 points (0.004 to 0.007) relative to the control and below the 1.080 level desired for processing when vines were killed with diquat at all harvest dates in 1997. Giesel (1985, 1986) reported 4 to 11 point (0.004 to 0.011) reductions in Russet Burbank specific gravity from desiccation although specific gravity was never reduced below 1.080. These results support the analysis of Murphy (1968) that vine killing before "normal vine maturity" reduces specific gravity. As reported in Section 4.2, tubers were actively sizing in late August and early September of 1997. In halting the translocation of sugars from leaves and stems to the tubers, desiccation reduced the specific gravity of the vine killed treatment relative to the control. Water absorbed by the plant's roots after vine killing has also been shown to contribute to lower tuber specific gravity (Wilcockson et al., 1985). A comparison can be made between the specific gravity of the control treatment on the early harvest date (1.0774) and that of the desiccated treatment on the late harvest date (1.0749), which was killed September 10th, the date of the early harvest. In the two week interval, specific gravity

was reduced by 2.5 points (0.0025) in the desiccated treatment. Not only were these tubers no longer accumulating dry matter, but they were also absorbing water, ultimately reducing their specific gravity. Wilcockson (1986) measured a similar rate of decline in specific gravity (1.3 points/week (0.0013/week)) with the variety Pentland Crown after vines were killed with diquat.

The late season application of chlorothalonil and copper hydroxide reduced specific gravity in 1997, compared to not applying a fungicide. This application may have delayed the maturation of the vines, reducing the rate of dry matter accumulation. Alternatively, copper hydroxide has been reported to have phytotoxic effects, and if the vines were stressed as a result of the fungicide application, it is possible that tuber solids were reduced accordingly. However, no obvious phytotoxicity was observed.

The 1997 results also emphasize the importance of the month of September to Russet Burbank tuber quality in Manitoba's short growing season. Warm days and cool nights favour the assimilation of starch in tubers and can lead to substantial increases in specific gravity late in the season (Halderson et al., 1988). Tuber solids were still increasing in mid-September, although a killing frost on September 20th prevented the specific gravity from increasing further at the late harvest date. In contrast, tuber solids of Russet Burbank peak and sometimes decline towards the end of the season in areas such as Idaho which have longer production seasons (Werner et al., 1998).

The response of specific gravity to desiccation is more difficult to interpret for the 1998 results. As late blight developed rapidly on the foliage in late August and early September, the control treatments senesced, often as quickly as the vine-killed treatments (Section 4.1). The only significant reduction in specific gravity occurred at the early

harvest date (5 points), for which vines were initially desiccated August 21st. The vines in the control treatment were still building tuber dry matter through this period as foliar disease levels did not exceed 50% until September 1st. In contrast, on September 3rd, when the desiccation treatment for the late harvest was initiated, average disease severity was >75%. Consequently, vine killing did not reduce tuber dry matter to the same degree at the middle and late harvest dates. The link between defoliating diseases like late blight and lower tuber dry matter is well documented (Stark and Love, 2003).

As in 1997, water uptake after desiccation appears to have reduced specific gravity in the vine-killed treatment. The specific gravity of the desiccated treatment on the late harvest date (1.0797) was lower than that of the control treatment on the early harvest date (1.0808). The 1.1 point decrease over two weeks was smaller than the 2.5 point decrease in 1997, perhaps because roots were less active in absorbing water due to the advanced maturity (Wilcockson, 1986). The downward trend in the tuber solids of the control treatment between harvests is most probably linked to the same phenomena.

4.4 Process Quality

4.4.1 Sucrose

4.4.1.1 Preharvest Sucrose

Sucrose levels were tracked prior to harvest beginning in mid-August. Sucrose monitoring was used as an indicator of the relative maturity of the crop in each year (Sowokinos and Preston, 1988). In both years, sucrose levels were >2 mg g^{-1} on the date of the first application of diquat, 2 weeks before the early harvest date (Figure 4.13). Sucrose content decreased in late August as the crop matured dropping below 2 mg g^{-1} in

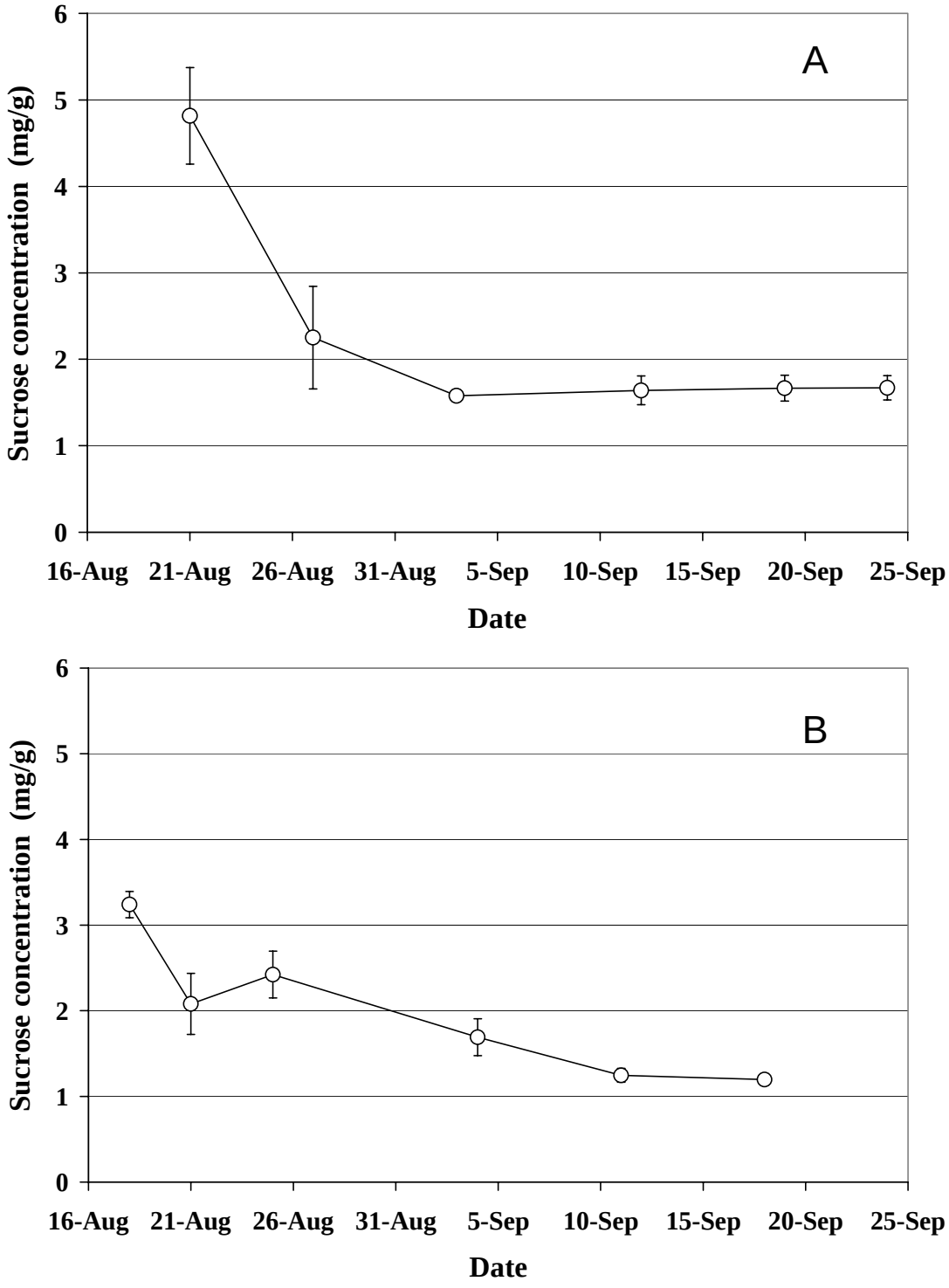


Figure 4.13. Preharvest sucrose concentration as influenced by time of sampling at Carberry, MB in 1997 (A) and Winkler, MB in 1998 (B). The initial application of diquat for the early harvest was on August 27 in 1997 and August 21 in 1998. (Bars represent SEM).

both years by September 1st (Figure 4.13). Similar trends in sucrose content in maturing Russet Burbank tubers were reported by Iritani and Weller (1977) and Pritchard and Adam (1992).

In 1997, tubers were also sampled from the desiccated treatments on September 3rd, one week after the first application of diquat to these plots. Sucrose levels were lower in tubers sampled from desiccated vines (1.19 mg g^{-1}) compared to the control (1.58 mg g^{-1}) (data not shown).

4.4.1.2 Sucrose at Harvest

Sucrose concentrations at the time of all harvests in 1997 and 1998 were below <1.75 mg g^{-1}, levels characteristic of tubers at chemical maturity (Figure 4.14A and Figure 4.15A). Russet Burbank tubers with sucrose levels of <2.8 mg g^{-1} at harvest are referred to as chemically mature and process acceptably out of long term storage (Pritchard, 1993b). Differences in the sucrose level at the time of harvest were not observed, except in 1998 when the sucrose level at harvest was notably higher in tubers on the early harvest date. Desiccation did not lead to a significant reduction in the sucrose level at harvest in either year (Figure 4.14B and Figure 4.15B).

4.4.1.3 Storage Sucrose

Average sucrose content in storage was lower in 1998 (0.68 mg g^{-1}) than in 1997 (0.83 mg g^{-1}). The lower sucrose levels in storage reflect the earlier maturity of the crop in 1998 compared to 1997. The average P-day accumulation at harvest was 29 P-days higher in 1998 (868 P-days) than in 1997 (839 P-days) (Figure A.1).

In 1997, sucrose levels decreased gradually in storage from an average of 1.62 mg g^{-1} at harvest to 0.92 mg g^{-1} 7 weeks later and 0.24 mg g^{-1} 29 weeks later (Figure 4.14A). The repeated measures analysis of variance reported highly significant harvest date ($p = <0.0001$) and desiccation effects ($p = 0.008$) on sucrose concentration in storage (Table 4.6).

Although sucrose levels measured at the time of harvest were similar in 1997, treatment effects were apparent in the first sample taken from storage 7 weeks later (Figure 4.14B). The sucrose content of tubers from vines killed with diquat was lower than that of tubers from non-desiccated vines for much of the storage period (means 0.77 mg g^{-1} and 0.90 mg g^{-1}, respectively). Tubers from the late September harvest maintained a higher average sucrose concentration (0.97 mg g^{-1}) during storage than tubers from the early (0.79 mg g^{-1}) or middle (0.72 mg g^{-1}) harvest dates (Figure 4.14A). A -3.4°C frost September 20th, four days before the late harvest, is likely responsible for the higher sucrose levels during storage (Pritchard and Adam, 1992). Others have reported that low storage temperatures result in increased sucrose formation (Coffin et al., 1987; Gichohi and Pritchard, 1995).

Storage sucrose levels dropped rapidly in 1998 from an average of 1.41 mg g^{-1} at harvest to 0.28 mg g^{-1} 6 weeks later and remained low (0.35 mg g^{-1} at 17 weeks after harvest) until the last assessment was made 30 weeks after harvest (0.68 mg g^{-1}) (Figure 4.15A). At that time tubers were beginning to sprout which may account for the increased sucrose concentrations measured (van Es and Hartmans, 1987b), although no concurrent increase in glucose levels was observed (Figure 4.17A). As in 1997, the between-subjects effects harvest date ($p = <0.0001$) and desiccation ($p = 0.037$) significantly affected

Table 4.6. Repeated measures analysis of variance for effects of harvest date and preharvest management storage processing quality of Russet Burbank potatoes grown at Carberry, MB in 1997.

Carberry - 1997

Source of variation	df	Mean Square		
		Sucrose	Glucose	Fry Colour
Replication (BLOCK)	3	0.0906 ^{NS}	0.3923 *	0.3190 ^{NS}
Harvest Date (HVST)	2	0.9933 ***	1.1486 ***	1.6069 ***
Desiccation (VINE)	1	0.5667 **	0.0581 ^{NS}	0.0147 ^{NS}
HVST X VINE	2	0.0229 ^{NS}	0.9210 ***	0.2066 ^{NS}
Preharvest Fungicide (FUNG)	1	0.0946 ^{NS}	0.0079 ^{NS}	0.1880 ^{NS}
HVST X FUNG	1	0.0126 ^{NS}	0.0471 ^{NS}	0.6153 ^{NS}
VINE X FUNG	1	0.0004 ^{NS}	0.4790 *	0.4471 ^{NS}
HVST X VINE X FUNG	1	0.0430 ^{NS}	0.0339 ^{NS}	0.2580 ^{NS}
Error	26	0.0676	0.0967	0.1617

***,**,*, and NS indicate significance at 0.001, 0.01 and 0.05 levels of probability and not significant, respectively.

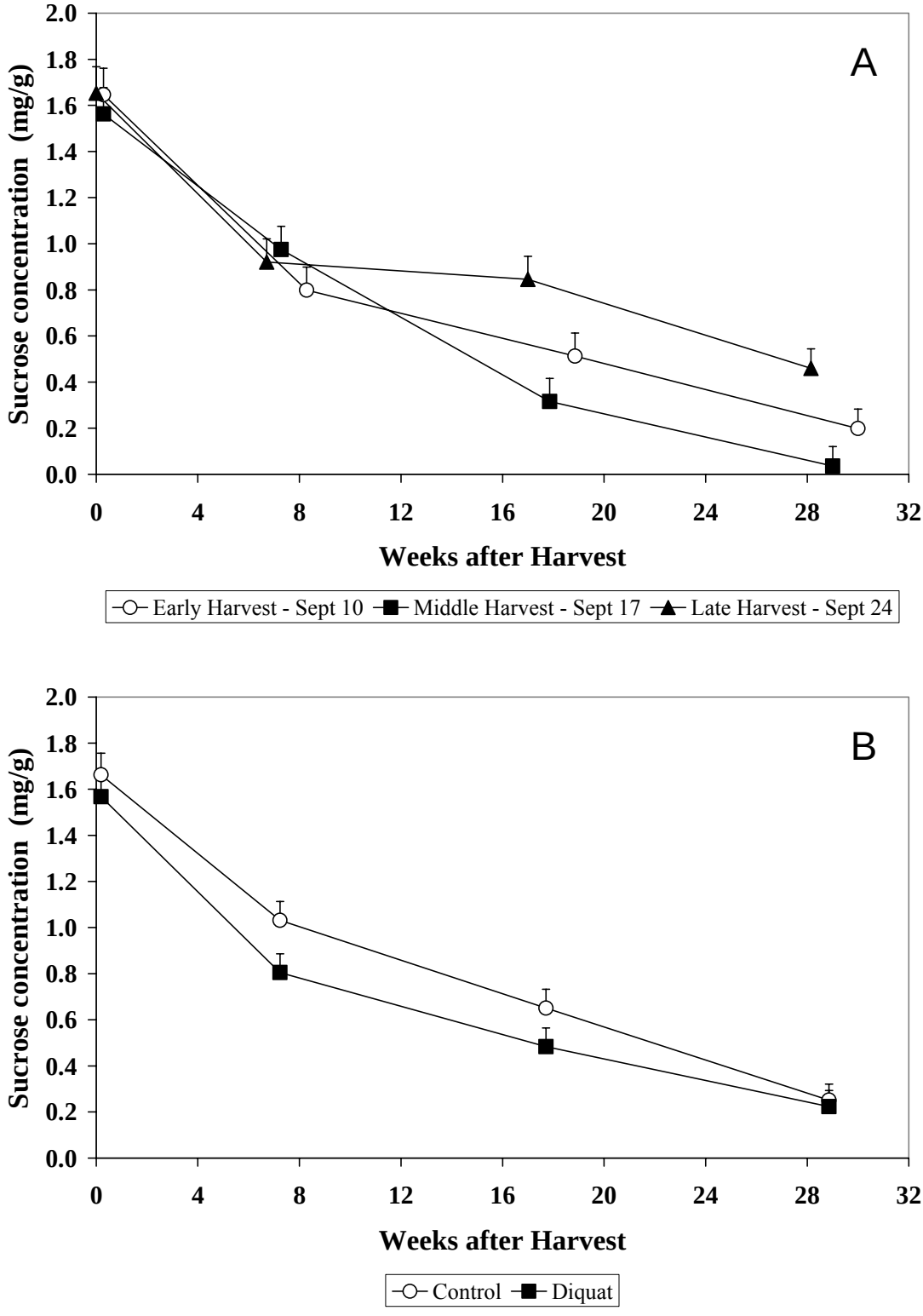


Figure 4.14. Storage sucrose concentration as influenced by time of harvest (A) and desiccation (B) at Carberry, MB in 1997. (Bars represent SEM).

Table 4.7. Repeated measures analysis of variance for effects of harvest date and preharvest management on the storage processing quality of Russet Burbank potatoes grown at Winkler, MB in 1998.

Winkler - 1998

Source of variation	df	Mean Square		
		Sucrose	Glucose	Fry Colour
Replication (BLOCK)	3	0.0228 ^{NS}	0.0276 ^{NS}	0.4005 ^{NS}
Harvest Date (HVST)	2	1.9078 ***	0.3333 ***	0.5506 *
Desiccation (VINE)	1	0.1541 *	0.0258 ^{NS}	1.3846 **
HVST X VINE	2	0.0267 ^{NS}	0.0136 ^{NS}	0.3201 ^{NS}
Preharvest Fungicide (FUNG)	1	0.0333 ^{NS}	0.1487 *	0.0004 ^{NS}
HVST X FUNG	2	0.1072 ^{NS}	0.0283 ^{NS}	0.0074 ^{NS}
VINE X FUNG	1	0.0204 ^{NS}	0.0408 ^{NS}	0.2833 ^{NS}
HVST X VINE X FUNG	2	0.0546 ^{NS}	0.0047 ^{NS}	0.1508 ^{NS}
Error	28	0.0321	0.0274	0.1455

***,**,*, and NS indicate significance at 0.001, 0.01 and 0.05 levels of probability and not significant, respectively.

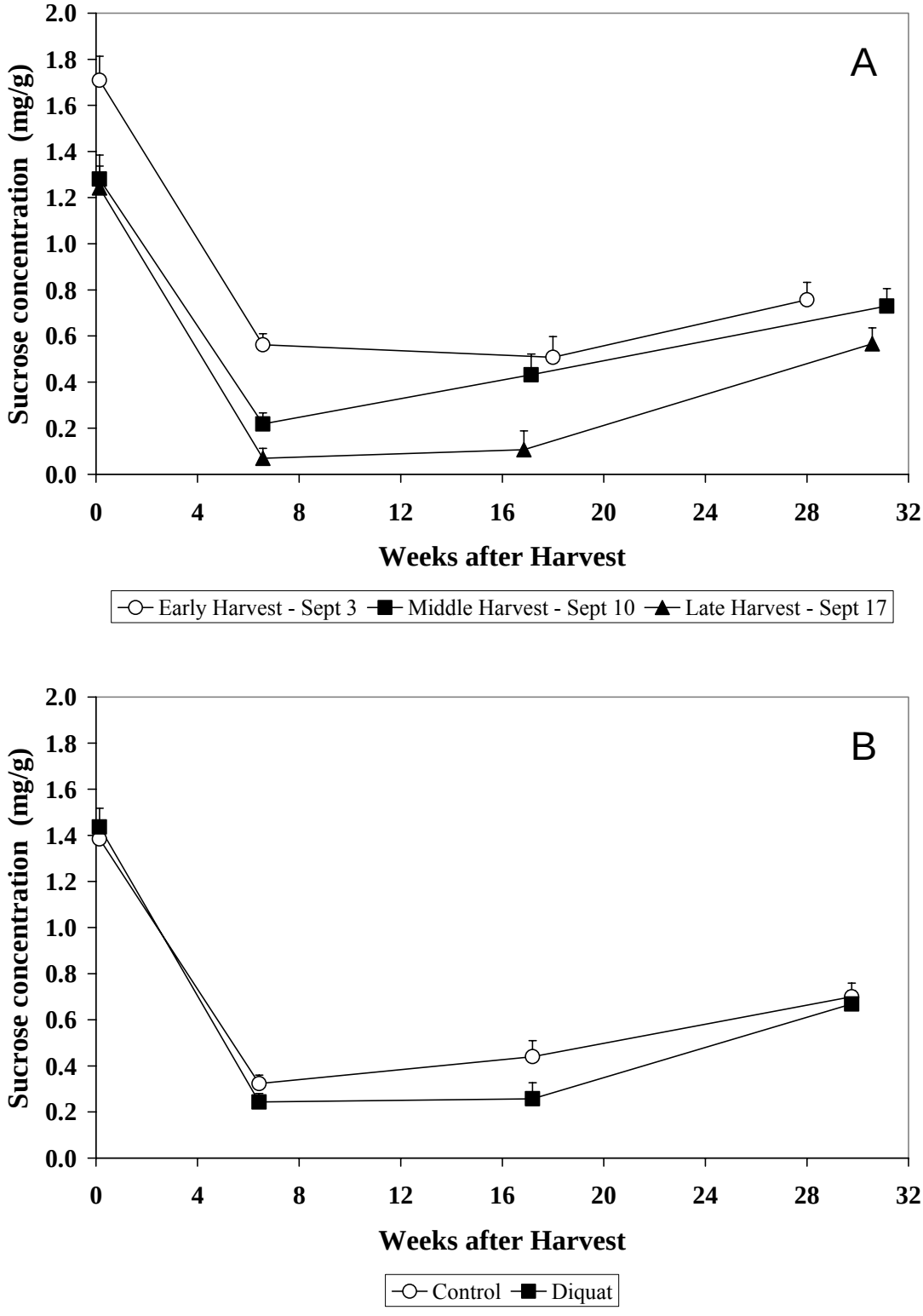


Figure 4.15. Storage sucrose concentration as influenced by time of harvest (A) and desiccation (B) at Winkler, MB in 1998. (Bars represent SEM).

sucrose levels in storage in 1998 (Table 4.6).

Sucrose levels were lower in tubers from desiccated vines than non-desiccated vines in 1998 (means 0.65 mg g^{-1} and 0.71 mg g^{-1}, respectively) (Figure 4.15B). The effect of desiccation on storage sucrose concentration was less pronounced than in 1997, except at the early harvest date (data not shown). As anticipated, the average sucrose content of tubers from the early harvest (mean 0.88 mg g^{-1}) was higher than that of the middle (mean 0.67 mg g^{-1}) or late (mean 0.50 mg g^{-1}) harvest dates (Figure 4.15A).

Lower sucrose levels were measured in tubers from desiccated vines when samples were taken one week before the early harvest in 1997. However, at the time of the early harvest, and at subsequent harvest dates, no significant reduction in sucrose concentration was observed in either 1997 or 1998. These results are similar to those reported by Duncan and Boyd (1986) and Halderson (1989). If tubers had been chemically immature at the time of harvest, the effect of desiccation may have been more evident.

Vine killing did significantly reduce sucrose levels in storage in both years of the study. Larger differences in storage sucrose concentration were observed between the control and vine-killed treatment in 1997, than in 1998. In 1998, the vine maturity of the control treatments was approaching that of the vine-killed treatments, so it is expected that the response would be less evident.

The lower sucrose level in tubers from the vine-killed treatment did not result in reduced glucose levels in storage (Section 4.4.2.2) or improved french fry colour (Section 4.4.3.2).

4.4.2 Glucose

4.4.2.1 Glucose at Harvest

In 1997, glucose levels at the time of harvest were higher in tubers from the early and late harvest dates than from the middle harvest (Figure 4.16). The higher glucose concentration in tubers from the early harvest reflects the immaturity of the tubers on that date. The higher glucose levels in tubers at the late harvest are as a result of low temperature sweetening caused by frosts on September 20th and 23rd. The increase in glucose due to tuber chilling was greater in the vine-killed treatment than the non-desiccated control (Figure 4.16C). No differences in glucose levels at the time of harvest were observed over the three harvest dates in 1998 (Figure 4.17A). Desiccation had no effect on the glucose level at harvest in either year, with the exception of the late harvest date in 1997 as previously noted.

4.4.2.2 Storage Glucose

Glucose levels increased in storage in 1997 from an average of 0.52 mg g^{-1} at harvest to 1.82 mg g^{-1} 7 weeks later before leveling off and holding above 1.5 mg g^{-1} when measured at 18 and 29 weeks after harvest (Figure 4.16). Harvest date ($p = 0.0002$), and the interactions of harvest date X desiccation ($p = 0.0008$) and desiccation X fungicide ($p = 0.035$) were determined to have significant effects on glucose concentration in storage (Table 4.6).

The highly significant harvest date X desiccation interaction arises from the differing response of storage glucose levels to vine killing at the early and late harvest dates. Compared to the non-desiccated control, vine killing reduced glucose levels at the

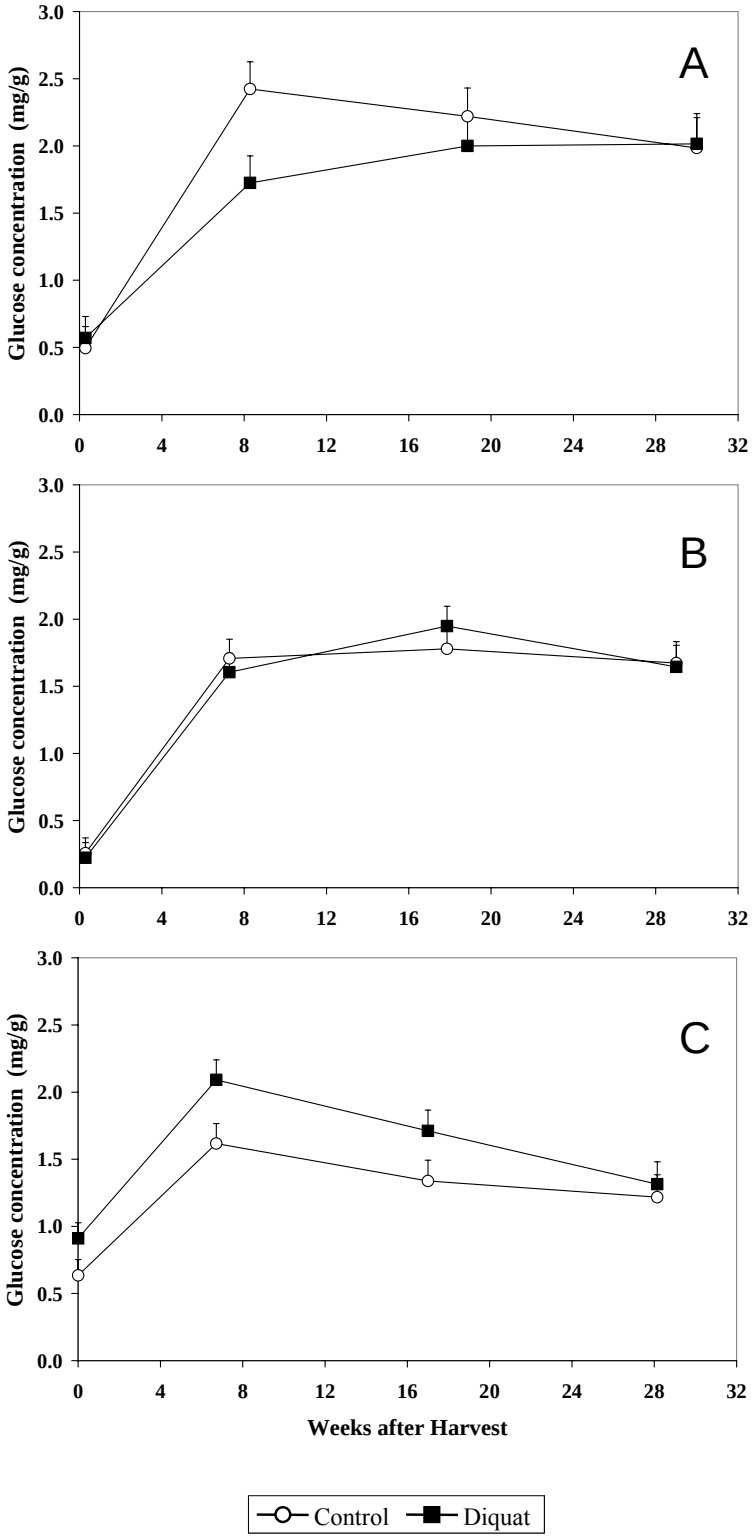


Figure 4.16. Storage glucose concentration as influenced by desiccation at Carberry, MB in 1997. A = Early Harvest – Sept 10. B = Middle Harvest – Sept 17 C = Late Harvest – Sept 24. (Bars represent SEM).

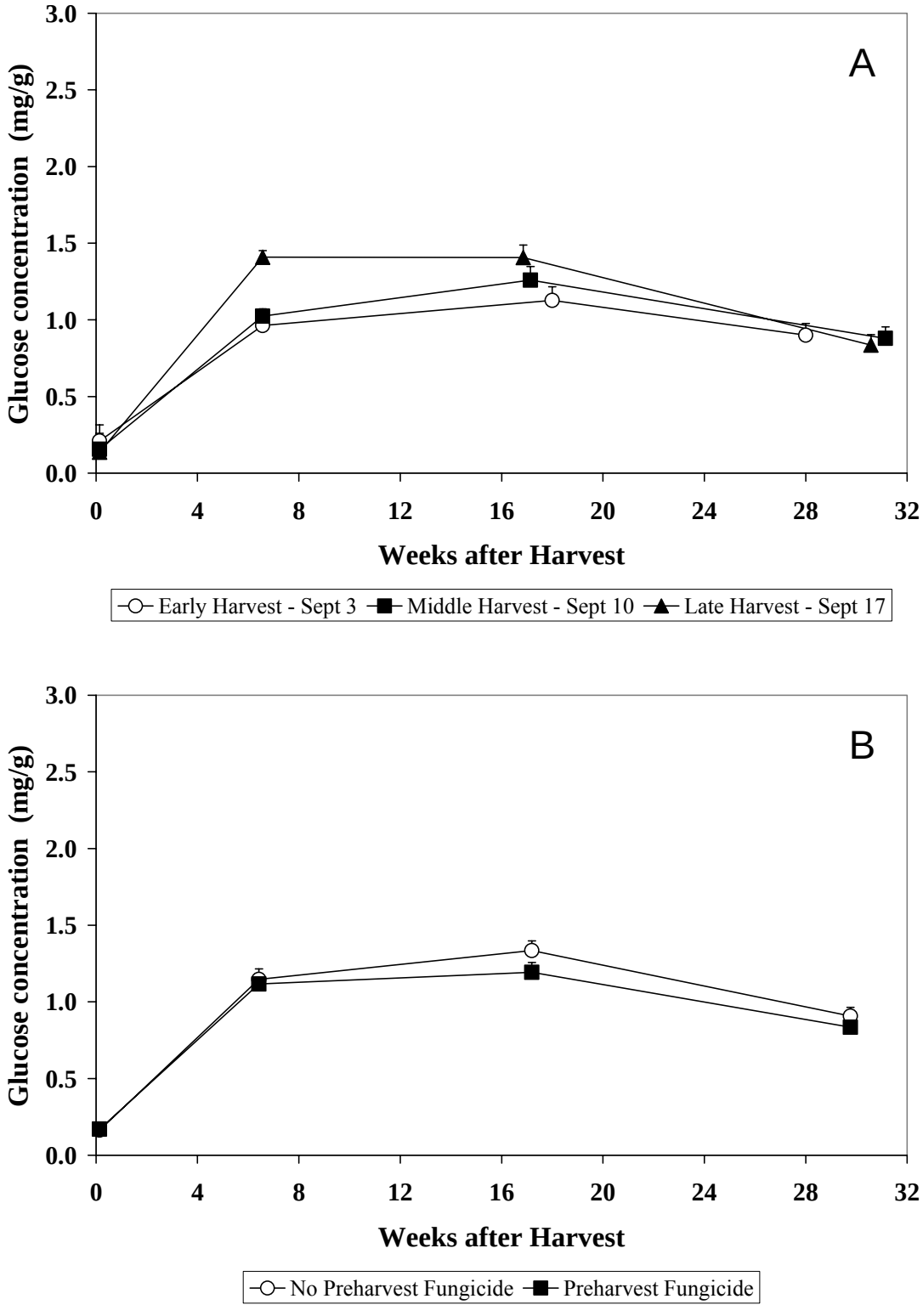


Figure 4.17. Storage glucose concentration as influenced by time of harvest (A) and late season fungicide (B) at Winkler, MB in 1998. (Bars represent SEM).

early harvest (means, 1.78 mg $g^{-1}$and 1.58 mg g^{-1}, respectively) but increased concentrations at the late harvest (means, 1.20 mg g^{-1} and 1.51 mg g^{-1}, respectively). The effect of desiccation on storage glucose levels was variable for the middle harvest date. Although the desiccation X fungicide interaction was statistically significant, no identifiable trends were observed with respect to this interaction. Glucose levels in storage differed significantly between replicates ($p = 0.017$) (Table 4.6).

In 1998, glucose concentration during storage followed a trend similar to that observed in 1997, however, levels stayed markedly lower overall. From an average of 0.17 mg g^{-1} at harvest, glucose levels had increased 6-fold to 1.13 mg g^{-1} when measured 7 weeks later. Glucose concentration held steady until a small decrease was measured 29 weeks after harvest (0.87 mg g^{-1}) (Figure 4.17). The repeated measures analysis of variance revealed significant harvest date ($p = 0.0002$) and fungicide effects ($p = 0.027$) on glucose concentration in storage (Table 4.6). Desiccation did not significantly affect glucose levels in storage ($p = 0.34$) in 1998.

Tubers from the late September harvest maintained a higher average glucose concentration (0.95 mg g^{-1}) during storage than tubers from the early (0.80 mg g^{-1}) or middle (0.83 mg g^{-1}) harvest dates (Figure 4.17A). Tubers from vines sprayed with chlorothalonil and copper hydroxide before harvest maintained a slightly lower glucose concentration in storage (mean, 0.83 mg g^{-1}) than tubers from vines which received no preharvest fungicide application (mean, 0.89 mg g^{-1}) (Figure 4.17B).

Fuller and Hughes (1984) reported that the ratio of glucose to fructose is roughly 1:1 in stored tubers of the cv Record and that glucose levels measured with a YSI

biochemical analyzer could be used to accurately predict total reducing sugars. Gichohi and Pritchard (1995) also found that levels of glucose and fructose tracked similarly in storage Russet Burbank. Consequently, the glucose concentration in tubers was measured as an indicator of total reducing sugars.

Lower average glucose levels in storage in 1998 (0.86 mg g^{-1}) compared to 1997 (1.42 mg g^{-1}) reflect the superior chemical maturity of the crop in 1998 (Section 4.4.1.2). The link between low sucrose levels at harvest and lower reducing sugar levels in storage is well established. However, significantly lower storage sucrose levels observed in tubers from desiccated vines in 1997 and 1998 did not result in lower glucose levels in storage, except at the early harvest date in 1997. Vine killing resulted in increased glucose levels in storage for tubers from the late harvest. This seemed to be related to freezing temperatures that occurred in the interval between vine killing and harvest. Without the protection afforded by green vines, tubers in the desiccated treatment would have been more exposed to chilling and, as Walsh (1995b) suggested, more prone to sweetening.

With the advanced vine maturity of the control treatment at the middle and late harvest dates in 1998, it is not surprising that there was not a significant desiccation effect on glucose levels in storage. It is noteworthy that storage glucose levels were highest for the late harvest in 1998. The higher glucose concentration at the late harvest date was not in response to low temperature stress as it was at the late harvest date in 1997. These results suggest that vine death, by desiccation or disease, may lead to higher glucose levels in storage in certain circumstances. Knowles et al. (2001) reported that vine killing led to earlier and greater accumulations of reducing sugars in stored Ranger Russet.

Walsh (1995b) also found that desiccated tubers were more prone to reducing sugar increases after harvest. Knowles et al. (2001) found tuber respiration rates in storage were higher when vines were not desiccated and suggested this might account for differences in storage sweetening due to more rapid utilization of the free sugars.

Marginally higher glucose levels in storage were observed in tubers from vines which were not sprayed with a fungicide before harvest. This effect is difficult to explain and may not represent a true response.

Based on the 1.6 mg g^{-1} threshold put forward by Pritchard and Adam (1994) for glucose concentration in storage, fry colour would have been darker than required for maximum bonus during much of the storage season in 1997 but light enough to earn full colour bonus in 1998.

4.4.3 French Fry Colour

4.4.3.1 Harvest French Fry Colour

Fry colour at the time of harvest was acceptable in all treatments in both years of this study. In 1997, french fry colour was darker at the early and late harvest dates than the middle harvest (Figure 4.18). No differences between treatments or harvest dates were observed in the french fry colour at the time of harvest in 1998 (Figure 4.19A).

4.4.3.2 Storage French Fry Colour

French fry colour deteriorated in storage in 1997 from an average U of M french fry colour of 2.5 at harvest to a score of 3.5 seven weeks later. French fry colour continued to be darker than 3.5 when tubers were fried 18 and 29 weeks after harvest

(Figure 4.18). Only harvest date ($p = 0.0006$) was found to have a significant effect on storage french fry colour in 1997 (Table 4.6).

Average fry colour was darkest in tubers from the early harvest date (3.6), followed by the late harvest date (3.4), and lightest in tubers from the middle harvest date (3.2). While the effect of vine killing on fry colour out of storage was not significant overall, average french fry colour was lighter from the desiccated treatment (3.6) than the control treatment (3.7) at the early harvest date. In contrast, french fry colour was darker in the vine-killed treatment (3.4) than the non-desiccated control (3.3) at the late harvest date. As reported earlier, the darker fry colour at the late harvest date appears to be linked to low temperature sweetening.

Fry colour was notably lighter in 1998 (mean, 2.7) than 1997 (mean, 3.3) (Figures 4.18 and 4.19A). From an average fry score of 2.1 at harvest, fry colour declined in storage to between 2.8 and 3.1 for the remainder of the 1998 storage season (Figure 4.19A). The repeated measures analysis of variance indicated significant harvest date ($p = 0.035$) and desiccation effects ($p = 0.005$) on french fry colour in storage.

Tubers from the late September harvest in 1998 maintained slightly better average fry colour (2.6) during storage than tubers from the early (2.7) or middle (2.8) harvest dates. Although there was no significant effect of desiccation on glucose levels in 1998, tubers from vines desiccated with diquat produced darker french fries out of storage (mean, 2.8) than tubers from the control treatment (mean, 2.6) (Figure 4.19B). This effect was most apparent at the middle and late harvest dates (data not shown).

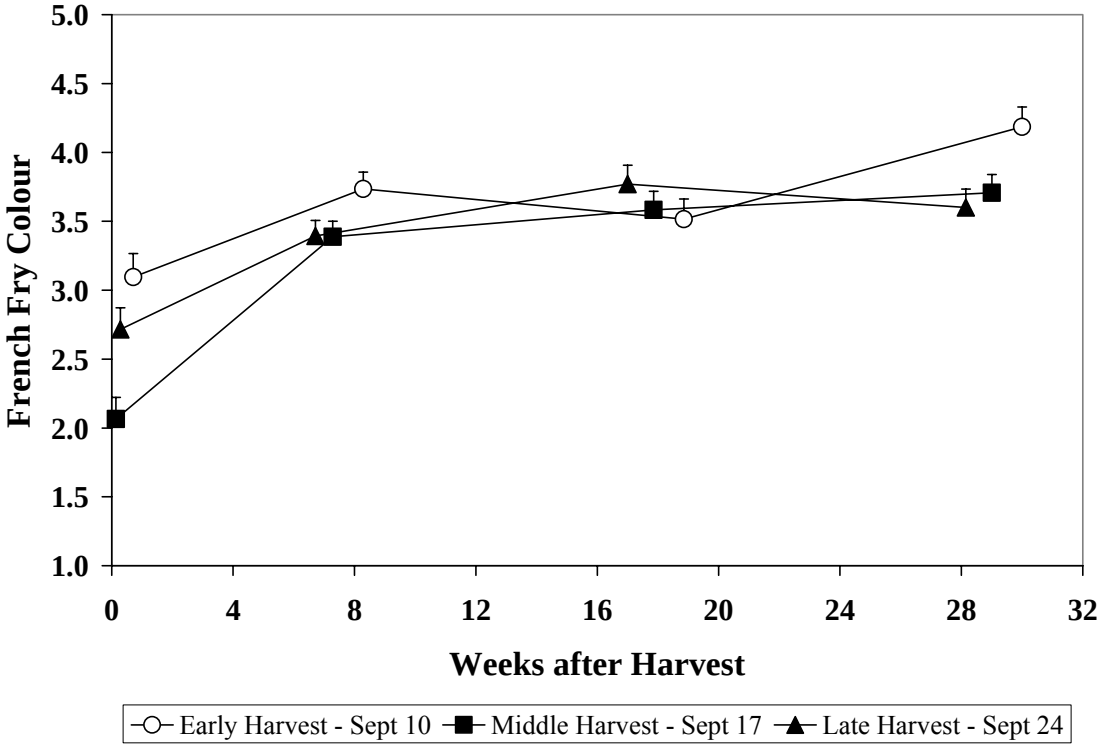


Figure 4.18. Storage french fry colour as influenced by time of harvest at Carberry, MB in 1997. (Bars represent SEM).

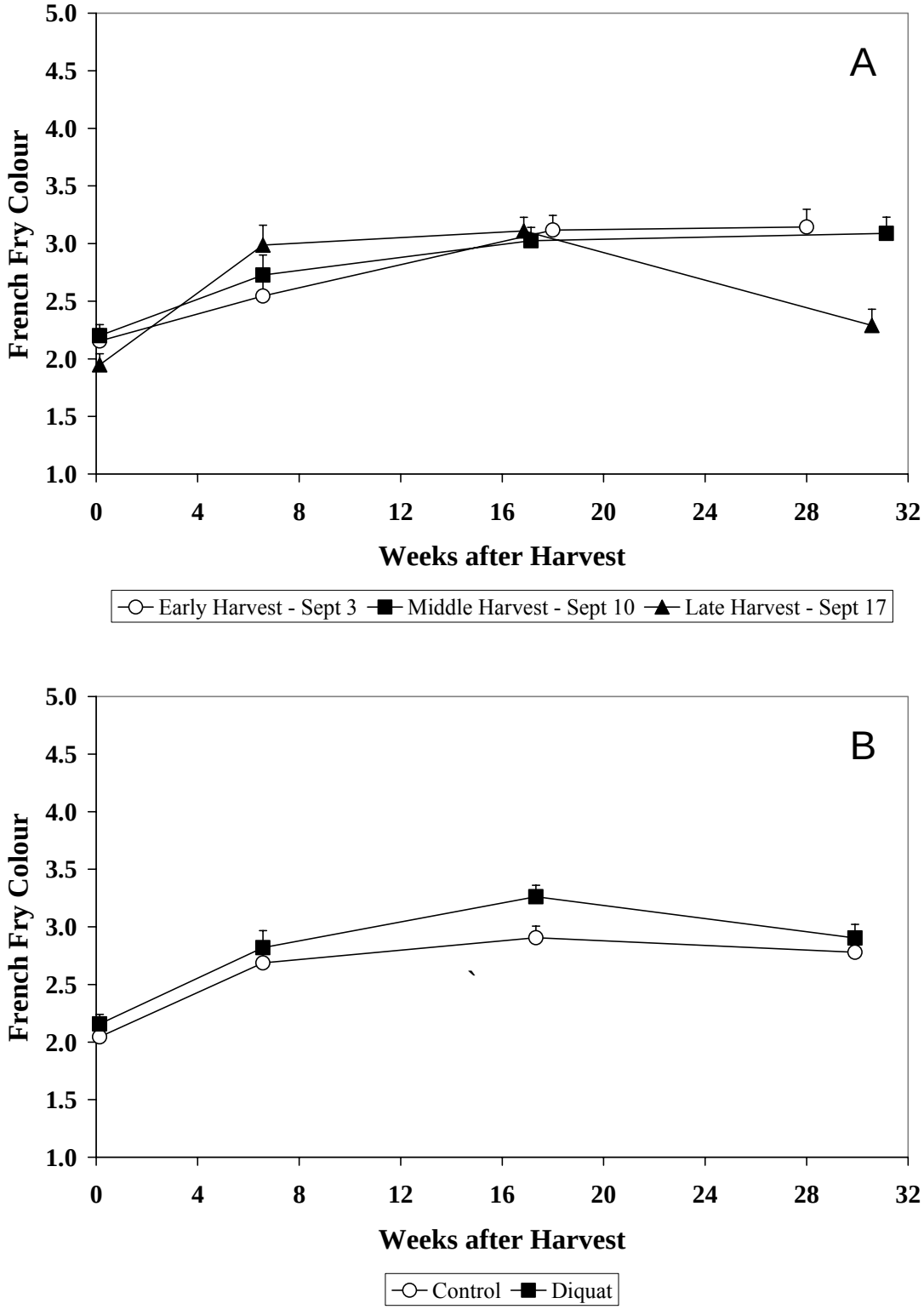


Figure 4.19. Storage french fry colour as influenced by time of harvest (A) and desiccation (B) at Winkler, MB in 1998. (Bars represent SEM).

A uniform light brown finish-fried colour is desirable for both french-fried potatoes and potato chips. Ensuring that there is a year-round supply of potatoes which meet the specifications of the processing industry is a challenge, particularly with fry colour. Earlier research has shown that a fry colour of 3.5 (on the 1-7 U of M colour scale) or lower is required to attain maximum colour bonus on processing contracts in Manitoba (Pritchard and Adam, 1994).

Storage french fry colour was at or slightly darker than 3.5 for much of the storage period in 1997, whether tubers were harvested from desiccated vines or not. Tubers from all treatments in 1998 produced fry colours that would have earned maximum bonus out of storage. These results highlight the importance of chemical maturity to better storage fry colour, a relationship often reported for late maturing varieties like Russet Burbank (Pritchard, 1993a).

Vine killing did not improve fry colour at harvest or out of storage in 1997 and, in 1998, caused a small but significant reduction in the processing quality of tubers from storage. The storage fry colour results from 1998 do not reflect the trends observed for storage glucose levels.

4.4.4 Relationship between Glucose concentration and French Fry Colour

The concentration of reducing sugars is a major factor influencing the acceptability of potatoes for processing as chips or french fries. Fuller and Hughes (1984) reported strong correlations between fry colour and either glucose, fructose or total reducing sugars measured from the same region of the tuber, regardless of whether colour was measured objectively or subjectively. Pritchard and Adam (1994) demonstrated that

the fry colour of Russet Burbank potatoes is more closely associated with glucose concentration than with fructose, total reducing sugars, sucrose, or total sugars. Since fry colour and glucose concentration were determined using the same tubers, it was anticipated that changes in french fry colour during the storage period would mirror changes in the glucose levels in tubers.

French fry colour was closely associated with glucose concentration for the combined 1997 and 1998 data (r^2 = 0.57) (Figure 4.20). Similar coefficients of determination were reported for fry colour and glucose in Russet Burbank by Pritchard and Adam (1994) and Gichohi and Pritchard (1995). The correlation between fry colour and sucrose was low (r^2 = 0.17) (data not shown), as has been the finding of others (Mazza, 1983b; Pritchard and Adam, 1994; Gichohi and Pritchard, 1995).

Using the regression equation for fry colour and glucose level for 1997 and 1998, tubers with a glucose concentration below 1.7 mg g^{-1} would produce a fry colour of 3.5 or less and earn maximum colour bonus under Manitoba french fry processing contracts (Figure 4.20). Pritchard and Adam (1994) reported a similar threshold glucose concentration for maximum Russet Burbank colour bonus in their study (1.6 mg g^{-1}).

4.4.5 Stem-end Discolouration

No stem-end discolouration (SED) was observed in tubers from vines that were desiccated for harvest in the fall of 1997. Some vascular discolouration was observed in tubers from the 1998 harvest (data not presented). However, the discolouration was not consistently observed at the stem end of tubers, or in tubers from the desiccated treatment. It is probable that the vascular discolouration observed was net necrosis caused

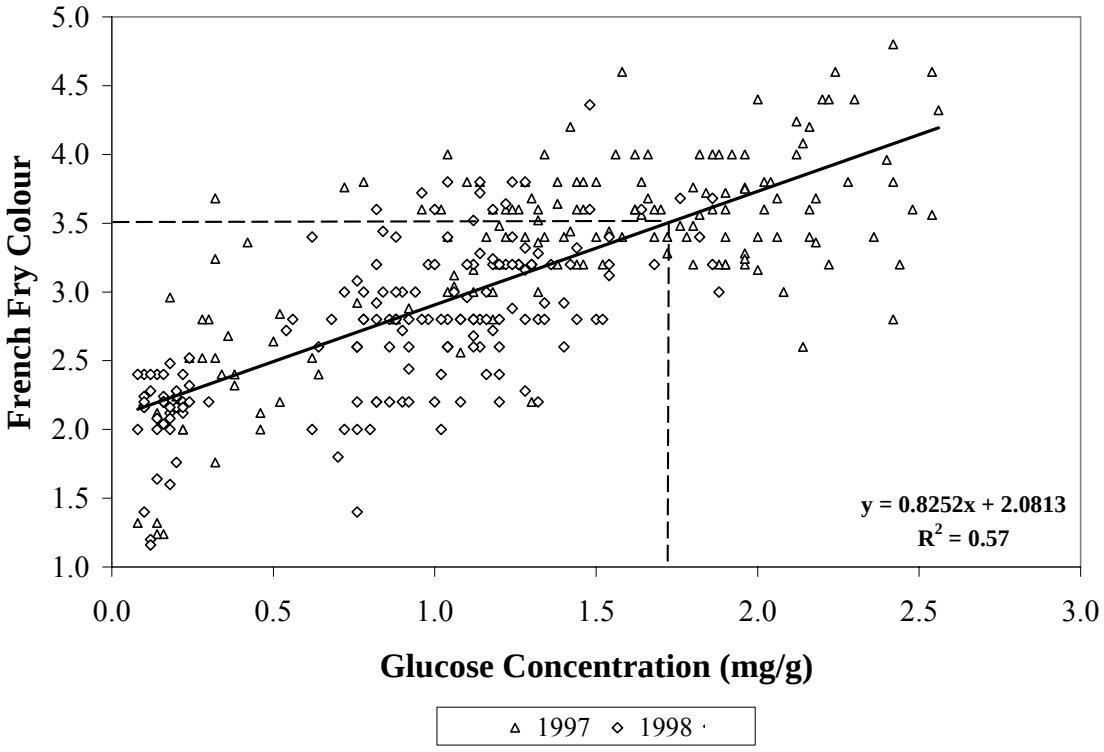


Figure 4.20. Relationship between storage glucose concentration and fry colour at Carberry, MB in 1997 and Winkler, MB in 1998.

by the potato leaf roll virus, a disease that was prevalent in the southern Manitoba in 1998 (Manitoba Agriculture, 1998a).

Past research has implicated vine maturity, soil moisture at the time of vine kill and type of desiccant as factors that influence the level of tuber SED. In this study, vines of varying maturity were desiccated under a range of conditions without causing SED. While recommendations for minimizing SED should be followed, the relative importance of vine maturity and environmental conditions in SED development remains in question (Olson et al., 2003).

4.5 Skin-set

Skin-set varied between treatments and years ranging from 270 to 362 mN•m in 1997 and 287 to 359 mN•m in 1998 (data not shown). Resistance to skinning was significantly higher ($p = 0.006$) in 1998 (332 mN•m) compared to 1997 (324 mN•m) (Table A.1).

In 1997, pre-harvest skin-set measurements were taken September 3rd from the early harvest treatments, seven days after the first application of diquat to the vine-killed treatments. Resistance to skinning was marginally but not significantly higher ($p = 0.051$) in tubers from the vine-killed treatment (221 mN•m) compared to the control (200 mN•m), one week after desiccation (data not shown). Similar results have been reported by others (James, 1993a; Pavlista, 2002). This finding is in keeping with the recommendation given in most production areas to delay harvest for 14 to 21 days after vine killing to allow for adequate skin-set development (Stark and Love, 2003).

The analysis of variance of skin-set measurements collected in 1997 revealed a significant harvest date X desiccation interaction ($p = 0.047$) (Table 4.7). Resistance to skinning was consistently higher in tubers from the desiccated treatments, however, the response of skin-set to vine killing was not as marked at the late harvest date (Figure 4.21A). Nevertheless, a discussion of the highly significant response of skin-set to the main effects of harvest date ($p = <0.0001$) and desiccation ($p = <0.0001$) is justified. Mean resistance to skinning increased from 293 mN•m at the early harvest date to 323 mN•m and 341 mN•m at the middle and late harvest dates, respectively. Vine-killed treatments, on average, exhibited superior skin-set (343 mN•m) over the control treatments (305 mN•m). Resistance to skinning was higher in the desiccated treatments at each harvest date (Figure 4.21A), although the difference was not significant ($p = 0.06$) at the late harvest date. A significant harvest date X fungicide interaction ($p = 0.039$) was also observed in 1997. Application of chlorothalonil and copper hydroxide resulted in significantly lower skin-set readings at the middle harvest date ($p = 0.040$), however, the results were reversed at the late harvest date (Figure 4.21B).

The interaction of the harvest date and desiccation main effects was also statistically significant in 1998 ($p = 0.045$) (Table 4.8). The response of skin-set to desiccation was not consistent over the three harvest dates (Figure 4.22). Consequently, the highly significant harvest date effect ($p = <0.0001$) is overlooked and only the simple effects reported. At the early harvest date, the skin-set of tubers from the desiccated treatments (319 mN•m) was significantly higher than that of the untreated control (291 mN•m) ($p = 0.017$). At the middle and late September harvest dates, skin-set readings were numerically higher in the control than the vine-killed treatment, although the

Table 4.8. Analysis of variance and associated contrasts for effects of harvest date and preharvest management on the skin-set of Russet Burbank potatoes grown at Carberry, MB in 1997.

Source of variation	df	Mean Square
Replication (BLOCK)	3	148.37 ^{NS}
Harvest Date (HVST)	2	5549.62 ***
Desiccation (VINE)	1	14275.12 ***
HVST X VINE	2	1249.74 *
Preharvest Fungicide (FUNG)	1	244.14 ^{NS}
HVST X FUNG	1	1717.05 *
VINE X FUNG	1	0.05 ^{NS}
HVST X VINE X FUNG	1	72.44 ^{NS}
Error	26	362.81
Contrast	**df**	**Mean Square**
Early Harvest - Control vs Diquat	1	4009.60 **
Middle Harvest - Control vs Diquat	1	12166.64 ***
Late Harvest - Control vs Diquat	1	1368.30 ^{NS}
Middle Harvest - No Preharvest Fungicide vs Preharvest Fungicide	1	1703.42 *
Late Harvest - No Preharvest Fungicide vs Preharvest Fungicide	1	319.03 ^{NS}
CV (%)		5.89

***,**,*, and NS indicate significance at 0.001, 0.01 and 0.05 levels of probability and not significant, respectively.

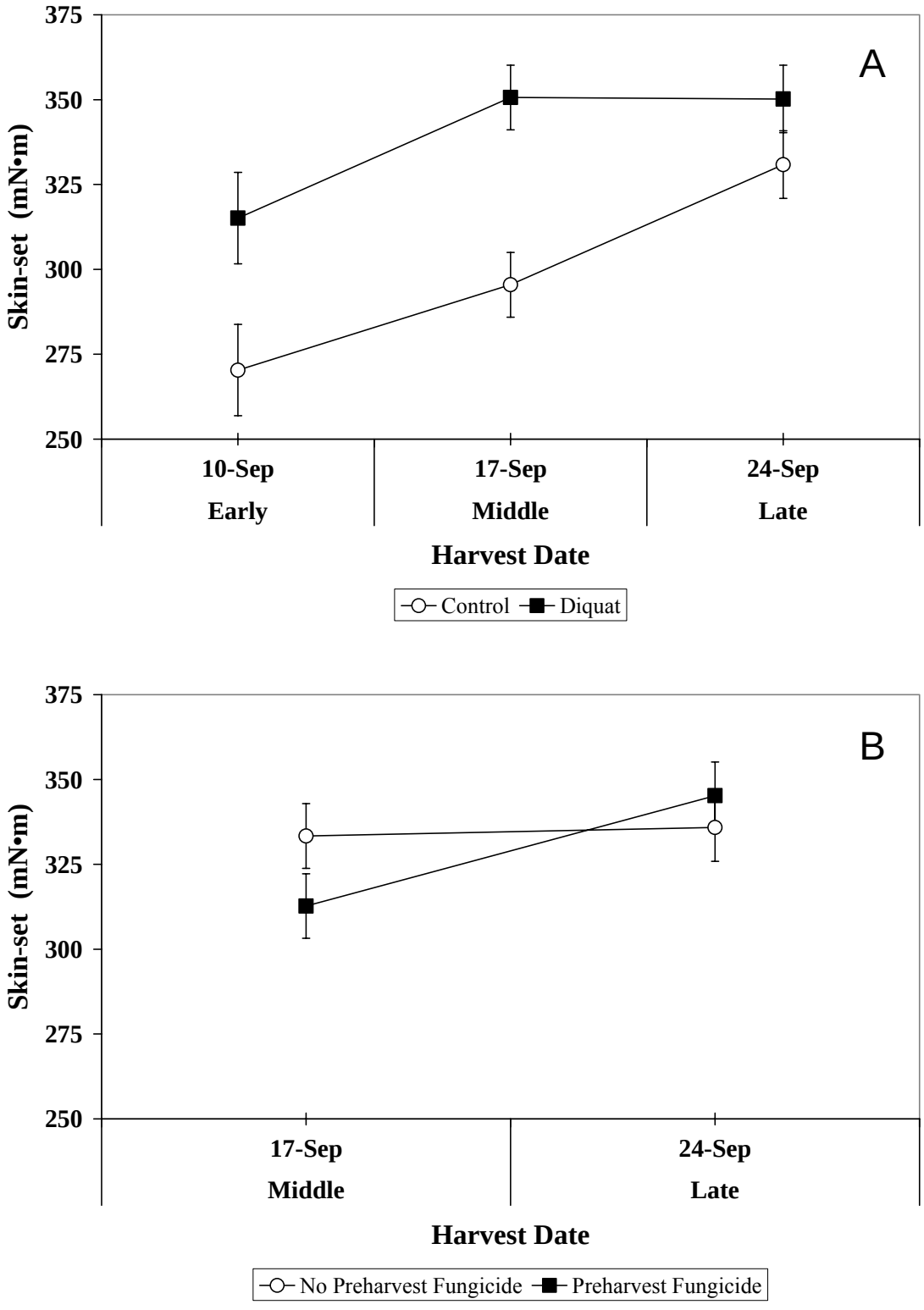


Figure 4.21. Skin-set as influenced by desiccation (A) and late season fungicide (B) at Carberry, MB in 1997. (Bars represent SEM).

Table 4.9. Analysis of variance and associated contrasts for effects of harvest date and preharvest management on the skin-set of Russet Burbank potatoes grown at Winkler, MB in 1998.

Source of variation	df	Mean Square
Replication (BLOCK)	3	1255.36 *
Harvest Date (HVST)	2	8115.41 ***
Desiccation (VINE)	1	309.21 NS
HVST X VINE	2	1237.27 *
Preharvest Fungicide (FUNG)	1	266.75 NS
HVST X FUNG	2	20.27 NS
VINE X FUNG	1	32.15 NS
HVST X VINE X FUNG	2	205.25 NS
Error	28	356.09
Contrast	**df**	**Mean Square**
Early Harvest - Control vs Diquat	1	2287.21 *
Middle Harvest - Control vs Diquat	1	330.51 NS
Late Harvest - Control vs Diquat	1	13.23 NS
CV (%)		5.64

***,**,*, and NS indicate significance at 0.001, 0.01 and 0.05 levels of probability and not significant, respectively.

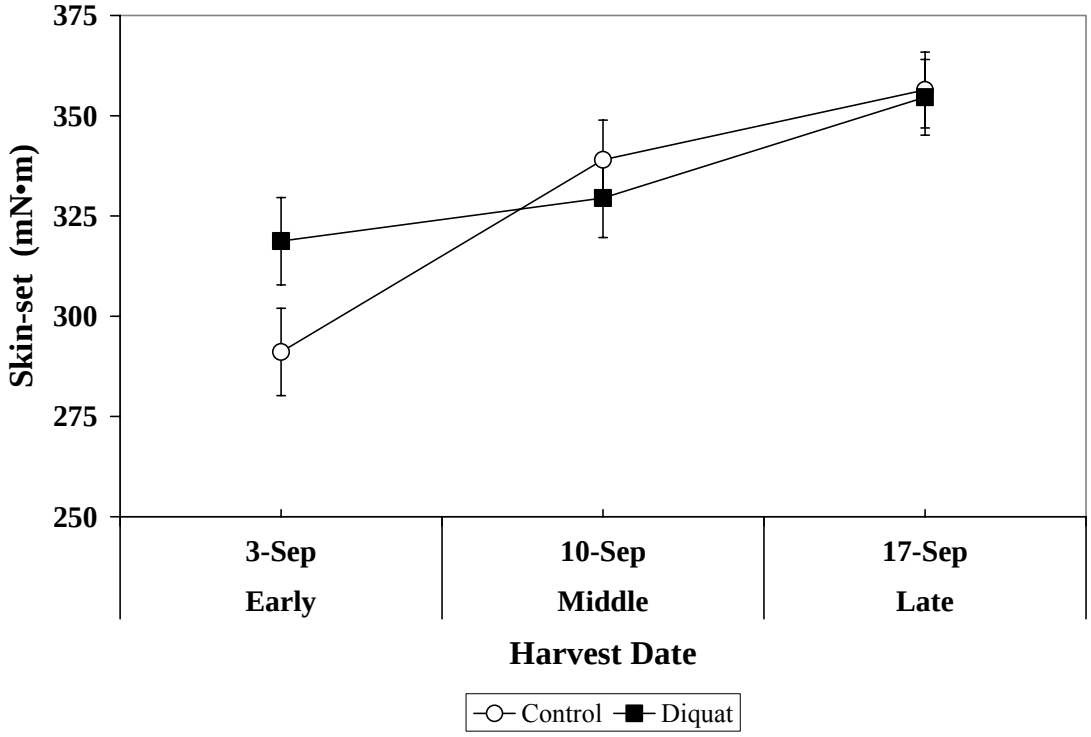


Figure 4.22. Skin-set as influenced by desiccation at Winkler, MB in 1998. (Bars represent SEM).

differences were not significant, ($p = 0.34$ and $p = 0.85$, respectively). The lack of a response to desiccation at the middle and late harvest dates in 1998 is explained by the advanced maturity of the non-desiccated treatments brought on by late blight (Section 4.1). Non-replicated skin-set measurements taken from severely blighted plants corroborate this hypothesis. Tubers from these diseased plants had better skin-set (334 mN•m) than tubers harvested two days later from vine-killed plants (319 mN•m). Skin-set also differed significantly ($p = 0.028$) between replicates. Resistance to skinning was highest in tubers from the 3rd replicate (345 mN•m; data not shown).

Changes in resistance to skinning measured over time and in response to desiccation compare well to readings obtained by other researchers using the skin-set torque wrench and a similar methodology (Lulai, 2002; Pavlista, 2002). Lulai (2002) reported the resistance to skinning of "nearly mature" Russet Burbank periderm to be 325 mN•m. In 1997, this level of resistance was achieved through vine killing two weeks before the middle and late harvest dates and through natural maturation at the late harvest date. Both the control and vine-killed treatments exhibited mature periderm by the middle harvest date in 1998. This result indicates that, in the case of a severe late blight epidemic, the plant senescence brought on by stem and leaf lesions is equally effective as chemical desiccation in eliciting periderm maturation.

Tubers from vines killed two weeks before the early harvest date did not achieve a level of skinning resistance equivalent to nearly mature Russet Burbank potatoes in either year of the study. Others have reported that vines must be maturing at the time of desiccation to achieve good skin-set development (Lulai, 1997).

Pavlista (2002) characterized the relationship between the amount of surface skinning of a tuber to its skin's resistance to shearing by an applied torque for the cvs. Atlantic and Snowden. Mean torque meter readings of 330 mN•m for Atlantic and 370 mN•m for Snowden were characteristic of lots which showed less than 20% skinning at 95% certainty. Although percent tuber skinning was not quantified in this study, it was observed that tuber skinning was minimal when the resistance to skinning was 325 mN•m and higher.

Measuring increases in resistance to skinning above 350 mN•m was likely beyond the range of the skin-set torque wrench. When the skin was well set, the skin-set torque wrench had a tendency to slip on the skin surface when turned rather than shearing off a disk of skin. This limitation was also noted by Pavlista (2002). In 1997, there was no measured increase in the resistance of tubers to skinning between the middle and late harvest dates, when skin-set was >350 mN•m. Furthermore, in 1998, the skin strength of the control and vine-killed treatments at the late harvest date were nearly identical (356 mN•m and 355 mN•m, respectively). Nevertheless, tuber skinning in this experiment was minimal when skin-set was 325 mN•m or higher so the need to measure higher levels of skinning resistance is diminished.

4.6 Weight Loss in Storage

In 1998, the weight loss from tubers in storage was measured 15 days after harvest and approximately every 30 days following, for a total of seven assessments.

Weight loss was rapid early in the storage period (15 day mean; 0.093% day^{-1}). More than one-fourth of the total weight loss occurred in the first month of storage

(Figure 4.23). By the third month of storage, the rate of weight loss had stabilized and continued at an average of 0.028% day^{-1} for the remainder of the storage season.

The repeated measures analysis of variance revealed that harvest date had a significant effect ($p = 0.028$) on weight loss in storage (Table 4.9). Tubers from the late September harvest lost less weight after 210 days of storage (5.3%) than tubers from the early (6.4%) or middle (6.8%) harvest dates (Figure 4.23). Desiccating vines before harvest did not have a significant effect on the weight loss of tubers in storage ($p = 0.90$) in this study. Although this was a departure from what was expected this result can be accounted for. Weight loss in storage differed significantly between replicates ($p = 0.021$) (Table 4.9). Tubers from the 3rd replicate lost less weight throughout the storage period (210 day mean; 5.3%). Resistance to skinning was also highest in tubers from the 3rd replicate (Section 4.4).

Weight loss in storage in 1998 followed the well established pattern of higher shrinkage losses during the wound healing period than the holding period (Schippers, 1976). Delaying the time of harvest significantly reduced storage weight loss. Pritchard and Adam (1992) also reported that mature tubers, harvested later, lost less weight during storage than more physically immature tubers harvested early. While other researchers have reported significant reductions in weight loss in storage when vines were desiccated before harvest, this was not observed in 1998. The rapid development of late blight on vines in late August and early September (Section 4.1) caused the control plots to senesce early, increasing the resistance of those tubers to skinning (Section 4.4). Since weight loss in storage is closely linked to the degree of skinning at harvest, it follows that there

Table 4.10. Repeated measures analysis of variance for effects of harvest date and preharvest management on the storage weight loss of Russet Burbank potatoes grown at Winkler, MB in 1998.

Winkler - 1998

Source of variation	df	Mean Square
		Weight Loss
Replication (BLOCK)	3	8.4173 *
Harvest Date (HVST)	2	9.0390 *
Desiccation (VINE)	1	0.0381 NS
HVST X VINE	2	0.7116 NS
Preharvest Fungicide (FUNG)	1	2.2954 NS
HVST X FUNG	2	3.6123 NS
VINE X FUNG	1	0.1445 NS
HVST X VINE X FUNG	2	0.2556 NS
Error	28	2.2111

***,**,*, and NS indicate significance at 0.001, 0.01 and 0.05 levels of probability and not significant, respectively.

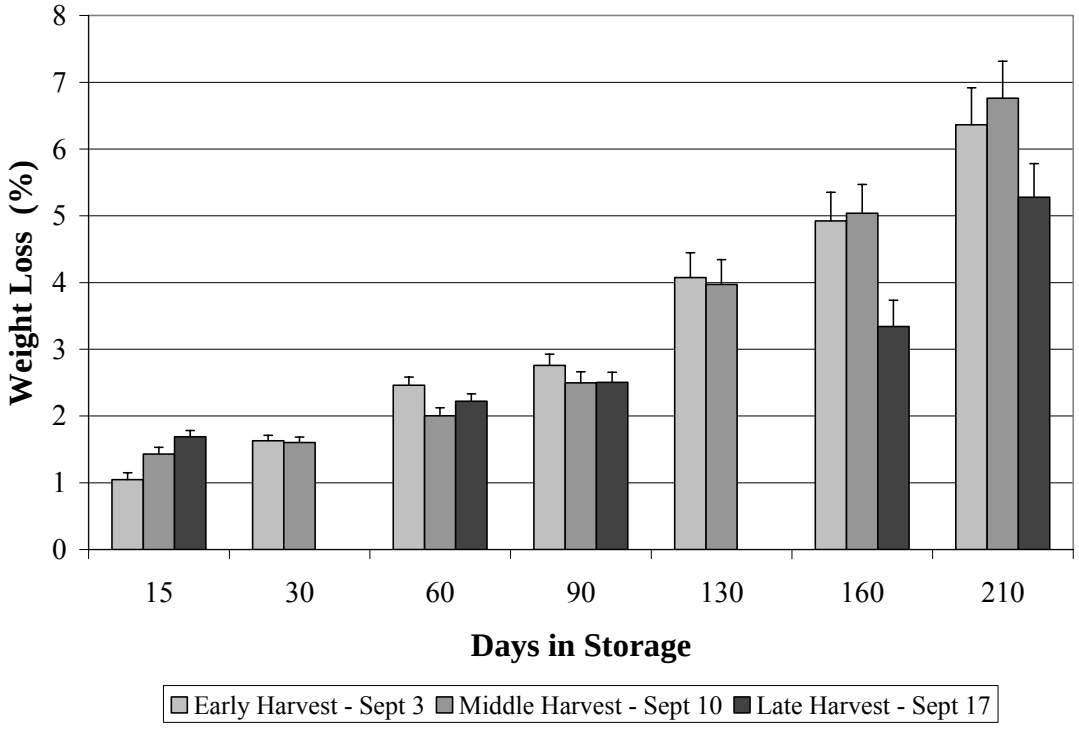


Figure 4.23. Storage weight loss as influenced by time of harvest at Winkler, MB in 1998. (Bars represent SEM).

would be no effect from vine killing on storage weight loss. Iritani et al. (1977) reported comparable levels of shrinkage in storage when vines died prematurely due to lack of nitrogen or when vines were harvested 3 or more weeks after vine killing.

Shrinkage loss in storage is important to quantify as linking a reduction in weight loss to vine killing would offset the more obvious deleterious effects on tuber yield and size prior to harvest. The broader range of physical maturity between the early and late harvest dates in 1997 would have been ideal for evaluating the effect of desiccation on weight loss.

4.7 Tuber Rot

The incidence and severity of rot in tubers from the early and middle harvest dates in 1997 was determined after approximately 4 months of storage. The symptoms observed in tubers were primarily dry rot (caused by *Fusarium* spp.) and, to a lesser extent, leak (caused by *Pythium ultimum)*. Observations were not made on tubers from the late harvest because, at the time, it was thought that there were no trends in the data attributable to the treatments.

Desiccating vines with diquat significantly affected ($p = 0.0002$) the incidence of tuber rot in storage in 1997 (Table 4.10; Figure 4.24). Vine killing reduced the incidence of tuber rot by nine-fold at the early harvest date ($p = 0.001$) and by four-fold at the middle harvest date ($p = 0.007$) (Table 4.10; Figure 4.24). Time of harvest ($p = 0.28$) and application of a late season fungicide ($p = 0.40$) had no effect on the incidence of diseased tubers in 1997 (Table 4.10). The incidence of tuber rot in storage differed significantly ($p = 0.02$) between replicates. The incidence of tuber rot was highest in the

Table 4.11. Analysis of variance and associated contrasts for effects of harvest date and preharvest management on the incidence of storage rot of Russet Burbank potatoes grown at Carberry, MB in 1997.

Source of variation	df	Mean Square
Replication (BLOCK)	3	42.41 *
Harvest Date (HVST)	1	11.66 NS
Desiccation (VINE)	1	217.81 ***
HVST X VINE	1	17.18 NS
Preharvest Fungicide (FUNG)	1	7.00 NS
HVST X FUNG	0	-
VINE X FUNG	1	0.62 NS
HVST X VINE X FUNG	0	-
Error	23	9.17
Contrast	**df**	**Mean Square**
Early Harvest - Control vs Diquat	1	142.21 **
Middle Harvest - Control vs Diquat	1	87.70 **
CV (%)		66.81

***,**,*, and NS indicate significance at 0.001, 0.01 and 0.05 levels of probability and not significant, respectively

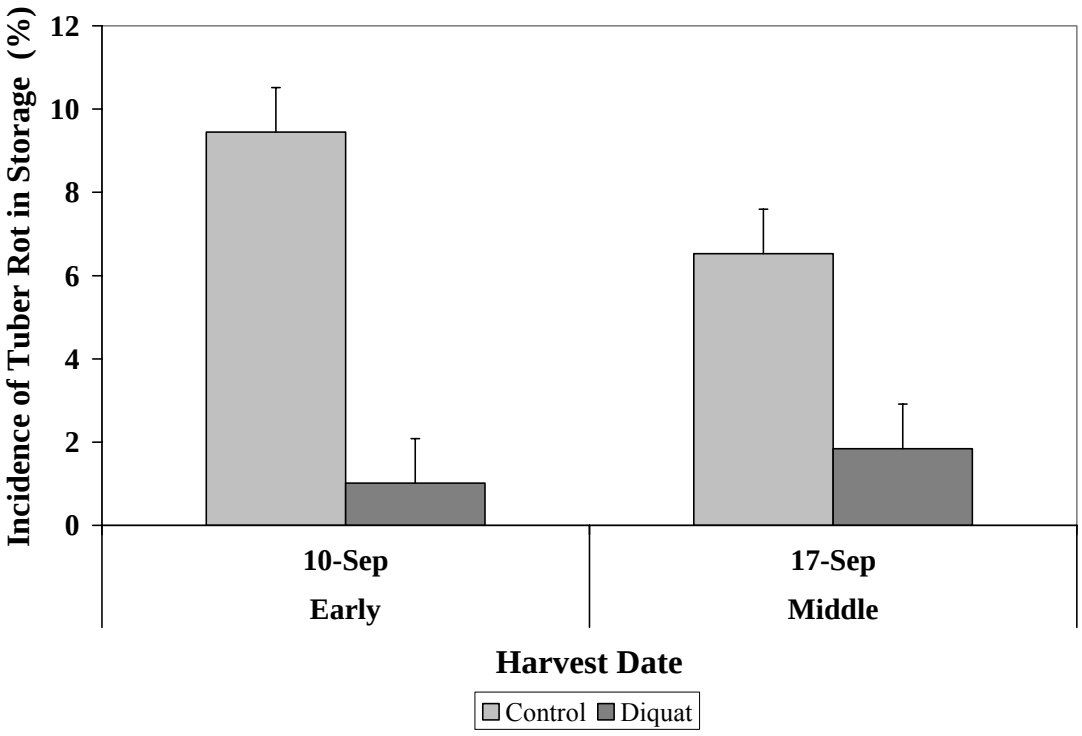


Figure 4.24. Incidence of tuber rot in storage as influenced by desiccation at Carberry, MB in 1997. (Bars represent SEM).

first replicate (data not presented).

The extent of rot development was variable amongst tubers ranging from minor *Fusarium* infections in harvest wounds to tubers which were completely broken down with *Pythium* and/or *Fusarium*. Based on symptom records for the diseased tubers, the severity of tuber rot was determined for each treatment. While measurements of disease incidence are useful, the severity of tuber rot is a better reflection of the potential for losses in storage.

Tuber rot severity was also significantly affected by desiccation ($p = 0.0004$) in 1997 (Table 4.11; Figure 4.25). Vine killing reduced the severity of tuber rot by sixteen-fold at the early harvest date ($p = 0.0007$) and by two-fold at the middle harvest date ($p = 0.032$) (Table 4.11; Figure 4.25). Time of harvest ($p = 0.26$) and application of a late season fungicide ($p = 0.15$) had no effect on the severity of tuber rot in 1997 (Table 4.11). The severity of tuber rot differed significantly ($p = 0.045$) between replicates. Tuber rot severity was highest in the first replicate (data not presented).

Tuber rot levels were assessed twice during the fall of 1998. Initially, the weight of visibly diseased tubers was determined during the grading process. The weight of rotten tubers was divided by the total harvested yield to quantify the severity of tuber rot at the time of harvest. A second assessment was performed after ~50 days in storage by determining the number of rotten tubers in a sub-sample taken from the harvest of each plot. The symptoms on diseased tubers were characteristic of late blight (*Phytophthora infestans*) and the secondary decay organism, bacterial soft rot (*Erwinia* spp.).

Tuber rot severity at harvest was low and not significantly affected by time of harvest ($p = 0.33$), desiccation ($p = 0.32$), or late season fungicide ($p = 0.33$) (Table 4.12;

Table 4.12. Analysis of variance and associated contrasts for effects of harvest date and preharvest management on the severity of storage rot of Russet Burbank potatoes, grown at Carberry, MB in 1997.

Source of variation	df	Mean Square
Replication (BLOCK)	3	6.57 *
Harvest Date (HVST)	1	2.69 NS
Desiccation (VINE)	1	39.65 ***
HVST X VINE	1	6.92 NS
Preharvest Fungicide (FUNG)	1	4.36 NS
HVST X FUNG	0	-
VINE X FUNG	1	0.04 NS
HVST X VINE X FUNG	0	-
Error	23	9.17
Contrast	**df**	**Mean Square**
Early Harvest - Control vs Diquat	1	34.82 ***
Middle Harvest - Control vs Diquat	1	10.74 *
CV (%)		64.30

***,**,*, and NS indicate significance at 0.001, 0.01 and 0.05 levels of probability and not significant, respectively

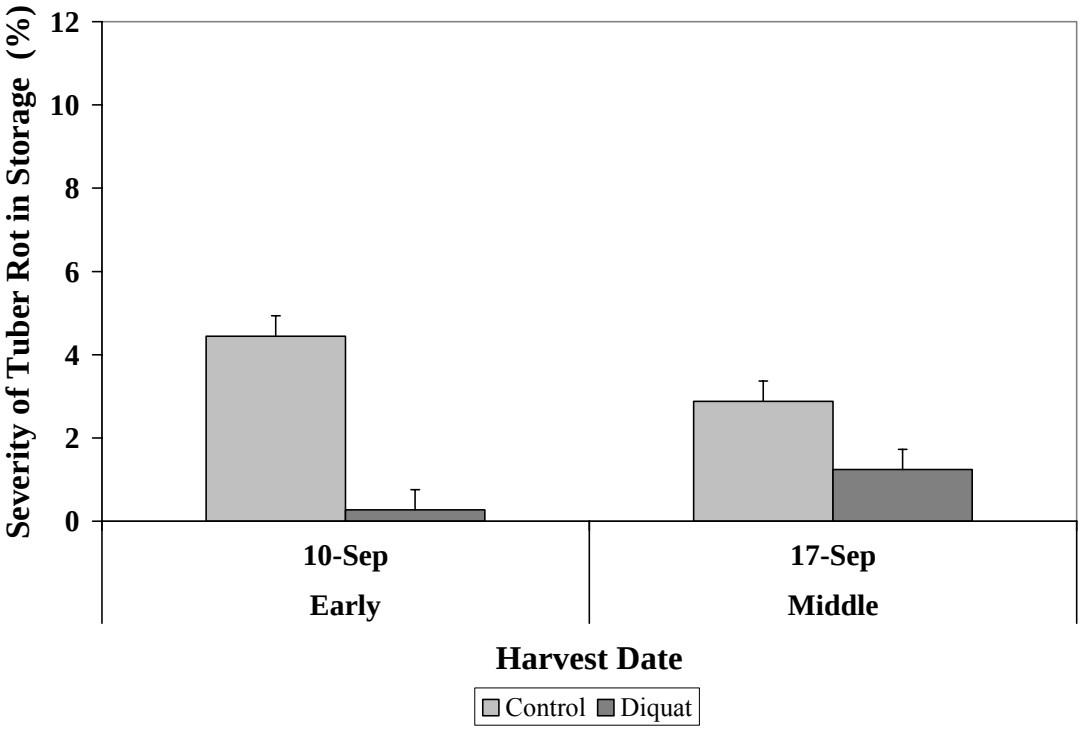


Figure 4.25. Severity of tuber rot in storage as influenced by desiccation at Carberry, MB in 1997. (Bars represent SEM).

Figure 4.26). The higher level of tuber rot in the vine-killed treatment on the middle harvest date can be traced back to one plot in the fourth replicate which had considerably more tuber rot at harvest (14.7%) than any other plot. This plot was adjacent to the guard rows where foliar blight was first discovered and the foliar epidemic progressed most rapidly (Section 4.1).

Disease incidence in storage served as an accurate measurement of disease intensity in the 1998 harvest as all tubers infected with late blight rotted completely with soft rot. The response of tuber rot in storage to desiccation was not consistent between harvests; the interaction of the harvest date and desiccation main effects was significant ($p = 0.004$) (Table 4.13; Figure 4.27). Consequently, the highly significant time of harvest effect ($p = 0.006$) is overlooked and only the simple effects reported. For the early harvest date, the level of tuber rot in storage in the desiccated treatment (0.9%) was significantly lower than that of the control (6.3%) ($p = 0.001$) (Table 4.13). At the middle harvest date, the incidence of tuber rot was higher in the vine-killed treatment (2.7%) than the control (0.9%), however, the difference was not significant, ($p = 0.19$). (Table 4.13). The higher incidence of tuber rot in the vine-killed treatment on the middle harvest date could again be traced back to high levels of storage rot (13.1%) in tubers from one plot in the fourth replicate which was located next to where late blight was first found and disease developed rapidly (Section 4.1). Application of a late season fungicide application had no effect on tuber rot levels in storage in 1998 ($p = 0.40$) (Table 4.13).

The significant reductions in tuber rot in storage observed in 1997 when vines were desiccated two weeks prior to the early and middle harvest dates are in keeping with the assertions of Plissey (1993) and Platt (1994) that immature tubers are more

Table 4.13. Analysis of variance and associated contrasts for effects of harvest date and preharvest management on the severity of late blight tuber rot at the time of harvest of Russet Burbank potatoes grown at Winkler, MB in 1998.

Source of variation	df	Mean Square
Replication (BLOCK)	3	5.96 ^{NS}
Harvest Date (HVST)	2	5.76 ^{NS}
Desiccation (VINE)	1	5.00 ^{NS}
HVST X VINE	2	4.20 ^{NS}
Preharvest Fungicide (FUNG)	1	4.81 ^{NS}
HVST X FUNG	2	4.69 ^{NS}
VINE X FUNG	1	4.21 ^{NS}
HVST X VINE X FUNG	2	2.99 ^{NS}
Error	28	4.96
CV (%)		402.39

***,**,*, and NS indicate significance at 0.001, 0.01 and 0.05 levels of probability and not significant, respectively

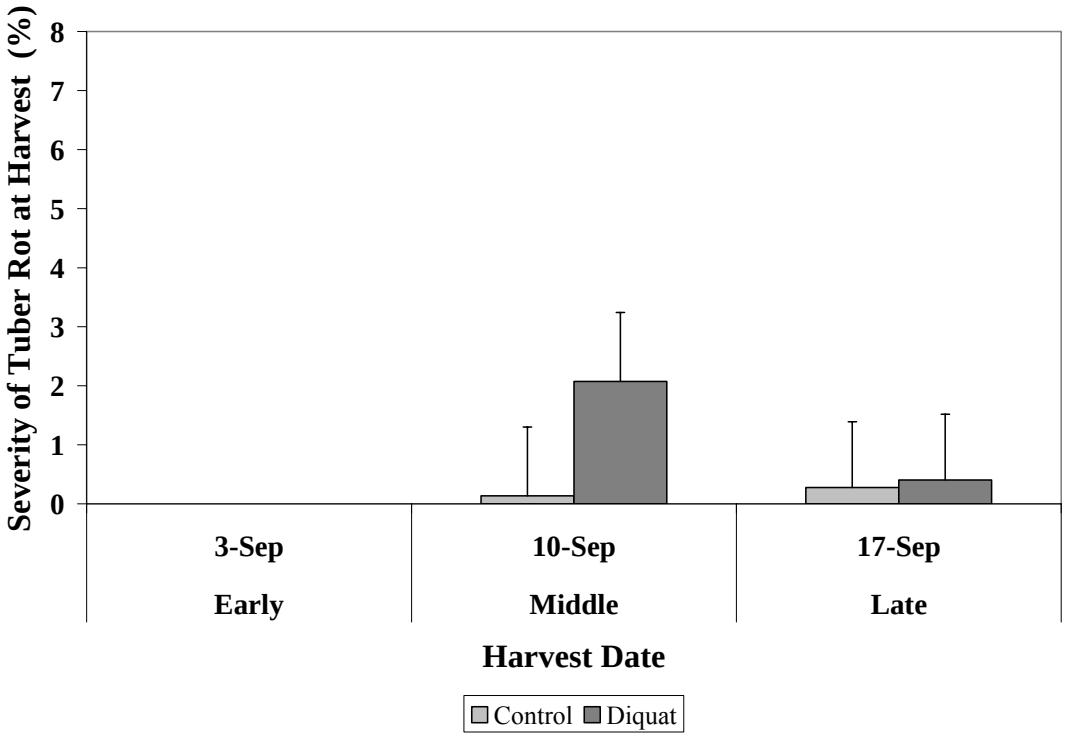


Figure 4.26. Severity of late blight tuber rot at harvest as influenced by desiccation at Winkler, MB in 1998. (Bars represent SEM).

Table 4.14. Analysis of variance and associated contrasts for effects of harvest date and preharvest management on the incidence of late blight tuber rot in storage of Russet Burbank potatoes grown at Winkler, MB in 1998.

Source of variation	df	Mean Square
Replication (BLOCK)	3	4.22 ^{NS}
Harvest Date (HVST)	2	41.58 **
Desiccation (VINE)	1	14.54 ^{NS}
HVST X VINE	2	44.14 **
Preharvest Fungicide (FUNG)	1	4.90 ^{NS}
HVST X FUNG	2	1.78 ^{NS}
VINE X FUNG	1	0.05 ^{NS}
HVST X VINE X FUNG	2	3.11 ^{NS}
Error	28	6.63
Contrast	**df**	**Mean Square**
Early Harvest - Control vs Diquat	1	84.91 **
Middle Harvest - Control vs Diquat	1	11.71 ^{NS}
Late Harvest - Control vs Diquat	1	0.00 ^{NS}
CV (%)		146.05

***,**,*, and NS indicate significance at 0.001, 0.01 and 0.05 levels of probability and not significant, respectively

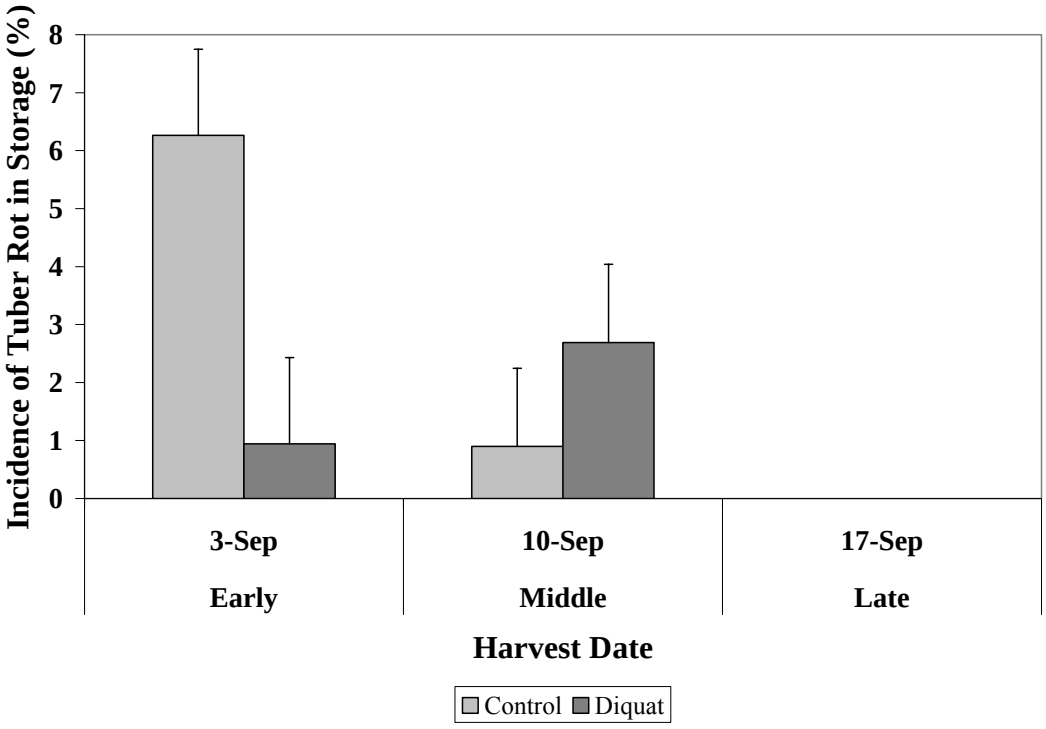


Figure 4.27. Incidence of late blight tuber rot in storage as influenced by desiccation at Winkler, MB in 1998. (Bars represent SEM).

susceptible to infection by diseases through harvest damage. Significant increases in the resistance of tubers to skinning were observed in tubers from desiccated vines at both dates (Section 4.5). Had the level of rot in tubers from the late harvest date been assessed, this would have provided valuable insight into whether vine killing reduced tuber disease when there was no significant difference in the level of skin-set compared to the control. Vines separated from tubers more easily in the vine-killed treatments than the controls. In the plots that were harvested green, vines bunched up on the primary of the single-row harvester and there was a tendency for tubers to remain attached to stolons. Consequently, tubers from the vine-killed plants suffered less handling injury during harvesting. Others have reported reductions in harvest damage (Thornton and Sieczka, 1980) and gains in harvest efficiency (Plissey, 1993) with vine killing.

Thurston and Schultz (1981) suggested that blighted tubers were more readily identified and removed before storage when vines were killed before harvest. Although tuber rot was observed at harvest and during grading of the middle and late harvests, there was no significant increase in the severity of rot from plots that were desiccated. There are a number of possible explanations for this. During the timeframe when diquat was being applied to desiccate vines for the middle and late harvest dates, vines in the control treatment were also being destroyed by late blight. Had the control treatments not been so mature, perhaps differences in the level of rot would have been observed. Much of the literature recommends a longer interval between vine killing and harvest than was allowed in this study. For many production areas, the recommendation is that vines are completely dead for two weeks before tubers are lifted (Stevenson, 1993; Nolte et al., 2000). For the early harvest, vines were completely dead no earlier than 5-6 days before

lifting took place. Perhaps, the interval was too short. Alternatively, it could be that soil conditions were too dry to favour the development of secondary decay organisms.

The incidence of late blight tuber rot in storage was significantly reduced at the early harvest date when vines were desiccated two weeks before harvest. Others have reported that harvesting tubers from late blight infected vines can lead to significant losses during storage (Schwinn and Margot, 1991). It would seem that the conditions were favourable for disease transmission in the control treatments on the date of the early harvest, September 3rd, as tuber rot developed in storage that wasn't visible at harvest. Indeed, the day before the early harvest, September 2nd, was a cool and humid day (maximum temperature; 20°C average relative humidity; 77%) with some precipitation (0.4 mm). Such conditions are known to be conducive to sporulation of the fungus (Stevenson, 1993).

No reduction in the level of storage rot was observed when vines were desiccated in advance of the middle and late harvest dates. There are a number of possible explanations for this. Vines in the control treatment were nearly completely destroyed by September 10th – the date of the middle harvest. There were few active lesions left to produce spores at the time of harvest. Moreover, environmental conditions were not suitable for disease spread on either date. Maximum temperature and average relative humidity on September 10th and September 17th were 36°C and 61% and 29°C and 68%, respectively. Johnson et al. (2003) recommend harvesting in dry weather to prevent late blight tuber rot.

5.0 GENERAL DISCUSSION

Creating the field conditions required to assess the effect of preharvest management practices on the development of late blight in storage proved difficult in both years of this study. Although late blight was present in the Carberry region in 1997, the field plots did not become infected. In 1998, late blight was first observed in the trial in mid-July and, with the contribution of infected spreader plants, disease developed. Unfortunately, the epidemic progressed more rapidly than was desirable and the plant canopy in the control treatments was nearly completely blighted by the middle harvest date. Consequently, conditions were not conducive to tuber infection at harvest in the untreated plots on the middle and late harvest dates. Of the six harvest dates over two years of research, only one – the early harvest date in 1998 – reflects the circumstances that this project set out to study.

This research did establish, more definitely than has been done before, the effect of vine killing on tuber yield, specific gravity, processing quality and skin-set, under Manitoba growing conditions.

Vine killing two weeks prior to harvest typically reduced tuber yield and size. The degree to which yield was affected depended on plant health and maturity at the time of vine kill. In 1997, the crop was actively bulking through September and, as a result, marketable yields were 9 to 26% lower in the desiccated treatments over the three harvest dates. Bonus yield was reduced by 39% at the early and 23% at the middle harvest dates. Tuber bulking rates were lower in 1998 because of advanced maturity and foliar late blight which reduced the productivity of vines. Total and marketable yields were 17%

lower when vines were killed two weeks before the early harvest date. The effect of desiccation on yield and size was less at the middle and late harvest dates because of the rapid development of foliar late blight in the control treatments, highlighting the importance of disease control to preventing yield loss.

In a crop grown for the processing market, early vine desiccation would be unacceptable to growers and processors because of the effect on tuber yield and size. Considerable reductions in disease and weight loss in storage would have to be demonstrated to justify vine killing for a targeted mid-September harvest date. When late blight has already severely damaged the crop canopy, the effect of vine killing on yield and size is less compared to the effect on a healthy canopy.

Tubers harvested from desiccated vines generally had lower specific gravity than those from untreated vines. Desiccation prevented further translocation of carbohydrates from the vines to tubers, moreover, water uptake by plant roots continued after treatment, resulting in the lower specific gravity when vines were killed. As with yield, the degree to which specific gravity was reduced by vine killing could be linked to crop maturity at the time of application. In 1997, the specific gravity of tubers from the desiccated treatments was 4 to 7 points lower than the controls over the three harvest dates. Specific gravity was less affected by vine killing in 1998 due to the advanced maturity of the control treatments at the middle and late harvest dates. The specific gravity of tubers from vines killed two weeks before the early harvest date was 5 points lower than the control. Under severe disease pressure, the specific gravity of tubers from the control and desiccated treatments at the middle and late harvest dates were not significantly different.

This result underscores the effect of defoliating diseases like late blight on specific gravity.

The specific gravity of tubers from the desiccated treatments was below the minimum level desirable for processing (1.080) at all three harvest dates in 1997 and at the early and middle harvest date in 1998. Moreover, under the present process contract in Manitoba, potatoes from the early and middle harvest dates in 1997 would have been subject to refusal and deductions would have been made for the other harvest dates. So, from the perspective of processors and growers, the effect of vine killing on specific gravity is not acceptable.

The effects of harvest date and desiccation on sugar levels and fry colour out of storage were largely inconsequential. In 1997, sugar levels were lowest and fry colour was lightest for the middle harvest date. In 1998, the late harvest date had the lowest sucrose levels and lightest fry colour. Vine killed treatments maintained lower sucrose levels in storage in both years, as was also reported by Sowokinos and Preston (1988). However, this did not translate into lower glucose levels or better fry colour from storage. In fact, storage fry colour was darker when vines were desiccated in 1998. Of note, in 1997, tubers under desiccated vines accumulated more glucose in storage after being chilled prior to the late September harvest. Walsh (1995b) also observed that tubers were more sensitive to low temperature sweetening when vines were killed because the invertase pathway is no longer blocked.

While vine desiccation did not improve fry quality in this study, the results show that this practice has minimal negative effects on sugar levels and fry quality.

Vine desiccation two weeks before harvest improved tuber skin-set, except when vines in the control treatments were destroyed by late blight ahead of the middle and late harvest dates in 1998. Under severe foliar disease pressure, tubers from the control and vine-killed plots reached a similar level of skin-set. The significance of these results is that desiccating vines, in the late stages of an epidemic, will not increase the resistance of tubers to skinning and, consequently, may not have an effect on tuber infection at harvest. Vines killed two weeks in advance of the early harvest date did not develop the level of skin-set usually associated with nearly mature Russet Burbank in either year of the study, confirming what others have reported that plants must be maturing at the time of vine kill to achieve good skin-set (Lulai, 1997). Delaying time of harvest improved skin-set in both years – whether vines were desiccated or not. In 1998, tubers from the late harvest date lost less weight than tubers from the early or middle harvest reaffirming the importance of a mature periderm in reducing storage weight loss.

Tuber rot levels in storage were reduced when vines were desiccated before harvest, except for the middle and late harvest dates in 1998. In 1997 storage rot incidence and severity were reduced when vines were desiccated. The tuber diseases *Fusarium* dry rot and *Pythium* leak require skinning or wounds to infect tubers. Consequently, tubers that are harvested immature are more prone to infection and the resulting decay in storage caused by these organisms. Vine desiccation had no effect on the severity of late blight tuber rot at the time of harvest in 1998. However, the incidence of blighted tubers in storage was reduced when vines were desiccated two weeks before the early harvest date. The level of late blight tuber rot in storage in the control treatment (6.3%) was above the 5% that is generally regarded as a level which can be stored (Nolte

et al., 1999). No reduction in storage rot was observed when vines were killed two weeks before the middle and late harvest dates because the blighted foliage in the control plots was no longer actively sporulating, moreover environmental conditions were not suitable for disease spread.

In other production areas, the fungicide combination of chlorothalonil and copper hydroxide has been credited with reducing the infection of tubers by the late blight fungus during harvest (Platt, 1994). However, no reduction in tuber rot was observed when these products were applied pre-harvest alone or along with vine killing.

5.1 Implications of Research for Growers

The negative effects of vine killing on yield and specific gravity preclude it from being adopted as a standard preharvest practice by Manitoba processing growers, at least as long as Russet Burbank is the standard cultivar being produced.

Although harvesting immature tubers from late blight infected vines does, in all likelihood, lead to increased losses due to disease during storage, desiccation of late-maturing varieties cannot be justified if the loss in tuber yield and quality outweighs the benefit from lower tuber blight levels (Cox, 1967). This difficult trade-off was clear in 1998 when the incidence of late blight tuber rot in storage for the control treatments from the early harvest was 6%. The incidence of blighted tubers in storage for the desiccated treatments was only 1%. One could conclude that desiccation would have prevented a storage breakdown as even with good storage facilities and careful management, it is difficult to successfully store tubers with a 5% level of infection. While this may be true, the effects of vine killing two weeks before the early harvest date on yield and specific

gravity were also significant. Relative to the untreated controls, marketable yield was reduced by 17% and specific gravity was 5 points lower. Factoring in the cost of diquat and application costs, this treatment would have reduced the grower's return at harvest by 20% (Table 5.1). In a circumstance like this, most growers would take their chances by storing potatoes with some risk of problems rather than accepting a 20% loss in return.

Indeed, the results of this study suggest that to realize the benefits of desiccating vines, like improved skin-set and reduced storage rot, vines must be killed before they mature naturally. This, unfortunately, results in undesirable reductions in yield and specific gravity.

While there may be certain situations when the risk of storage losses due to disease warrants the application of a desiccant, in spite of the trade-off in yield and quality, this breakpoint was not identified in this study.

There are precautions that growers can take when planning to harvest and store tubers from blighted vines that will not be desiccated. Fungicides should be continued until harvest to keep disease in check. Harvesting when the plant canopy is dry will reduce the number of spores on infected leaves and stems. Harvest should also be delayed as long at possible to allow vines to mature naturally and tuber skin-set to develop. Storage temperature and relative humidity should be reduced in light of the potential risk.

Table 5.1. Economics of Vine Desiccation for Russet Burbank potatoes grown at Carberry, MB in 1997 and Winkler, MB in 1998.

Carberry - 1997	Treatment	Marketable Yield (tonnes/ha)	Bonus Yield (%)	Adjusted Crop Value [a] ($/ha)	Difference in Return ($/ha)	Reduction in Return (%)
Early Harvest	Control	38.45	25.7%	$5,287.76		
	Diquat	28.32	15.8%	$3,615.05	$1,672.70	31.6%
Middle Harvest	Control	40.17	31.5%	$5,690.18		
	Diquat	34.19	24.1%	$4,541.14	$1,149.04	20.2%
Late Harvest	Control	41.52	32.5%	$5,906.71		
	Diquat	37.96	28.8%	$5,183.79	$722.93	12.2%

Winkler - 1998	Treatment	Marketable Yield (tonnes/ha)	Bonus Yield (%)	Adjusted Crop Value [a] ($/ha)	Difference in Return ($/ha)	Reduction in Return (%)
Early Harvest	Control	30.85	8.5%	$4,072.77		
	Diquat	25.55	6.3%	$3,248.94	$823.83	20.2%
Middle Harvest	Control	31.99	10.0%	$4,223.29		
	Diquat	29.54	8.4%	$3,776.23	$447.07	10.6%
Late Harvest	Control	32.58	9.7%	$4,300.86		
	Diquat	31.40	8.6%	$4,021.55	$279.31	6.5%

[a] Assumptions made in determining crop value include a processing price of $6/cwt = ~$132/tonne. A premium of $0.66/tonne was included for each percent of tubers >283 g above 18%, up to a maximum bonus of $11.24/tonne at 35% >283 g. The cost of diquat (including application) was valued at $123.60/ha.

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7.0 APPENDIX

Table A.1. Summary of pooled analyses of variance for effects of harvest date and preharvest management on the yield and quality of Russet Burbank potatoes grown at Carberry, MB (1997) and Winkler, MB (1998).

Source of variation	df	Mean Square					
		Total Yield	Marketable Yield	Undersized Yield	Bonus Yield	Specific Gravity	Skin-set
YEAR	1	NS	***	***	***	***	**
BLOCK(YEAR)	6	**	**	*	NS	***	NS
Harvest Type (HTYPE)	2	***	***	NS	***	**	***
YEAR X HTYPE	2	NS	NS	NS	*	NS	NS
Desiccation (VINE)	1	***	***	NS	***	***	***
YEAR X VINE	1	NS	*	NS	**	**	***
HTYPE X VINE	2	**	*	NS	NS	NS	*
YEAR X HTYPE X VINE	2	NS	NS	NS	NS	NS	*
Preharvest Fungicide (FUNG)	1	NS	NS	NS	NS	NS	NS
YEAR X FUNG	1	NS	NS	NS	NS	**	NS
HTYPE X FUNG	2	NS	NS	NS	NS	NS	NS
VINE X FUNG	1	NS	NS	NS	NS	NS	NS
YEAR X HYTPE X FUNG	1	NS	NS	NS	NS	NS	NS
YEAR X VINE X FUNG	1	NS	NS	NS	NS	NS	NS
YEAR X HTYPE X VINE X FUNG	3	NS	NS	NS	NS	NS	NS
Error	54						
CV (%)		8.02	9.06	18.01	23.70	0.27	5.76

***,**,*, and NS indicate significance at 0.001, 0.01 and 0.05 levels of probability and not significant, respectively.

HTYPE = Harvest Type (Early, Middle, Late)

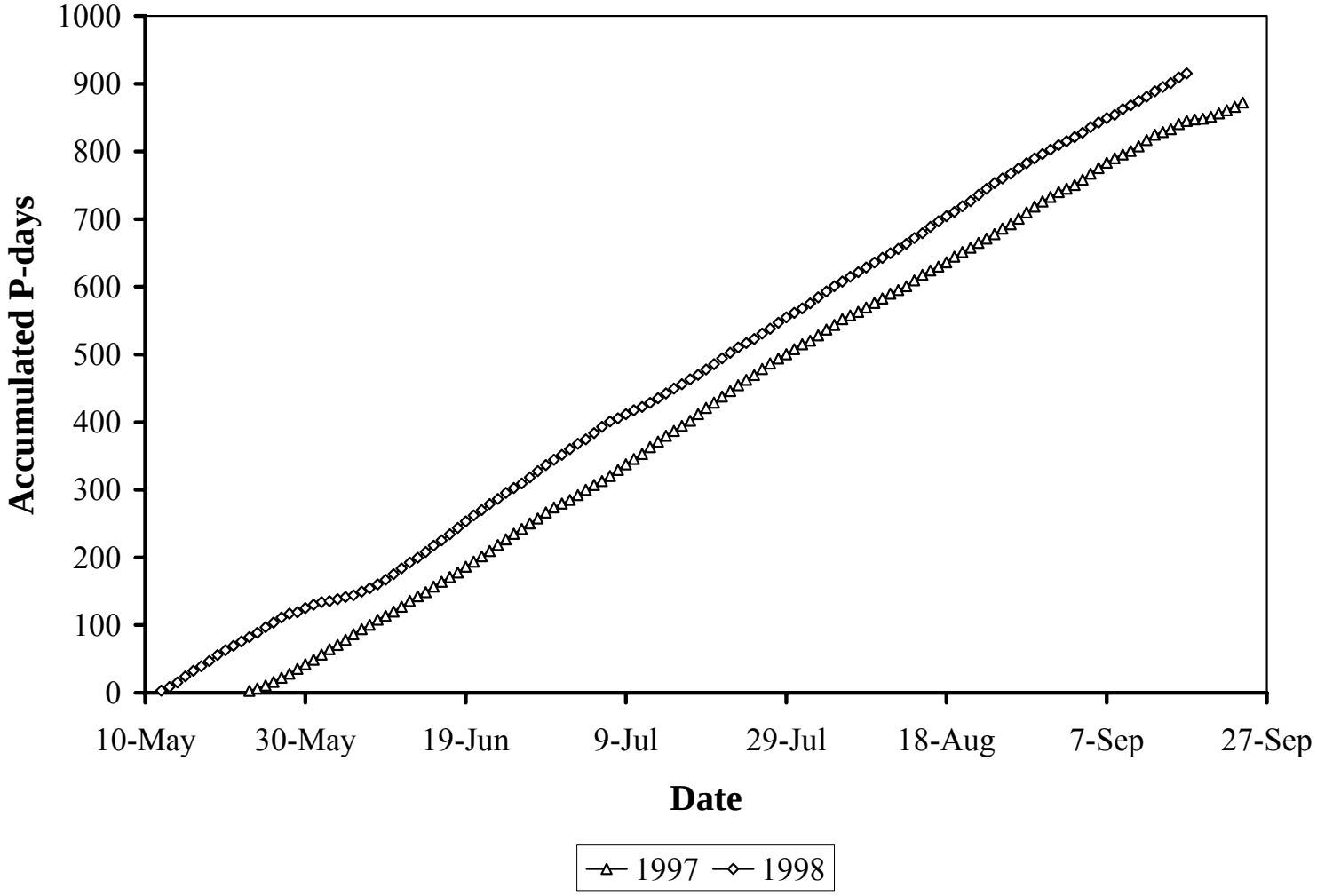

Figure A.1. Pattern of P-day accumulation at Carberry, MB in 1997 and Winkler, MB in 1998.